Mathematical Modeling of Manufacturing Process
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Lecture - 18
Fusion Welding Processes-1

Good afternoon everybody. Today I will discuss module 6 of mathematical modeling of manufacturing processes. So the discussion will be focus on specifically the welding process.

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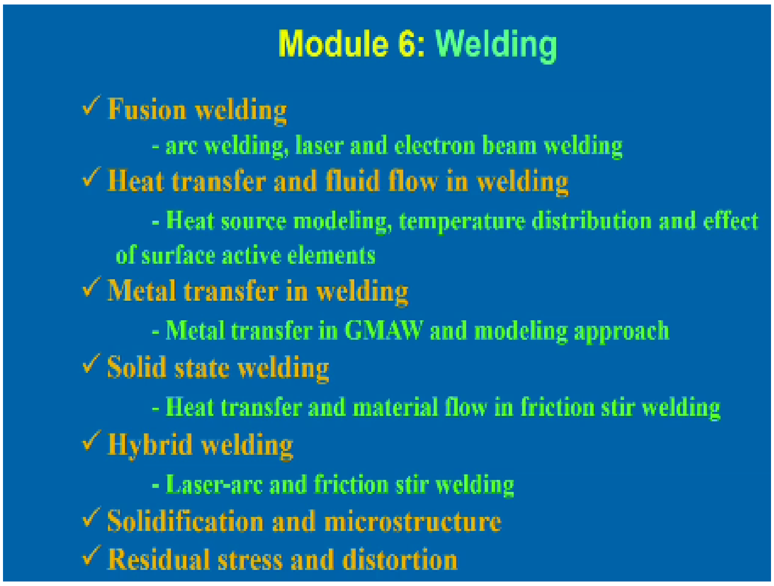

So far we have discussed different manufacturing processes, but if you look this welding process the modeling approach in welding process involves several physical phenomena. For example, heat transfer, material flow then stress analysis or maybe generation of the stresses and microstructural transformation even in case of arc welding there is a involvement of the electromagnetic force.

So almost each and every most of the physical involved in the welding process that becomes the modeling approach in welding specifically the fusion welding process becomes more complicated, but definitely if you look into the different perspective of the modeling approach. In case of fusion welding as well as the solid state welding processes. So probably the solid state welding processes the approach maybe more easier as compared to the more complex fusion welding process.

So first if we look into the different subsections in welding process or we can say that first we will try to discuss not in broad maybe the basic processes in different fusion welding. For example, the arc welding laser and electron beam welding mainly we will try to cover on the basic aspect of the different fusion welding processes. Then we will try to look into that in general how heat transfer and material flow can be modeled or can be analyzed in fusion welding process.

So to do that first we would look into that how to represents the heat source that means there is a different types of the welding process, arc welding process, laser and electron beam, but how to represent that in the mathematical form that is the first task to understand the different heat source modeling or different representation of the heat sources. Second some simply analytical approach to estimate the temperature distribution in the workpiece.

Then finally we will try to look into what is the importance of the material flow in fusion welding process that is maybe more significant or maybe more relevant. When we try to look into that fusion welding process using some surface active elements. So that case probably material flow consideration of the material flow is the more representative to describe the different typical physical phenomena in fusion welding process

After that we will look into that what are the different metal transfer. So basically when we try to look into that welding processes involve the consumable electrode in that case what may be the modeling approach can be adopted in case of fusion welding process and there is a material deposition then we look into the different solid state welding process for example friction stir welding processes and how heat transfer modeling or material flow modeling can be done in this solid state welding process.

Definitely we will try into the different analytical approach and then some little bit discussion about the hybrid welding processes. So hybrid fusion welding processes mainly the laser assisted hybrid welding process and the second one is the hybrid friction stir welding processes this should be the another approach or how to model this hybrid welding process we will try to discuss and finally the solidification behavior.

And how the purpose of the solidification behavior to understand or maybe to make a link between the different solidification parameters and the microstructural phenomena which is more significant in fusion welding processes that actually helps to predict the different microstructural phenomena is fusion welding processes. So we will try to look into the basic solidification theory.

And specifically what are the significant parameters relevant to the solidification behavior of the fusion welding process and finally some basic calculation of the stress generation or residual stress because of the thermal strain and how to relate between stress and strain and what are the different modeling algorithm or modeling approaches generally we consider to predict the residual strains in fusion welding processes.

And of course apart from the residual stress the distortion generally we will try to predict using stress and different stress analysis model in case of specific to fusion welding processes. So in general this will be the coverage of the welding process in the perspective of the mathematical modeling of the welding process. Now before start the modeling approach of welding process we need to understand the physical aspect or physical behavior involved in the welding processes or some basic idea about the welding processes.

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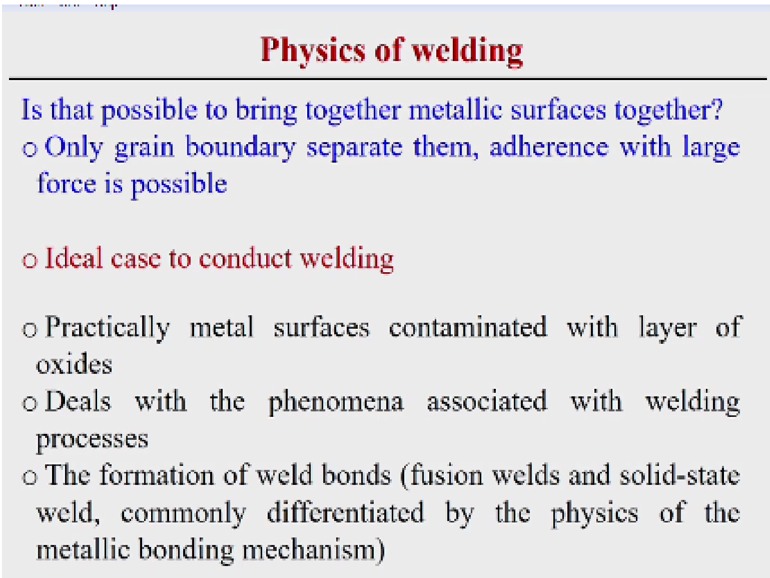

So first question is that welding mean we try to join between the 2 components it can be metallic components, non metallic components, but what is the way out to bring together the metallic surface connect the 2 metallic surfaces. If we look into the very ideal situation that most of the metallic surface is actually there is mainly in the contaminated layer and oxide layer exist on the surfaces if it is possible to remove that contaminated layer and the oxide layer from the surfaces.

And then bring together 2 different material then it is possible to join this 2 metallic components by the inter atomic forces, but in this case the ideal situation is that there should not be any kind of contaminated layer. This practically it is not possible to create that kind of ideal situation when we try to join between the 2 components. So most of the metallic components having some sort of metallic layers on the surfaces or contaminated layer on the surfaces.

And that to remove that layer we need some sort of deposition of the energy to the surfaces such that this layer contaminated layer or oxide layers can be removed and then the 2 metal can come in contact and the coalescences between these 2 metallic components happens and then finally it produce a weld joint. So that is the typical mechanism or joining of this 2 components, but it depends on up to what extent or what type of materials we are trying to join based on that what is the amount of the energy is required.

And according to that different type of the heat sources and different type of the welding processes actually developed. So if you look into this slides that ideal case to conduct the welding that the formation of the weld bond actually happens between either in the fusion welds or in the solid state, but only differentiated by the physics of the metallic bonding mechanism.

For example in fusion welding processes with the application of the heat source we basically melt the surfaces and after that we allow some cooling that means during that cooling period solidification happens and the coalescences of the metal happens, but in case of solid state welding process not necessary to join in the 2 components by melting. So that maximum temperature within the system in case of solid state welding process is below the melting point temperature.

But in this case some source of mechanical energy is required, Plasticization of the material is required so that they form or they can create the bond between the 2 components specifically in the solid state process. So in that sense the solid state welding process is advantageous that range of temperature in this case requirement is the less as compared to the fusion welding process.

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Physics of welding

Principles of fusion welding

- Fusion welds are created by the coalescence of molten base metals mixed with molten filler metals
- Metals must be heated to melting point for fusion welds to be produced
- Phase transitions inherent to these processes, a heat-affected zone is created
- The cooling of fusion zone is associated distortion, residual stress and metallurgical changes

Principles of Solid-state welds

- ✓ at temperatures below the melting point
- ✓ are created by either the macroscopic or microscopic coalescence of the materials in the solid state

So in short the principles of the fusion welding process that fusion welds are created by the coalescence of the molten base metals mixed with or without the filler materials. So sometimes to join the 2 components also the third material can be added to the component such that it helps to make the joining between this 2 components and of course metals must be heated above the melting point temperature.

Then when it cross the melting point temperature then this involve the phase transformation in the sense from solid phase to liquid phase and when solidification happens the vice versa liquid phase to solid phase and then after that during this below the melting point temperature there may be some sort of solid state phase transformation also happens during the process. So based on that their microstructural changes happens and based on the phase changed from liquid to solid phase we can define that what is the molten pool size or weld zone as well as the heat affected zone.

