Basics of Mechanical Engineering-2

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Week 07

Lecture 24

Basics of Welding (Part 1 of 7)

Welcome to the next topic in this course: welding. Welding is a very important topic in manufacturing. So here, we try to look into the science of joining. You know very well that many large structures cannot be constructed either by the casting process or by the forging process. Now, what is the next alternative?

The next alternative is to make small pieces and try to join those small pieces. So, welding is a process wherein it tries to take care of all these things. So, if you want to construct a large plane, if you want to construct a bridge, a test rig, or a rocket holding device, or if you go to the other extreme end, the artifacts you see in the showcase of your house, very small, very flimsy, but they have multiple small parts joined together by a soldering process or a brazing process. Welding also leads toward additive manufacturing, which we will try to cover later in this course. So, welding is a very important process.

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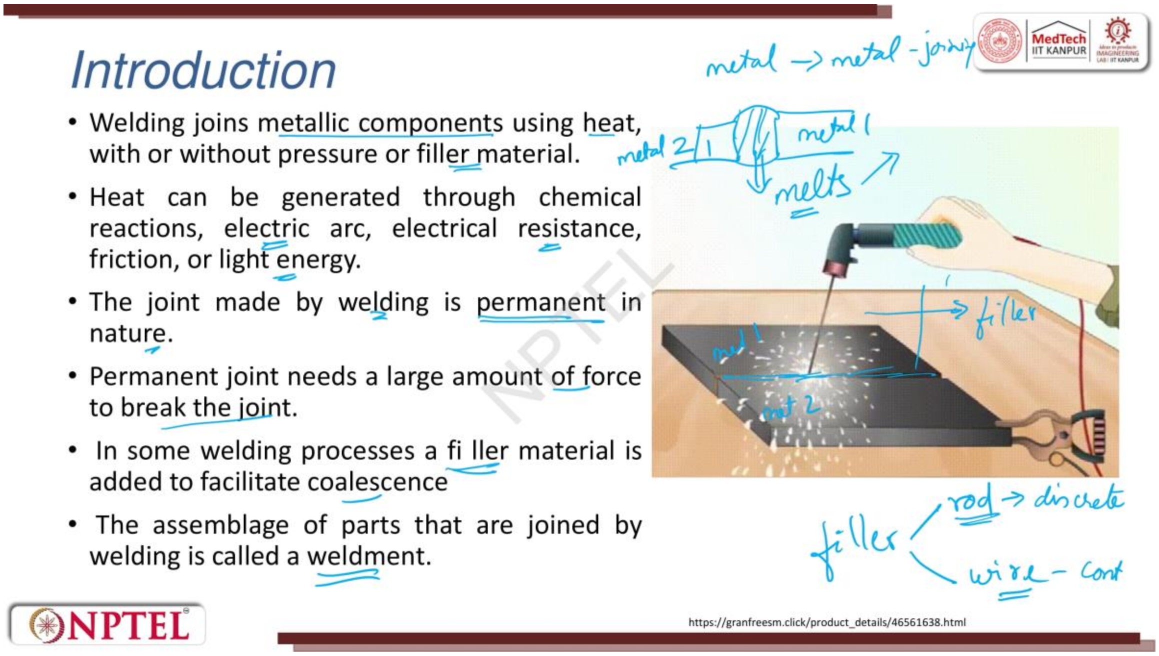
https://tristatefabricators.com/types-of-welding/

The content of this lecture is going to be an introduction, a small history. I always try to cover a small history because you would like to know how did this evolve. Today we are in a very advanced stage. If you look at IC chip where in which a small legs are joined, very small, very nano it is joined. So, if you understand the history, you will also see how did the history grow and where are we today. So, history, then the classification of welding process.

It is not only one process like in casting we saw many, in forging we saw many, in welding also we see many. Then fusion welding, solid state welding, gas welding, these are all falls under the classification. Applications and the welding process also has lot of inbound defects. We will see few of them. Then once the defect happens, how do you inspect.

And what are the inspection methods we use to check the defects. So we will see that and finally we will try to have a recap of welding process itself. Ship manufacturing involves welding. And if you look at it pretty interesting, submarine, when they have some small rework to be done on the base or ship it has to be done. Then the same welding has to happen underwater.

Look at the challenge. Underwater, they also do welding. In open atmosphere, they do welding. On tall structures, they do welding. The Statue of Unity, which is in India, has many rods joined together by welding. The Howrah Bridge involves welding. So, welding is a very interesting and important process.



What is welding? Welding means joining metallic components. When we have metals, we generally try to apply heat,

with or without pressure or filler material. What we are trying to say is, welding is metal-to-metal joining. The first point. When two metals have to be joined. So now we have to look into how this metal will join with the other metal.

One, you can apply enormous pressure, and it will join. Which is elastic, plastic; you enter into the plastic zone and then you apply. The pressure can be applied and kept for a longer time, or the pressure can be applied by impact load. For a short instance, pressure joining. If I cannot generate so much pressure, then the other way around is to apply heat and try to melt.

When I melt, the material softens. It will not go to the casting stage, completely making a bucket of molten metal. Here at the edge, there will be softening, a little bit of going down or going up toward the melting point. It will be there, and then we try to join. When we try to join, you can again apply pressure, or it can be joining without pressure.

So that is what we talk about, friends. The welding process is also common for polymer joining. Though in this course, we will not cover polymer joining. But polymer-to-polymer joining also happens by a process called welding. The only difference between metallic components and polymers is the temperature involved.

And you should also understand that thermosets cannot be joined. So it will be either thermoplastic or it will be elastomer joining. So, joining is not only for metallic materials, it is also for non-metallic ones. Joining metallic components uses heat with or without pressure. And here, until now, I said it is only by applying pressure or by applying temperature.

