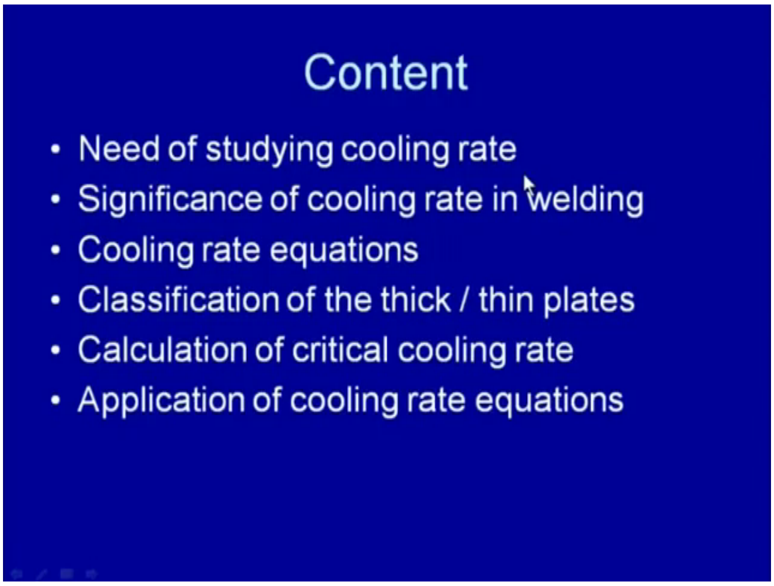
Mechanical Engineering Welding Engineering

Prof. Dr. D. K. Dwivedi
Department of Mechanical & Industrial Engineering
Indian Institute of Technology, Roorkee

Module - 5
Heat flow in welding
Lecture - 3
Cooling rate

So, dear students this is the third lecture on the heat flow in welding. And this lecture will be based on the cooling rate and its effect on the performance of the weld joint. We will also talk about that how cooling rate can be calculated in the weld zone and the areas close to the fusion boundary. We know that in the fusion arc welding processes heat is applied with the help of arc for melting the faying surfaces, once the heat is applied for melting purpose the solidification take place. So, during the solidification the heat is extracted from the weld region as well as from the regions close to the weld zone. And because of this, the different cooling rates are experienced by the different locations in the weld region as well as in the heat affected zone.

(Refer Slide Time: 01:49)



Content

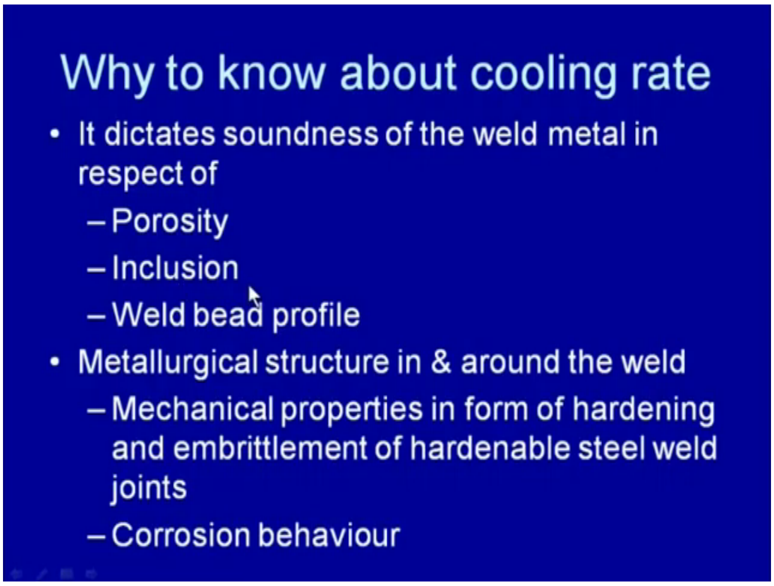
- Need of studying cooling rate
- Significance of cooling rate in welding
- Cooling rate equations
- Classification of the thick / thin plates
- Calculation of critical cooling rate
- Application of cooling rate equations

We have learnt from the weld thermal cycle that the weld thermal cycle of the each location is found to be different. And the cooling rate at a particular location will be the function of the time as well as will be the function of the temperature. So, the role of the cooling rate and the methods used for calculating the cooling rates and its applications will be presented in this lecture mainly.

As far as content is concerned in this presentation, we will be talking about the need of studying the cooling rate, significance of cooling rate in the welding, cooling rate equations, classification of the thick and thin plates, because these cooling rate equations are different for the different thicknesses means the plates of the different thicknesses. And the how to calculate the critical cooling rate under the welding conditions. And what are the different applications of the cooling rate equations in the welding.

So, we know that heat affected zone and the weld region are subjected to the different cooling rates during the welding and the cooling rate being experienced by the material at each location is found to be different. It is important to calculate and to find out the cooling rate at a particular location, so that it can be controlled in a proper way. Otherwise, it can lead to have some undesirable effect because cooling rate dictates the soundness of the weld metal especially in respect of the porosity inclusion and the well bead geometry.

(Refer Slide Time: 03:32)



Why to know about cooling rate

- It dictates soundness of the weld metal in respect of
  - Porosity
  - Inclusion
  - Weld bead profile
- Metallurgical structure in & around the weld
  - Mechanical properties in form of hardening and embrittlement of hardenable steel weld joints
  - Corrosion behaviour

We know that the cooling rate directly affects the time available for the solidification and so if under the conditions of the high cooling rates the solidification time will be less. And in this in case of the short, very short solidification time, there will be chances for the entrapment of the gases leading to the development of the porosity as well as the impurities, which are present in the weld region forming the slag. And if they are not able to come up to the surface of the molten metal then they will be present in form of the inclusions.

Similarly, if the very less amount of the heat is available with the weld metal then it will be leading to the reduced fluidity of the weld metal and the weld bead will be very peaked kind. And this peaked beads frequently leads to the high stress concentration and cause the premature failure of the weld joints under the fatigue root conditions. So, the flatness of the bead or the weld bead profile is affected by the cooling rate being experienced by the weld metal during the solidification.

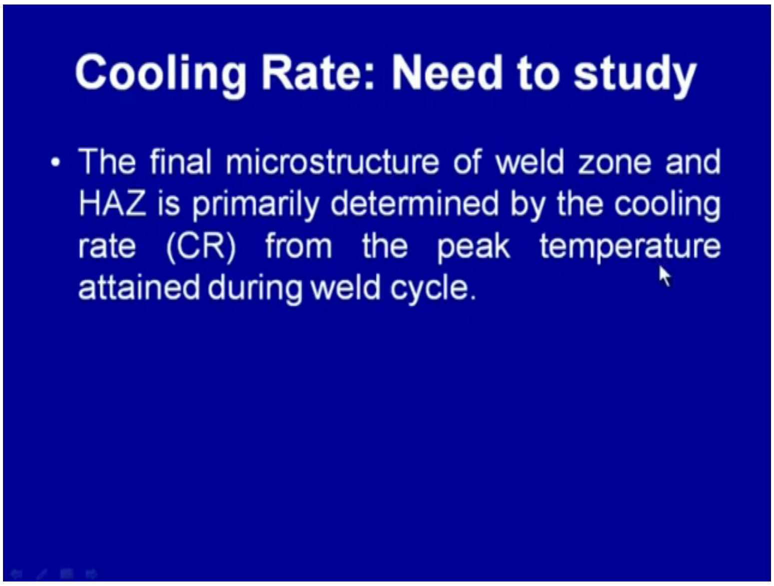
Apart from the soundness of the weld joint the cooling rate also affects the mechanical properties and the metallurgical structure. Because of the variation in the metallurgical structure in the weld region and the heat affected zone, the variation in the mechanical properties as well as corrosion behavior has been observed. Since, due to the direct effect of the cooling rate on the metallurgical structure in and around the weld zone the mechanical properties in form of the hardening and embrittlement of the hardenable steel is noticed and because of this it is, it is frequently desired to have the controlled cooling rate.

Especially in the heat affected zone, so that metallurgical structure can be controlled in our favor in order to avoid any such kind of the embrittlement or the excessive hardening of the heat affected zone. So, that cracking tendency can be avoided. Further, in some of the steels like stainless steels, austenitic stainless steels where the chromium carbide formation take place in the heat affected zone under the slow cooling conditions in a sensitive temperature range that leads to the loss of the corrosion resistance of even of the stainless steel.

So, to avoid such kind of unfavorable metallurgical structures in the heat affected zone, the heat cooling rate is also controlled. That control is made in form of the faster cooling through the sensitive temperature range where the chromium carbide precipitation can take place. So, the cooling rate in the heat affected zone can affect the metallurgical structures which can influence the mechanical properties as well as the corrosion behavior.

Because of these things it is, it becomes important to understand the kind of cooling rate which will be experienced by the weld zone and the heat affected zone. So, the things that affect the cooling rate and how, the methodologies which are used for calculating the cooling rate in during the welding of the plates of the different thicknesses will be focused in this presentation.

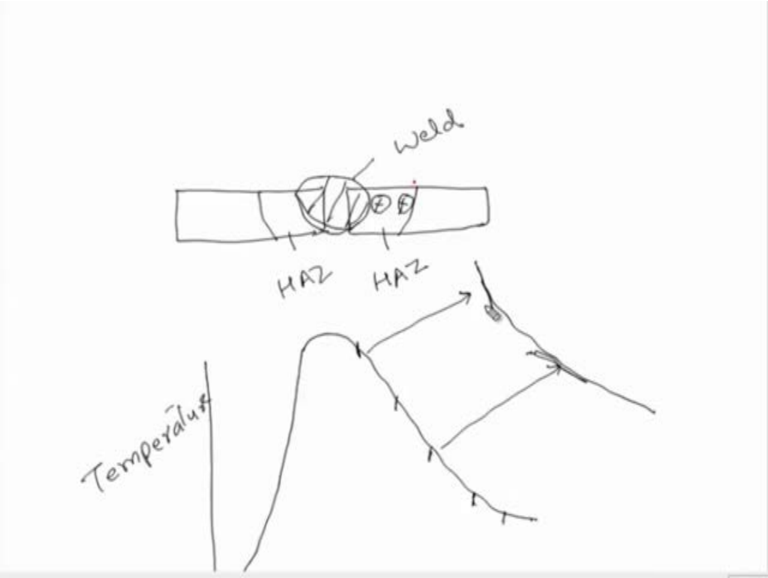
(Refer Slide Time: 06:32)



Cooling Rate: Need to study

- The final microstructure of weld zone and HAZ is primarily determined by the cooling rate (CR) from the peak temperature attained during weld cycle.

