Module 42

Physical metallurgy of metal joining

Lecture 42

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Keywords : Common methods of metal joining, bonding mechanism, wet-ability, effect of local heating, laws governing heat flow, temperature profile around stationery and moving heat source, weld pool geometry, weld solidification, structure of weld metal, heat affected zone, hardness profile

Introduction

In this module we shall learnt about the structural changes that might occur while joining two similar or dissimilar metals. There are several ways two parts can be joined. Some of these are as follows:

- Rivets / nuts & bolt: friction
- Adhesive: synthetic polymer
- Soldering: low melting metals
- Brazing: T_m higher than solder
- Welding: similar metals

Rivets or nuts & bolts hold two parts together primarily due to friction. You may need to drill holes in the parts to be joined. If it is done with a little care you do not expect any structural change within the metal. Adhesive used to join two parts makes use of synthetic polymer that sets under pressure or under a little thermal exposure. Once the adhesive sets it holds the two parts because of friction, Van der Waal force or chemical bonds. Even if a little thermal exposure is needed it is never high enough to induce any structural changes within the metals being joined. Soldering is done with the help of low melting alloys. Often these are binary eutectic. The bond between the solder and the metal is primarily due to van der Waal forces although diffusion may play some role. The main purpose is to provide a good contact between the parts being joined. It plays a major role in providing good electrical and mechanical contacts between different components in an electronic circuit. The process of brazing is similar to that of soldering. However the melting point of the brazing alloy is much higher than that of the solder. Unlike soldering or brazing in the case of welding the filler metal is similar to that of the parts that are being joined. Therefore a part of the two components being joined would melt and get mixed with the filler metal and solidify resulting in a much stronger bond. This is where you expect maximum change in the structure of the metals being joined. Therefore the main focus in this lecture will be on welding. In the process we shall learnt about:

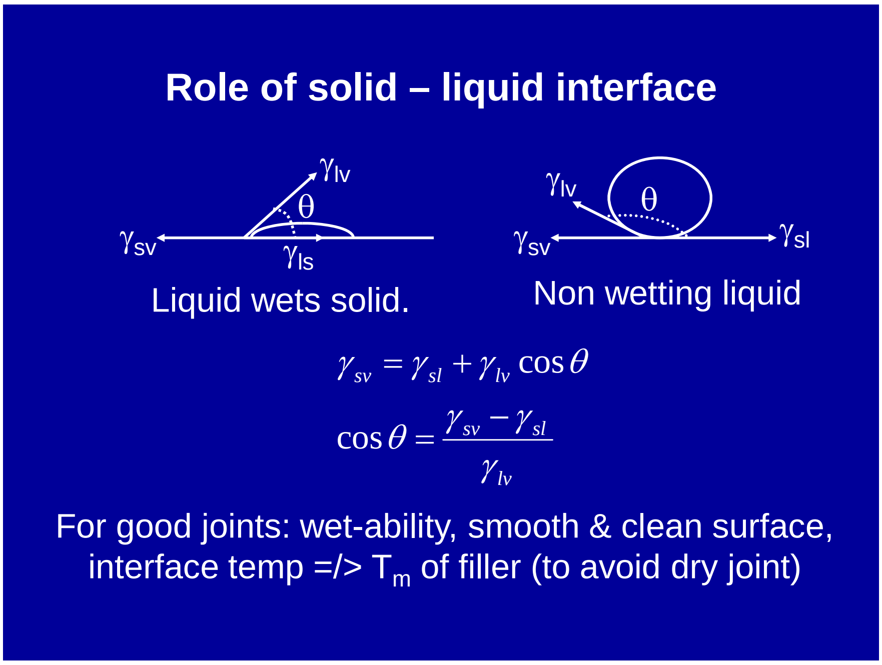
- Bonding mechanisms
- Structural changes
- Effect of processing parameters
- Heat affected zones
- Properties of joints

- Effect of service exposure

Where ever possible we shall illustrate these with specific examples.