But now, what I am trying to introduce is one more component: I put an intermediate phase in between and then I try to join. So the function of the intermediate phase, the black—whatever I have here, the pen—is an intermediate phase. If you see it like this, it is an intermediate phase. The intermediate phase can be another material. That material is called a filler material.

So the advantage here is the filler material. So you have one metal, you have another metal, and you have filler here. So now this is metal 1. It can be the same metal or it can be a different metal. Then it has a filler in between.

This filler material alone melts. And then it tries to join both the pieces. So, for example, I have two hands. Assume that I am the filler material. I fill the gap and attach myself to the two metals.

It can be the same metal or it can be a different metal. For example, it can be metal 1 and metal 2, or it can be metal 1 and metal 1. So that means it can be a homogeneous material. It can be a heterogeneous material, or I will put it in simpler terms. It can be similar material or dissimilar material.

So here, the filler—you can always choose what the melting point will be. When we do soldering, the melting point is extremely low. Just above room temperature. When you talk about heavy metal welding, the temperatures go very high, depending on the melting point of the filler.

The heat can be generated through chemical reaction, electric arc, electric resistance, friction, or light energy. So now, I said the heat will be applied. Now, how do you apply heat? I can apply heat through a flame. When I apply it through a flame, what happens?

The flame diameter is very large. So now, when it is large, what happens? Then you have to use a large amount of filler material. Or there will be more melting happening at the joining portion. So now, what we do is we change the flame to an electric arc, which is focused.

Now, from that, if I want to have much more focus, I try to have a plasma, a photon—that is, light energy. So I apply electric arc, electric resistance, and light. And it is not only this, because if you try to apply electric arc, flame, and light, it is going to be energy-consuming. So now, I also can generate heat by friction.

Friction can generate heat. Now, between the two surfaces, if I rub them, heat is generated. And when the heat is sufficient enough for these two metals to join, then friction can also be used. Today, we talk about friction stir welding.

What we do is we have two metals to be joined, and there is a rod or a tool which goes in between. And it tries to create friction between the two materials. So friction works the other way around. The difference between arc and resistance:

I can place two pieces together and apply a high current. So now the current passes through them, and due to the resistance and Joule heating effect, the joining can happen. This is electric resistance. When I have two electrodes, I heat them, and there will be a discharge happening. Through this discharge, there will be melting—an electric arc. Finally, a chemical reaction occurs.

When I try to take two electrodes. Different chemical compounds and mix them together. There can be two types of reactions. One is an exothermic reaction. The second one is an endothermic reaction.

When I have an exothermic reaction, explode, expo, exothermic reaction. Then the exothermic reaction tries to heat the metal which is in the vicinity. So that heat takes it to melting and joining can happen. The railway tracks are done by chemical reaction. So these are the possible ways you can try to apply heat.

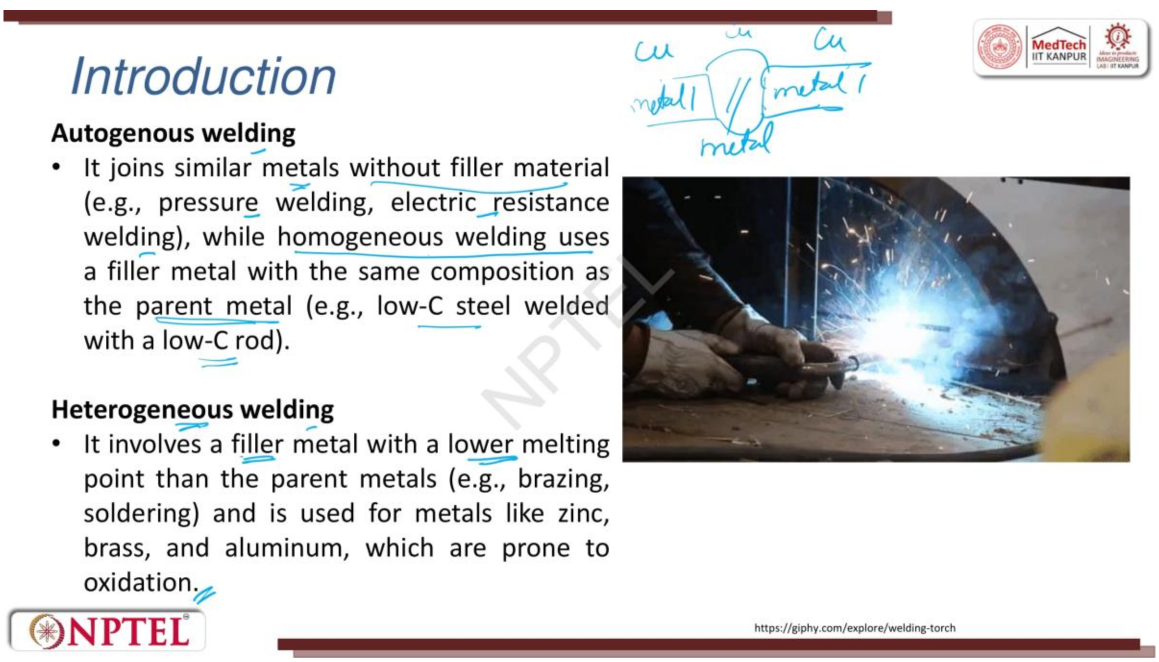
So when I apply heat, when I apply pressure, or both between two metals, I can join them. So that is what is told here. The joint may be welded and is permanent in nature. So, why am I putting this permanent point here is because whatever joining happens, it is permanent.

