Principles of Physical Metallurgy

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Lecture No. #42
Metal Joining

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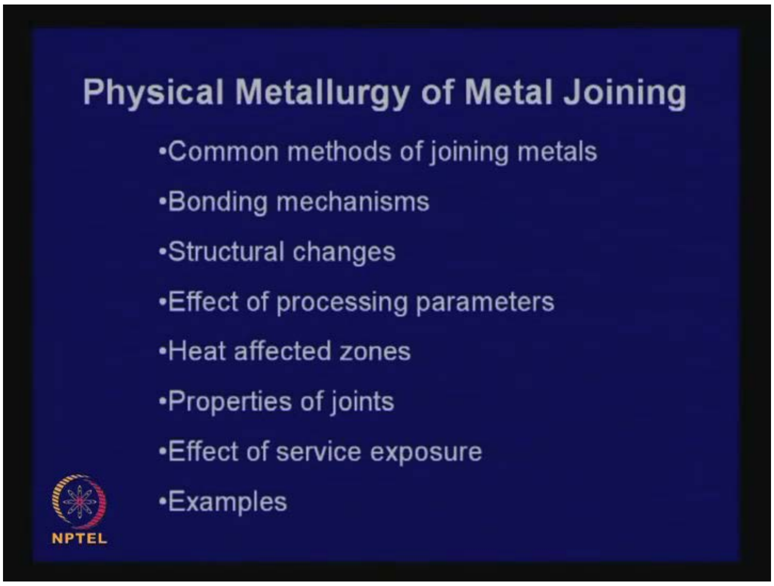

Good morning, in today's class we will look at physical metallurgy of metal joining. Now, under this, these are the topics we are going to look at. We will look at common methods of joining, although there are several methods of joining, we will primarily concentrate on wielding. We will look at the bonding mechanism; look at the structural changes, that take place during the process of joining, effect of processing parameters, how the structures get affected in the heat affected zone. We will also look at properties of joints and effect of service exposure and many of these we will be talking about with few examples.

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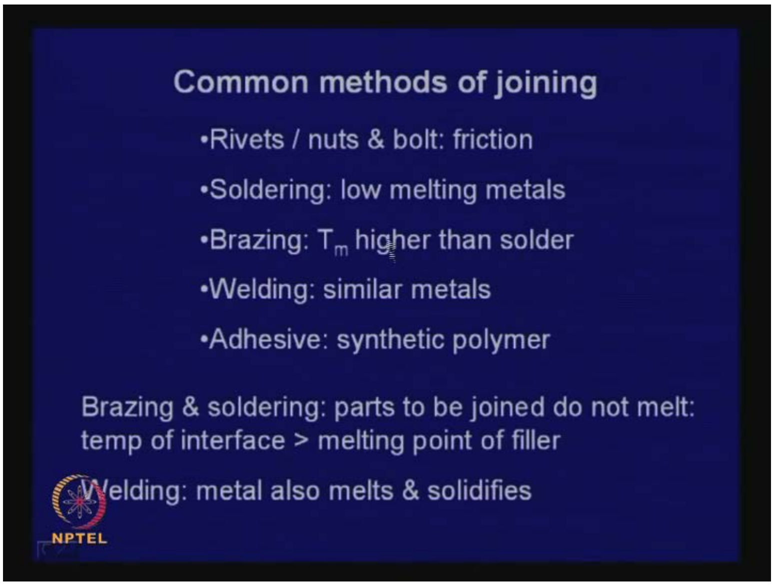

Now, the common methods of joining, these are listed here. Rivets or nuts and bolts here, that means, joining force is by friction, two parts held by friction and the force, the normal force is applied either by the rivet or nuts and bolt. Now, soldering, brazing and welding, here between the two joining parts we apply a molten metal. Now, here soldering the molten, there melting point of the molten, that metal that lies in the interface is very low, it is a low melting metal. In the case of brazing, we do use a little higher melting point metal, but it is definitely much lower than the melting point of the metal that we are joining.

Now, in welding, that melting point of the metal is close to that of the part that is being welded and in fact, a part of the, small portion of the parts, which are joined, they also melt to provide better bonding. Another way of bounding is adhesive, A 1 uses synthetic polymer, but primarily we will look at the structural changes particularly, that takes place during welding.

Now, brazing and soldering, here the parts in this particular case, we have just mentioned, that parts to be joined, they do not melt, that we will, temperature of the interface is higher, temperature of this interface is the, temperature of this interface could be, we will see, we will talk about is what should be the temperature of the interface with respect to the melting point of the filler.

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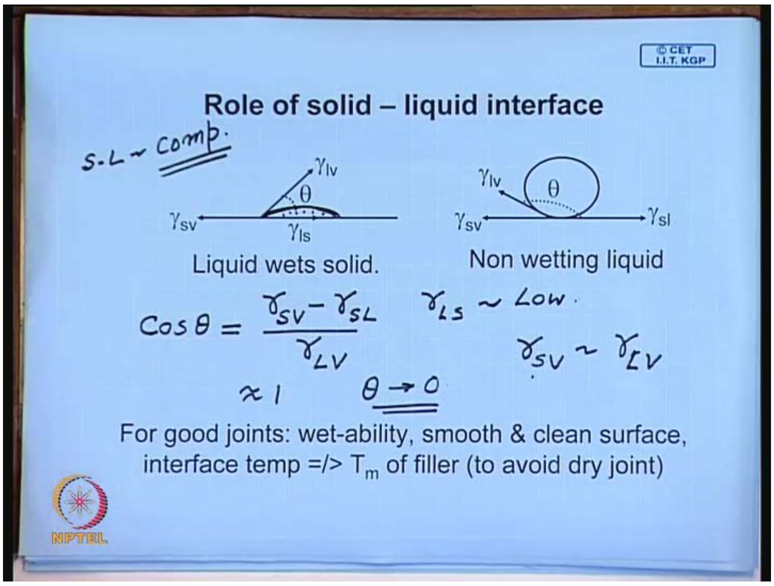

Now, to understand this it is quite important, that role of that solid-liquid interface is quite important. Suppose, this is the solid layer on which if you put a drop of molten metal, not depending on the surface tensions, the respective surface tensions, this is the solid-vapor surface tension, this is the solid-liquid surface interface energy and this is the liquid way for interface energy. And in fact, depending on their respective magnitudes, does angle at which, that wetting angle is actually a function of the magnitudes of these surface energies, and which is listed over here.

This is the expression, that it is just simple balance of force. If you balance the force along this axis, then this is the x component of LV, that gamma LV cos theta and they must be equal. And therefore, this wetting angle is a function of this surface tension ratio, the difference in the surface tension, solid-vapor minus solid-liquid over gamma liquid vapor. Now, if this is low, that means, theta is nearly equal to 0, then it is a good wet-ability and in fact, for good joining what need is the thin layer of molten metal between the two wetting surfaces. So, therefore, it must be wet-able.

Whereas this is an extreme case here, this is a non-wetting liquid and for good joints we need wet-ability and apart from the wet-ability we need smooth clean surface. And also, the interface temperature should at least be equal or greater than melting point of the filler, and this will help avoid dry joint. And a quick look, you know, it is quite interesting to look at, we will look at the magnitudes of the, relating magnitudes of this surface energy.

Now, in case of welding, you know, in case of a welding, the mean difference in wielding is, this is the molten pool of metal and the metal, that is solid and liquid, they have nearly same composition, this has same composition. So, therefore, it is very likely, that gamma liquid solid, this will be very low. So, therefore, if you look at the expression for that cos theta, which is gamma SV minus gamma solid liquid over gamma liquid vapor. Now, what we know, say this solid and liquid they are nearly same, so therefore, what we expect, that this is low and gamma SV is nearly equal to gamma LV, therefore this is nearly equal to 1, therefore theta will approach 0. So, therefore, welding, this is assured. So, whereas, in other cases you have to select the metal that you join, you know, you have to select, a choice of that filler metal also is quit important there and this case you have to select such a metal, so that it wets the surface.