Even mathematically also we can measure the weld pool zone and heat affected zone by defining the different isotherm contour. Similarly, principle of solid state weld shows that the temperature is actually below the melting point temperature and the macroscopic or microscopic coalescences of the materials happens in the solid state. So here also we get mainly the different heat affected zone, thermo mechanically affected zone.

And since the solid state welding process mostly involve some source of energy by mechanical means is required in this case. Now after that first we start with the apart from the different welding processes we will start with the different basic processes of arc welding. In arc welding process we need the energy supply in terms of the some electrical energy required. So here we need to define the voltage and current.

So current means the flow of the charged particles we can say flow of the electrons within the circuit and then it forms in arc welding actually there is a formation of the electrical circuit

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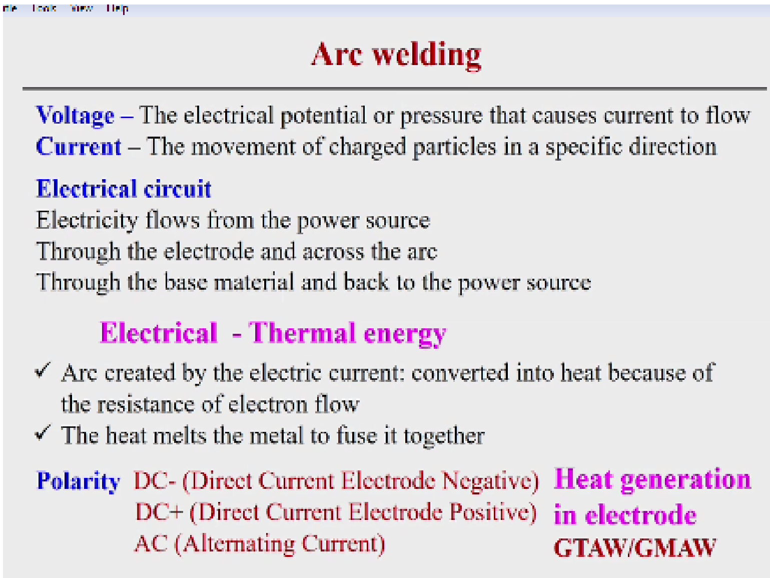

And then electricity flows from the power sources and it comes through the electrode and passes through the arc and then connect with a work piece and then it creates one complete circuit basically the electrical energy is converted to the thermal energy by creating the arc and then arc by this arc melt the material and then after melting the fused together 2 components and then join the 2 different components and specifically the metallic components.

Now apart from the electrical circuit there is another important aspect to look into that that is the polarity. Polarity means how the current passes the current whether it is AC current DC current and whether it is whether one is cathode which one is anode that actually decided by the different type of the welding processes, materials based on that we adopt the different kind of the polarity.

For example, we normally use in case of arc welding process is the direct current, but direct current electrode negative that is a one polarity direct current electrode positive or there maybe need of the alternative current. Now depending upon this polarity actually what is the amount of the heat generation within the electrode or when you create the arc within the workpiece that depends on what are the type of polarity we choose.

For example, direct current electrode negative. So direct current electrode negative and if we keep the workpiece as positive then there is a flow of the electrode when you create the arc and there is a flow of the electron from negative terminal to the positive terminal workpiece so that in sense there is a flow of the electron so positive terminal will attract the flow of the electron.

So maximum amount of the energy by the electron will be released to the positive side that means on the workpiece and minimum energy will be created to the electrode. So in that case approximately 70% of the energy will be created a thermal energy will be created to the workpiece side, but 30% energy will be created in the electrode side. So that is why so DCEN polarity is normaly used in case of the gas tungsten arc welding process.

So in this case there is a requirement of the maximum amount of the energy release or maximum amount of the thermal energy can be created to the workpiece. In other case for example direct current electrode positive in this case the maximum amount of the energy will be created to the electrode side, but minimum amount of the energy will be created to the workpiece side.

So when there is a requirement of the consumable electrode then DC+ that means direct current electrode negative is more suitable in that case such that so it helps to create the more amount of the thermal energy towards the electrode. So third one is the AC current so AC current there is a change in the polarity from positive to negative energy each and after half cycle.

So during that AC current when that kind of material the (()) (15:40) easily from the oxide for example aluminum so in that case to remove the aluminum oxide and at the same time to join this 2 aluminum components so in that case AC current is more suitable so because this half of this in this case the cleaning action is required. The cleaning action means the removable of the aluminum oxide is required in this case.

So that is why it is more suitable so depending upon the type of material and whether we are using consumable electrode or non consumable electrode based on that we can decide whether we need to use what type of polarity in case of welding process.

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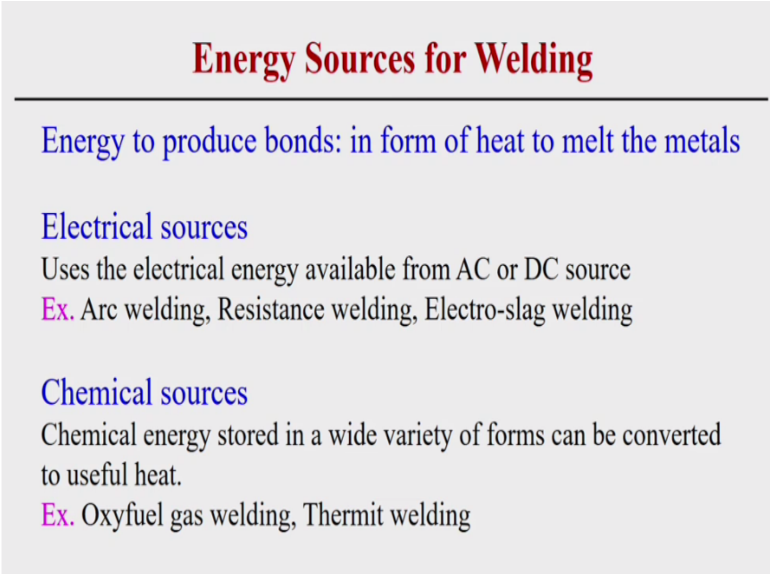

Now if we overall look into what are the energy sources specifically used for different welding process that we see the electrical energy is the one kind of the sources. So electrical energy is available from the either AC or DC current. Example arc welding process, resistance welding process, electro slag welding process all this cases we use the electrical sources source of energy from the electrical means.

So the discussion of the different type of welding process we will later on, but apart from electrical sources we use the chemical sources of the energy. For example, chemical sources and varieties in different forms can be converted to the useful heat for example oxyfuel gas welding. In this case we use some kind of the fuel thermit welding processes. So in this case we use the either exothermic or kind of endothermic reaction.

Such that the reaction will generate some amount of the heat so that is responsible to join to create the join between that components. So this chemical kind of the heat sourcing.

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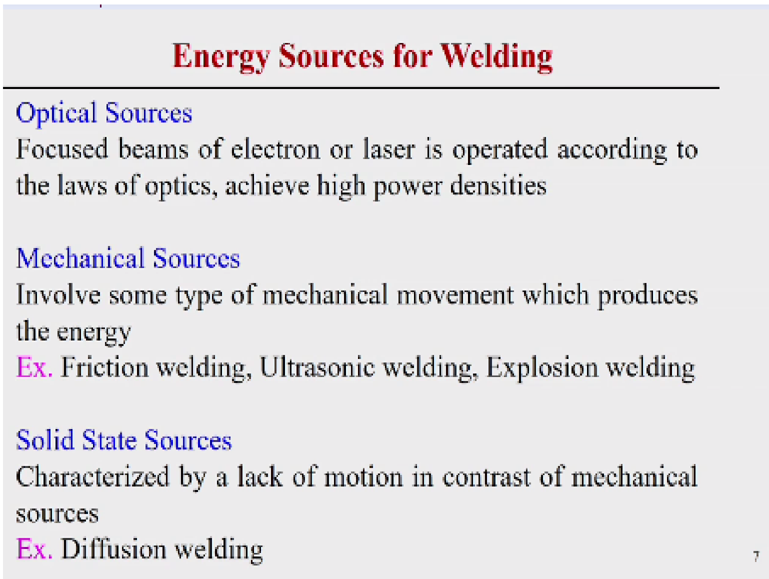

Apart from that is the optical sources. So focused beam of electron or laser which is operated according to the law of optics and normally we focus in a small zone and high power density is created and that kind of source of the energy is used in case of welding processes. Example of this optical sources used for example electron beam welding process and laser beam welding process.

Also mechanical sources so in some cases frictional heat generation is also required to generate the heat mainly friction stir welding process, ultrasonic welding process, explosion welding process. In this case that involve some kind of the mechanical movement is required. So that is responsible to generate the heat. Another one the source of the heat that is called the solid state sources.

So in this we use the mechanical source similar to, but there is no need of kind of relative motion between the workpiece and the source of the heat so lack of motion. So in this case probably there is a need of the constant application of the load or pressure is required just example diffusion welding. So apart from that there is a need of maybe added by the temperature to raise the temperature.

So pressure and temperature these are the parameters normally used in case of solid state sources to coalescences of the metal example is the diffusion welding which is more closer to the ideal welding situation what we discussed at the very beginning that means if very good surface preparation is required in this case.