(Refer Slide Time: 07:11)



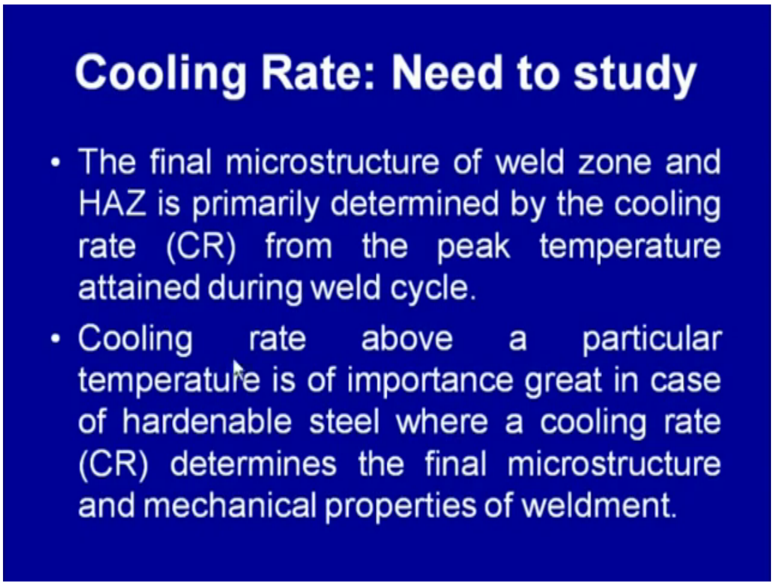
So, this is what we have seen that we have already discussed that the final structure in of the weld zone and the heat affected zone is primarily determined by the cooling rate. And this cooling rate actually varies with the temperature of a particular location and this cooling rate also varies with the temperature at a particular moment of the time. From the, from the weld thermal cycle we know that the cooling rate being experienced by a particular location varies as a function of time and as a function of the temperature.

To understand this we will focus in this diagram here we can see that if we have a weld joint, if there is a plate which is being welded by the fusion arc welding process by applying the heat and melting of the faying surfaces and the weld is being made like this. So, the kind of the weld metal or the weld portion, so the reason close to this weld zone will be heat affected zone or the region which is being affected by the application of the heat and to the faying surfaces.

So, in this heat affected zone if we plot the weld thermal cycle of any point then we will see that as a function of time the temperature varies and this variation in temperature during the heating phase it increases very abruptly and then in cooling phase it comes down gradually. So, if we notice this, this is steepness becomes more at the higher temperature and then it will keep on decreasing. So, basically this slope becomes of the decreasing kind indicating that the slope is more here at the upper level. And this slope will keep on decreasing here at this location say the slope has reduced. The slope indicates the cooling rate. So, at the higher temperature the cooling rate will be high while at the lower temperatures cooling rate will be low.

We know that the different locations are subjected to the different peak temperatures. So, accordingly the different locations will be subjected to the different cooling rates also. So, if we consider this location and this location then the cooling rate experienced by the region very close to the weld will be subjected to the higher cooling rate as compared to the location which is away from the fusion boundary. So, these variation in cooling rates will be leading to the difference in the metallurgical structure of the hardenable steels particularly. So, these cooling rates are controlled in such a way in heat affected zone that the favorable structures are formed. So, that unnecessary embrittlement of the heat affected zone can be avoided in case of the hardenable steels.

(Refer Slide Time: 09:44)



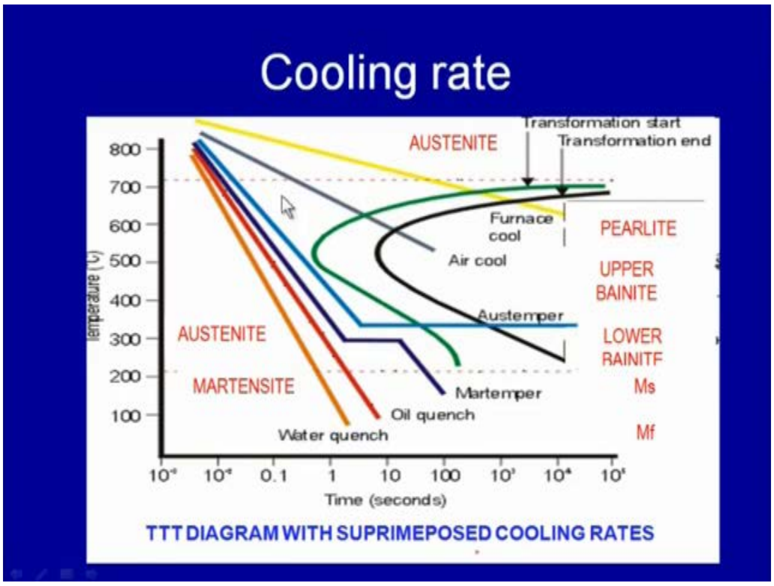
Cooling Rate: Need to study

- The final microstructure of weld zone and HAZ is primarily determined by the cooling rate (CR) from the peak temperature attained during weld cycle.
- Cooling rate above a particular temperature is of importance great in case of hardenable steel where a cooling rate (CR) determines the final microstructure and mechanical properties of weldment.

The cooling rates above a particular temperature is of the great importance in case of the hardenable steels where a cooling rate determines the final structure of the heat affected zone and on the mechanical properties of the weldment. So, here to understand this we can see this diagram.

(Refer Slide Time: 10:05)

Cooling rate



TTT DIAGRAM WITH SUPRIMEPOSED COOLING RATES

Here we say the, all the regions in the plain carbon steel which are heated above the 730 degree centigrade; that is above this line with they will be in the austenitic state. This is basically that triple T diagram, time, temperature, transformation diagram where we have superimposed cooling rate lines. So, these different lines are corresponding to the different cooling rates. So, the lower is the slope will be indicating the lower cooling rate.

So, under this we know that since this, the steel will be in the austenitic state above the 730 degree centigrade. For this particular form of steel say it is eutectoid steel and when the temperature, when the steel is subjected to the slow cooling rate then we will be able to see that the as soon as the temperature say for this cooling rate, as soon as the temperature comes down below this the green line the transformation starts. So, this green line corresponds to the transformation start and this, the black line corresponds to the transformation end.

So, here along this between these two lines we will be having the transformation zone for austenite to the pearlite transformation. And this, under these slow cooling conditions basically we get the very coarse pearlite because each, this transformation occurs very gradually and very slow nucleation takes place under these conditions. And because of this whatever grains are nucleated they will be growing to the larger extent and will be resulting into the very coarse pearlite.

If we see here, another cooling rate, according to this cooling rate the transformation of austenite will be starting at this point and into the pearlite. And then again it will be completing at this point will be, but in this case due to the higher cooling rate which is being applied through the air cooling, typical steel air cooling in the mid conditions. The structure of the pearlite will be the final one. So, the difference in these two cooling rates is one is being applied through the furnace cooling and the second is being applied through the still air cooling in the ambient condition.

So, in one case, first case we will be getting the coarse pearlite. In the second case we will be getting to the fine pearlite. If we, if we follow the another temperature line that is corresponding to this nose. We are just crossing this nose portion of the diagram and after reaching to this we are holding it at a constant temperature. Then this will be resulting in the bainite. So, here austenite will be transforming into the bainite. So, here we will have upper and the lower bainite situations. So, here above this we will be getting the upper bainite and below this here we will be getting the lower bainite.

Further, if we do not hold this means after cooling at this rate and then holding at this particular temperature will be leading to the development of the bainite. And if we, if we avoid this, if we keep on cooling at that constant rate say like this using this the pink line then we will be able to have that austenite is transforming into the martensite. So, martensitic transformation in case of steels will be occurring in both these two cooling rates.

So here, this is achieved by the oil quenching or the water quenching; oil quenching results in somewhat lower cooling rates as compared to the water quenching. But in both the cases austenite will be cooled, means steel will be cooled in the, from the austenitic state to the very low temperatures and will be resulting in the transformation into the martensite. So, again here we have the martensite start and martensite finish temperature conditions. So, when the quenching is done below the martensite finish temperature conditions the whole of the austenite transforms into the martensite.

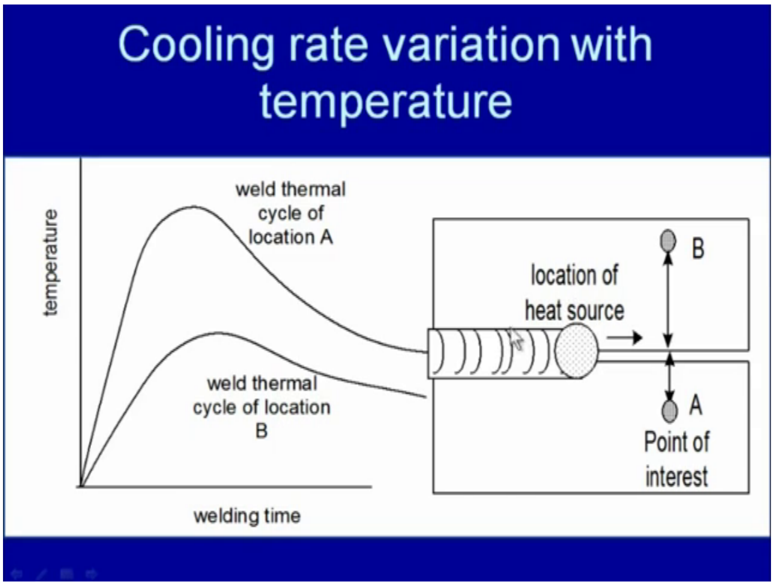
And whenever steel forms the martensite we get very hard and brittle structures with the, with the tensile residual stresses and because of this steel has the cracking tendency. And in the weld joint it is very common to have the cooling rates corresponding to these two lines where the, where the cooling rates are much higher than the cooling rates required for having the soft phases like the bainite and the pearlite or fine or of the coarse pearlite. So, in the steels which are hardenable in nature because of the existence of these higher cooling rates than the critical cooling rate required to the formation of the, from the austenite to the matensite.

It is frequently observed that the heat affected zone in hardenable steel forms the martensite. And formation of this martensite leads to the embrittlement of the weld joint. So, to avoid this brittle embrittlement and the cracking tendency it becomes necessary to avoid these higher cooling rates in the steels, so that the cracking tendency can be avoided. So, if we see here if you want to avoid the cracking tendency it becomes necessary to have somewhat softer phases, so that the, so that reasonably good strength can be obtained without having the cracking tendency and the excessive hardening of the heat affected zone.

And to achieve this different cooling rates during the welding where invariably high cooling rates are observed the pre heating is applied. So, we know that the welding conditions significantly affect the cooling rate being experienced by the material at a particular location. And these the, these parameters, these the input conditions during the welding that effect the cooling rate are primarily the heat input which is being applied for the welding purpose and the initial plate temperature before the welding.