It is not like your nut and bolt. Finally, if you see, I want to join two pieces. I can always drill a hole, put a bolt and a nut and join. When you are trying to do many of the assembly in automobile industry or in cycle. You will see lot of temporary assembly is done.

Nut and bolt will be used. But when we use welding, it is called as permanent joining. Permanent joint needs a large amount of force to break the joints. In some welding process, a filler, that is what I said, intermediate metal is used to facilitate the coalescence. The assembly of parts that are joined by welding is called as weldment.

So here you can see there is an electrode. This is an electrode which is there. This is a filler material. This is a filler material which goes. This is metal 1 and this is metal 2 which I was talking.

And here there is a circuit which is there. So there is a flow of electrons happens like electric arc. There is a flow which melts the filler and the material is getting filled between this region. This is how we try to do ship, rocket and other large assemblies.



So, there are majorly two different types of welding. So, autogenous welding and heterogeneous welding. In autogenous welding, similar metals without filler material is joined by applying pressure electric resistance welding. So, is it clear? So, we are trying to join metal one and metal one. Mild steel, copper, titanium, stainless steel.

Similar metals are joined. But without adding a filler. I don't add a third party inside. It is without that I try to apply heat and then join. Or I try to apply pressure and then join.

While homogeneous welding uses a filler material with the same composition as the parent material. Is that clear? So, autogenous welding, no filler. Homogeneous welding, same composition. That means to say, I use metal 1 and the filler is also metal 1.

For example, I take copper and then I use a filler also made of copper. I use aluminum, titanium, or stainless steel. I am giving an example. So, while homogeneous welding uses a filler with the same composition as the parent material. Low-carbon steel is welded with low-carbon rods.

The filler, if you see in the previous one, is a rod. So, the filler can be either a rod or a wire. When it is a wire, it is continuous in nature. When it is a rod, it is discrete. What is discrete?

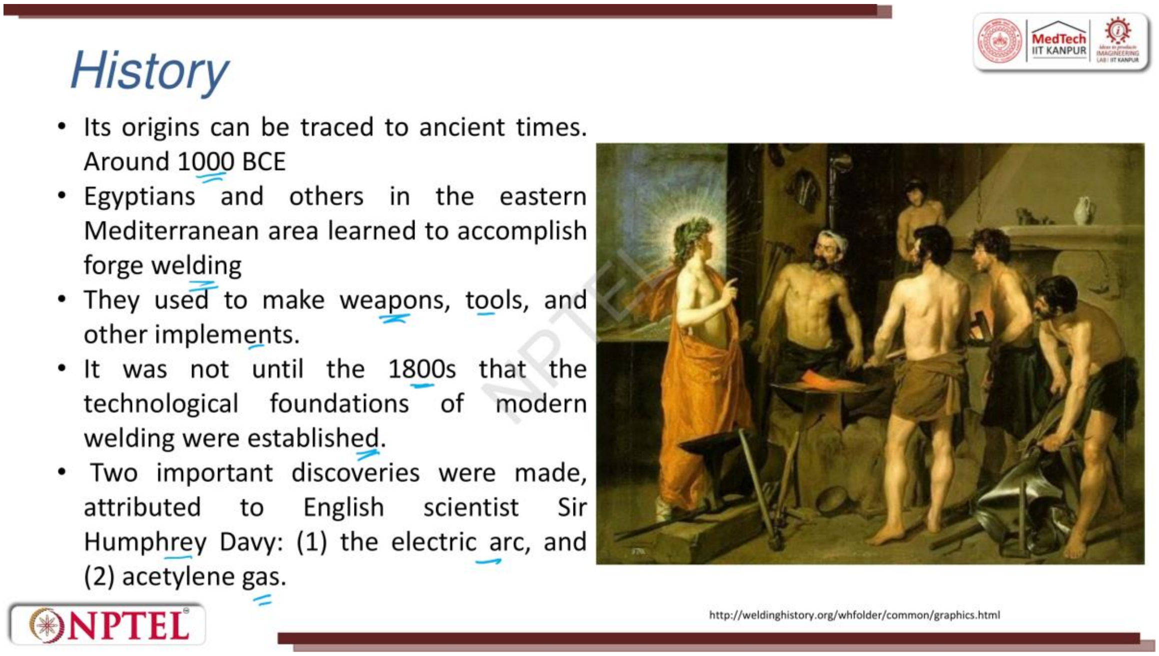
As and when the stick moves, see when you try to create an arc. There will be a melting phenomenon happening. The melting phenomenon will allow the filler to be placed in between the two joining metals. So once that happens, it is like a pencil; you sharpen it, and the length keeps reducing. In the same way, the filler rod also keeps reducing.

So after the filler rod is consumed to a certain length, you replace it. It can be a few minutes, or it can be a few tens of minutes. So the filler gets consumed. So if you want to have continuous welding, then we start using a wire. Heterogeneous welding.

It involves a filler metal with a low melting point. Heterogeneous welding uses a filler material with a lower melting point than the parent metal. And it is used for metals like zinc, brass, and aluminium, which are prone to oxidation. So in heterogeneous welding, the important points are: the filler is used. The filler need not have the same composition as the parent material.

It is used in zinc, brass, and aluminium because of aluminium. When you heat it to a certain temperature, oxidation happens immediately. Because of that, what we do is we do not try to melt the parent material. But we only try to play with the filler material. Brazing and soldering are all examples of heterogeneous materials.

So now I am sure you will be able to see the difference between autogenous, homogeneous, and heterogeneous. Autogenous means I do not use a filler. Homogeneous means I use a filler of the same composition as the metals I have to join. Heterogeneous means I use a different composition to join. Why do I do this? Because I do not want to change the parent properties of both metals.