And if we put the 2 components and with the application of the load or with the application of the pressure for a long time and of course sometimes added by the temperature that is the principle of the diffusion welding.

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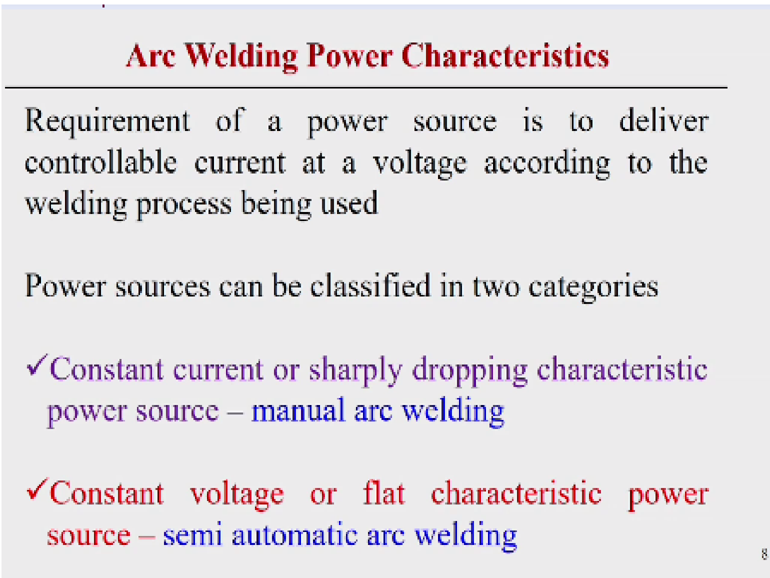

Now we look into that in arc welding processes apart from the different sources of the energy is required in different welding process. So if we look it only on the arc welding processes there is a requirement of the arc power characteristics. In this case there is a need to controllable current at a particular voltage according to the welding process being used how is it that.

So power sources can be classified into 2 different categories if we look into that one is the source of the current, but that is a constant current or sometimes it is called sharply dropping characteristic power source. So this type of characteristic power source is required in case of the manual arc welding because during the manual arc welding the gap or maybe length of the arc may not constant it can vary also.

And of course the speed also may not uniform when you try to operate manually the welding process. So there may be chances of the fluctuation of the welding the arc gap. So to execute this kind of the welding process the power characteristic should be kind of typical constant current or sharply dropping characteristic source is required. So other kind of the power source that is called the constant voltage or flat characteristics power source.

So constant voltage in this case is more suitable in case of semi automatic arc welding processes because in semi automatic arc welding process when you try to move the welding source from one point to another in this case since automatic it is not involved any manual operating of the system. So in that case we normally or approximately keep the arc length as constant.

And of course it is possible to conduct the experiment at almost constant velocity. So there is a chances of the variation of the arc length is less so this type of welding process the constant voltage is the more suitable power source in this kind of the automatic welding process. So depending upon whether we are using manual welding process or we try to use some automated system welded system accordingly we have to add on the different type of arc power characteristics.

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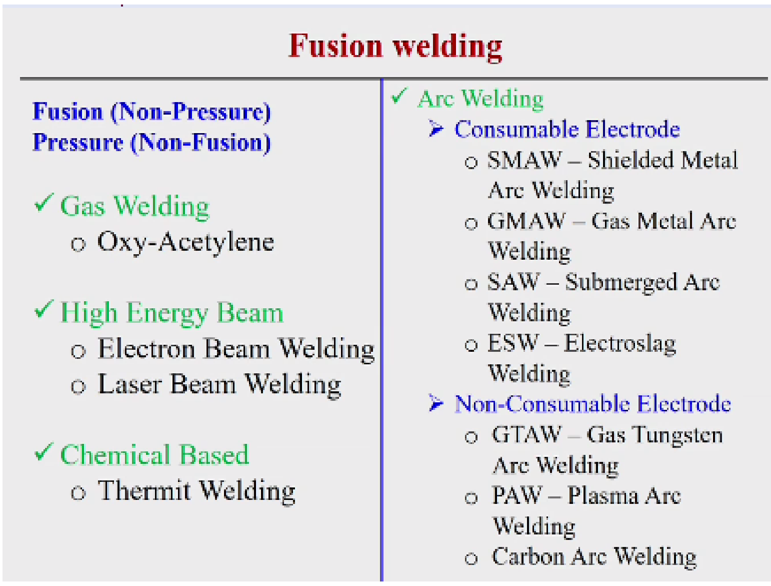

Now if you look the fusion welding, the different category of the fusion welding, but not in broad I have mentioned very few which is very basic processes because to know about different type of welding process that is not the aim of this course rather we try to look into the different mathematical aspect involved in the different welding process in general that is the main focus.

So if we look that fusion welding processes we can see 2 categorization gas welding, high energy beam welding process, chemical based welding process, arc welding. See the different process involved. Gas welding process mostly use the oxy-acetylene process, high energy beam we can use the electron beam and laser beam welding process chemical bonding most commonly used the thermit welding process.

And arc welding process we use the either consumable electron or we use the non consumable. If in the welding process if we use the consumable electrode then these are the different process are shielded metal arc welding, gas metal arc welding, submerged arc welding and electroslag welding process. So these are the very basic processes and non consumable electrode we see that gas tungsten arc welding, plasma arc welding and carbon arc welding process.

But this fusion welding is (()) (23:29) if we see relate to this thing that fusion welding process normally no involvement of the pressure or load is required, but there is involvement of some kind of the thermal energy to melt the surface, but if we look into the other welding process there may be other that is called there is requirement of the pressure that is the non fusion welding process.

So in that non fusion welding process there may be must involvement at least some amount of the pressure or load is required. So in that sense we can divide the fusion welding and non fusion welding processes. Now I will try to look into that to look into the typical aspects or typical characteristics of the different fusion welding process.

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Oxy-Acetylene Gas Welding

✓ Mixing of acetylene gas and oxygen in the welding nozzle
✓ Proportional of gases decided the nature of flame

Neutral Flame: Ratio of oxygen to acetylene, in the mixture leaving the torch, is almost exactly one-to-one.
Ex. Welding of mild steel, stainless steel, copper, aluminum

Carburizing Flame: **Lower temperature than neutral flame (excess carbon)**
Oxidizing Flame: **Used for Copper base metals and zinc base metals**

So first we look that oxy acetylene gas welding process. Here mixing of the acetylene gas and oxygen certain proportion so proportional of the gases decide the nature of the flame. So here by using the acetylene gas along with the oxygen there is a creation of the flame and that flame is basically used to heat the substrate material, but there is a different types of the flames can be created one is the normally called neutral flame.

So definitely in this cases the ratio of acetylene and oxygen is 1:1 the mixture and it is almost exactly 1:1. So this type of neutral flame is more suitable or the different type of the materials we see the welding of the mild steel, stainless steel, copper, aluminum so mostly used we use here we need to use the neutral flame that means the ratio of the acetylene and oxygen should be 1:1, but apart from neutral flame the carburizing flame can also be created.

In carburizing flame, the ratio of the acetylene and oxygen is more basically acetylene percentage is more as compared to the oxygen. In this carburizing flame actually creates the lower temperate than the neutral flame. So but one difficulty or maybe you see the typical characteristics of the carburizing flame is since the acetylene percentage is more than it can create the excess carbon means creates the carbides.

So if there is a need such situation we need to create more carbides and iron carbides maybe in case of iron or steel in that case we should use the carburizing flame. So carbide is normally hard or it makes the weld joint more brittle. So depending upon the application which we can may or may not use the carburizing flame, but oxidizing flame in other cases that in that case the temperature is more than that of the neutral flame or of course oxidizing flame means the percentage of oxygen is more as compared to the acetylene gas.

So since temperature is very high as compared to the neutral flame. So when there is this kind of flame is more applicable when there is in case of very high conductive material for example copper based alloy, zinc based alloy they are more suitable using the oxidizing flame.

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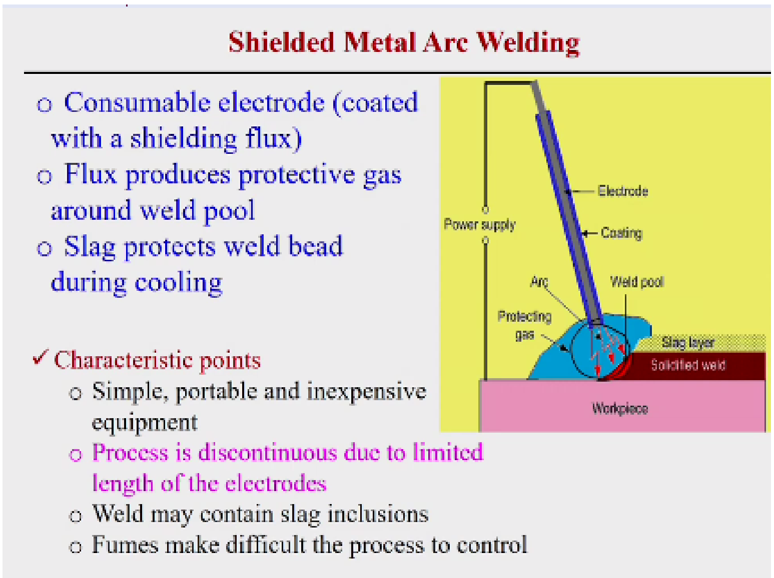

Now look into that shielding metal arc welding process we mostly use the shielded metal arc welding what are the basic steps to learn the different welding processes. So shielding metal arc welding process if we look into this picture that we use the some kind of consumable electrode of course coated with the shielding flux. So actually there is we use during the welding processes there is need of some kind of the shielding.