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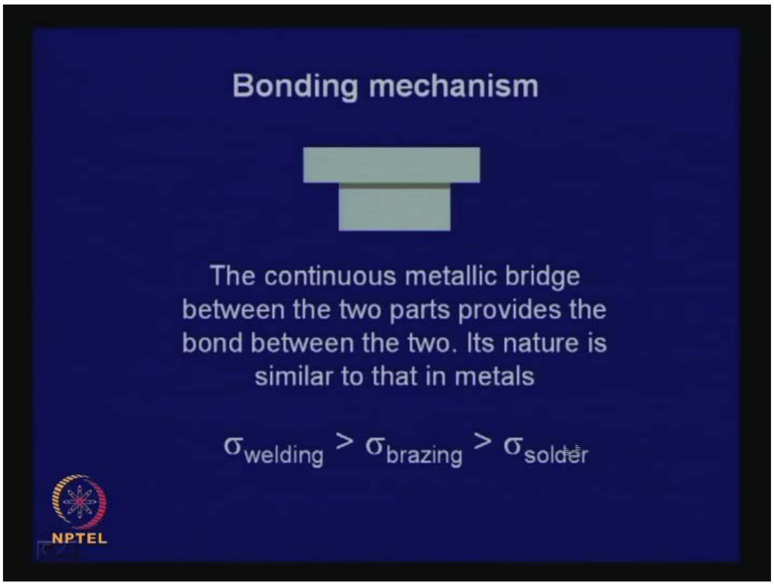

Now, this slide looks at, gives a, in the bonding mechanism, if it is a good wet-able, that filler metal, then this will spread easily along this and this and once it solidifies it forms a metallic bridge between the two parts, the joint. Therefore, bonding is essentially metallic. In fact, even if it is a solder joint, the melting point of the solder material is low, their diffusivity will be relatively higher, although you know, and they can, at the interface they can react with metals, form inter-metallic compound or it can diffuse through it, that interface and there will be a thin layer of diffusion layer and which gives the bonding. But nevertheless, the welding where the filler metal is almost similar to this and where part of this solid also melts, so their definitely the bond is going to be much, much stronger and in fact, if you look at that relative strength of the welding, bracing and soldering, you know, this will be in this order, this will be the strongest, solider will be the weakest.

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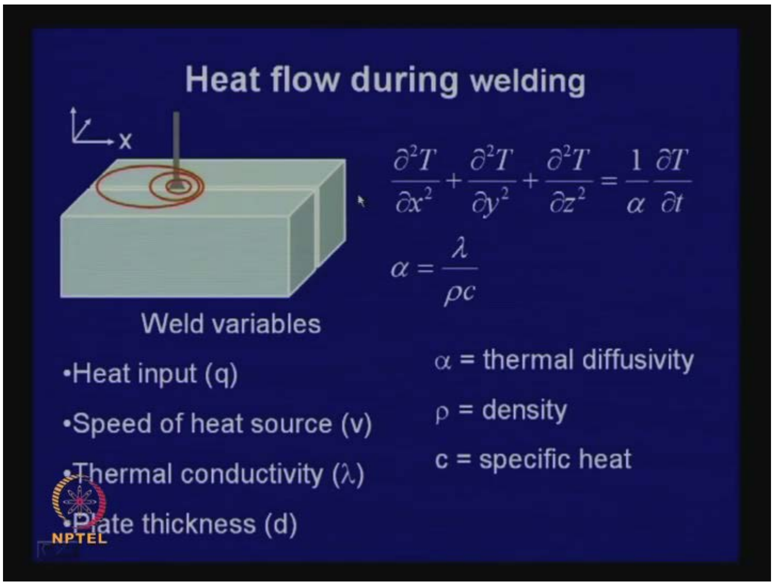

Now, to understand the process of joining what happens it is necessary to know, you know some amount, some idea about the heat flow that takes place during the joining process. And we will primarily consider the process of welding and in fact, the concept that we learn here can also be applied to other cases as well. And this is the famous, this primarily the metals, they are conductor.

The heat flow that takes place through metal will be primarily by conduction and this is the expression, general expression for heat transfer by conduction. So, these are, T is the temperature; x, y, z, this is the coordinate and in fact, this small t represents time and alpha is thermal diffusivity, which is a function of thermal conductivity over density times specific heat. Now, normally, so this is the expression, which is valid when the source is stationary. Say, suppose we strike an arc, do not move, so that is the time that this will give the temperature a distribution how it will change with time around that heat source. Now, but in real welding, there will be a speed, I mean, that heat source will be moving and let us say, that heat source moves with velocity v.

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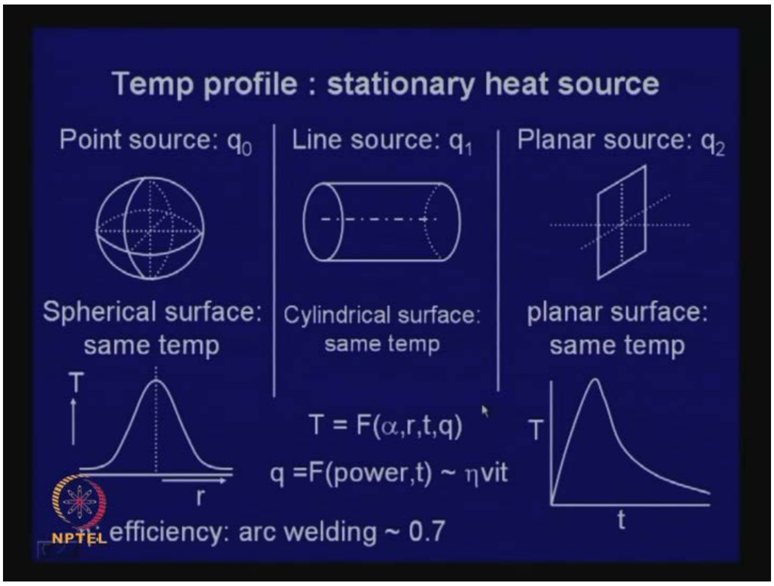

Now, in that case it is quite possible, I mean, quite easy to visualize what will be the temperature profile around the heat source. We consider three hypothetical cases, say it is quite possible to, I mean, from our physical concept it is possible to visualize what will the temperature profile look like around the source. Suppose, we have a point source, certainly a hypothetical case, say, which certainly within a solid, at a certain point we heat it to a very high temperature. Never mind, you know, what is the method of heating, this is a hypothetical case and in that case, the conduction, heat will flow by conduction in all possible directions and conductivity will assume, does not depend on direction, it is same that in all direction; the thermal diffusivity is same in all directions.

In that case, obviously, that temperature control will be represented by a set of spherical surfaces, they will be concentrate spherical surfaces and in fact, and we extend the same thing if we assume the source to be a line source. In that case, the contour, by applying the same logic, heat will flow in all directions on the surfaces. So, in fact, in this particular case the line sources, the surfaces will be a cylindrical surface, the constant temperature surfaces will be cylindrical surface.

Similarly, we can think about a planar source. If we have a planar source like this, in that case, this contour will be just planar surface, one after the other, but this temperature will therefore, you know, vary from this source, heat source with the distance with respect to the heat source. And this is, at any instant the temperature will be a function of the distance; temperature at a particular point will depend on the distance from the source, and this will be something like this. Similarly, at any point, the temperature will also go up because we are, we are just heating it and just withdrawing the source, some at a particular point the temperature will go up, reach a maximum and there, there after it will go down exponentially or something like this, it will go down something like this.

So, in, in general, what we can say? The temperature at a point will be a function of several factors. It will be the material parameter, thermal diffusivity, distance from the heat source, the time and the heat, that you have put in and how do you find the heat that you put in. So, this will be, say, suppose in case of welding we can usually, if it is an arc welding we can know the power that we put in, the power, that we will put in will be a product of voltage times ampere and the time for which we apply it times time. But this is the power we put in, but the material may not absorb whole of it and we can say, that efficiency of arc welding is usually, there is an efficiency factor eta. So, 0.7 is a rough efficiency of arc welding. So, in that way, we can we can get some estimate of q and let us see how do we use these concepts.