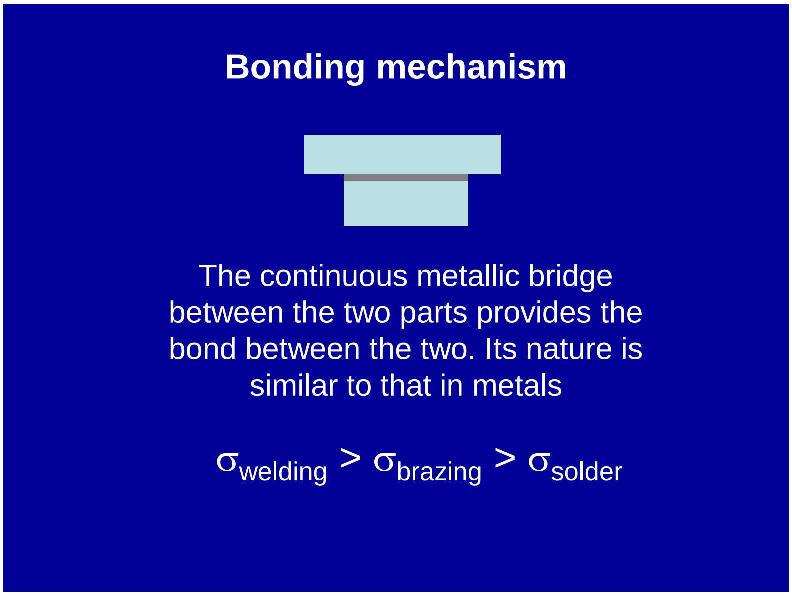
Bonding mechanisms:

The bond between the parts being joined by soldering, brazing or welding start developing right from the stage the molten filler metal comes in contact with the interfaces. Therefore how it flows on the surface of the metal is of considerable interest. Slide 1 gives what is likely to happen if a drop of molten metal rests on a solid surface. There can be two distinct situations depending on whether the liquid metal wets the surface or not. This depends on the magnitudes of the forces acting along the three different surfaces. Note that γ denotes surface tension. It is a measure of the energy of the surface or the interface between two different phases. The suffix denotes a pair of interfaces. For example γ_{sv} denotes the energy of the surface of the solid and vapor (atmosphere or environment). Look at the two sketches in slide. The angle θ denotes the contact angle between the liquid and the solid. The forces acting at the point of contact (see slide 1) must balance. This gives a definite expression (see slide 1) for θ in terms of the surface tensions of the three interfaces. The sketches in slide 1 show that low θ means good wet-ability. This would ensure a large area of contact. The expression for θ given in slide 1 clearly suggests that γ_{sl} should be as low as possible for good wet-ability. Addition of flux may also help improve wet-ability. The strength of the bond would certainly depend on the quality of the contact between the filler metal and the interfaces. Therefore wet-ability is a major criterion for good bonding.

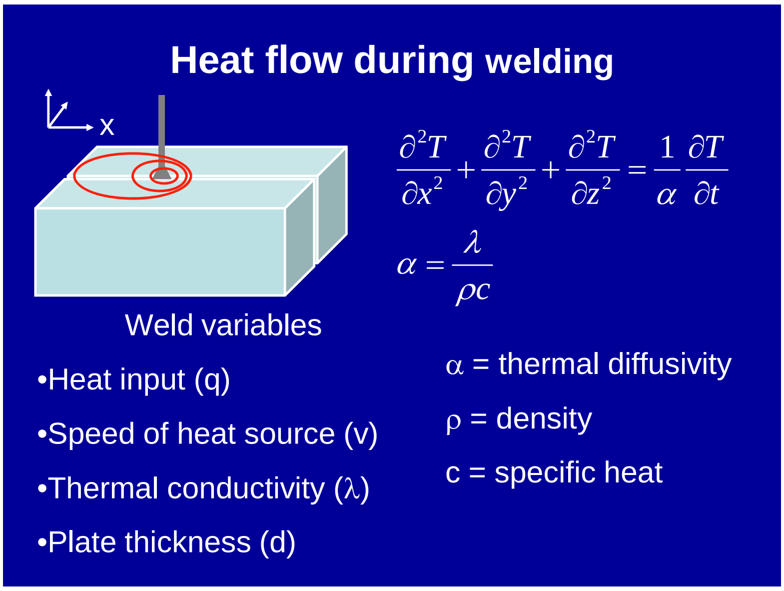


Slide 1

Apart from good wet-ability you also need to have clean and smooth surface so that the molten filler metal could flow easily. The temperature of the interface is also of considerable interest. It should be close or greater than the melting point of the filler alloy. This is necessary to ensure that the filler alloy does not solidify before it spreads over the surface. A low interface temperature may lead to a dry joint. This suggests that preheating of the components being joined may be necessary even during soldering and brazing. In the case of welding the heat input is so intension that a part of the metal melts. Once the molten filler alloy solidifies it acts a bridge between the two parts that were joined. This is illustrated with the help of a sketch in slide 2. In the case of welding the composition of the filler metal is same as that of the two parts being joined. However in the case of brazing and soldering the composition of the filler metal is different. The strength of filler metal depends on its melting point. Since the filler metal used in welding has the highest melting point, the strength of welded joint too is the highest. This also explains why a solder is the weakest of the three.