This shielding actually protect the molten pool from the contamination from outside atmosphere. So this shielding can be created in different ways. One maybe using the coating of the shielding flux or sometimes we can use the directly the shielding gas also so at different welding process, but shielded metal arc welding process we use the create the shielding gas or protective gas or that kind of atmosphere by using the coated shielding flux.

That coating is mainly done over the electrode. So flux produces the protective gas around the weld pool and after doing the welding process there is a formation of the slag and the slag mainly remains over the welded surface and once the welding done we just simply remove the slag from the surface. So slag actually protect the molten pool at the same time or maybe during the solidification this solidified zone is protected from the outside (()) (28:24) by the layer of the slag so that is the advantage of this.

But if you see this process overall the workpiece is there and that there is a creation of the electrical circuit workpiece and the other terminal is connected with the electrode and see there is a focus creating the arc at this point and then it melts the substrate pool or workpiece material and creates the solidified zone. So after solidification there is a slag layer form, but if you see the outside the electrode there is a coating.

So in the form of the coating actually we supply the shielding material to the welding process. So if we look into that what are the typical characteristic point related to this shielding metal arc welding process. First it is a very simple portable and inexpensive equipment and of course, but one limitation is that this is a discontinuous process and that discontinuous process in the process that.

Once there is a electrode the electrode is having some finite length or certain length so once it is finished then we have to again put the electrode then we have to start the welding process so that means it is a discontinuous process. Of course weld may contain some slag inclusions and fumes makes difficult the process to control. So to make the this process as a semi automatic or automatic process is really difficult.

One reason is for that limited length of the electrode and of course secondary reason is the there is a fumes formation of the fumes that is why it is very difficult to control.

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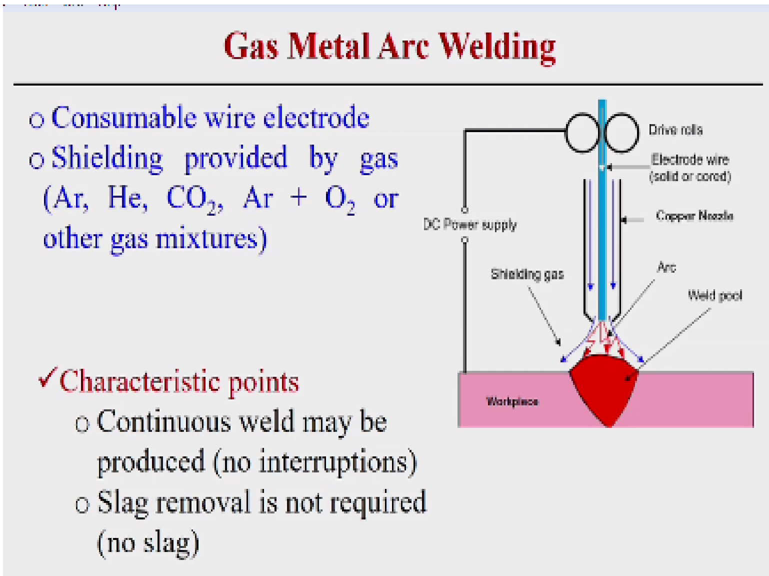

Apart from shielding metal arc welding we normally use in case of specifically for consumable electrode, the gas metal arc welding process. So here the consumable electrode and shielding gas can be different type of inert gas or mixing of the inert gas with the 2 different types of inert gas or inert gas with the oxygen or argon or any other different types of the gases can be used in case of the gas metal arc welding process.

So if we look in the gas metal arc welding process. In this cases the shielding is provided not in terms of the coating rather in terms of the separately shielded gas in this case and here we create the electrical circuit also and there is a continuous feeling of the electrode consumable electrode. So as compared to the other process it is a continuous process there is no interaction of the electrode supply.

And of course another advantage is that there is not necessary to remove the slag because we are not using any kind of there is no formation of the slag we can directly using the shielding gas.

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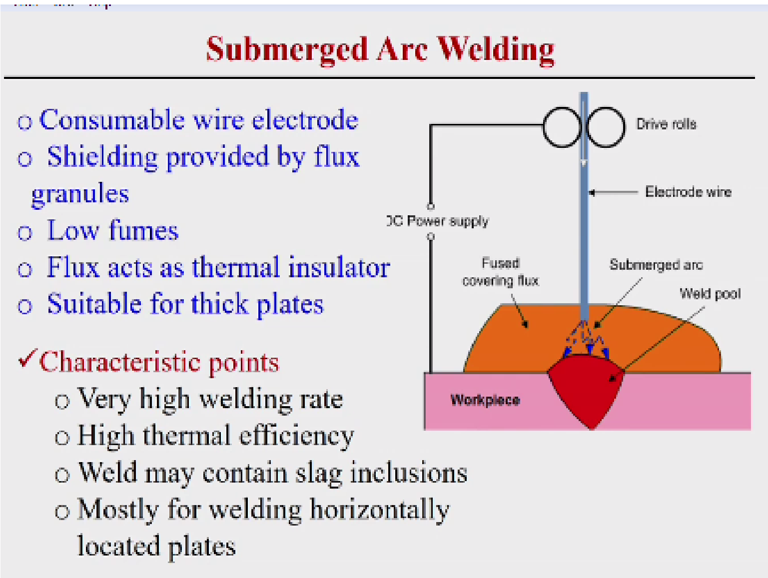

Then we look into the submerged arc welding process is almost similar to gas metal arc welding process, but in this case we use the shielding fused we basically cover the zone which is suppose to weld that zone is covered by the flux and that submerged arc is created under this flux. Let us say it is called the submerged arc welding process. So similar way we continuously (()) (31:47), but the difference as compared to the gas metal arc welding process first this process is deposition rate is very high.

When there is a thickness or there is requirement of the high material deposition a very high thickness material in that case submerged arc welding process is more suitable and of course in this case the fume because it mostly cover by the flux so there is a low fumes is created and a flux acts as the actually the thermal insulator and specifically thickness for the very thick plates but since the arc is created and it is covered with the flux.

So thermal efficiency is actually very high in this submerged arc welding process. So characteristic points very high, welding rate, deposition rate is very high, high thermal efficiency, weld may contain slag inclusion but there may be in the solidified structure we can found some kind of the slag, but limitation is mostly for welding horizontally located plate that is the only limitation in this process.

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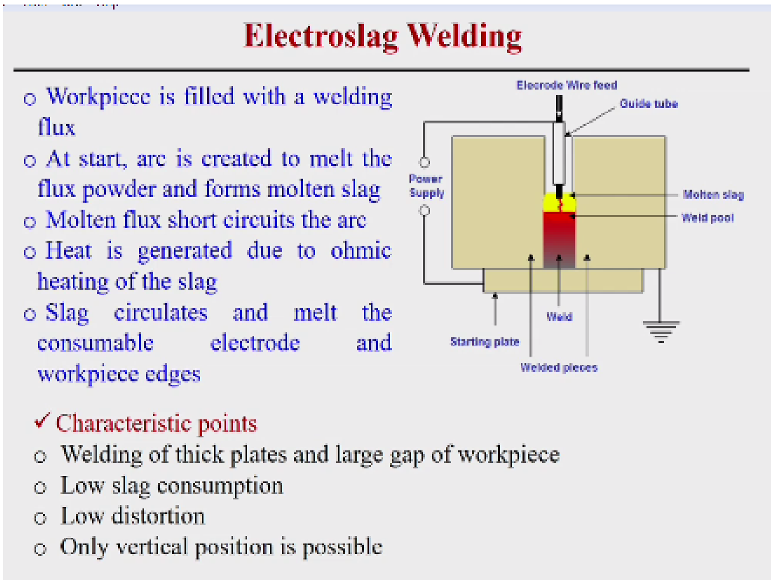

Electro-slag welding process here we can see that workpiece is filled with the welding flux and at the start arc is created to melt the flux powder from the molten slag. Actually molten flux short circuits the arc and therefore heat generation in this process mainly happens due to the ohmic heating that means similar principle of the resistance heating. So here it is generated and once in this case we start the process from the bottom and then we move the electrode with upward direction.

And the molten metal from the electrode actually melt the 2 sided of the workpiece and then we join these 2 component. So in this case the typical characteristic points the welding of the thick very thick plate and of course if there is a large gap between the 2 components in that situation this process is more suitable, low slag consumption as compared to the other processes because it starts from the bottom and from the bottom the molten the consumable electrode fill from bottom sides.