So, heat input in general when we increased the heat input the cooling rate is reduced while the low heat input results in the higher cooling rate. Similarly, on the other hand the increase in the preheat temperature generally causes the reduction in the cooling rate. And therefore, the preheating of the plate is frequently performed to avoid the critical cooling rate conditions and so as to avoid the martensitic transformation in the heat affected zone to avoid the cracking tendency and the embrittlement of the heat affected zone.

(Refer Slide Time: 17:11)

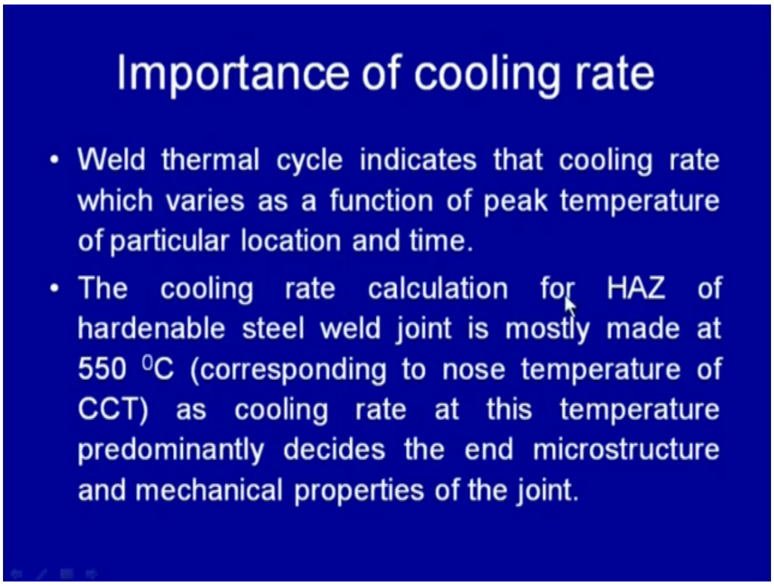


Cooling rate variation with temperature

This is the diagram, which shows that the cooling rate being experienced by the different locations varies with the time and the temperature. So, if we see here the location which is far away from the weld line, the weld thermal cycle is this and if we see this slope of the cooling portion of the weld thermal cycle, this is the slope of this curve is somewhat lower as compared to this one. So, this suggests that the cooling rate being experienced by the location A will be much higher than that of the location B.

And further we can see the slope at the high temperatures of the cooling portion of the weld thermal cycle are higher than the slope of the curve at the lower temperatures. And at very low temperature all these slopes becomes almost equal to the each other means the cooling will be occurring at very slow rate when the, when the temperature comes down to almost close to the room temperature conditions. So, weld thermal cycle indicates that the cooling rate varies as a function of the peak temperature of a particular location at the time ((Refer Time: 18:21)) time.

(Refer Slide Time: 18:23)



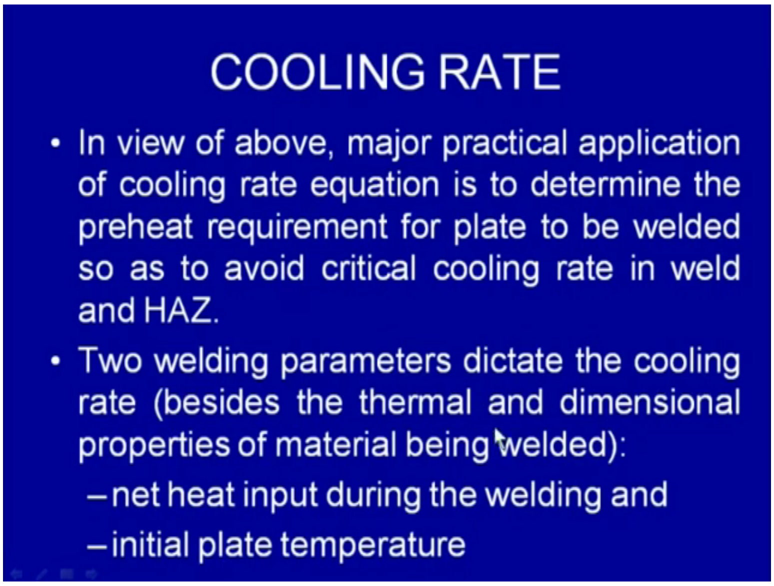
Importance of cooling rate

- Weld thermal cycle indicates that cooling rate which varies as a function of peak temperature of particular location and time.
- The cooling rate calculation for HAZ of hardenable steel weld joint is mostly made at 550 ^{0}C (corresponding to nose temperature of CCT) as cooling rate at this temperature predominantly decides the end microstructure and mechanical properties of the joint.

And the cooling rate calculations for the heat affected zone of the hardenable steel mostly done at the 550 degree centigrade. We know that since the cooling rate varies with the temperature. At high temperature cooling rate will be high, but the temperature which is of the great importance is of the 550 that is corresponding to nose of the continuous cooling diagram or the triple T diagram. Because it decides the cooling rate which will help to either avoid the martensitic transformation or to have the soft phases like bainite and the pearlite.

So, that the temperature correspond the, corresponding to the nose of the continuous cooling temperature diagram or triple T diagram, this becomes the 550 degree centigrade. That is why frequently the cooling rate in the heat affected zone is calculated at the 550 degree centigrade. So, this becomes the temperature of interest at which we would like to calculate the cooling rate during the welding in order to avoid the martensitic transformation tendency, as the cooling rate at this temperature predominantly decides the end structure and mechanical properties of the weld joint.

(Refer Slide Time: 19:34)



COOLING RATE

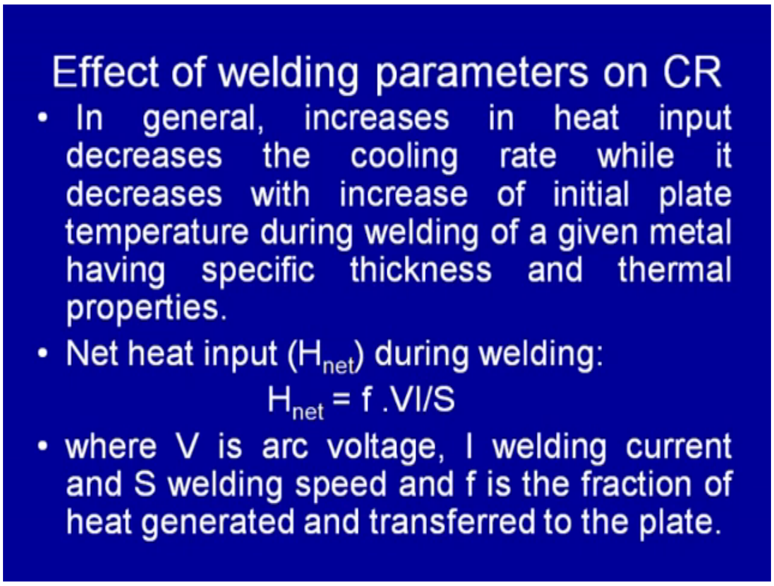
- In view of above, major practical application of cooling rate equation is to determine the preheat requirement for plate to be welded so as to avoid critical cooling rate in weld and HAZ.
- Two welding parameters dictate the cooling rate (besides the thermal and dimensional properties of material being welded):
  - –net heat input during the welding and
  - –initial plate temperature

In the, in view of above the possibilities related with the cooling rates, the practical application of the cooling rate equation is to determine the preheat requirement for the plate to be welded, so as to avoid the critical cooling rate in the weld and the heat affected zone. So, this is the main application of the cooling rate calculations that we can determine the preheat temperature, so that the critical cooling rate in the heat affected zone and in the weld zone can be avoided.

So, as to avoid the unnecessary embrittlement of the heat affected zone and the weld region. The two welding parameters that primarily dictate the cooling rate besides the thermal and the dimensional properties of the material being welded are the net heat input is one during the welding and the two the initial plate temperature. So, for a plate of the given thermal properties and the given thickness the two parameters like the net heat is being supplied during the welding that is in terms of the kilo joule per mm.

So, net heat being supplied during the welding is one of the very important parameters that effect the cooling rate and second is the initial plate temperature. In general increase in the heat input during the welding decreases the cooling rate while the increase initial plate temperature decreases the cooling rate. So, both increasing heat input and increase in initial plate temperatures in general decrease the cooling rate being experienced by the weld metal and the heat affected zone in a particular location.

(Refer Slide Time: 21:20)



Effect of welding parameters on CR

- In general, increases in heat input decreases the cooling rate while it decreases with increase of initial plate temperature during welding of a given metal having specific thickness and thermal properties.
- Net heat input (H_{net}) during welding:

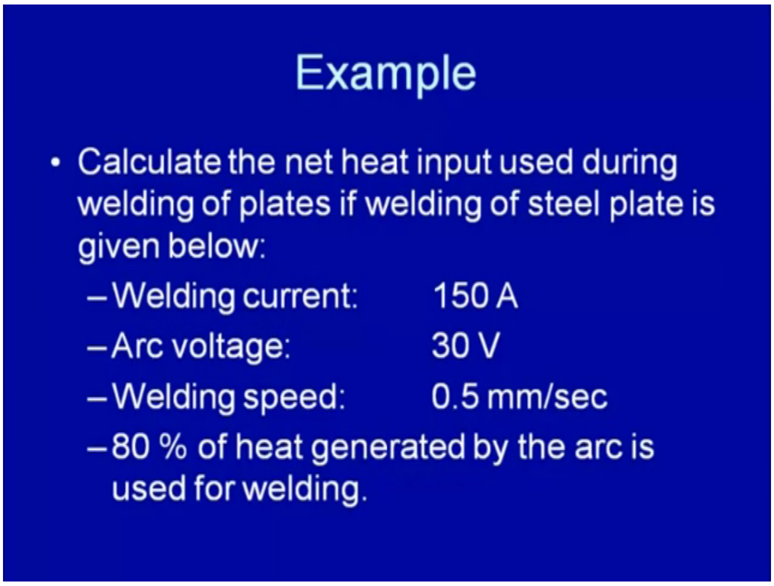
$$H_{net} = f\,.VI/S$$

- where V is arc voltage, I welding current and S welding speed and f is the fraction of heat generated and transferred to the plate.

In general, increase in heat input decreases the cooling rate while it decreases with the increase in initial plate temperature. So, during the welding for a given metal having the specific thickness and the thermal properties and to calculate the net heat input the heat input we generally calculate from the product of the welding current and the arc voltage. Since, the arc is moving at a particular speed, so by dividing the welding speed with the product of the welding current and the voltage we can obtain the net heat input.