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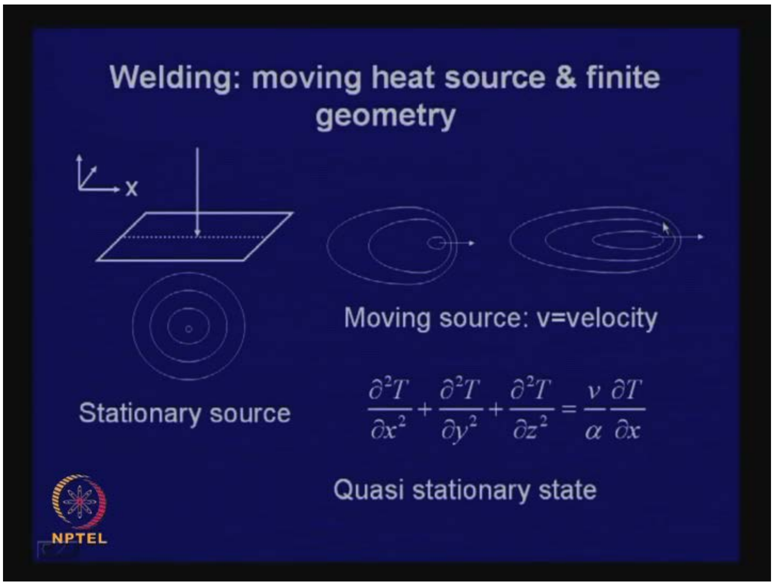

Now, in welding, the source it does not remain stationary, it moves. Say, if, if the source is stationary, suppose on this surface, here we have suddenly rise the temperature.

Thereafter, by applying the same logic if we try and plot the temperature contour on the surface, it will be a set of concentric circle and the center of this circle is the stationary heat source. Now, suppose, if we continue to move it, so if you move it, then you know, it, this will get distorted, say something like this.

In fact, that equation (( )) is possible to show is (( )), this velocity is v for a quasi stationary state at a particular time. Say, if we want to find out the temperature control, we can take it to be a quasi stationary, ignore the time part. So, this is the, the velocity term comes over here and physically what we can say, that this source, you know, we are pulling it like this, so heat source moves closer to these surfaces, therefore they will be at a higher temperature. So, here you know, it gets distorted like an elliptical, this kind of a distorted circle you can say and then it is a distorted ellipse. And in fact, here the contours are closer, means the gradient is high, in this side the gradient is low and if we increase the velocity, it will get again, you know, further elongated like this.

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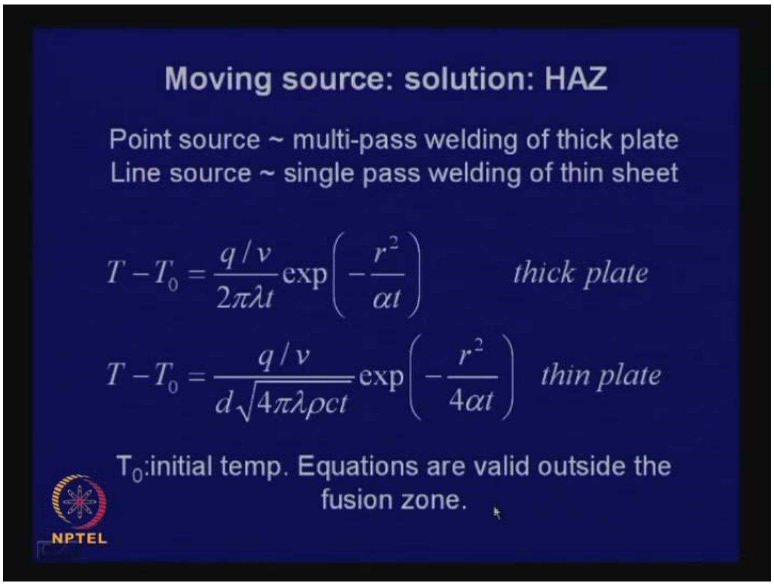

It is possible to obtain some solutions and a certain boundary conditions, like if we assume a point source and usually point source represents multi-pass welding of the plate. We will in little while see why then a line source will represent a single pass welding of thin sheet. And this expression, if you solve these equations and in r theta coordinates, in this distance cylindrical coordinate is possible to solve and this is the nature of solution that you expect for thick plate.

This is the expression, q is the heat input, v is the velocity, lambda is conductivity, alpha is the thermal diffusivity, r is the distance from the heat source at a particular instant and t 0 is the initial temperature of the plate you are joining and these equations are valid outside the fusion zone.

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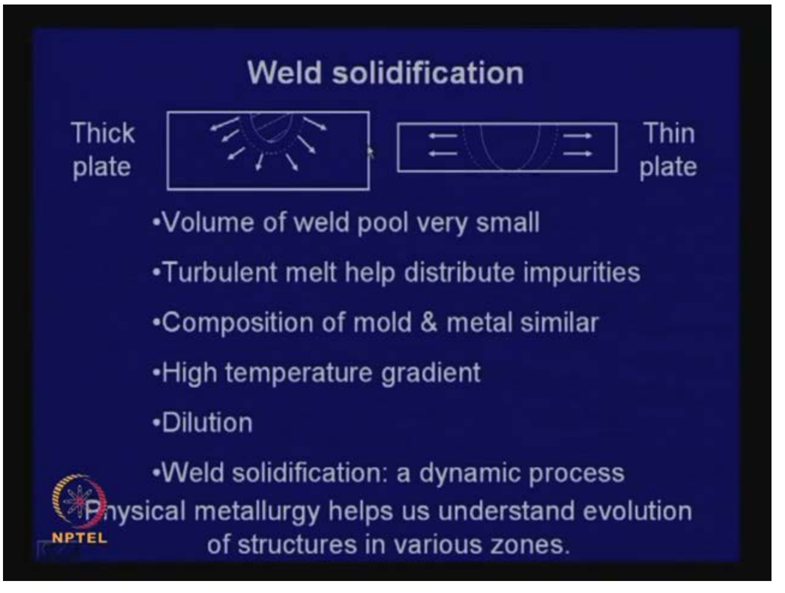

And schematically, that heat transfer is shown here for two cases thick plate. Now, thick plate, imagine, here this is the molten pool. So, this is the molten pool and surrounding, somewhere, you know, a thin layer gets melted and they get mixed up here. So, very thin layer over here where we will get a melt along with and get mixed up with the weld pool and here, the heat can flow in all direction through the thickness direction, in all directions it will move.

Whereas, so if you go back to the previous, what you see, that point source, this was more or less it is moving in all possible directions beneath, that beneathed arc. So, here, this represents a point source, whereas in the other case if it is a thin plate, then you know, this is the molten pool and the, it, it is the molten pool and the heat is flowing in two directions only. So, we will just look at this here.

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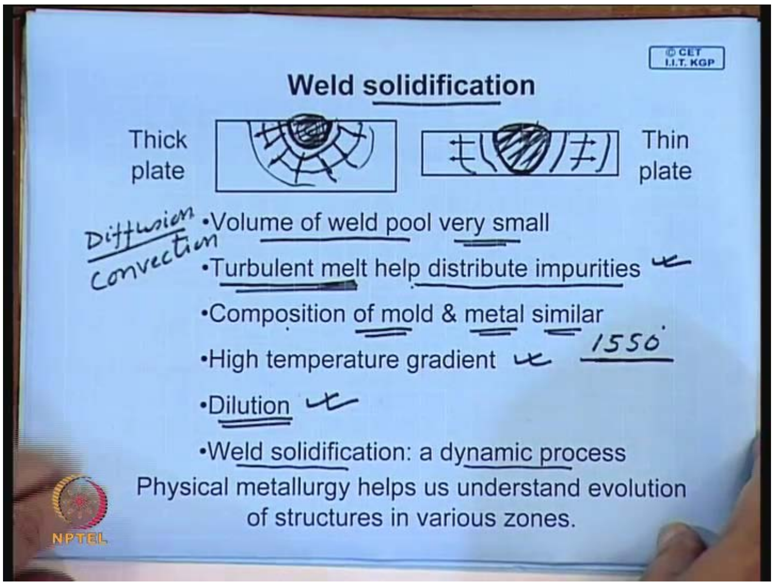

So, here you know, the, this is the molten pool, this is the molten pool. In fact, this will be slightly raised. So, here also, this is the molten pool, a thin layer beneath this solid will also melt and in this particular case, beyond this fusion zone heat can flow in all possible directions. So, we can visualize something like this, this we approximate as a point source with respect to the thickness of the plate and heat is flowing to all possible directions in the 3-D.