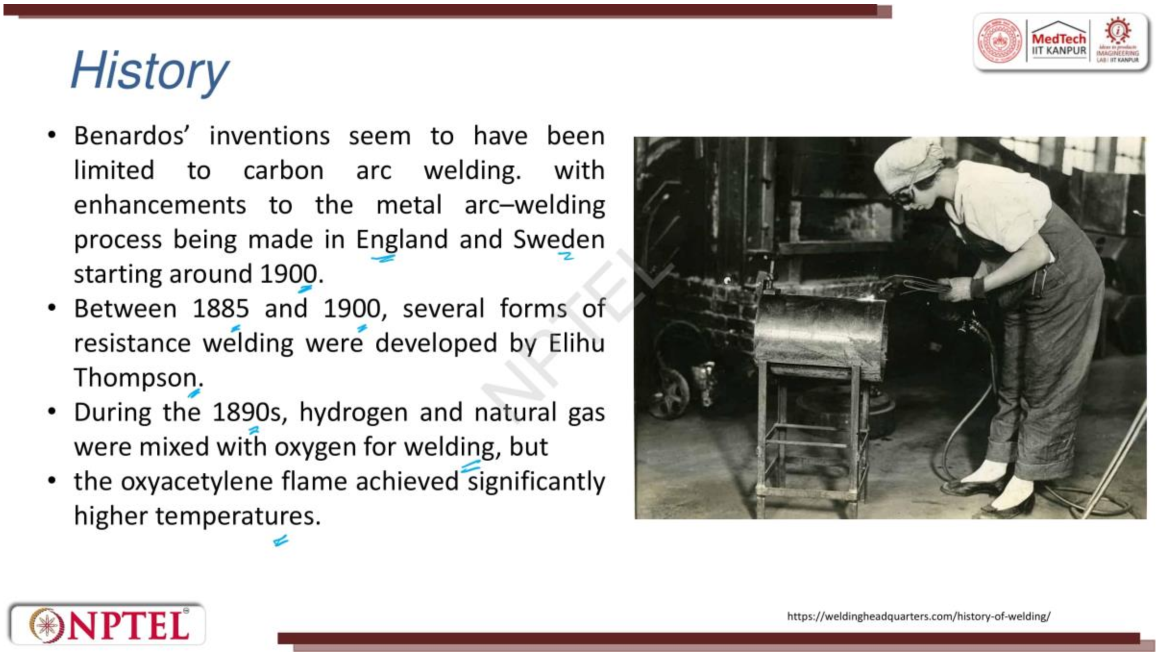
Let us get into history and see why. How did welding happen or when did it happen? Its origin can be traced to ancient times around 1000 BC. Egyptians and others in the eastern Mediterranean area learned to accomplish forge welding.

That means they had two different materials. They placed one above the other or beside each other and applied huge pressure. What is the pressure? See, in those days, there were no machine tools. There were no machines.

So, they used to do it manually, or what they did was always try to apply an impact load. Impact load means they would try to use a heavy wheel. They would rotate the wheel, and once the rope tried to lift a stone or something, it would go to a higher distance, from where they would instantly release it. So, drop forging was extensively used, or they would beat it repeatedly and then forge it.

They used to make weapons, tools, and other implements. It was not until the 18th century that the technological foundation of modern welding was established. It was done primitively, and in those days, they were always interested either in artifacts or in artillery. They were always trying to make weapons or tools for whatever reasons they needed. Two important discoveries were made, attributed to the English scientist Sir

Humphrey Davy. One is electric arc, and the other one was acetylene gas. So, these two things brought a big difference in the welding process.

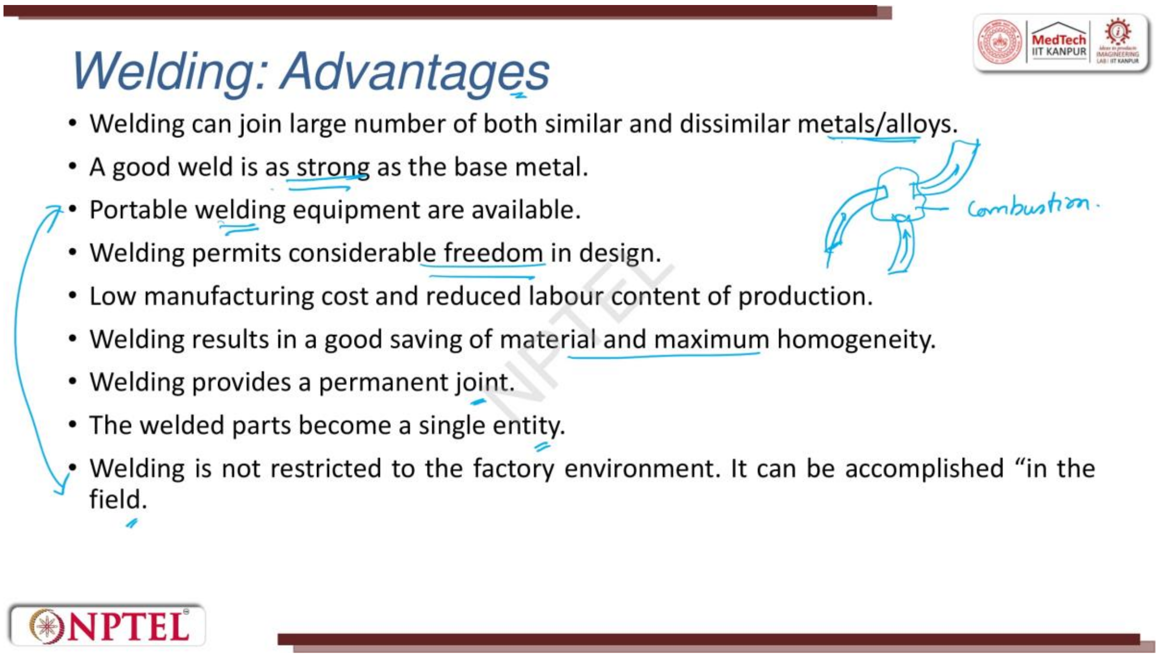


Bernard Doss's invention seems to have been limited to carbon arc welding with enhancements to the metal arc. The welding process was being made in England and Sweden starting around the 19th century. Between 1885 and 1900, several forms of resistance welding were developed by Thomson.