So, to calculate the net heat input the V I that is the voltage and the current being used for the welding purpose divided by the welding speed. And this is the amount of heat being generated and if it is a fraction is being transferred to the base metal then that fraction f is applied. May be 0.9 or 0.95 or 0.98 depending upon the kind of welding process, the different fractional value can be used to calculate the net heat input. If we see this equation in the V is the arc voltage, I is the welding current and S is the welding speed and f is the fraction of heat generated and transferred to the fraction of the heat generated which is being transferred to the plate during the welding.

(Refer Slide Time: 22:42)

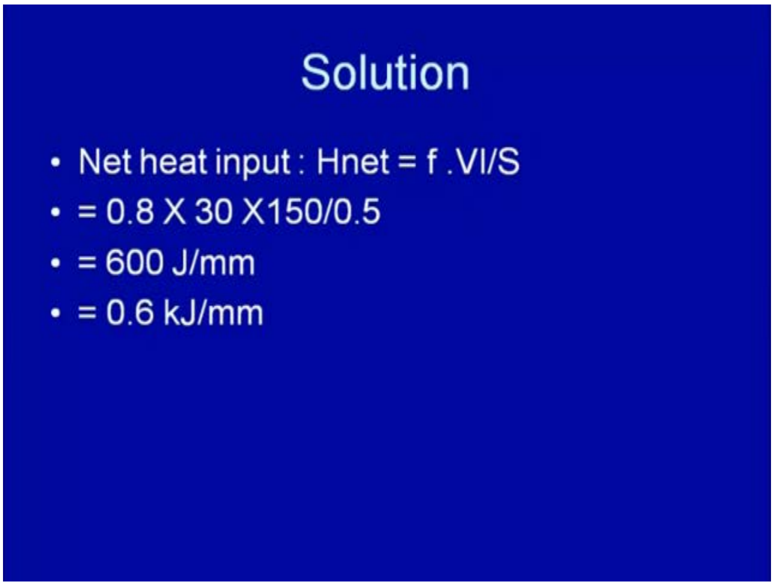


Example

- Calculate the net heat input used during welding of plates if welding of steel plate is given below:
  - Welding current: 150 A
  - Arc voltage: 30 V
  - Welding speed: 0.5 mm/sec
  - 80 % of heat generated by the arc is used for welding.

Now, we know that the heat input significantly affect the quality of the weld joint and the soundness of the weld joint. So, it is important to calculate or to know about what heat input is being used during the welding of the heat sensitive materials specifically like the steel plates. So, here we will see one example which will show that how net heat input can be calculated for a given set of the welding conditions. So, say welding current is of the 150 ampere and the arc voltage is 30 volt and the welding speed is being used of 0.5 mm per second then.

(Refer Slide Time: 23:35)



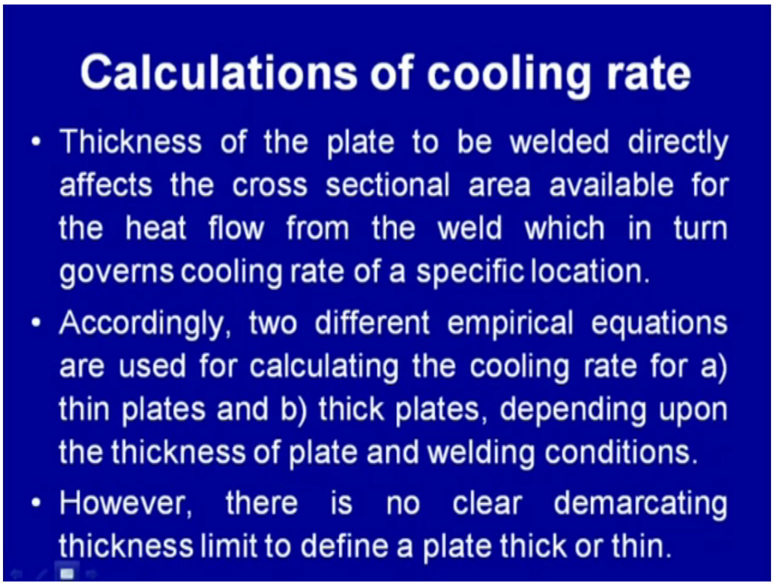
Solution

- Net heat input : $H_{net} = f\,.VI/S$
- $= 0.8 \times 30 \times 150/0.5$
- = 600 J/mm
- = 0.6 kJ/mm

And say assuming that 80 percent of heat generated by the arc is used for the welding purpose then we can calculate the heat being generated using this equation, net heat, heat generated is obtained simply from the V I that is the arc voltage and the product of the welding current. So, arc voltage multiplied by the welding current gives us simply the heat being generated, but since the arc move is at constant speed or set certain speed and of, only a fraction of the heat generated by the arc is used for the melting purpose or for the welding purpose.

And that is why the net heat input is calculated using the f that is a fraction of the heat generated in the arc zone is being used for the welding purpose multiplied by the V I that is the heat generated in the arc zone or arc power divided by the welding speed. So, if we put the values in this equation in 0.8 that is a fraction of the heat being used, 80, if the 80 percent of the heat is being used for the welding purpose then 0.8 multiplied by 30; that is the arc voltage multiplied by 150; that is the welding current divided by 0.5; that is the welding speed in mm per second until it give us the 600 jewel per mm and its convince, normally the heat generated is expressed, net heat input is expressed as a 0.6 or in kilo joule per mm. So, it will be 0.6 kilo joule per mm.

(Refer Slide Time: 25:10)

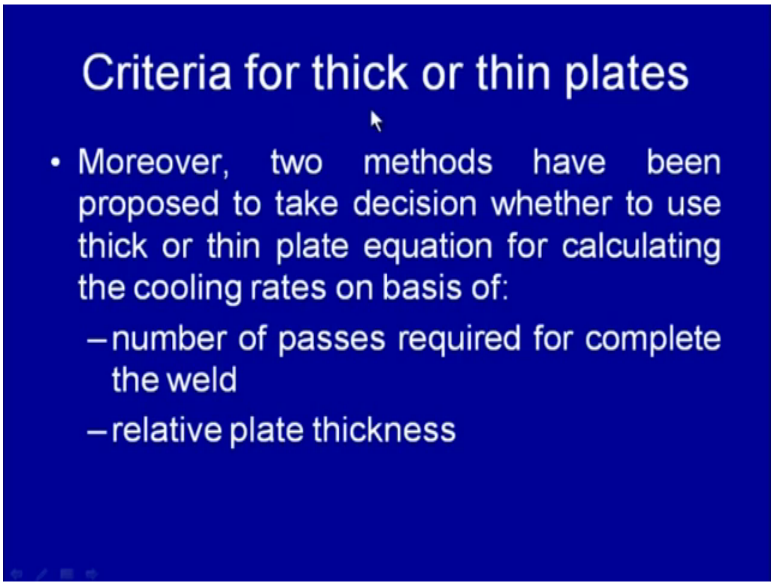


Calculations of cooling rate

- Thickness of the plate to be welded directly affects the cross sectional area available for the heat flow from the weld which in turn governs cooling rate of a specific location.
- Accordingly, two different empirical equations are used for calculating the cooling rate for a) thin plates and b) thick plates, depending upon the thickness of plate and welding conditions.
- However, there is no clear demarcating thickness limit to define a plate thick or thin.

Because it primarily affects the cross sectional area available for the flow of heat which in turn governs the cooling rate in big way. That is why the plate thickness is to be, is a first thing which is considered for calculation of the cooling rate. So, the two different empirical equations have been developed for calculating the cooling rate. One for, is used for thin plate conditions and another thick plates depending upon the thickness of the plate and the welding conditions being used. So, here, but which plate can be considered as a thick and which plate can be considered as a thin, there is no clear cut demarcating thickness limit to define the plate as a thick or the thin. Therefore, the two criteria's are used for this classification of the plate into either thick or the thick thin plates.

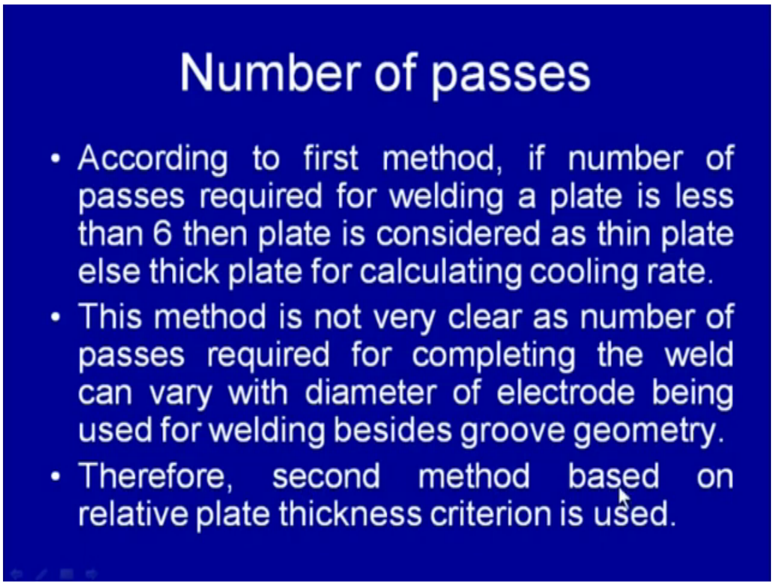
(Refer Slide Time: 26:05)



Criteria for thick or thin plates

- Moreover, two methods have been proposed to take decision whether to use thick or thin plate equation for calculating the cooling rates on basis of:
  - number of passes required for complete the weld
  - relative plate thickness

(Refer Slide Time: 26:52)



Number of passes

- According to first method, if number of passes required for welding a plate is less than 6 then plate is considered as thin plate else thick plate for calculating cooling rate.
- This method is not very clear as number of passes required for completing the weld can vary with diameter of electrode being used for welding besides groove geometry.
- Therefore, second method based on relative plate thickness criterion is used.

So, the two methods have been purposed to take a decision whether to use the thin plate or the thick plate equation for calculation of the cooling rate. These two criteria's are based on the number of passes required for completing a weld joint and the relative plate thickness. So, depending upon the number of passes we need to complete the weld. The plates are categorized as a thick plate or thin plate and depending upon the value of the relative plate thickness relative, depending upon the relative plate thickness value also we categorize whether the given, whether we should use the thin plate or the thick plate equation. So, if we consider the number of passes criteria.