Slide 2

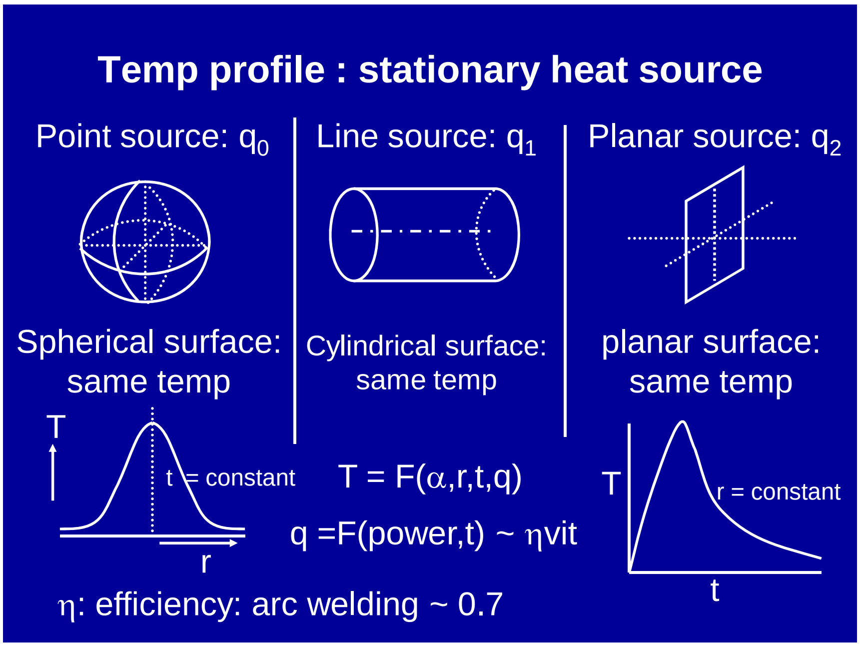


Slide 3

Effect of processing parameters:

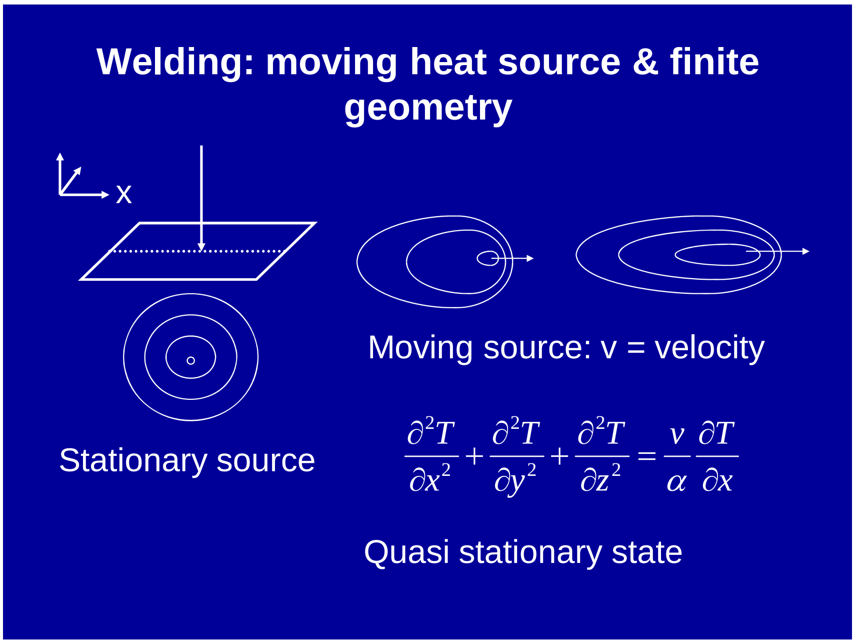
The three joining methods can be visualized as a two step process consisting of local heating for a short duration followed by rapid cooling. The structural changes that may occur would therefore depend on the peak temperature and the cooling rate. Without going into details let us try to have a rough idea about the nature of the temperature profile around a moving heat source.