Why? Because electric energy generation was slowly trying to gain a hold on it. During the 1980s, hydrogen and other natural gases were mixed with oxygen for welding. That is what I said: oxyacetylene flames were used. But the oxyacetylene flames achieved significantly higher temperatures.

So, there are two things that happened in parallel. One is electricity, electric and resistance, and other things were going on. And the other way is people started using gas. They started mixing gas, understanding the flame characteristics, and taking it to a higher temperature. They were now looking into whether they could go for homogeneous or heterogeneous welding.

So, the major problem. Evolution or development happened after 1880 and maximum we could reach by 1950. After that, we started doing delta x improvement in the welding process and lot of hybrid process was also evolved. So, this is a small history. So, I thought I should bring it to you. So, you can understand it.



So, now let us see what are all the major advantages of welding. By this time, you would have yourself perceived. Some of the joining process which is around you. So, welding can join large number of both similar and dissimilar metals alloys.

A good weld is as strong as the base material. Please do not think that when I try to fill a material. I will not get the same strength as the parental. No, you will get the same strength or sometimes you can get much higher. Many a times when we do a welding test like UTM, universal tensile testing you do.

You will see that the weld will be exactly placed as the metal gets fractured. The portable welding equipments are also available. So that means to say on-site preparation. This a typical example is any construction industry. If you see for example house construction, heavy engineering like making a ship, a plane, a boat, heavy engineering.

And then you there you see the welding equipment is transportable. So moment it is transportable then it gives you much bigger advantage for example train engine, right. You always do lot of welding there, so portable welding equipments are available. So the source for joining is possible when you use heat pressure means again you will have a problem. But only heat portable came into existence that means to say you can think of electric or you can think of gas.

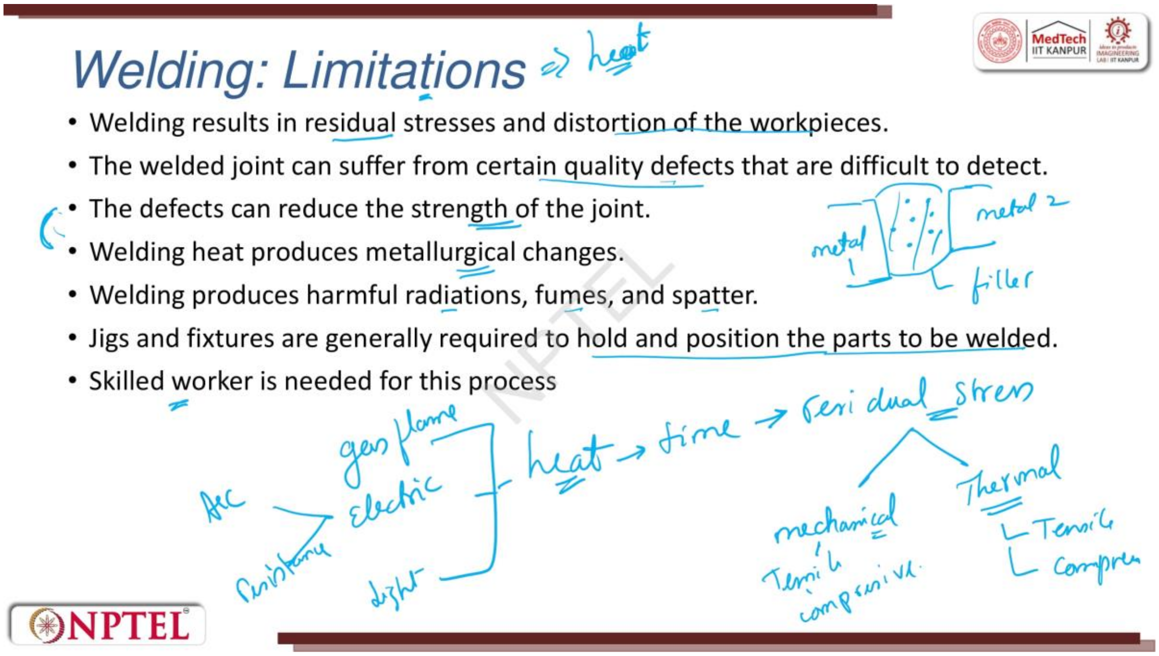
Or you can think of light or as the heat source for joining. Then welding permits considerable freedom in design. For example, you have a structure like this. There are pipes, right. So, you want all these pipes to be joined.

Maybe there is a flow from this portion, there is an exhaust, there is one more flow happening here. Assuming that here, there is a combustion happening. So, you see here, there can be a different design and they can be from multiple directions. Like it can be something like this. So one from this direction, one in this direction, one in this direction.

They all get joined at the base. So welding permits considerable freedom in design. Low manufacturing cost and reduced labor content of production. So that is why welding is now trying to be used exhaustively. Welding results in a good saving of material and maximize homogeneity.