Whereas, in this particular case, this is the thin fusion layer and this is the molten pool and the heat is flowing in all possible directions. So, here, contours will look like this, temperature contours in this direction will look like this, here temperature contours will look like this. And now, the solid pool, that welding, that solidification in that weld metal is also quite important. This will depend on the volume of the weld pool. We can always assume, usually this is very small and that will be a turbulence and the melt helps good mixing.

Normally, we have seen in that alloy solidification mixing is quite important and, and in fact, if that mixing does not take place properly and if, if see, in the liquid the mixing can take place through diffusion, which will always take place along with that convection, convection or because of some starring force. Sometimes arc applies some force, so there will be some kind of agitation and circulation, so that a helps in a good mix up and it distributes the impurities. So, it is quite important, that turbulence in the weld pool is quite important in getting a good weld pool structure. It will also depend on the composition of the mold, so that is the metal, that, which is being joined.

And usually metals, we use similar metal as a fill metal, so they have some similar characteristics. There is also the solidification, in this case, is taking place under a high temperature gradient because the mould is made up of metallic, which has good conductivity and possibly, this may be in many cases at room temperature. So, the molten temperature is a 1500 or 1550 degree centigrade to room temperature. So, you can imagine, within a short distance such a high gradient existing. So, this also affects the structure that you get in the solidified metal.

Now, dilution is also an important factor. A part of this metal, which melts and mixes with the metal mould weld pool and this, is also quite important in forming good bonding. And well, solidification is therefore, it is a dynamic process and this physical metallurgy, whatever we have learned does help us in understanding the evolution of structures in various zones in a welded component.

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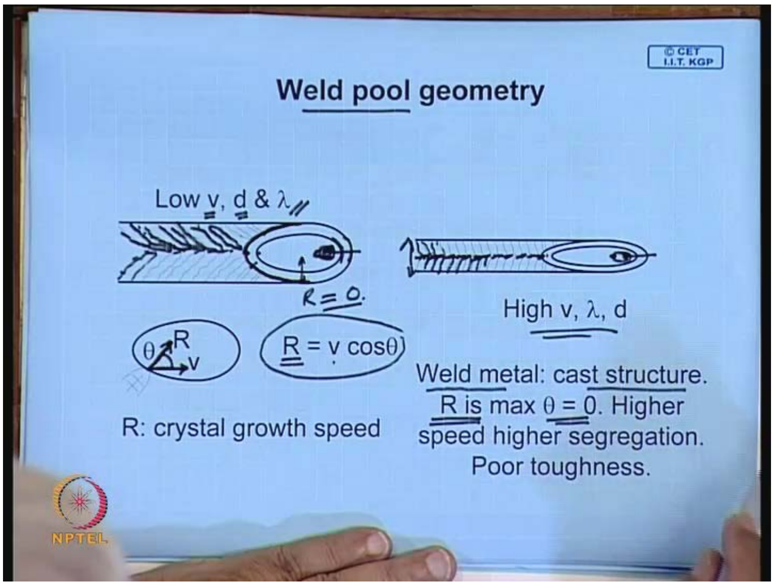

Now, if you look at that weld pool geometric, you know, say what will (( )) we have just, seen, that this will get distorted, source is here and these lines, here these will be closer. So, this direction, the gradient is very high, so here this is a, this is the weld pool and this side the gradient is very high and this side the gradient is less. And when this weld pool, a progress is, it is quite interesting to see what will be the distance between the contours?

i is the distance between the temperature contours, this has, let us say this is, this, this is the liquidous surface, so this, where that solidifications starts liquidous. So, this is where that solidification is about to begin.

So, imagine, this, this is a grain, this will grow, as this moves this will grow and growth direction will always be perpendicular to the surface. So, that means, which is shown over here, that this is the growth direction, that is R and if this heat source is moving at a velocity v and this is the angle between the perpendicular to this interface and velocity, so the growth velocity of the crystal, that solidifying front will be equal to v cos theta. So, higher maximum, so where theta is 0, so this is the point, the growth rate will be maximum. This is the point where growth rate will be minimum because here theta is 90. So, this is, R is 0, this point.

So, now, it is quite interesting if you can see that this geometry of this weld pool will be a function of several factors. It will depend on velocity, it will depend on the size, it will depend on lambda, the conductivity and if these are low we will find, that these greens, which are growing, they grow and then this, sometime these directions also growth will change and this is the type of growth, which will take place they will all be inclined like this. The directions keeps on changing and in fact, in this particular case, segregation if at all is taking place will all be distributed, whereas if this, these are high, in that case this actually, this is distorted like this. So, in this case this width is also very small and in and also you will get this kind of a columnar, a cellular growth and always you will find, that impurities they get segregated here.

So, all high energy welding process is so, this is a problem, so this, so these, all these segregations will be pushed to this center line of the world and they will be the source of weakness. So, these are the lines along which often, the fracture takes place. So, weld metal, the structure is essentially the cast structure. And rate of crystal growth is maximum when theta equal to 0. So, that means these points, so that is why always it is elongated like this. But if it is very fast, in that case, these, you get this kind of a cellular growth and you have segregations here. And therefore, this center line segregation is a source of weakness and is a cause for poor toughness.

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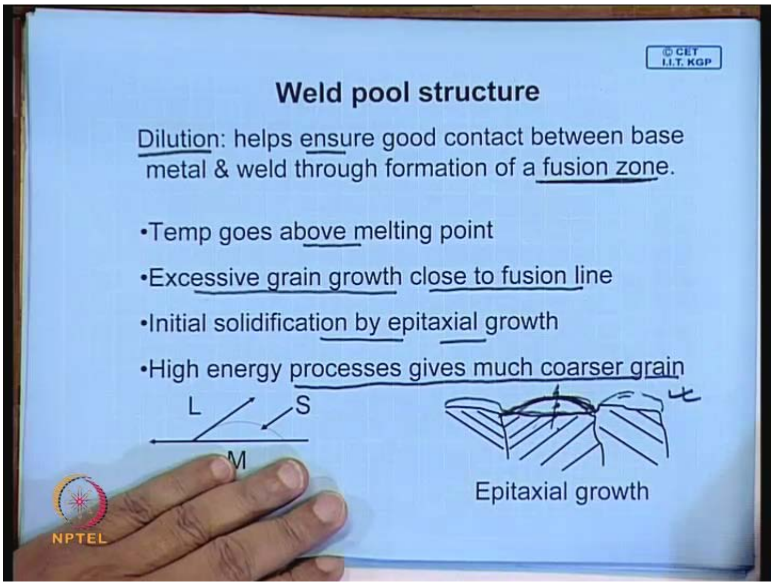

Now, if you look at weld pool structure little carefully, here the dilution plays an important role, it helps ensure good contract between base metal and weld through formation of a fusion zone. That means, a part of the metal, base metal also melts, it mixes with weld metal and solidifiers.