So exactly when there is a arc at this point there is a slag exist at that point at that zone basically molten slag, low distortion. Since we are not directly melting rather the workpiece directly on the surface of the workpiece rather we create the molten slag and that molten slag resistance heating so 2 sides of the component is joined by this processes. So in this case we can expect a very low distortion.

And of course only vertical position is possible that means this configuration whatever shown in this figure with that configuration the weld join is possible.

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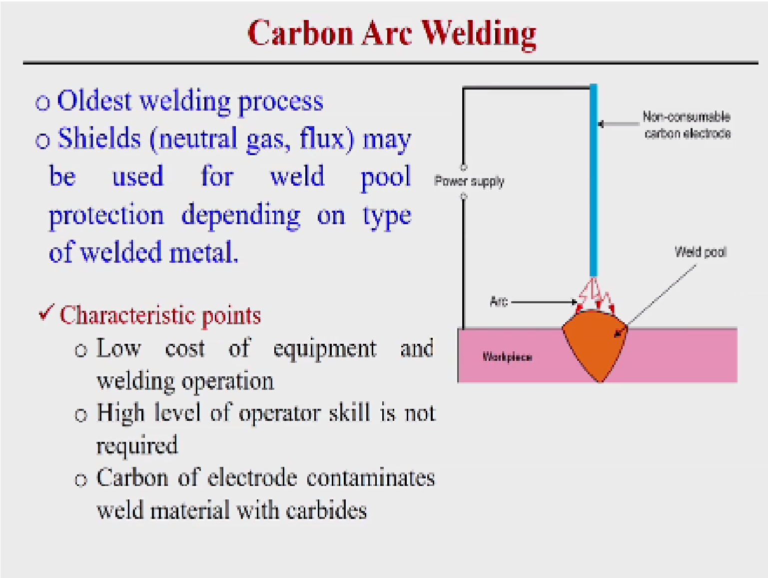

Next is the carbon arc welding. This is a very simple process and very oldest welding processes. So shielding gas may not may not using use the non consumable electrode that is made of carbon and then create the electric arc and then between the workpiece and the electrode there is a creation of the arc, but typical points in this case definitely it is a low cost, high level of operating skill is not required very simple process.

But difficulty is that carbon of the electrodes sometimes contaminates with the weld material and may form the carbide that is the only difficultly. So carbon arc welding.

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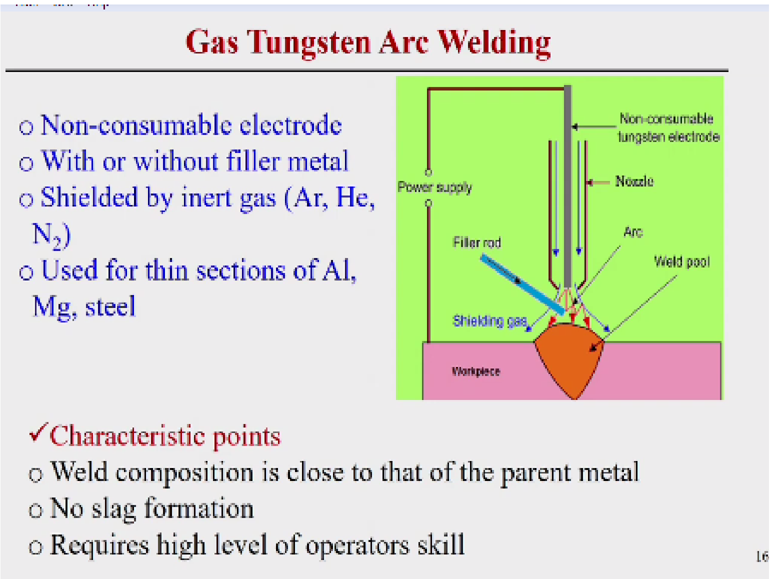

Apart from that then we look into that gas tungsten arc welding process. So in gas tungsten arc welding process electrical circuit is there, but in this case we use a non consumable electrode mainly the tungsten electrode because temperature of this hot hardness properties is very high heat resistance properties is very high in case of the tungsten electrode so normally we use the tungsten electrode in case of the gas tungsten arc welding process.

So through the nozzle there is a supply of the shielding gas and that protect the molten pool, but it is different from other welding processes that most of the cases we do not use any kind of the filler rod this is basically optional and therefore this process is very much suitable when there is a thin sheet of material we try to join no slag formation because directly we are using the shielding gas and shielding gas in the form of argon, helium, nitrogen or mixture of them can be used as a shielding gas.

And most of the metals for example aluminum, steel, magnesium they can be welded using the gas tungsten arc welding process and of course no slag formation, but it requires the high level of the operation skill, but one advantage of the non consumable gas tungsten arc welding process that we can control the heat input using the pulse mode so that is the one advantage.

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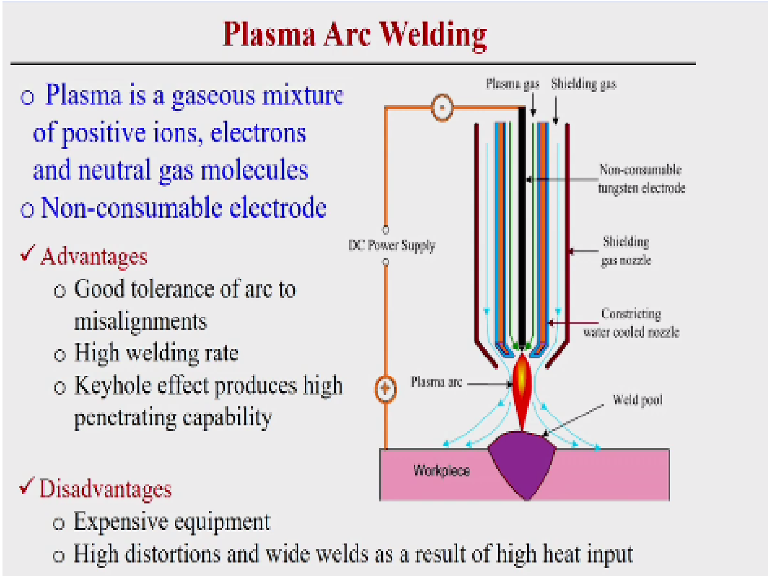

We can use the plasma arc welding process also, but in this case it is different from the gas tungsten arc welding process. Here there is a 2 supply of the gas one is the shielding gas and other one is the plasma gas, but can be the similar kind of inert gas or maybe different gases. So plasma gaseous mixture is a positive ion, electrons and actually neutral gas molecule. So here also use the non consumable electrode and there is a gap between the non consumable electrode and we create the arc and that is the plasma arc.

The plasma created between the electrode and the workpiece that plasma generates the heat and melt the surface and of course secondary source we use another shielding gas that protects the molten material. So it is advantageous as compared to the gas tungsten arc welding process in the sense that if we look into this figure that electrode is placed in such a way that by changing the electrode length there is a constriction or may be depending upon the flow situation of the plasma gas it is possible to constrict the plasma arc.

So if there is a need of the high depth of penetration in that case plasma arc welding is more suitable as compared to the gas tungsten arc welding process because gas tungsten arc welding process the electrode (()) (38:27) electrode it is opened to create the arc between these things, but in this case it is possible to create the constricted arc. So in that sense in terms of the heat concentration or may be in terms of the power density the plasma arc welding is more suitable as compared to the gas tungsten arc welding process.

Apart from that there is another mode of plasma arc welding process we can use transferred arc or non transferred arc that we can create, but before that we can look into that what are the typical advantage of using the plasma arc welding processes. One is the good tolerance of the arc misalignment. Second was the high welding rate. Second was the high welding rate and of course there is a possibility of creating the keyhole effect in case of the plasma arc welding process.

So in that sense this plasma arc welding process sometimes can be a substitute or maybe alternate as compared to the laser welding process, but disadvantage expensive equipment and high distortion wide weld as a result of the high input may create but that disadvantage is very relative depending upon by choosing the process parameters or what types of materials w are using. But apart from that plasma arc welding can also be used in the other mode also.

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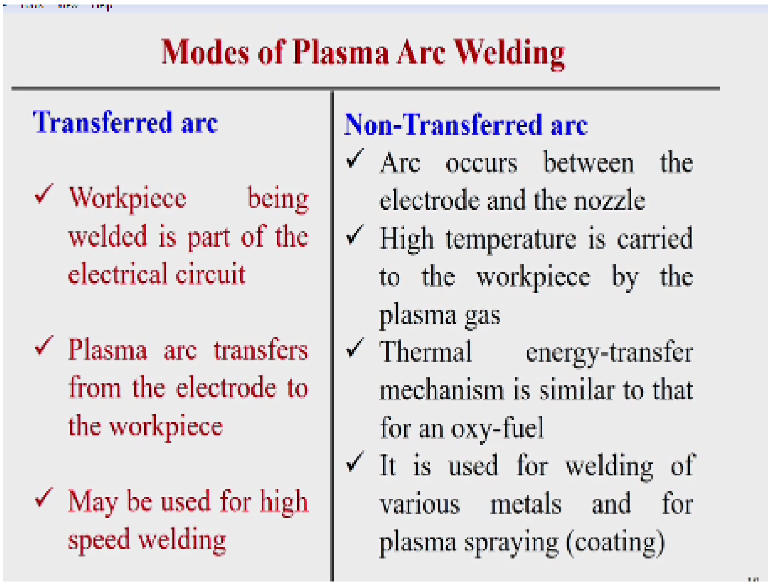

That by creating the transferred arc or non transferred arc. In transferred arc workpiece being the welded is part of the electrical circuit if you see and plasma arc transfers from the electrode to the workpiece maybe used for the speed welding specifically this thing. If we look into this picture you see that there is a creation of the arc between the electrode and the workpiece.