Welding provides a permanent joint. Welded parts become a single entity. Welding is not restricted to the factory environment. It can be accomplished in the field. So this point and this point are linked.

Portability plays a very important role. You can start using it anywhere. So, these are the advantages. For example, you cannot take a rolling machine and start producing on-site. It is difficult. Because there, only pressure is involved, and that has to be in a machine environment.



So, what are the limitations? The limitations are that it results in residual stress and distortion in the workpiece. Why? Because there is a component called heat.

Heat is linked with time. If you instantly release the heat, the time is too short. This leads to residual stress. Residual stress can be of two types. One, it can be mechanical in nature.

The other can be thermal in nature. Thermal in nature also leads to both tensile and compressive stresses. Mechanical forces also lead to tensile and compressive stresses. It can be like this. So when I bend it, it is mechanical.

The outer portion undergoes tension; the inner portion undergoes compression. The same way, residual stress also happens. When the heat is instantly released, the metal can be pulled and joined, or it can be. When it is pulled and joined at the top, it is tensile, or you can say compression. So then the bottom undergoes tension.

So residual stresses are prone to happen because we are trying to use heat. Distortion also comes into existence. Why heat? Because the heat comes from a gas flame. You can use it for joining, or you can use electricity, in which you have two things.

One is arc. The other one is resistance. and here you can try to have light as photon. So, because of the three, there is a heat, heat with respect to time. And so that leads to distortion, that distortion leads to residual stress.

This is one of the biggest limitation of welding process. So, sometimes you can see a heavy plate welded and later it will warp. It will bend, that is because of welding difficulty. The welded joints can also suffer from some quality defects such that are difficult to detect. So, what happens is when there is a melting and flowing of metal between the two plates to be joined.

There can be very small types of pores, right, between this. This is the filler material. This is filler. So here when you try to pour there can be oxygen which is there or while pouring there can be difficulty in while solidification. Also these pores can happen which we saw in casting.

So, these are some of the small defects which are extremely difficult to detect by any non-destructive testing methods. Unless you slice it, put it under a microscope, zoom in, and observe, you cannot see such small defects. So, that is what we try to say. So, certain defects are prone to occur, which are very difficult for us to see. So, that leads to poor service performance.

The defects can reduce the strength of the joint due to the heat involved. The strength of the parent material can decrease. When heat is involved, metallurgical changes also occur. These two points are linked. The weld produces harmful radiation, fumes, and spatter during the joining process, as you can see here.

You see there is spatter happening here as well as here, something like a Diwali pataka. You see, that is called spatter. So, spatter is a blast of liquid that spreads out. So, fumes, radiation, and spatter can be present. Jigs and fixtures are required to hold and position the part for welding.

So while welding, what happens? Sometimes while welding itself, there can be distortion happening. So there can be, because of the liquid which is getting filled. There can be a buoyancy force which will try to move the plates, the parent material to be joined. So this has to be avoided.

So what do we do? We try to place it in a jig and a fixture. A fixture is to hold. A jig is to guide the tool. So we need jigs and fixtures such that it can be done.

Sometimes it needs a skilled worker to do the operation. For example, underwater welding. It always needs a skilled person. A normal man cannot do it. And when we are trying to do brazing, soldering, where you are trying to join very thin wires, thin sheets.

Again, you need to have a skilled person. So, that is what the So, by and large, the limitation revolves around heat. That is it. Heat leads to residual stress, heat leads to defects, heat tries to change the microstructure.

Because of the change in microstructure, the strength goes down. Because of the heat, radiation fumes and spatter occur. So, because of the heat, you need to hold it properly. So, all these things are related to it. And welding, if you want to become a highly skilled welder, there are several trade tests and certifying agencies.

What we do in the engineering college and practice is only an exposure. If you want to become an expert, there are certifying agencies; you have to undergo several tests. They check the theory as well as the practical to make you a skilled worker.

Where are the applications? Pressure vessels—I did not touch on this topic. Pressure vessels are boilers. You can see where the steam turbine is connected, electricity is produced, water is heated, and the heated steam is pushed in. This pushed steam hits the turbine, the turbine rotates, then it is attached to a generator, and you get electricity. So, pressure vessels. The other thing is you can also see them for storage purposes, such as storing fuel energy.

For example, I have several tons of wheat that need to be stored. Then what do I do? I make something like a big vessel and fill it up with grains. I protect it from the environment. So you need a huge container.

That container cannot be made by forging or rolling processes. It will be done piecemeal and then attached. Bridges and buildings are other major applications you can see. Then you can see aircraft, spacecraft, and shipbuilding are part of it. Here, building refers to civil construction, and here it is shipbuilding.

Then in automobiles, where you have different shapes. So in automobiles and electronic components, we use a lot of welding processes. Defense transportation tankers use welding processes. Then welded pipes, chains, and LPG cylinders also use welding. The steel furniture, doors, refrigerators, ovens, etc., which are household items, also use welding.

The only difference between the high-end and the low-end. That means to say, pressure vessels and refrigerators differ in the amount of heat involved. And the technique we use. So, in all places, we try to use welding. And here, I am trying to demonstrate and show how a robot can be used.

Because today we talk about cobots, collaborative robots where humans and robots can work together. What a man was doing, now a robot will do the same operation, and you can try to get the best out of it. So you can see here critical portions where a man is involved, where pipe joining is done by a robot. And it is by a single robot, and here you have multiple robots. So, parallelly two things can be done.

This is what I was trying to talk about, the chemical. We in the railway track, you fill it up with some chemical, expose it to heat, and an explosive reaction occurs. So there will be heating there, melting there, and joining happens between the rails.