Slide 3 gives a schematic representation of how the temperature (T) contours around a moving point source may look like. It also gives the equation that governs heat flow in a continuous 3D medium. The location of a point is given by the Cartesian co-ordinates x, y, z. Small t denotes time and the constant 'α' is known as the thermal diffusivity of the medium. It depends on the density, thermal conductivity and specific heat of the medium. For simplicity let us assume that these are independent of temperature and composition. Apart from these the temperature distribution at any instant would also depend on the strength of the heat source or heat input per unit time, the speed & geometry of the heat source and the size (thickness) of the medium. If the source is stationery we expect the heat to flow uniformly along all directions in a plane. Therefore the shape of the temperature contours in a plane should be circular. Note that a line or a curve joining points having identical temperatures is a contour. Heat flow direction is always perpendicular to the direction of the contour. In the case of a moving source it gets a little distorted or stretched along the direction of motion. The contours in a plane are more closely spaced near the heat source. These are wide apart at a distance far away from the source. The spacing is an indicator of temperature gradient.



Slide 4

Slide 4 shows the effect of the geometry of a heat source on the shape of the temperature distribution profile around it. From a point source heat can flow at the same rate along all possible directions. Therefore at any instant the temperature at all points at identical distance from the source should be the same. The temperature contours around a point source should consist of a set of concentric spheres. The same logic can be extended to the case of a line source to show that the contours (surface having identical temperature) would consist of a set of cylindrical surfaces with the heat source being the common axis. Note that there is no temperature gradient along the heat source therefore heat cannot flow along this direction. In the case of a planar heat source the temperature at all points on the plane are identical. Therefore heat can flow only in a direction perpendicular to it. The isothermal surfaces would consist of a set of parallel planes. Slide 4 also includes a plot representing the variation of temperature at a given time as a function of distance along a direction perpendicular to the isothermal surfaces. Note the symmetry of the plot on the two sides of the source. Slide 4 also has a plot denoting how the temperature at a point (r = constant) is likely to vary with time once the source is switched off after some time. It keeps increasing with time until it reaches a peak and thereafter it decreases continuously. The temperature a point near a heat source of a specific geometry is therefore a function of r (location), t (time), α (thermo-physical properties), and q (heat input or the power of the heat source). During welding the heat input would depend on the Voltage (V), current (i) and time (t) an arc spends at a point. In the case of a continuously moving source the time spent at a point is inversely proportional to its speed. In addition the expression should have a term representing the efficiency (η) of heat absorption. It is around 0.7 in the case of arc welding.