Now, temperature goes above definitely this zone, the temperature goes above melting point and if the temperature goes above melting point, just surrounding region, the temperature will be so high, that there is likely to be excessive grain growth close to the fusion line. And say, suppose this is, I mean, schematically have shown you this excessively large grains and when solidification starts, you know, this is the same metal. So, this solidification orientation of the crystal solidifier will actually be an extension of this crystal and it will grow in this direction. Similarly, this may have another different direction, some growth. So, finally, so this, this is how the growth will take place and this type of growth, where the base structure, that this interface determines the orientation of the new, that, that is the crystal, that is forming will have exactly same orientation as this. So, if these grains are coarsed, that initial solidifier layer will also be coarse, so this is the quite critical, important. So, therefore all high energy processes where the temperature goes very high for a short duration, but since the temperature is very high, there will be such large grain growth and initial solidification will always be through epitaxial growth.

So, therefore, it is, even in a fine grain structure there is very likely, that near the fusion zone you will have extremely coarse grains.

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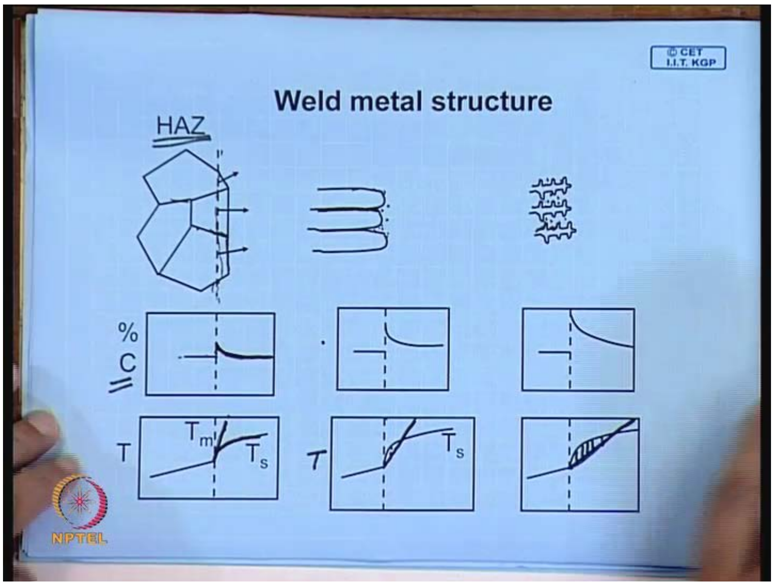

And the nature of that weld metal will also depend on the gradient, thermal gradient and also, the nature of that interface structure. As we said, that in the heat affected zones, since the temperature goes very high you have coarse grain, so there is an epitaxial growth taking place.

So, that means same crystal, this is the fusion zone boundary here, they start growing like this. And we have seen, we feel, looked under solidification, this is the kind of the solute builds up near that liquid, that interface because the solid, which solidifies fast, first they are purer. So, here, there is a lower concentration of a solute and here there is a mix up and in fact, there will definitely be some mix up, but still there may be some concentration gradient in the liquid.

And the nature of that solidification will depend on, on, that whether the front will be planar, will depend on the gradient. If this temperature gradient is very high and initially, always here it is very high. So, there, it will be planar and when it slightly deviates from planar, say something like this is the gradient, this is the concentration gradient and this is the temperature gradient. And in this particular case, this is slightly less than this gradient here; there will be a cellular type of structure.

So, you have these, all these impurities are pushed, these parts, you know, this is the part of intensity, this the material, they are pushed like this, this impurities and in case this gradients becomes even lower, say something like this, there, there will be substantial constitutional super cooling and leading to the formation of dendritic structure. And here in this (( )) channel you will have segregations. So, this explains, you know, the, we have just seen how our knowledge on the solidification can be applied to understand the structure, that develops in the weld metal, but the properties of a welded structure depends a lot on the zone, that surrounds that weld metal and this zone is known as heat affected zone.

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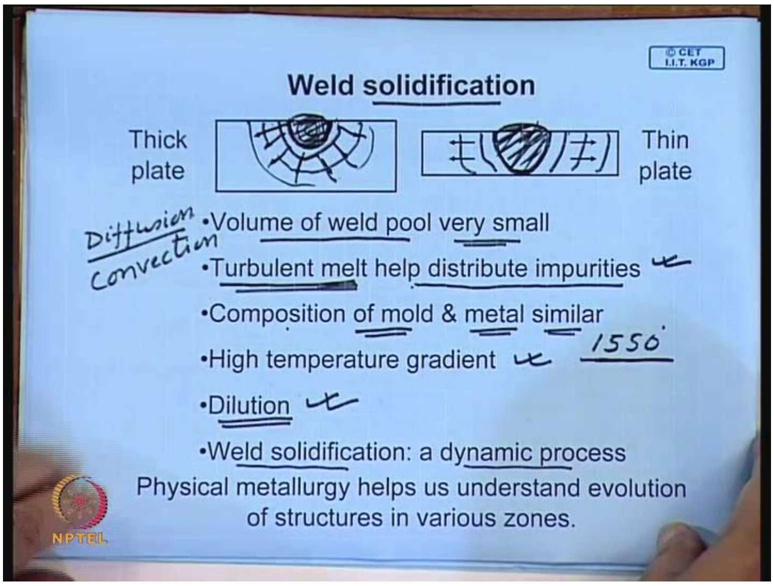

And let us see what is the, what changes take place in the heat affected zone. Now, we will look at this with reference to steel. So, you recollect, that face diagram, iron-carbon face diagram, this is the austenite, this is the liquid region, this is ferrite plus cementide structure. Say, suppose, most of the cases, the steel, that we will be welding will be low carbon or medium carbon. So, this is, say, suppose this is the composition of the steel. So, initially, there will be this molten zone and here, the temperature is this portion, it is liquid and this is a schematic diagram of a weld joint. So, you can think of clearly different zones.

So, you will be zone over here, which is molten, so above this. And next, there will be a zone where it just melts, that, that base metal, here part of it, it is partially, if you use somewhere in this temperature region and this is number 2, this is 1, this is 2 and there will be also a zone just after this, which will be heated to this region. So, this is zone 3 and there is another zone, which is related here, which is a normal heat treatment region. So, this, the zone that is 4, there will be another zone, which is heated in this zone, so this is 5. We can think of another, which is heated in this region, which is 6 and then beneath this. The temperature is so low, where we do not expect any structural change. So, we can clearly think of such seven zones in a welded joint and which are listed here. So, this seven zone is the unaltered zone.

Now, what will happen? The weld metal, we have just seen, these will have a cast structure, then partially melted zone, you know, it will melt and again solidify. So, here, it has partly melted. So, these are the zones, which are partially melted and re-melted and re-solidified zone. So, you will have a mixed type of structure, then this is a region where many of this steel you have, like alumina, these types are particles in steel inclusions, titanium nitride, vanadium nitride, carbides and they block, they are very good aluminum nitride, they are, they inhabit grain growth, but they also dissolve beyond a particular temperature.

And when you heat it over here, these precipitate also dissolve, that is all, then the grains will grow, that will be abnormal grain growth. Grains will become very large, so this is the excessive grain growth region. Whereas, this zone, austenite will form, but that heating time is very short. This austenite may not be very homogenous that will be fine. So, when it again cools this will have much finer structure, re-austenitized structure, there will also be quite fine structure. Then, there will be a region where you have partially austenite.

So, here, you have austenite plus ferrite and when it is cooled, this austenite will (( )) transform even to low transformation product and sometime if the cooling rate is high, imagine, say at this temperature zone this has this much amount of carbon, so when this is cooled, you may get some amount of martensite or you can some time, depending on some alloy content, you can also get (( )) structure. So, therefore, you, what you have in welded steel.