So this is called the transfer arc mode so this mode is suitable for the welding purposes, but what is non transferred arc. Non transferred arc that arc can be created between the electrode and one of the nozzle, but in this case the high temperature is carried to the workpiece by the plasma gas. So therefore when there is a need of the king of spraying or coating purposes. So this non transfer arc is actually more suitable.

So in that sense the plasma arc welding can also be used in the non transfer arc mode specifically useful for the plasma or coating purposes.

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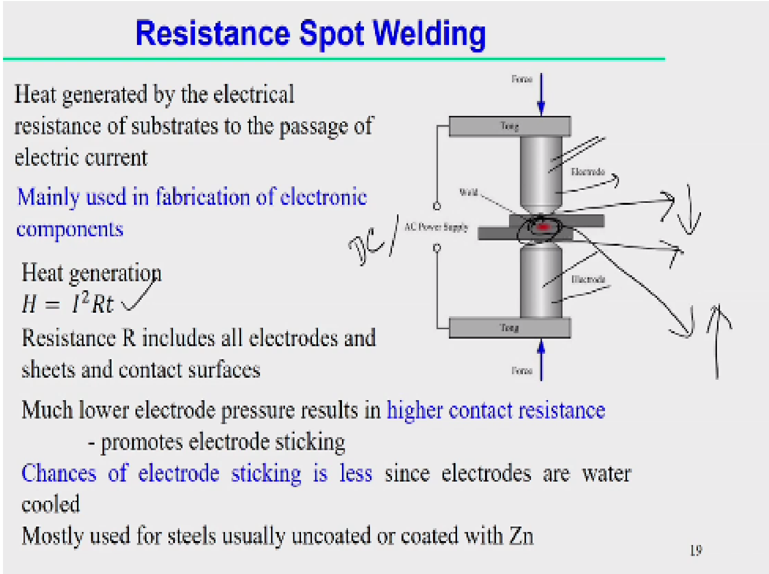

Resistance spot welding is another fusion welding processes. Here you see that we use the heat generated by the electrical resistance between the 2 contact surfaces and of course through the passage of the very high electric current. So mainly used in fabrication of the electronic components specifically in the small scale, but normal scale the resistance spot welding is more suitable in automobile industry.

So here in automobile industry we normally used the resistance spot welding process it creates the several spots in a specifically the car if you see the automobile car body, but applicable to in case of different graded or different kind of the steels mainly, but what is the principle of resistance spot welding process if we look into this picture there a AC power supply or maybe DC power supply.

And there is a electrode made of high conductive material and then in between the workpiece is there this is the workpiece and this is the electrode, this is another electrode and between the electrode there is a need of the application of the force once their intimate contact there is a passage of the current from the AC or DC power supply and then passage of the current for a very small time maybe in the order of the millisecond 300 to 400 millisecond kind of thing.

And then at the contact between the workpiece the contact resistance becomes very high. So at this point there is a generation of the heat by following this law=I square Rt. So here R actually is the resistance of the all electrode and steels definitely different contact surface, but the contact resistance other components are very less as compared to the contact between the 2 workpiece surfaces.

So the maximum energy, the maximum heat generation actually happens between the 2 contact surfaces. Now what will happen if there is a if you do not control the forces. So much electrode pressure or force results in basically high contact resistance. So that promotes the electrode sticking sometimes. So if there is no adequate force so there maybe chances of the electrode sticking between the workpiece and the surfaces.

So for that reason most of the cases we use the high conductive material and as the same time some water cooled system is normally involved within the electrode. So therefore that actually helps not to sticking with that electrode with the workpiece. So that point is that this contact surface between the electrode and the workpiece the contact resistance is very less. Here the contact resistance is very less.

But this surface at this surface actually contact resistance remains very high. So therefore maximum heat generation or maximum percentage of the heat generation mainly happens at this contact. So that is why this process is mostly suitable for the steels, but sometimes steels may be coated and uncoated. Most of the cases is the coated with the zinc because that is because that is more practical application we found in case of the automobile industry that is the typical application of the resistance spot welding.

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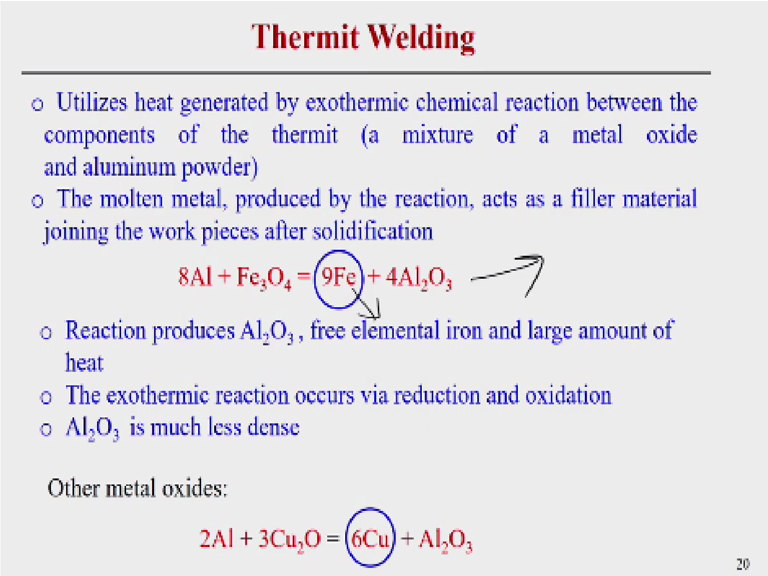

There are another welding processes that is thermit welding process. Here basically we use the heat energy by exothermic chemical reaction so from that principle there it is possible to join the 2 different components and mainly the components we have to choose the components in the correct way and a mixture of metal oxides and aluminum powder are mostly choose.

And now how it happens this thermit welding process and if you look this equation that aluminum powder and Fe_3O_4 we mix then if we mix this things it separate out this iron and creates the 4 aluminum oxide+ heat generation. So that generated heat actually melts the substrate material and they join the 2 components, but at the same time if we try to join the iron or maybe different steel then their creation of the iron it becomes part of the weld joint.

And of course aluminum oxide is mostly in lighter in weight. So that comes on the top surface and that later on it is possible to remove the aluminum oxide and of course this aluminum oxide density is very less so I think that is possible to remove easily and this exothermic reactions occurs in general it is called the via reduction and oxidation. So in remote location this kind of welding process is required this point is more suitable.

Because here we do not need any kind of the electrical source and other source maybe optical source is not required and of course other metal oxide can also be used instead of iron we can join the copper also that copper oxide and aluminum powder mix together and the similar kind of reaction happens and this copper becomes integrate part of the weld joints. So when you try to join the copper, copper based alloy this metal also this combination of the mixture is also suitable there.

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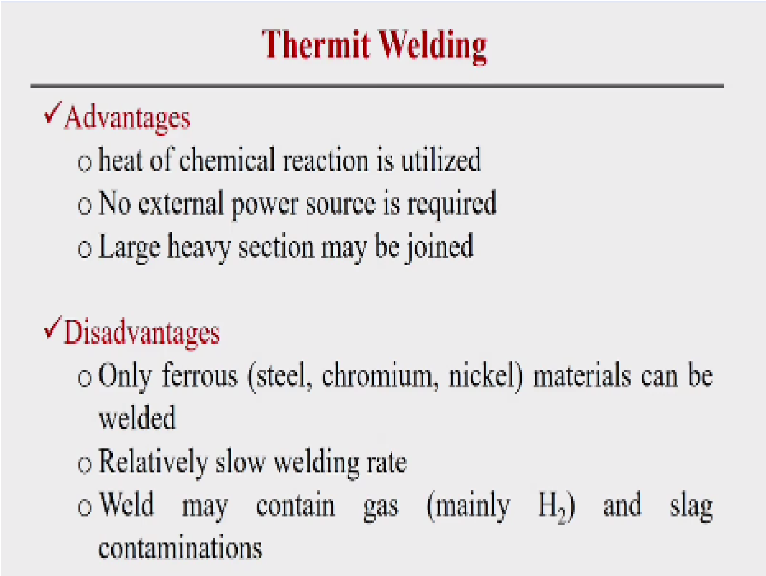

But what are the difficulty in this case because only ferrous, steel, chromium, nickel this process is applicable specially to very few materials can be welded. This is a very slow process not like that arc welding processes, different arc welding processes, but weld may contain the gases mainly the H2 or sometimes the slag contamination may be there in this welding processes.