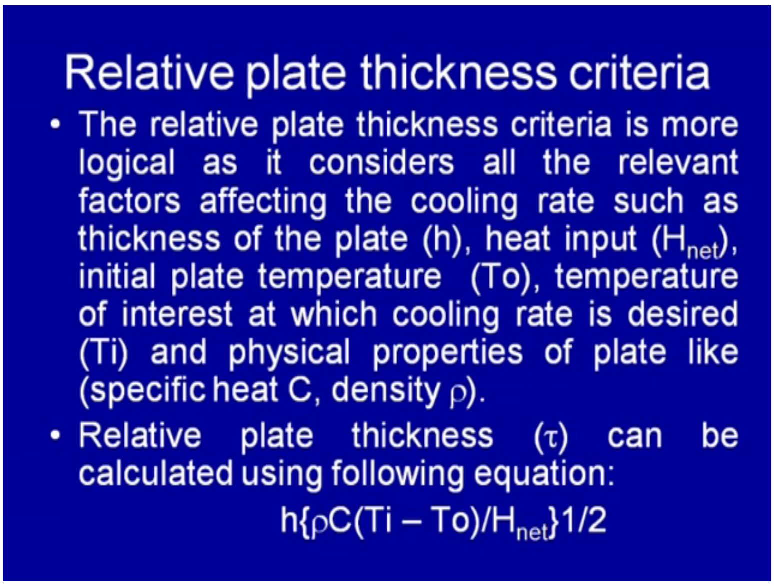
So, according to this method the number of passes required for welding a plate is less than the 6 number of, less than 6 then the plate is considered as a thin and otherwise the plate will be considered as a thick plate for the calculation of the cooling rates. So, according to this method number of passes required for welding a plate, if these numbers are less than 6 then the plate is considered as a thin; else thick plate for calculating the cooling rate.

So, we can see that this criteria is not very clear because the number of passes required for completing a weld can be significantly governed by the diameter of the electrode which is being used and the group geometry which is being used. We know that the for v group geometry we need to, we will require more weld metal to be deposited as compared to the u and the j groups. Similarly, if we use the large diameter electrodes then we will require fewer passes.

So, because of this ambiguity related with the number of pass criteria becomes difficult to, difficult to categorize whether the plate, whether we should use a thin plate equation or thick plate equation for calculation of the cooling rate for a given welding conditions. So, due to the non clarity as far as the number of passes required for completing the weld these criteria is not found to be effective because with the variation in the diameter of the electrode being used and the variation in the group geometry we may require the different number of passes for developing the weld joint.

For a given plate thickness if we use a small diameter electrode then we may require large number of passes and we may falsely consider the or we may incorrectly use the thick plate equation. And that is why this number of pass criteria is not very, not considered very effective for categorizing and using the thin plate or thick plate equations. Therefore, second method, which is based on the relative plate thickness is more effectively used.

(Refer Slide Time: 29:07)



Relative plate thickness criteria

- The relative plate thickness criteria is more logical as it considers all the relevant factors affecting the cooling rate such as thickness of the plate (h), heat input (H_{net}), initial plate temperature (To), temperature of interest at which cooling rate is desired (Ti) and physical properties of plate like (specific heat C, density ρ).
- Relative plate thickness (τ) can be calculated using following equation:

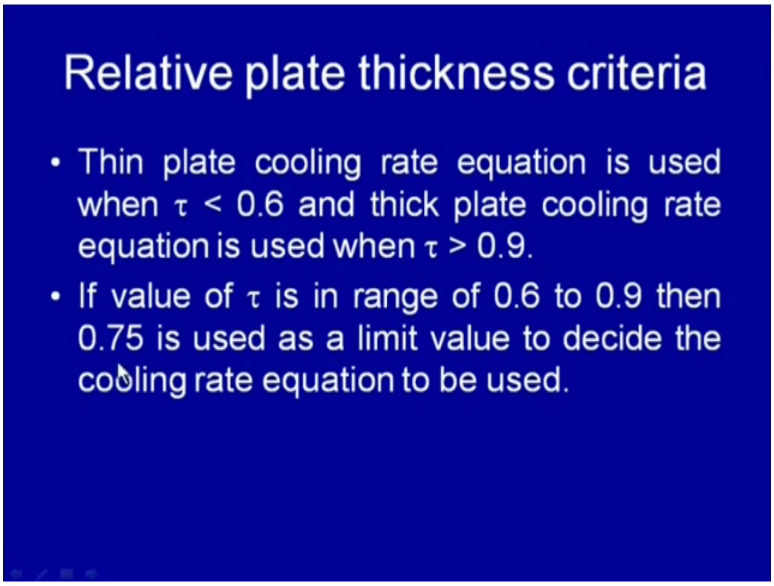
$$h\{\rho C(Ti - To)/H_{net}\}1/2$$

The, this relative plate thickness criteria is considered to be more effective because it considers all the factors which can affect the cooling rate during the welding of a particular location. And these parameters include the heat affect, heat being supplied, thickness of the plate, initial plate temperature and using these parameters we try to calculate the relative plate thickness. And if the relative plate thickness at a particular temperature of the interest is found to be below certain critical value then we consider it as a thick plate, thin plate or otherwise a thick plate.

So, if we see here the relative plate thickness criteria uses the thickness of the plate, the heat input initial plate temperature, temperature of the interest at which the cooling rate is desired and the physical properties of the plate being to be welded. So, the relative plate thickness criteria in light of above we can say it is more logical and this thick relative plate thickness can be calculated using this equation. This equation, the relative plate thickness equations is composed of the h multiplied by the rho C and within bracket T i minus T naught, T i is a temperature of interest, T naught is the initial plate temperature divided by the H net and the square root of this whole equation.

So, if we see here h is the thickness of plate, rho C is the, rho is the density and C specific heat initial plate temperature, final and the temperature of interest and the heat input. So, since all these parameters can affect the property, can affect the cooling rate of, cooling rate during the welding of a particular location that is why the relative plate thickness calculation can give a very logical criteria for taking decision whether we should use the thick plate equation or the thin plate equation for calculating the cooling rates.

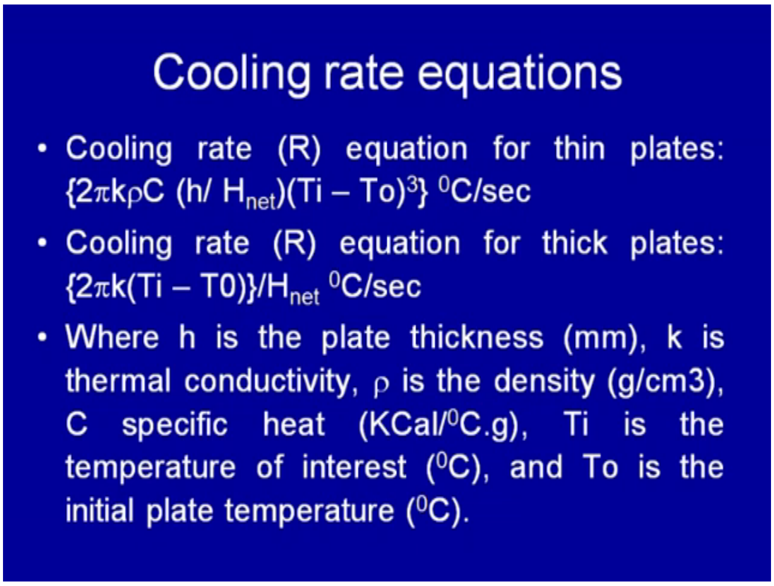
(Refer Slide Time: 31:11)



Relative plate thickness criteria

- Thin plate cooling rate equation is used when $\tau < 0.6$ and thick plate cooling rate equation is used when $\tau > 0.9$.
- If value of τ is in range of 0.6 to 0.9 then 0.75 is used as a limit value to decide the cooling rate equation to be used.

(Refer Slide Time: 32:02)



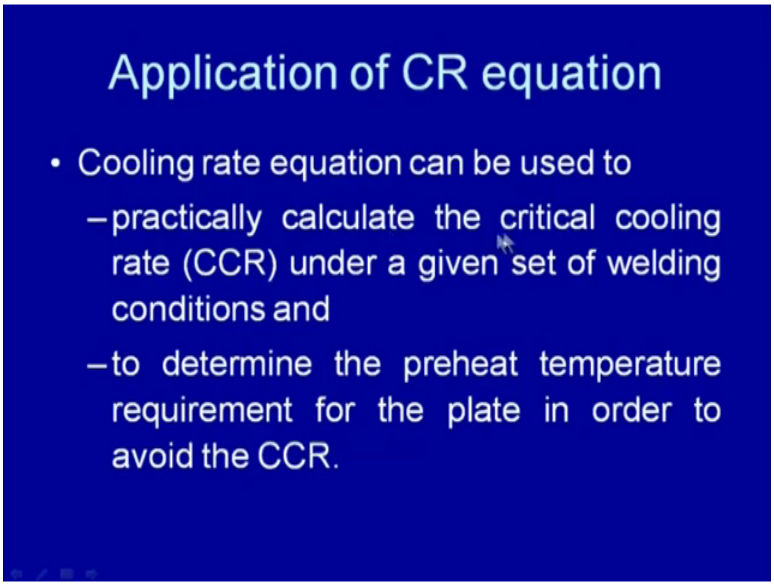
Cooling rate equations

- Cooling rate (R) equation for thin plates: $\{2\pi k\rho C\,(h/\,H_{net})(Ti - To)^3\}$ ^{0}C/sec
- Cooling rate (R) equation for thick plates: $\{2\pi k(Ti - T0)\}/H_{net}$ ^{0}C/sec
- Where h is the plate thickness (mm), k is thermal conductivity, ρ is the density (g/cm3), C specific heat (KCal/^{0}C.g), Ti is the temperature of interest (^{0}C), and To is the initial plate temperature (^{0}C).

According to the thin plate thin if based on the, so based on the relative plate thickness criteria, thin plate cooling, thin plate cooling rate equation is to be used when the relative plate thickness is less than 0.6 and the thick plate equation is used when the relative plate thickness is greater than 0.9. If the value of the relative plate thickness is in the range of 0.9 to the 0.6 to the 0.9 then 0.75 is used as a limiting value to decide the cooling rate equation to be used. Generally, the value, if the relative plate thickness is coming more than 0.75 then we use the thick plate equation for calculating the cooling rate, otherwise thin plate equation is used for the values below the 0.75.

So, for calculating the cooling rate, the cooling rate equation for the thin plate is shown in the screen. And this is the equation which is used for calculating the thick plates. So, if we see here the h is a plate thickness in mm, k is the thermal conductivity, rho is the density, C is the specific heat, T i is the temperature of interest which is mostly taken as 550 degree centigrade in case of the hardenable steels and T naught is the initial plate temperature in degree centigrade.