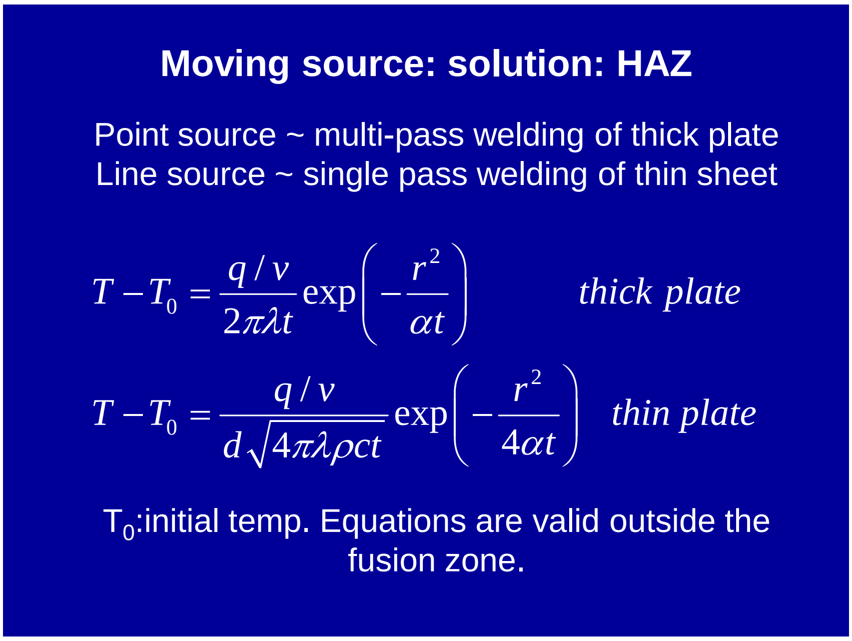


Slide 5

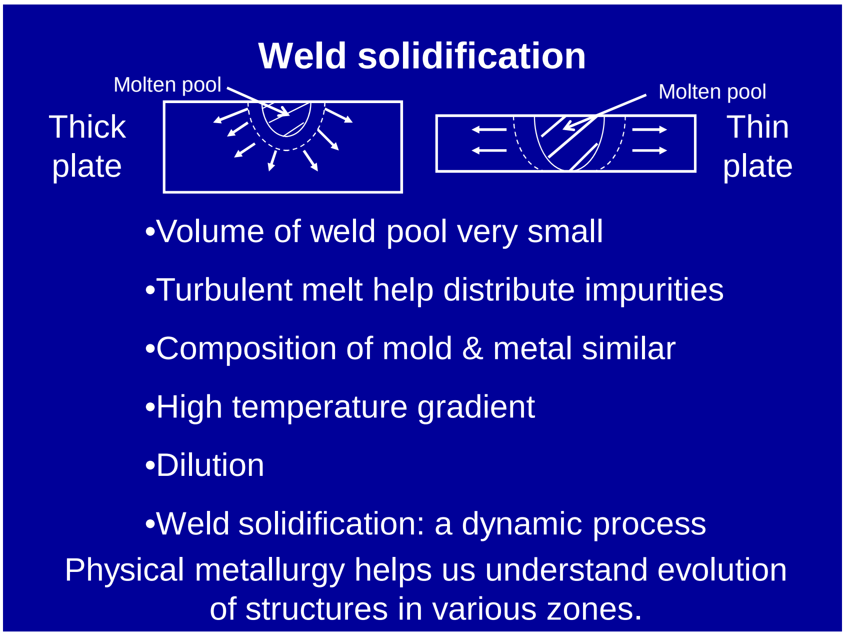
Slide 5 shows the effect of velocity (v) on temperature distribution at a given time around a point source. If it stationery the contours consist of a set of circles. In the case of a moving source the shape gets stretched along the direction of motion. The equation that describes the heat flow in the case of a moving is given in slide 5. Note that time (t) has been replaced by x, the direction of the movement of the source. This is obtained by the following substitution in the expression given in slide 3.

$$\frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right) = \frac{1}{\alpha}\left(\frac{\partial T}{\partial x}\right)\left(\frac{\partial x}{\partial t}\right) = \frac{v}{\alpha}\left(\frac{\partial T}{\partial x}\right) \qquad (1)$$

What is the best approximation for the geometry of a heat source? This would depend on the size of the job being welded. If you are to weld a thick plate heat must flow along the length, width and the thickness. It is a case of 3D flow. Therefore point source is a better approximation. In the case of thin sheet a single pass welding is good enough. Heat flow along the thickness may not be important. Therefore a line source is a good approximation.