But advantage is that heat of chemical reaction is utilized so even for remote location it can be used, no external power source is required in this case and of course large and heavy section may be joined using this kind of the welding process.

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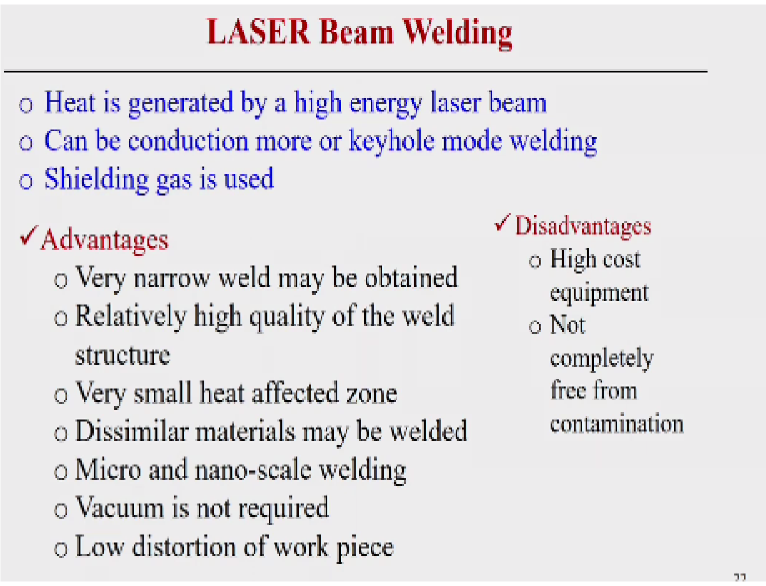

Now we try to look the laser beam welding process. In laser beam welding process heat is generated by a high amount of the energy from a laser beam. So this when you apply using the laser beam so depending upon the power density it can be conduction mode or keyhole mode if power density is very high then we can use the keyhole mode welding processes and of course shielding gas is used in case of laser welding processes.

In general, you see the advantage and disadvantage of the laser welding process is very thin or very narrow weld join can be created, high quality of the welded structure, very small heat affected zone and of course different combination or materials can be joined easily and of course the main advantage of this things even very small scaled welding process can be done using the laser because of (()) (48:21) control of the laser source.

Vacuum is not required and of course less distortion can be created using the laser welding. So these are the typical common advantage in case of laser welding processes. but mainly disadvantage is cost is very high and sometimes not completely free from the contamination if you compare as compared to the electron beam welding processes. So further on the laser beam welding processes.

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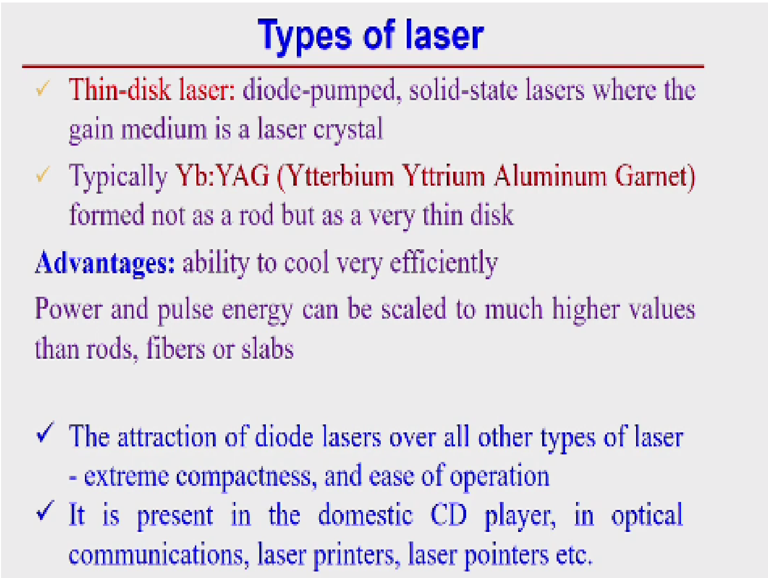

But what are the different types of the laser source can be used in case of the laser welding process. One is mostly the solid state laser. A solid state laser using crystalline rod which is sometimes which is sometimes doped with the doped that actually creates the laser radiation and then neodymium is the common dopant in various solid state laser crystals it is including that yttrium, aluminum, garnet.

So in that sense sometimes we mention this time Nd: YAG laser. It is a one kind of the solid state laser maybe lasing medium is in the solid state. So the Nd: YAG laser we can use or sometimes more advancement from Nd: YAG laser that is the laser amplifier when the light is guided to the total internal reflection that happens within in a single optical fiber.

So in that case this is called the fiber laser. So fiber laser actually more compact as compared to the Nd: YAG laser and life is more advantage and more focus beam diameter can be more since we are using the optical fiber in this case. So but lasing medium is almost in solid state in both the cases Nd: YAG laser as well as in case of the fiber laser. So apart from this solid state laser we use also gas laser for example mostly use the CO2 laser.

So lasing medium is in gaseous state that is why it is called the gas laser. So apart from that we use the disk laser also thin disk laser, diode laser also we use the disk laser is nothing but the gain medium is a laser crystal but in this case the solid medium not in case of Nd: YAG laser is the solid medium as a kind of rod cylindrical rod, but in this case the state of the rod we found a very thin disk.

And that is why it is very compact and it can very quickly cool down. So in that sense it is very effectively efficient or effectively effective as compared to the solid state other kind of Nd: YAG laser. Another advantage of disk laser is that power and pulse energy can be scaled to much higher values as compared to the fiber lasers. So apart from disk laser we use sometimes we use the diode laser also.

So here there is a pump in the laser to directly diode pump is used that what is wave length or energy emitted from the diode pump that is directed to created the laser. So in that sense it is very compact because there is a missing of the other components mirrors and other kind of components may not be there in case of the diode laser that is why most of the cases domestic CD player, optical communication laser printer and laser pointers most of the cases we use the diode laser.

But all this different types of the lasers can be used in case of the welding process. So of course that is not our scope to discuss what are the different types of the welding process, but in general this we can say that this type of the lasers is used in case of the welding process.

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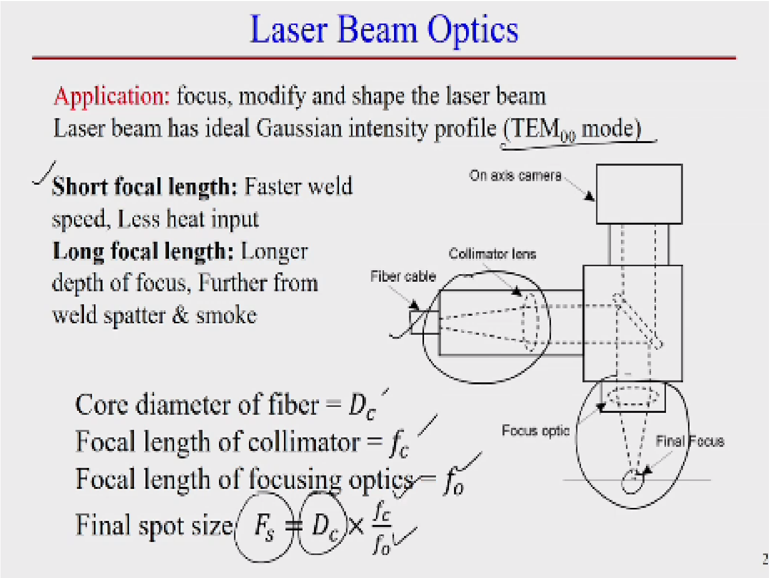

So now look into the basic parts of the laser welding process in the form of the laser beam optics to understand little bit about the laser beam optics. Forecast, modify, shape the laser beam and laser beam as actually having the Gaussian intensity profile that is the called the TEM00 mode. This is the laser beam profile that follows the theoretically Gaussian distribution.

So we look into that now what are the different modes using the laser can be created, but before that we will try to look into the focal length. So focal length is the laser light well exactly focus at this particular point so that is called the focal length between the length and the focal point. So faster weld short focal length the focal length means the focus point and the length that gap is very less then that is more suitable for the faster weld speed/

And definitely in case of the less heat input that creates the less heat input, but long focal length then longer depth of the focus is created and further from the welds spatter and smoke that is one difficulty. If that gap between the lens and the focal point is very high. So there is a possibility of during the welding process the smoke can be created and weld spatter that can damage the lenses.

So that is advantage of using the long focal length as compared to the short focal length. Now if we look into that the core diameter of the fiber is Dc and focal length of the collimator this lens is fc and focal length of the focusing optics is fo then final spot size you can estimate which is very useful. The final spot size in specifically in laser welding process based on that we can decide what is the power density of a particular laser source.

So that final spot size depends on this core diameter of the fiber and the focal length of this 2 fc and f0 and accordingly we can estimate the what is the final spot size.