(Refer Slide Time: 32:46)

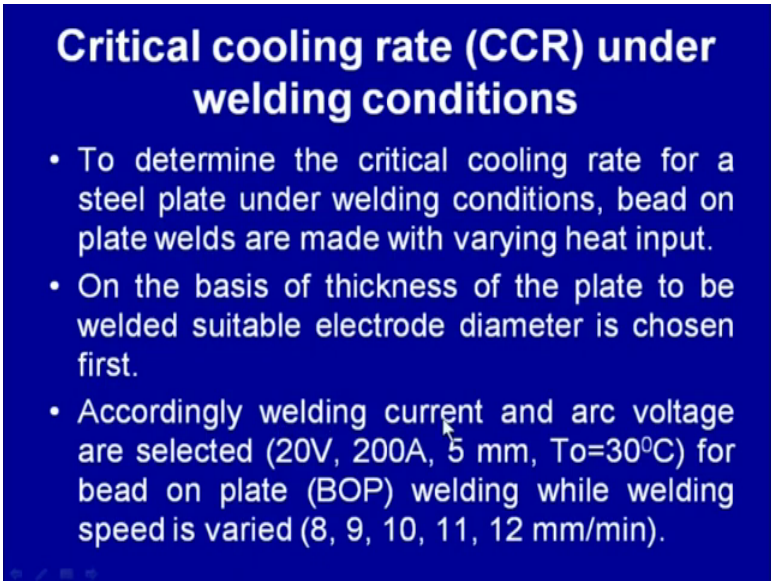


Application of CR equation

- Cooling rate equation can be used to
  - practically calculate the critical cooling rate (CCR) under a given set of welding conditions and
  - to determine the preheat temperature requirement for the plate in order to avoid the CCR.

So, if using the, these two equations can be effectively used for the purpose of practically calculating the critical cooling rate under the welding conditions. And also to determine the preheat temperature that we should use for preheating the plate, so as to avoid the critical cooling rate to avoid any kind of the austenite to martensitic transformation tendency, so as to avoid the tracking tendency and the embrittlement of the heat affected zone and of the weld metal. So, we will take up the first application where the cooling rate equations are being used for calculating the critical cooling rate under the welding conditions.

(Refer Slide Time: 33:23)



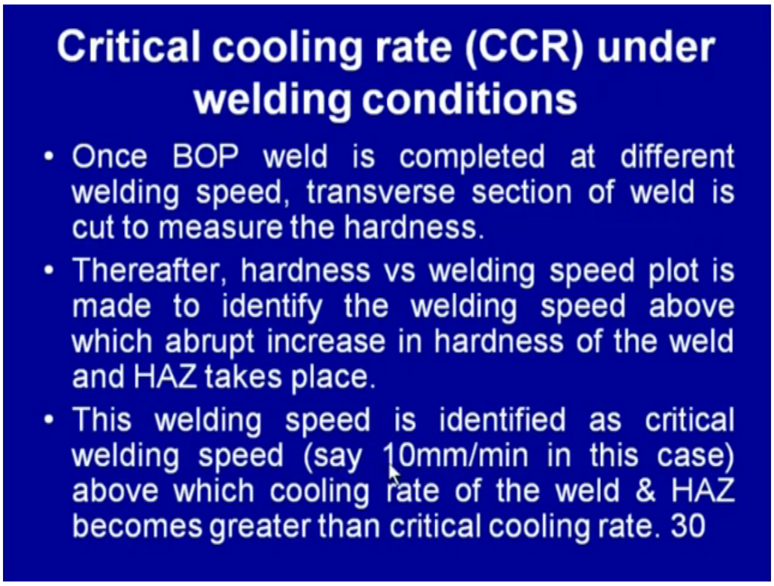
Critical cooling rate (CCR) under welding conditions

- To determine the critical cooling rate for a steel plate under welding conditions, bead on plate welds are made with varying heat input.
- On the basis of thickness of the plate to be welded suitable electrode diameter is chosen first.
- Accordingly welding current and arc voltage are selected (20V, 200A, 5 mm, To=30^{0}C) for bead on plate (BOP) welding while welding speed is varied (8, 9, 10, 11, 12 mm/min).

To determine the critical cooling rate for the steel plate under the welding conditions the bead on plate approach is used and in this approach the bead on plates are developed using the varying heat input. Means heat input is controlled and it is gradually decreased, so that in very controlled way cooling can be increased. So, on the basis of the thickness of the plate to be welded suitable electrode diameter is first chosen. So, the so for calculating the critical cooling rate on the basis of the thickness of the plate to be welded suitable electrode diameter is chosen because thickness of plate directly effects the current requirement and which in turn dictates the electrode diameter to be used.

So, for calculating the critical cooling rate under the welding conditions we deposit the bead on plate and for depositing the bead on plate on a given, the plate, we select first the electrode diameter. And accordingly we decide upon the welding current to be used and the arc voltage to be used for the, for developing the bead on plates. And say if we select the 20 volt and the 200 ampere current and for a plate of 5 mm thickness and the initial plate temperature of the 30 degree centigrade for developing the bead on plates while the welding speed is varied in very controlled way. And say bead on weld as developed using the speed first at 8 mm per minute, then 9, 11, 12. So, and the means by this way we will be developing the five different bead on plates.

(Refer Slide Time: 35:10)



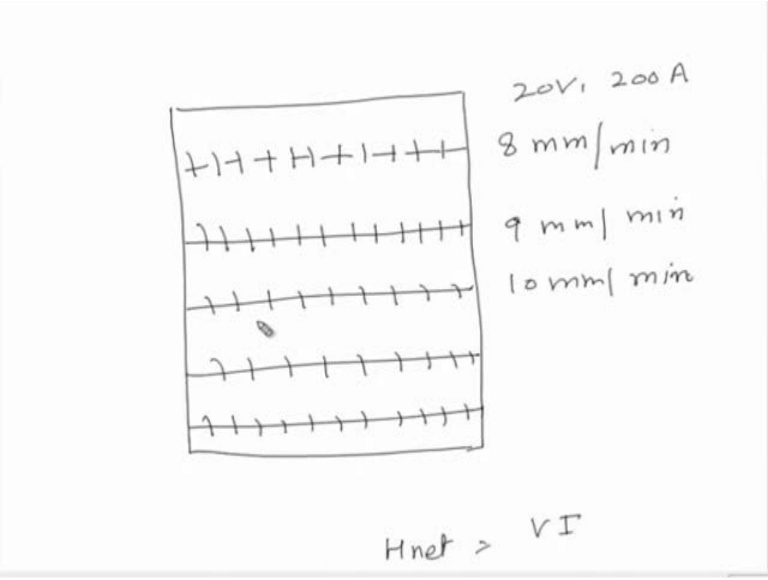
Critical cooling rate (CCR) under welding conditions

- Once BOP weld is completed at different welding speed, transverse section of weld is cut to measure the hardness.
- Thereafter, hardness vs welding speed plot is made to identify the welding speed above which abrupt increase in hardness of the weld and HAZ takes place.
- This welding speed is identified as critical welding speed (say 10mm/min in this case) above which cooling rate of the weld & HAZ becomes greater than critical cooling rate.

And after developing these bead on plates at different speeds the transverse section of the bead on plate is cut to measure its hardness. So, first we will be developing the bead on plate using the selected value of the welding current voltage and the welding speeds and after developing these bead on plates the transverse section of the beads is cut and the hardness is measured. And thereafter hardness verses welding speed plot is made to identify the welding speed above which abrupt increase in the hardness of the weld and the HAZ takes place. And this welding speed is identified as the critical speed.

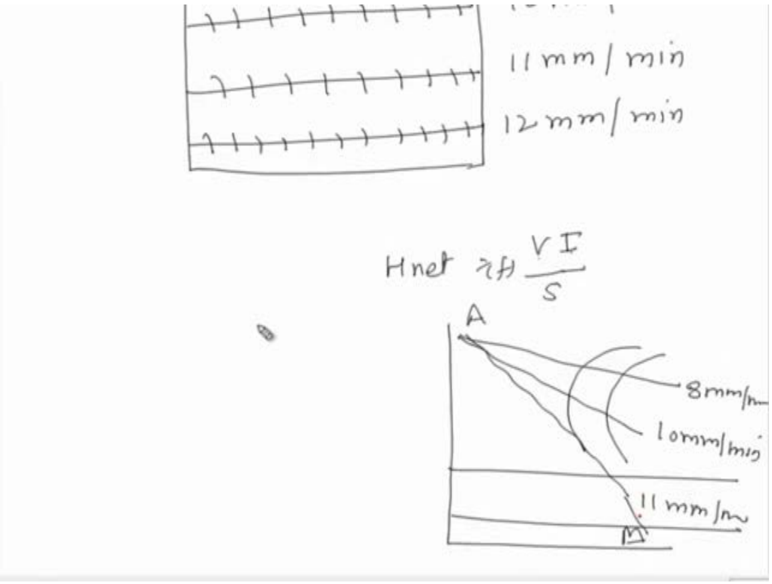
Say, if we get the welding speed above 10 mm per minute the abrupt increase in the hardness of the weld and the heat affected zone above which the cooling rate of the weld and the heat affected zone becomes greater than the critical cooling rate. Then that speed correspond then this welding speed results in the cooling rate which becomes more than the critical cooling rate and results in the austenite to the martensitic transformation for sudden increase in the hardness of the weld and the heat affected zone. To understand this we will use this schematic diagram.

(Refer Slide Time: 36:34)



So, according to this say we have one plate of a given thickness say of the 5 mm based on this we select suitable electrode and develop the bead on plate. First bead on plate we are developing say using the welding speed 8 mm per minute and this is the bead which is developed using one speed and say for given 20 volt and 200 ampere the welding current. So, using the same current and the same voltage the other beads at somewhat higher speed are developed.

(Refer Slide Time: 37:59)

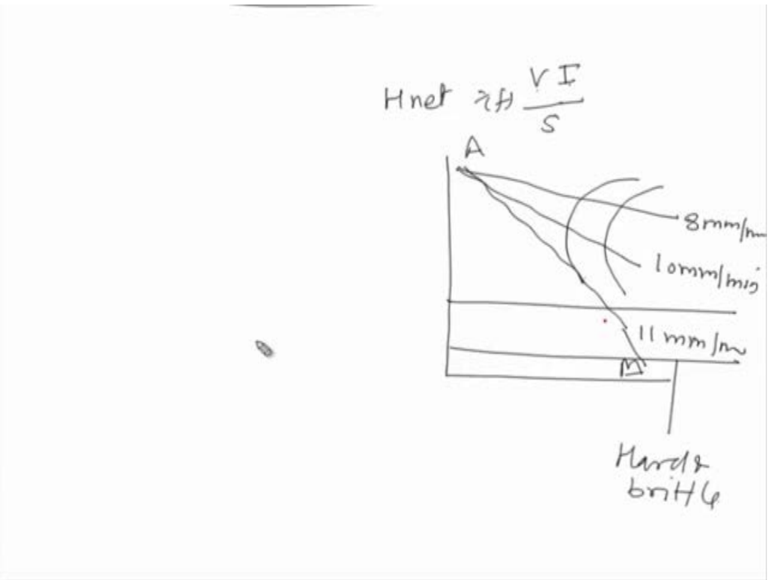


Say, another weld bead is developed at using 9 mm per minute welding speed. Similarly, we keep on depositing the weld bead at other higher speeds like this. Number of beads bead on plates are developed at the increasing welding speeds. So, we know that as the welding speed is increased net heat input to the weld decreases because the H net is obtained from the V I divided by S.