Welding Science

⇒ microstructural change ⇒ Phase change ⇒ mechanical pt

Power Density

- For metallurgical reasons, melting the metal with minimum energy is desirable, and high power densities are generally preferable.
- Power density can be computed as the power entering the surface divided by the corresponding surface area: $\boxed{PD = \frac{P}{A}}$ → laser ↑ → Electrical + gas flame.

Where, PD = power density, W/mm²(Btu/sec-in²)
P = power entering the surface, (Btu/sec); and
A = surface area over which the energy is entering, mm² (in²).

Welding Process	Approximate Power Density W/mm²	Approximate Power Density Btu/sec-in²
Oxyfuel welding	10	6
Arc welding	50	30
Resistance welding	1000	600
Laser beam welding	9000	5000
Electron beam welding	10,000	6000

So everywhere you look, there is a component called power density. What is the energy I apply per unit area such that the welding process can happen? It can be heat, it can be through forging, or it can be a combination, whatever it is. For metallurgical reasons, melting the metal with minimum energy is desirable. Why? Because there is always a microstructural change. Microstructural change leads to phase change.

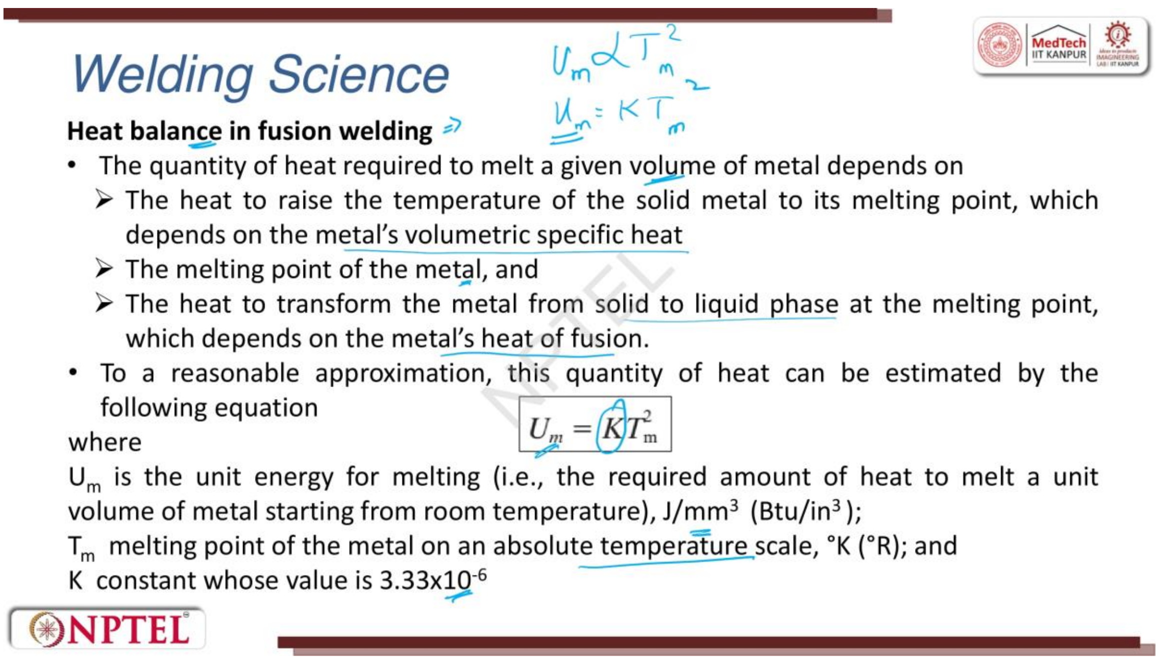
This phase change, in turn, dictates the mechanical property. So, that is why we always try to use minimum energy in doing the welding. So, melting the metal with minimum energy is desirable, and high power density is generally preferred. What is high power density? Power applied per unit area.

So laser has the highest power density in heat as compared to that of electrical and gas flame. The power is very high. The power density can be computed as the power required or power entering the surface divided by the corresponding surface area. So the power density is generally reported as watt because power is in watts, joules or watt divided by area, millimeter square. So power is entering the surface is P, the surface area over which the energy is entering is A.

So you can see here oxyacetylene flame. What is the power density? Then arc welding, this electric which I said is around about 50. Resistance welding is around about 1000. Resistance welding is what?

You join two metals and then you apply a current passes through it, joule heating effect, resistance welding. You see laser, it is around about 9000. And you see electron beam. Electron beam and arc welding are different. Arc welding has a lower resistance power density.

Generally what we do in construction industry and all we use arc welding processes and laser is used in in a company. Where the component size is small or you need a precise control we use laser beam. Where the power density is around about 9000 W/mm^2 Electron beam is used for joining of electronic materials, thin sheets or thin electrodes or thin legs they use. Here it is very high. It is done in a vacuum and it is very high. So you need to know this.



Which one do I choose such that I can try to bring the efficiency in the welding process? So then that the power density leads to heat balance. We will see fusion welding next, but heat balance now you can try to take in welding, just keep that in mind.

The quantity of heat required to melt a given volume of metal depends on. I have a lump, this lump has to be melt such that it flows inside or it has two metals it joins. So all I have to know is what is the volume I have to melt such that these two fellows can join. So there what we do is the heat to raise the temperature of the solid metal to the melting point. Which depends on the metals volumetric specific heat.

At what heat the change of phase happens. Then the melting point of the metal. Then the heat to transform the metal from solid to liquid phase at the melting point. Which depends on metal heat of fusion. So, approximately the quantity of heat can be estimated by this equation.