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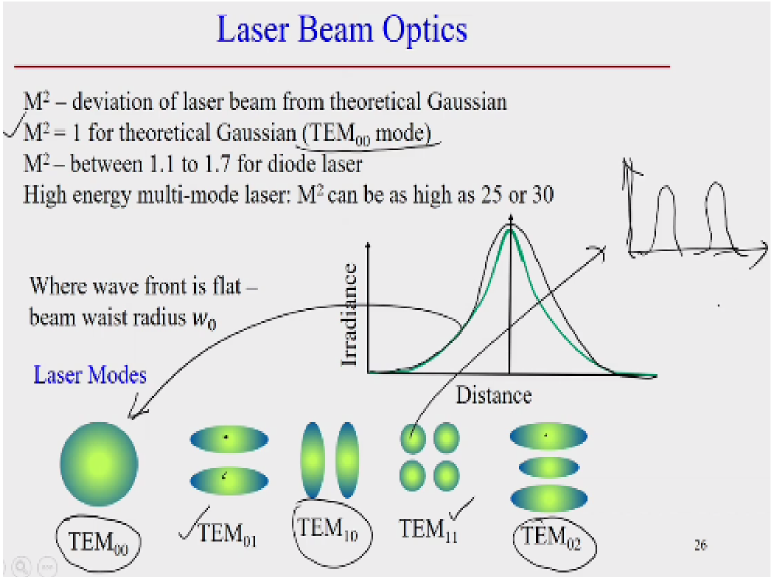

Now look into the laser beam optics a different mode. So actually there is a parameter M square which is actually deviation of the laser beam from the theoretical Gaussian. Actually if M square= it is a parameter of see to define the different modes of the laser if M square=1 then that is actually equivalent to the theoretical that actually follow the theoretical Gaussian distribution.

So it is also called the TEM00 mode, but actually M square is between 1.1 to 1.7 can be created in case of the diode laser for high energy multi-mode laser specifically M square can be as high as 25 and 30, but how we can decide. See this profile actually is normally the intensity laser intensity and the distance that follows kind of Gaussian distribution. So if this kind of profile which it corresponds to this/

If you color the intensity at the center the intensity is maximum and gradually towards the boundary or certain distance it is decreasing. So this is the mode that is equivalent to the theoretical Gaussian mode or we can say that TEM00 mode. but other different modes can be created using the laser source that is for example TEM01 multi-mode. Here intensity is very high at the center point, intensity is very high/

And gradually decreasing or it (()) (56:15) kind of electrical kind of this thing that is called the TEM01 profile or mode. Here we can see the TEM10 profile mode TEM11 profile. So there is a difference modes has been created TEM01 mode. See all this cases at the center point that indicates the intensity is very high and gradually decreasing. For example, if there is in this case we can represent the intensity distribution something like that.

This side is the intensity this is the distance so that way the intensity or distribution of the laser intensity or radiation intensity that theoretically they are different or practically also different kind of modes can be created and that can be utilized in case of the laser welding process, but most of the cases we use this kind of mode.

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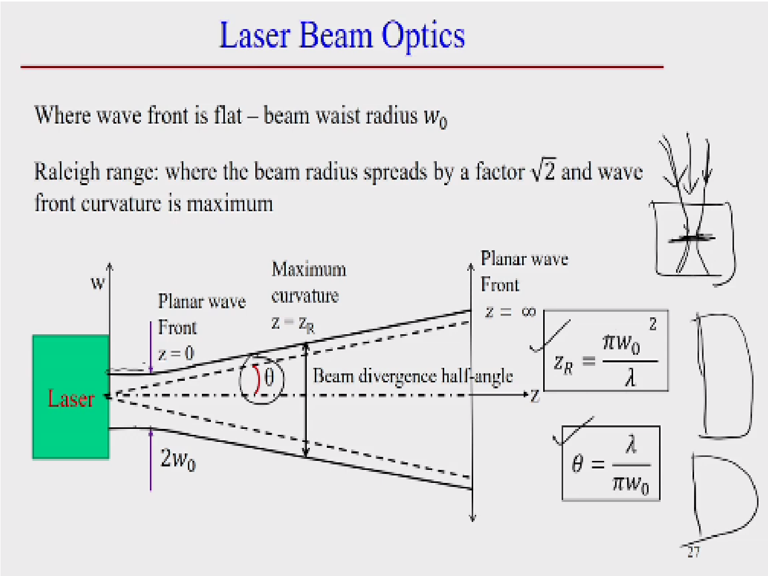

So apart from that other optics that beam waist radius because when we try to focus laser and it focus in any work when you focus on the laser in particular area or particular point after that focusing it becomes diverge can be created from the laser radiation. So at this point this the laser I think the focal radius is actually minimum in this case, but theoretically where wave front is flat beam waist radius=w0.

So here the wave front is flat means the distribution is almost uniform than wave front is flat almost that is the waist diameter beam waist diameter omega w0 and the Raleigh range which is defined the beam radius spreads by a factor of root 2 and wave front curvature is the maximum. So from here from this point to that point that can be decide along the z axis that is a Raleigh range from here to this Z=0 to Z=ZR.

But Z= Z are wave front curvature is the maximum so here it is not flat it can be like some curvature exist the distribution may not be very uniform or not be very flat. So that range is the Raleigh range. So here at this Raleigh range if you see the laser actually gradually diverge and we can measure the divergence half divergence angle theta. So that is called the beam divergence half angle.

Theta is called the beam divergence half angle that can be expressed in terms of the lambda means wavelength of the laser what type of laser we are using/omega 0. Omega 0 is the defined at Z=0 what is the beam radius. Of course ZR can also be calculated in terms of the wavelength and beam waist diameter. So these are the typical relation. So here we can roughly estimate the different parameters of the laser welding process by this calculation.

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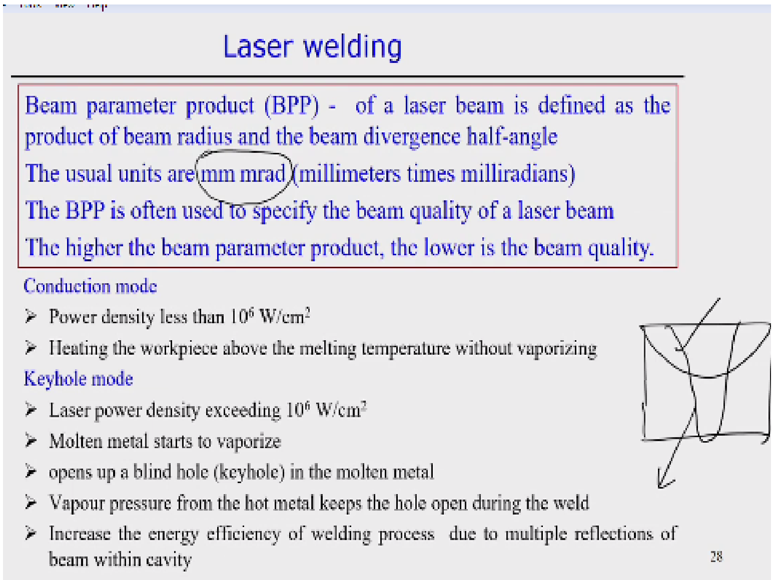

So you see that apart from the M square value the beam parameter product that is called BPP is sometimes used to define the laser beam quality. So which is defined by the product of the beam radius and the beam divergence half angle. The units are millimeter, milliradians. So millimeter times milliradians that is a unit I think BPP unit is this one and BPP is often used to specify the beam quality of the laser beam.

So the highest the beam parameter product BPP is that it indicates lower is the laser beam quality. Apart from that so laser welding can be categorized in the 2 different mode one is the conduction mode another is the keyhole mode. So conduction mode means based on the power density that means we can estimate roughly what is the focus diameter on the workpiece.

So that power density depends actually what is the focus diameter when laser is focusing on the workpiece on the workpiece surface what is the diameter so then power/by this area that actually define the power density. So if you can estimate the power density which is less than 0.6 word per centimeter square that is called we say that is a conduction mode. So there is no formation of any kind of the keyhole mode.

That means there is no chances of the vaporization of the material that means maximum temperature of the system is below the vaporization temperature of the workpiece material, but in other way keyhole. In this case power density is more than 10 to the power 6 word per centimeter square.

So there is a formation of the keyhole in the sense first try to create the molten metal vaporize and it creates the zone opens up blind hole which is called keyhole in the molten metal and of course vapor pressure from the hot metal keeps the hole opening during the welding process. So actually keyhole mode it creates a high depth of penetration. So when there is a requirement of the weld joint using the laser thickness is very high the keyhole mode is more preferable such that it can almost create the full depth of penetration using this keyhole mode.

But whereas as conduction mode is more suitable in case of thin sheet and conduction mode the profile can be like this the aspect ratio is probably low in this case width is more depth is less. So that is called the conduction mode with the low power density and but this is the keyhole mode aspect this is very high with respect to the width and the depth of penetration. So that is the keyhole mode welding process increase the energy efficiency of the welding process.

But one thing is that as compared to the conduction mode the keyhole is advantageous in the sense within the keyhole there is a multiple reflection of the beam capital. So efficiency absorption of the laser energy is basically more in case of the keyhole mode. So that means the efficiency is more thermal efficiency is more when there is a formation of the keyhole during the welding process as compared to the conduction mode.