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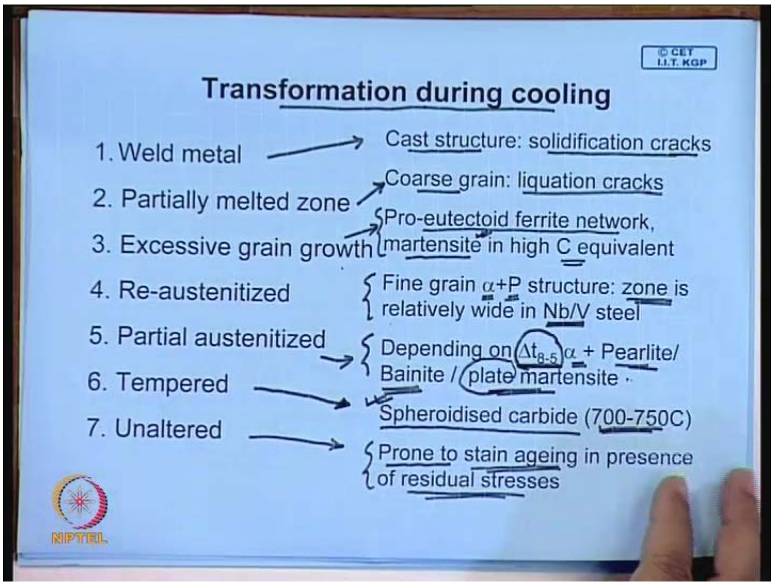

Then, a heat affected zone, a composite structure and these are summarized over here. The transformation during cooling, we have just seen the different zones, they are heated to different temperatures and this summarizes the different structures, that you are likely to get in these seven zones. So, weld metal, this is a cast structure, this is also the region, which is also prone to solidification cracks. So, if the, sometime the cooling rate is fast, so it has not solidified. There is a thin, there is segregations and then they can, this is prone to solidification cracking. Similarly, if it is a partially melted zone, you also have a coarse grain structure and these are the, here also you will have low melting liquid at the grain boundary and they can, are prone to leak creation cracking, then you have excessive grain growth zone.

So, this is, this part, so here you will have pro-eutectoid ferrite network. You can also have some amount of martensite, particularly if carbon equivalent is high and this martensite, so we, in this particular case since the grains are very coarse, so there hardenability will be higher and the cooling rate is high. Therefore, the martensite formation is likely, so this will have high hardness re-austenitised area. This will have fine grain of a, fine grain structure, ferrite, consisting of ferrite and primarily pearlite. And this zone is relatively wide because this is the area where in a, particularly in a niobium, vanadium containing steel, bulk of the steel, that are welded steels, they are micro-alloyed steel, they have some amount of niobium and vanadium as added and they are nitrides and carbides. They are grain bound and grain growth inhibited, they do not allow the grains to grow. Therefore, this particular zone, that re-austenitised zone, you know, is quite large usually in, in this type of steel.

Then, we have a partially auestinitised region and here we have seen the structure, that forms, depend on the cooling rate and we will talk about this temperature, what is this temperature? Delta t, the time it takes to cool through 800 to 500 degrees centigrade, this is an important parameter often people talk about in welding, we will, learn about it little later. So, here, main structure will consist of ferrite and pearlite, it can also form some kind of plate martensite, we just explained, because that austenite is high carbon austenite here. So, when it is cooled at a faster rate it is likely, that they can transform into martensite and this martensite will be plate martensite and certain grade of steel, you also get bainite.

There is also a region where gets, often here the hardness can drop, can become lower than the hardness of the parent metal and here, the spheroidisation process takes place. Carbide becomes spheroidised and particularly, the zone, which is heated to 700 to 750 degree centigrade. This is the zone, which is prone to this kind of softening process and after that you have this unaltered zone, but this zone, you know, since the temperature goes up, if there is a prior gold where or there are residual stresses, it is quite likely, that this interstitial atoms can move to certain preferred sites, the dislocation sites, dislocations and pin them and this causes stain ageing, which, which increases the strength and also decreases its toughness, it makes it brittle and prone to fracture. So, these are the likely, these are the, I mean, the transformations, which are possible in the heat effected zone.

Now, how do you measure it, heat affected zone property? It is, the simplest measurement could be, if you take a section, the hardness measurement is quite easy, so hardness profiles people have found out in the heat affected zone and also, you can develop microstructures in the different zone and look at the microstructure. And in fact, this has been done and whatever has been said, that, that is how the seven zones have been clearly identified in a welded structure.

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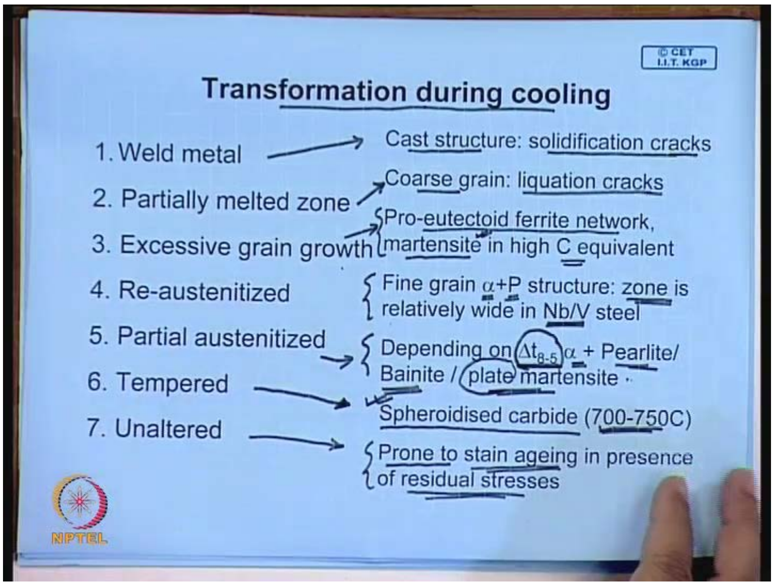

Now, if you look at these hardness profile and, and make a plot in the heat effected zone, you may find, say hardness is usually reported in a weakest hardness number. Now, depending on the carbon contents, say suppose, that if it is a medium carbon steel, say somewhere in the weld metal, we will forget, I mean, let us look at the heat affected zone, we said, that here there is a chance of martensite formation become the grains become very coarse.

So, this is the heat affected zone just outside that weld metal, we, where the metal has partially melted and you have excessive grain growth. This is the region where grain size is very coarse and you have martensite. So, therefore, this is the region you have maximum hardness and thereafter, further you go away from the fusion zone, the hardness goes on decreasing and there will be a region where there is no change. In certain cases, around 700, 750, in certain, depending on the initial structure there may be a tip observed also, this is because of spherodising, spheroidised structure.

And if you also look at the microstructure, you will find, this is the excessive grain growth area, they have grain size and grain size is usually, in steel, measured in terms of that austenite, I mean, ASTM grain size number; the austenite grain size is often represented as ASTM grain size number. We talked about in the lecture earlier and lower the number, coarser is the grain. So, here, this end, the scale is this side, so here the grain is coarse and as you go away from the fusion zone the grains become, start becoming finer and this is a zone here, the grain size can become quite fine also, because this is a re-austenitised region, where, and this re-auestenitisation, it takes place for a very short time. So, the grains can become finer than the initial and again, it comes back and this is that unaltered zone, this is the initial grain size. So, somewhere you also get a very fine structure.

So, in short this heat affected zone is a composite structure and the zone, which is more prone to failure is, this is the region. And if this hardness is very high, in that case the toughness will be low, low toughness and couple with it there is a gas related problem also.

During welding process if you are not able to protect the weld metal, you know, you are, now from the surrounding gases, then these gases can get dissolved and particularly among these gases hydrogen is quite damaging and hydrogen diffusivity is quit high. If the welding electrodes (( )) it they are not properly dried if, if the sag layer on the weld pool is not protective enough or the surrounding gas environment, which is maintained, is not protective enough, this hydrogen can diffuse into these regions and if these hydrogen are present here, we, often we may not see the crack immediately after you have welded and leave it for some time and then, you, you find there is a delayed cracking, hydrogen relates to delayed cracking and which is a major problem.

So, you have to control, that weld quality, that means, a welding electrode you have to bake them and proper heat treatment has to be given out. Depending on, sometimes depending on the composition you may have to give proper heating or post weld heat treatment will be required, particularly in cases if you look up, if this hardness is very high it is better to give a post weld heat treatment by which this structure will get tempered and by that you bring down the hardness.