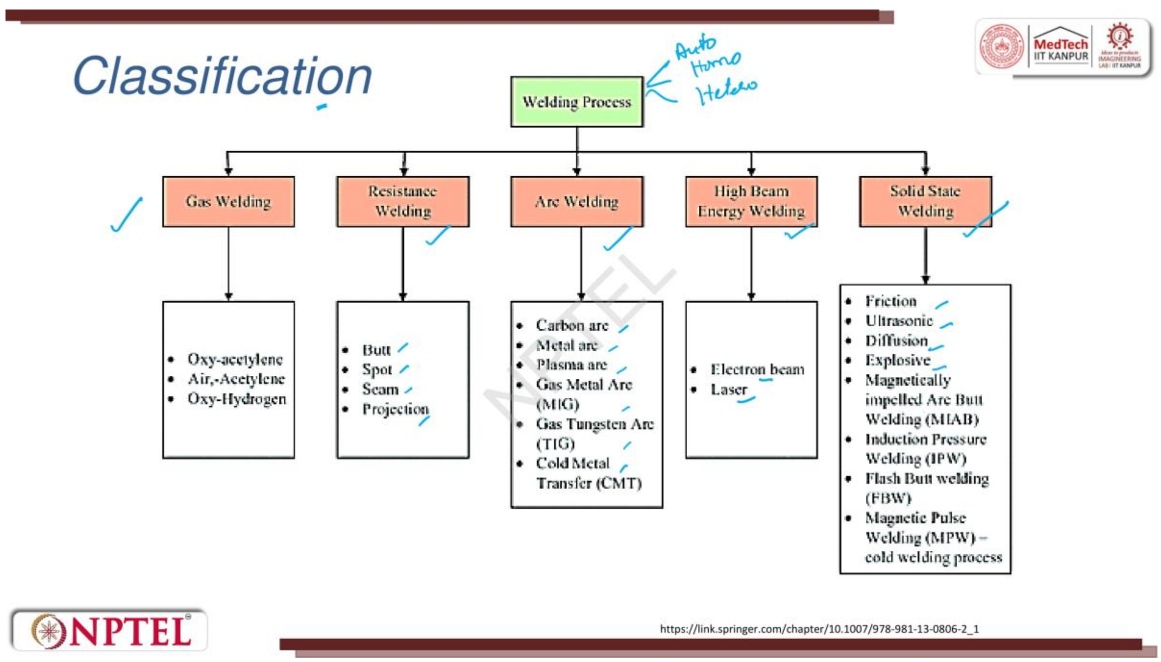
Which is unit energy required for melting, right. That is, the required amount of heat to melt a unit volume of metal starting from room temperature. Which is generally reported in J/volume, I said, mm^3. Then which is equal to K times, K is a constant which takes a value of 3.33×10^6. This is an empirical value.

They did lot of tests and then they have found out what is the K value there into Tm^2. What is Tm^2? It is the melting point of the metal on an absolute temperature scale which is in degree Kelvin is reported. So, generally what we say is $U \alpha Tm^2$, but you have to remove the proportionality. So, we try to introduce a terminology called as K through which what we try to get is we try to find out the unit energy required for melting.

Welding Science

Metal	Melting Temperature °K[a]	Melting Temperature °R[b]	Metal	Melting Temperature °K[a]	Melting Temperature °R[b]
Aluminum alloys	930	1680	Steels		
Cast iron	1530	2760	Low carbon	1760	3160
Copper and alloys			Medium carbon	1700	3060
Pure	1350	2440	High carbon	1650	2960
Brass, navy	1160	2090	Low alloy	1700	3060
Bronze (90 Cu–10 Sn)	1120	2010	Stainless steels		
Inconel	1660	3000	Austenitic	1670	3010
Magnesium	940	1700	Martensitic	1700	3060
Nickel	1720	3110	Titanium	2070	3730

So, for various metals, what are all the melting temperatures? We have just reported aluminium alloy, which is around 930. When you try to go towards brass and all, it is around 1160. Nickel is 1720 Kelvin. Titanium is around 2070 Kelvin.



Now, let us try to look into the classification of welding processes. Welding has several classifications. One is gas welding, depending upon the heat source—gas welding. Then it is resistance welding. Then it is arc welding, which is extensively used.

Then it is high-beam welding. Then solid-state welding. There are five categories. Gas welding, where the heat source is extracted from a gas. So we can have oxyacetylene, air acetylene, or oxyhydrogen as the heat source.

Through which you generate heat that tries to melt the material. Resistance welding is when we try to create resistance between the two metals to be joined. It can be a butt joint, spot joint, seam joint, or projection joint. In projection joints, there will be projections you can join together by resistance. So, projection joints.

Arc welding can be carbon arc, metal arc, plasma, gas metal arc, gas tungsten arc, or cold metal transfer welding process. They all fall under the arc welding process. The high ones I mentioned are laser and electron beam, which we already discussed a little bit in the past. Then, I will try to talk about fusion—sorry, solid-state welding process. In solid-state welding process, you can have friction or ultrasonic.

Friction generates heat, right, by friction. Ultrasonic is when you try to again— Agitated at a very high temperature, 21 kHz, with a small displacement to get— Then diffusion, explosive, or magnetic impelled arc butt welding. So that is also there because when you have a liquid source, molten metal, a liquid source.

You apply a magnetic field, then there is a Lorentz force which is created. And the metal will be thrown off. So the magnetic field also plays a very important role. Induction pressure welding process, flash butt welding process, magnetic pulse welding, and cold welding process. So these are some of the solid-state welding processes which exist.

So when I talk about welding classification, I have already mentioned autogenous, homogeneous, and heterogeneous. The other classification is this.

Thank you very much.