Say, f is fixed for a given welding conditions and given welding process H net sorry fraction of the heat being developed which is being transferred to the weld is fixed say 0.9. So, for given welding current and the welding voltage increase any speed will simply be decreasing the net heat input. So, if we keep on increasing the welding speed for depositing the different bead on plates, then it will keep on decreasing the heat input. So, decrease in heat input will be increasing the cooling rate and increase in cooling rate will be leading to the development of the different structures.

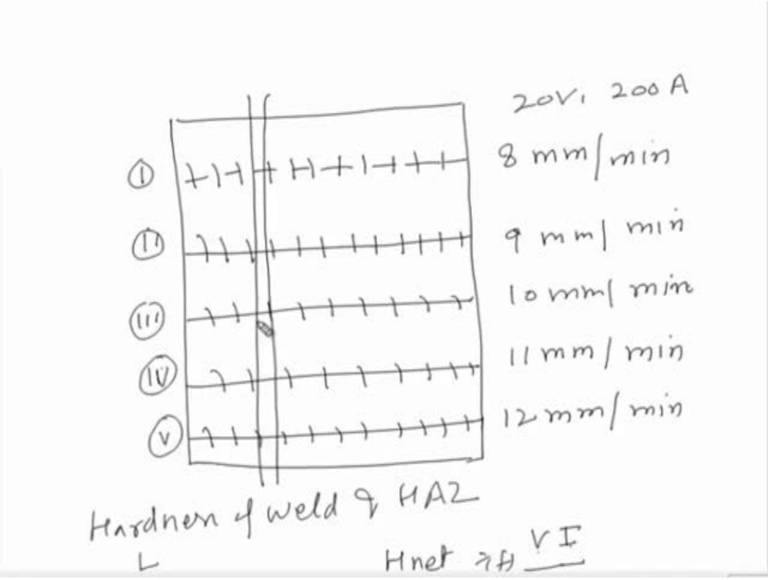
So, if we recall this diagram corresponding to the triple T diagram, so if say the low speed corresponds to the, this low speed means high heat input. So, high heat input means low cooling rate. This is corresponding which say for example, 8 mm per minute welding speed. If we take up another, this is corresponding to 10 mm cooling rate corresponding to the welding speed of 10 mm per minute. If we take up another one say this one, it is corresponding to the 11 mm per minute welding speed. So, in this situation the cooling rate is just crossing the nose of the triple T diagram and will be resulting the transformation of austenite into the martensite.

(Refer Slide Time: 39:47)

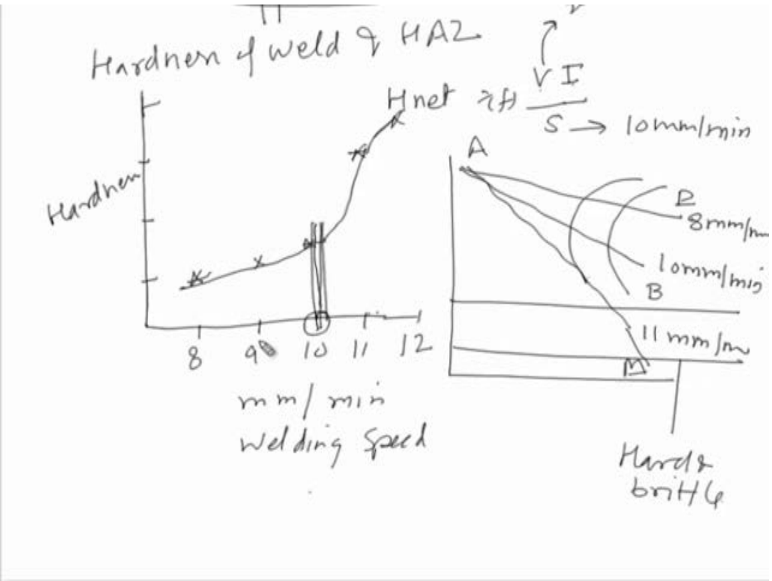


And because of this we will be getting the very hard and brittle, the weld and the heat affected zone. So, whether at what speed this condition is being achieved, at what speed the cooling rate is being obtained which is just touching to the nose and resulting in the austenite to the martensitic transformation. To obtain this only the different bead on plates are obtained.

(Refer Slide Time: 40:14)



(Refer Slide Time: 40:49)

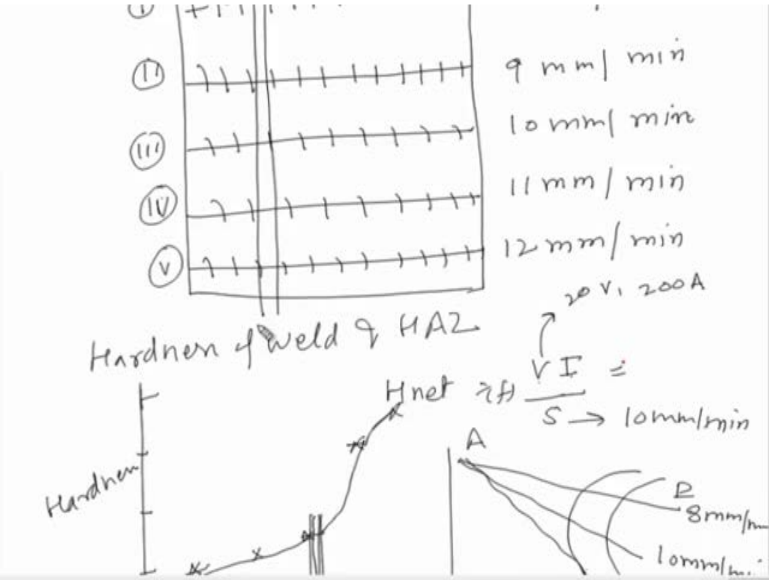


Once, these are developed we will cut the transverse cross section of all these samples. And after cutting these the hardness of each sample is obtained. So, one, two, three, four and five and so each transverse section, each sample will give the hardness of the weld and HAZ. So, that is obtained and measured. So, what is done?

This hardness is plotted as a function of welding speed say first corresponding to the 8, then 9, then 10, then 11 and then 12 meter per minute welding speed. Once this wave and in the vertical axis means in the y axis we can have the hardness, hardness of the weld as well as the heat affected zone. So, if we try to plot then say at low speed we will be having a high heat input. So, the low cooling rate will be resulting in the soft structure as the heat speed is increased resulting in the somewhat higher cooling rate will be resulting in the finer structures and then somewhat more finer structure.

Suddenly, we see that say at for example; at speed 11 the cooling rate becomes just greater than the critical cooling rate. And because of this austenitic from transformation from the austenite to the martensite starts while in other conditions it was either pearlitic or the bainitic one. So, under these conditions there will be sudden increase in the hardness and this will result in that here initially hardness was increasing gradually, because of the refinement of the structure.

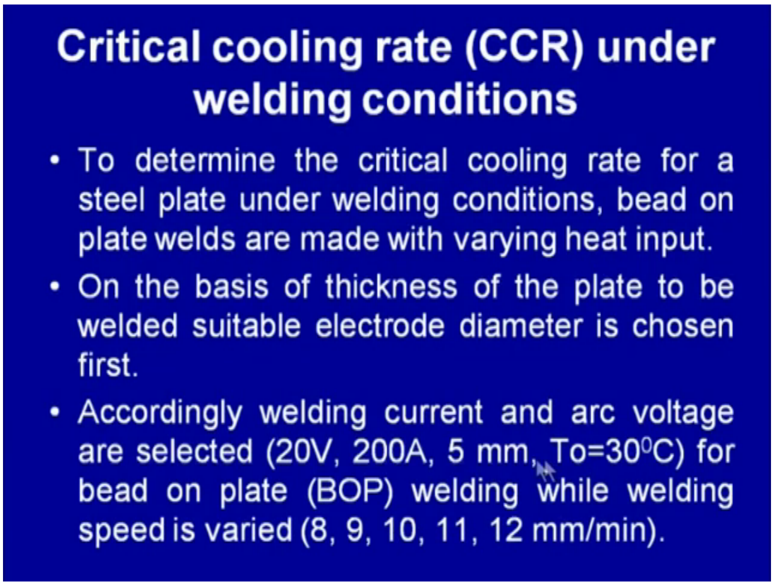
(Refer Slide Time: 43:17)



But as soon as the cooling rate becomes greater than certain critical cooling rate the sudden increase in the hardness of the weld and heat affected zone is obtained. So, this speed at which the sudden increase in the hardness is observed. Below that speed we consider as the critical speed above which the embrittlement of the heat affected zone and the weld will be taking place. So, this speed can be used for determining the cooling rate. Now, we have identified almost all the parameters which can be used for calculating the cooling rate.

So, if we use the welding speed, welding speed of the 10 mm per minute arc voltage, 20 volt and the welding current 200 ampere for calculation of the net heat input. So, the net heat input corresponding to this welding speed, this 200, 200 welding current and the 20 arc volt. So, this whatever net heat input is obtained corresponding to this whatever cooling rate is being developed in the weld region or in the heat affected zone that will be resulting in the critical cooling rate above which the weld will be subjected to the embrittlement.