Now, just now we looked at the transformation, which takes place in the heat affected zone and we also have talked about transformation diagram, like CCT diagram, TTT diagram. Now, during welding, now you do not have homogenous structure, you, though you do not have uniform grain size, certain places you have extremely high grain size, this regions may be very thin. But nevertheless, to understand the structure, therefore you need not the common normal transformation diagrams, which are, which are used to design heat treatment process, but we need a different kind of diagram and this diagram is known as the weld CCT diagram, which are little different than the normal CCT diagram one uses in heat treatment.

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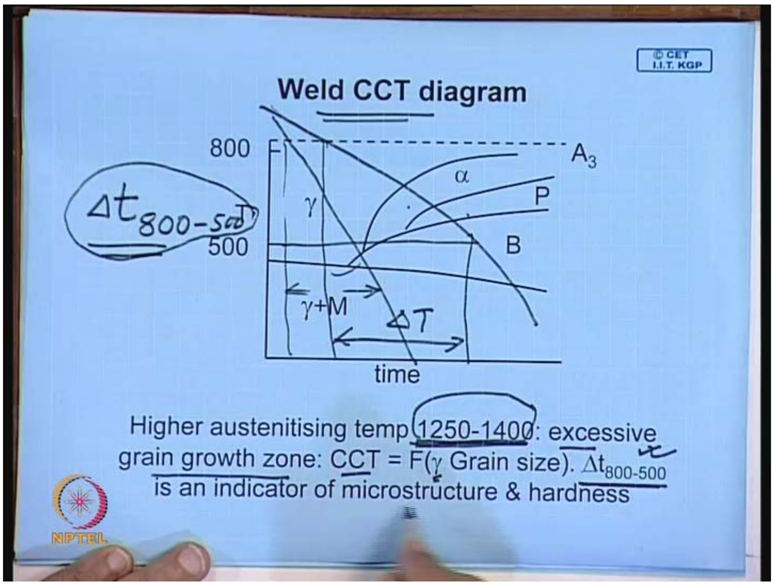

And one example, schematic diagram is shown over here, weld CCT diagram, but here, the transformation, by and large for more steels, the range in which transformation takes place, the diffusion control transformation takes place is around 800 to 500. So, therefore, all welding literature is, you know, a terminology, this temperature, the time it takes to cool through 800 to 500 degree centigrade is taken as, you can say, as measure of the cooling rate and this helps us to, I mean, relate this hardness or microstructure with properties. So, this particular parameter is quite important.

A typical diagram is shown over here, say, suppose something is a cooling at this low rate, so here it has a large delta t, this delta t is large. Whereas, somewhere, which cools fast, say something like this, in that case here, that delta t, this is more and you can clearly see, that here there is a chance of martensite, some amount of martensite forming, whereas in this particular case, these products ferrite and barlite is quite high, so that means, this type of diagram helps us to convert, you know, the cooling rate into microstructure and microstructure can then be related to hardness.

So, higher austenitising temperature, you know, is actually used and obviously, there will be a welded zone, will be and austenitising temperature as high as this, where there will be excessive grain growth. And this CCT diagram, we know, is a function of austenite grain size. Therefore, to understand this we need some method of calculating the CCT diagram.

In fact, this is an area of great interest for physical metallurgies. There are many simulation techniques because it will be extremely difficult to generate this experimentally. The volume of data, that will be required will be enormous, they can only be found out through simulation, but nevertheless, this indicator, this delta t 800 to 500 is an important indicator or parameter, which connects, I mean, cooling right to microstructure and hardness.

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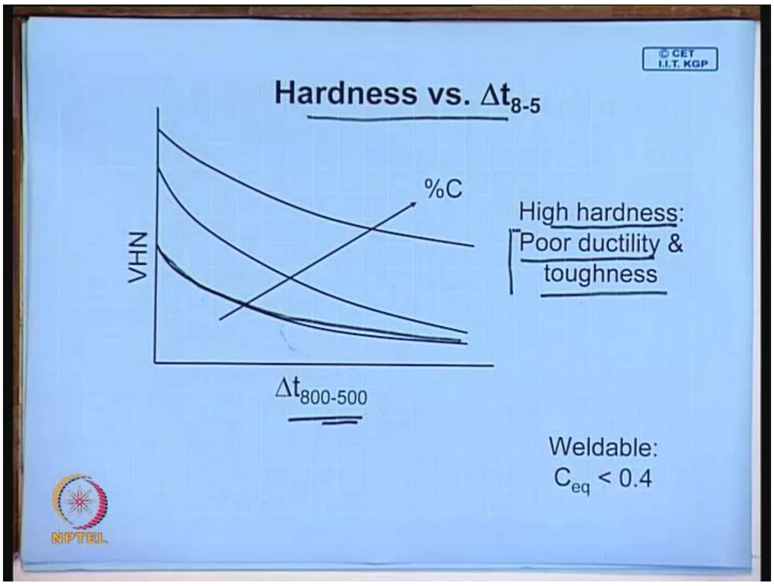

And in fact, one such plot is shown over here. If you plot hardness against this, depending on the carbon content of the steel you will have different types of relationships, say particularly low carbon, you get this type of relationships delta t; higher carbon, you get higher hardness in the welded zone, so high hardness is always, will always have poor ductility, poor toughness. So, these are the, steels will be where you get high hardness, they are the difficult to weld.

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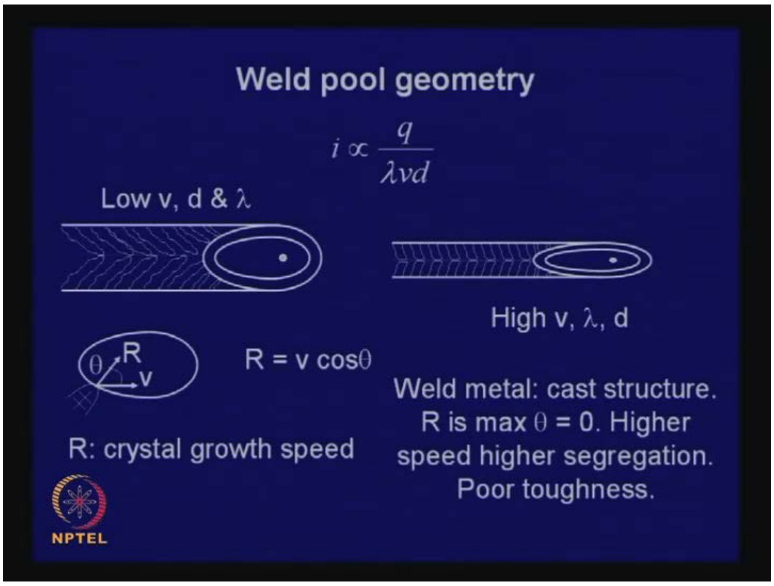

And in fact, one of the ways of knowing this is to know, or, or is to define, that carbon content, that you have that equivalent carbon content and if we look at this, there are several such expressions available for equilibrium, that several such expressions are there, such empirical expressions, which gives you carbon equivalent and these different alloy element, manganese, chromium, these are the common alloy elements, which are added and using this it is possible to find out carbon equivalent. And usually, steels where carbon equivalent is high, they are difficult to weld and you need a proper heating, preheating, post-heating, so that you can control the cooling rate, and in that case, but weldable grade; low carbon grades are easily weldable.

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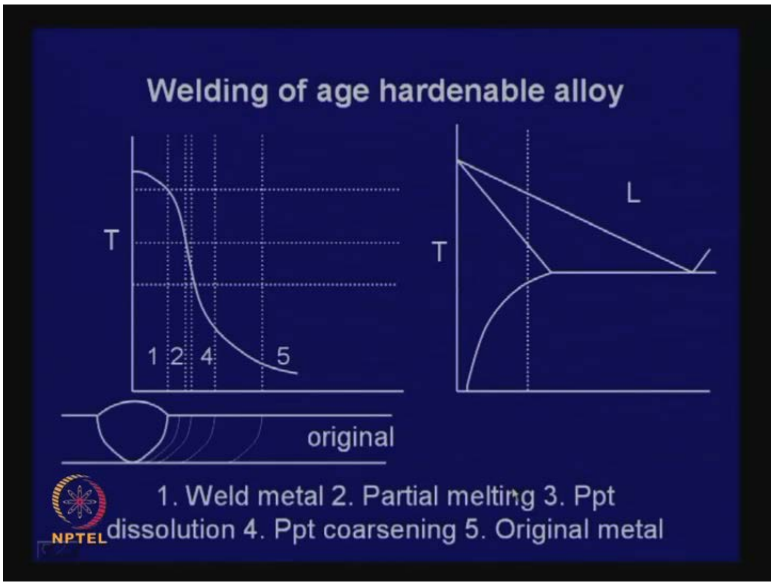

Now, this concept can also be applied to other alloys also, which do not undergo, that kind of transformation, like steel is a very special type of alloy where you have allotropic transformation, where with higher cooling rate you get a very high hardness product. But there are cases as, suppose we look at what happens if we try and weld and age hardenable aluminum alloy and which is pictorially shown over here.

And age hardenable aluminum alloy if you recollect, you know, this will have a terminal solid solution kind of system, this is a typical face diagram of an age hardenable aluminum alloy, this is liquid, this is alpha and what you do? Age hardening alloy, you know, you heat it to this region, quench and then age, and by aging you get higher hardness, but when you quench, your hardness is low, it is soft; under quench condition it is soft, when you age it becomes harder.

So, now what happens if we weld this alloy? So, here also you have to heat beyond the melting point. So, here also you can think of several zones. Obviously, this will be the weld metal, this will be the, partially there will also be the partially molten zone, this helps in mixing and bond formations and this is also quite important, that the base metal also should melt. So, therefore, you need to have matching electrodes and once, so this is a second zone, now that will be a third zone, you know where the precipitate will dissolve. So, the zone, which is getting heated to this region, although it is very, for a very short time, but it goes to a relatively high temperature. So, the precipitates can dissolve, whether partially or, or completely, this, there is a possibility, they can dissolve depending on the heat input and that whole time, that you are likely to have during that welding process.

Now, so you have and there will also be a region, which are the aged, over age somewhere here, wherever the initial precipitates, that are there, they can coarse and below you will have that original metal. So, here also you will have a composite structures starting from cast metal to, cast metal through partially melted zone. Then, with a coarse precipitate, then some of the cases you can also have that extreme case that is far, very far from the fusion zone you will have the weld metal.

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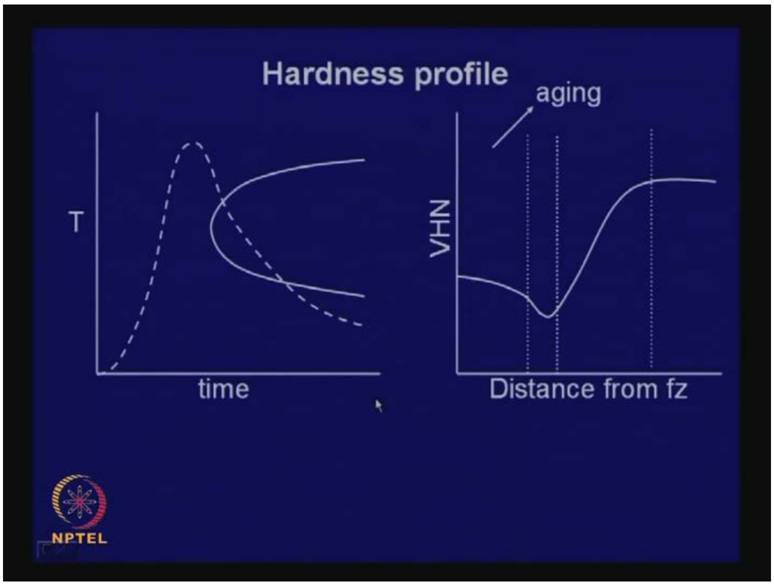

And here also it is possible to compare or predict the microstructure, for that you need to know the transformation diagram. Here also, you will have the, you will have learned about it, you have C-shape diagram, transformation diagram and on this, this is temp time, temperature diagram and this is the C-shape, the transformation, that precipitation begins. Now, here, when you are heating, there is a heating time, this temperature goes here, which is much above this and it can, say the heat affected zone. So, here is possibly it dissolve, you will have a super saturate, you have a solid solution and it is cooled fast and you, depending on the cooling rate if it is cooled very fast, you will get a super saturated structure where you will have a lower hardness. And whereas, in some region, which passes through this you will have some precipitate. So, if you look at the aging graph you may get a plot, say something like this. There will be a drop in hardness and, and some cases there can be a little increase in hardness also, say suppose a part of zone, which is formed as a super saturated solid solution and during that subsequent cooling they can get some amount of natural aging. So, therefore, this hardness can also go up here. So, you, this is the distance from the fusion zone.

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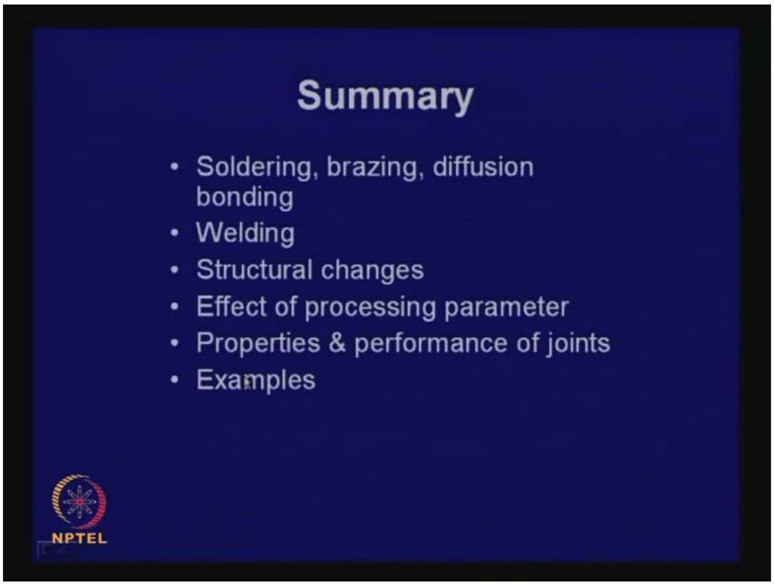

So, this, so that means, in short what we have learned here, that in the case of metal joining, you know, particularly we looked at welding in great detail. You are applying a very high or intense heat source in a localized area. So, at that time, you know, during the process, not only the temperature of that zone goes up, surrounding region. Because metal is conducting surrounding region, the temperature also will go up, it will go above the melting point, above the critical transformation temperatures and therefore, the final structure that we will get will depend on the cooling rate after welding. And so, in short, whatever we looked at is different types of welding processes at the joining processes.

But we looked at, in all these cases there is a diffusion bonding, which takes place in a welding, even the part of the metal also melts. So, bonding is much stronger, there will be structural changes in the heat affected zone. We talked about it and there is a, processing parameter is like some of the parameters we talked about. Apart from thermo-physical parameter it is the dimension of the job is also important, the preheating, that temperature of the job is also important. So, the speed of, which you do, that velocity of their weld, that heat source also of, it is the structure we talked about how it alters the shape, the temperature contours and therefore, the structure of the solidified metal and all these will affect properties.

We looked at hardness profiles and hardness has a direct correlation with toughness. Higher hardness means, by and large you have lower toughness, so that has to be avoided in steels. When you are getting a very high hardness in certain zone, you may have to give post-weld treatment to make it soft, to improve its fracture toughness and we, and we looked at all this with respect to say, to one is steel, a low carbon steel, a micro-alloyed steel, we did look at. And also, we talked about the welding of an age hardenable alloy. With this we complete the lecture on metal joining and also, the course of physical metallurgy.

Thank you very much.