(Refer Slide Time: 43:52)

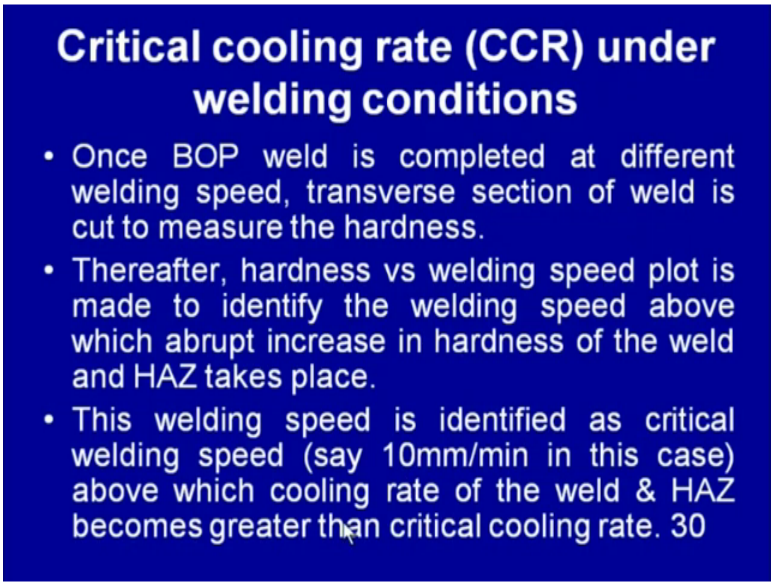


Critical cooling rate (CCR) under welding conditions

- To determine the critical cooling rate for a steel plate under welding conditions, bead on plate welds are made with varying heat input.
- On the basis of thickness of the plate to be welded suitable electrode diameter is chosen first.
- Accordingly welding current and arc voltage are selected (20V, 200A, 5 mm, To=30^{0}C) for bead on plate (BOP) welding while welding speed is varied (8, 9, 10, 11, 12 mm/min).

So, this is what we said that the weld bead on plate is developed at the different welding speeds. And once the bead on plate is completed at the different welding speeds transverse section of the weld is cut and the hardness is measured. Thereafter hardness versus welding speed plot is obtained to identify the welding speed above which abrupt increase in the hardness of the weld and the heat affected zone takes place. And the, this welding speed is identified as a critical welding speed above which the cooling rate of the weld and the heat affected zone becomes the greater than the critical cooling rate.

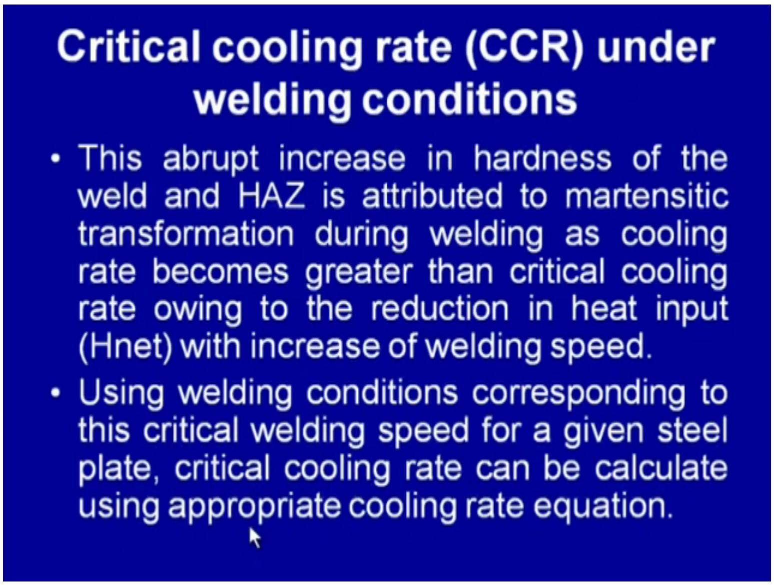
(Refer Slide Time: 43:58)



Critical cooling rate (CCR) under welding conditions

- Once BOP weld is completed at different welding speed, transverse section of weld is cut to measure the hardness.
- Thereafter, hardness vs welding speed plot is made to identify the welding speed above which abrupt increase in hardness of the weld and HAZ takes place.
- This welding speed is identified as critical welding speed (say 10mm/min in this case) above which cooling rate of the weld & HAZ becomes greater than critical cooling rate.

(Refer Slide Time: 44:26)

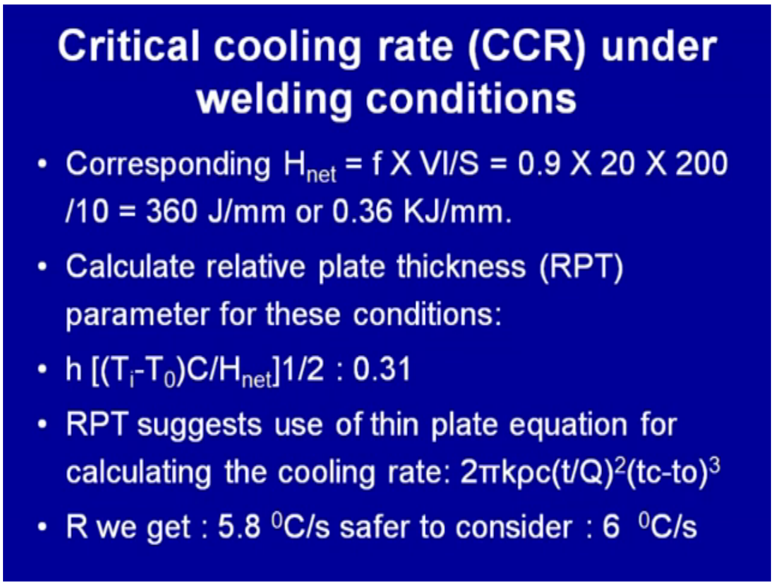


Critical cooling rate (CCR) under welding conditions

- This abrupt increase in hardness of the weld and HAZ is attributed to martensitic transformation during welding as cooling rate becomes greater than critical cooling rate owing to the reduction in heat input (Hnet) with increase of welding speed.
- Using welding conditions corresponding to this critical welding speed for a given steel plate, critical cooling rate can be calculate using appropriate cooling rate equation.

So, this abrupt increase in the hardness of the weld and the HAZ is primarily attributed to the martensitic transformation during the welding as the cooling rate becomes greater than the critical cooling rate due to the reduction in the heat input with a increase of welding speed. So, using the welding conditions corresponding to this critical speed for a given welding plate critical cooling rate can be calculated using the appropriate cooling rate equation.

(Refer Slide Time: 44:57)



Critical cooling rate (CCR) under welding conditions

- Corresponding H_{net} = f X VI/S = 0.9 X 20 X 200 /10 = 360 J/mm or 0.36 KJ/mm.
- Calculate relative plate thickness (RPT) parameter for these conditions:
- h $[(T_i - T_0)C/H_{net}]1/2$: 0.31
- RPT suggests use of thin plate equation for calculating the cooling rate: $2\pi k\rho c(t/Q)^2(tc\text{-}to)^3$
- R we get : 5.8 ^{0}C/s safer to consider : 6 ^{0}C/s

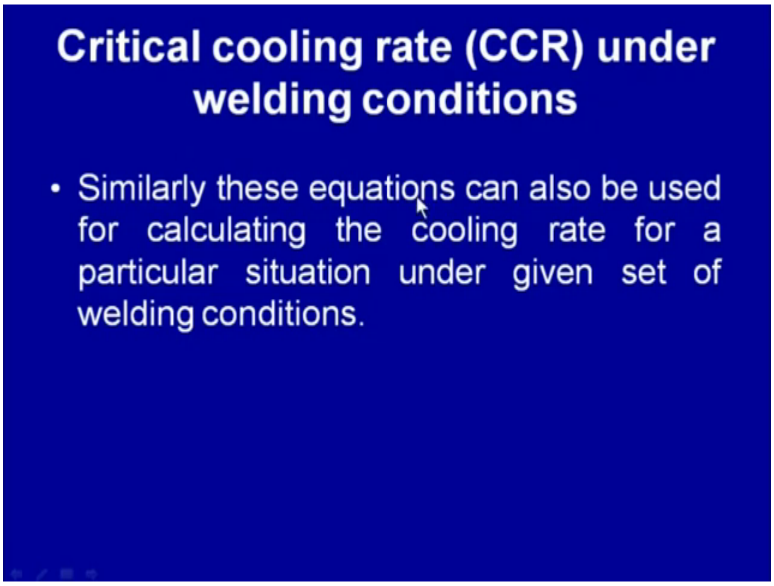
So, in this case, if we calculate the net heat input then the using equation f say, the 90 percent of the heat being generated by the arc is being transferred to the plate for development of the bead on plate and the welding voltage 20 and the welding current 200; and say critical speed identified as a 10 mm per minute. Then this will result in the net heat which is being supplied and resulting in the cooling rate which is just critical and above that the austenite to the martensitic transformation will be taking place.

So, here this net heat input comes out to be say 0.6 kilo joule per mm. Then using the relative plate thickness criteria for the given welding conditions if we calculate the relative plate thickness using the equation of the h multiplied by the T i minus T naught into the C divided by the H net and a square root of whole this. This will result in the relative plate thickness of the 0.31. So, we know that relative plate thickness if it is lesser than the 0.6 then it is considered as a thin plate and if it is more than 0.9 then it is considered thick plate.

And the relative plate thickness suggest the use of the thin plate equation for the calculating the critical cooling rate and using this equation for the critical cooling rate we can determine the cooling rate which will give us the critical cooling rate. Say, after putting the value of the various parameters of the steel, say thermal conductivity, density, specific heat, thickness, heat and net heat input temperature of interest that is 550 degree centigrade and the initial plate temperature say 30 degree centigrade. Then we get the critical cooling rate 5.8 degree centigrade per second.

So, just to be safe side we can consider this 6 degree centigrade per second. So, we can make sure that how to regulate the T naught temperature for given welding conditions. So, as to avoid the temperature cooling I mean so as to avoid the cooling rate greater than this 6 degree centigrade. So, if we go with the other welding conditions then the we can, we can see what heat input we can give in, so that the critical cooling rate can be avoided or what preheat we can use for avoiding the cooling rate, so that it is always lesser than the 6 degree centigrade per second.

(Refer Slide Time: 47:33)



Critical cooling rate (CCR) under welding conditions

- Similarly these equations can also be used for calculating the cooling rate for a particular situation under given set of welding conditions.

So similarly, these equations can also be used for calculating the cooling rate for particular situation under the given welding conditions. So, now here we will summarize this presentation which was mainly based on the heat flow in welding and the role of the cooling rate in the welding. We have seen that how we can calculate the cooling rate for the thin plate and the thick plate conditions and how we can use the cooling rate equation for calculating the critical cooling rate in the welding conditions.

And these equations can also be used for calculating the preheat requirement, so as to avoid the critical cooling rate in order to avoid the any embrittlement and the cracking tendency of the hardenable steels. However, the cooling rate during the welding of the aluminum alloys especially in the heat affected zone do not play any major role, but the cooling rate in case of the aluminum welds results in the finer structure or the course structure depending upon the cooling rate being experienced. So, the cooling rate conditions are more important for the hardenable steels while in case of the non ferrous metal systems like aluminum, cooling rate in the heat affected zone do not play the much role.

So, thank you for your attention.