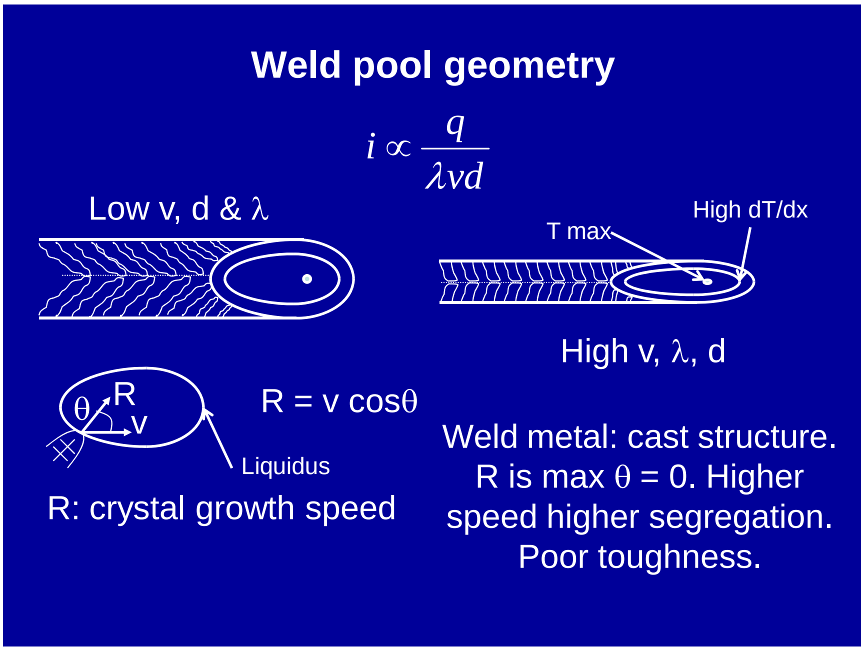
Slide 6



Slide 7

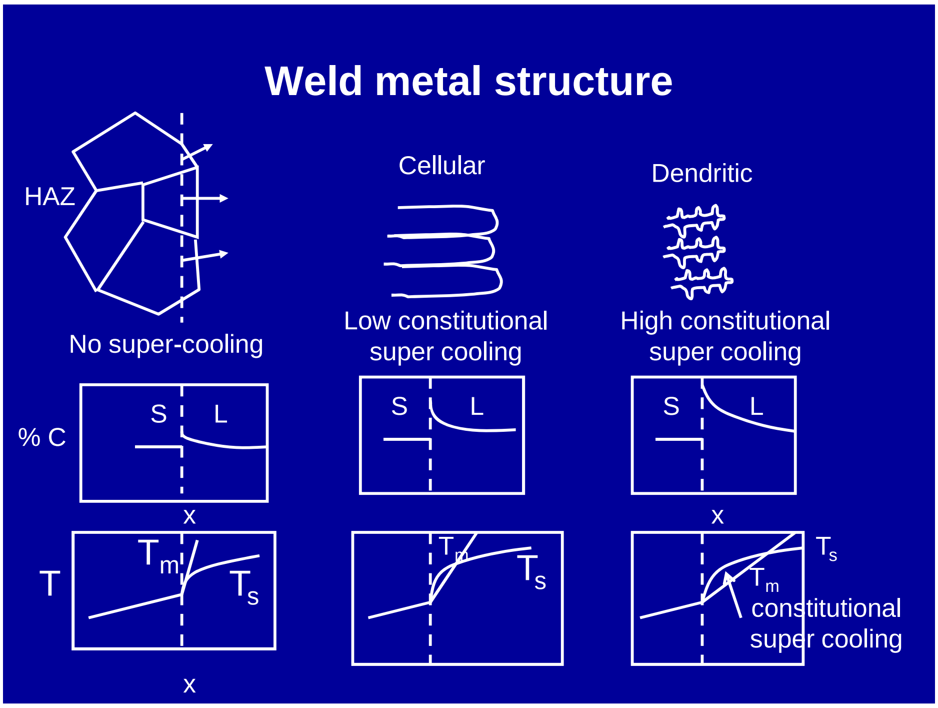
Slide 6 gives approximate solutions to the moving heat source problem described in slide 5. These equations are valid just outside the heat affected zone. This can be of help in predicting the evolution of structure in the heat affected zones of a weld joint.

Weld pool solidification: Welding represents solidification of a small pool of molten metal within a mold. Heat flows from the hot pool of molten metal into the mold surrounding it. This is illustrated with the help of two diagrams in slide 7. If the plate is thick heat flows in all the 3 directions. In the case of a thin sheet heat flows along the width of the plate as shown. A few major points that are worth considering are listed in slide 7. The size of the mold that acts as heat sink is very large. The temperature gradient within the mold is very high. The heat may get dissipated through the plate or the sheet very fast. The electric field may create turbulence within the molten pool. This may help distribute impurities. The composition of the mold or the metal that is being joined and the filler metal is usually similar. However the two may not be exactly the same. A part of the metal being joined melts and gets mixed with the filler metal. The turbulence within the pool helps mixing. In the absence of turbulence there will be segregation. The centre will be rich in filler metal whereas the side will have composition closer to that of the parent metal. The composition of the weld metal is generally an average of the two. This is known as dilution. The extent of dilution would depend on the amount of filler metal used and the amount of parent metal that melts. It may depend on the weld geometry. The weld solidification is therefore a complex dynamic process. Let us see how we could use what has been covered in this course on physical metallurgy to explain the evolution of structures within different zones in a welded component.



Slide 8

Weld pool geometry: Slide 8 shows with the help of a set of diagrams the effect of variables like velocity (v), size (d) and thermal conductivity (λ) on the weld pool geometry. The shape of the molten pool is like a distorted ellipse. The sketch at the bottom left corner of slide 8 shows the shape of the contour corresponding to the temperature of the liquidus. The front end of the distorted ellipse denotes the location where melting is about to begin. The tail end of this contour denotes the region where solidification is over. The direction of crystal growth is perpendicular to the liquidus. The angle between the direction of growth and the velocity of the weld pool (v) is θ. The rate of crystal growth R is equal to vcosθ. It is the highest at θ = 0. This corresponds to the tail end. R is zero where v is tangent to the distorted ellipse (or the molten pool). This is the point on the moving weld pool beyond which there is no nucleation or crystal growth. Solidification begins from the edge of the solid surface soon after the weld pool moves away from the point where θ was 0 a little earlier. Several nuclei may form but only those that are favorably oriented would grow. Depending on the thermal gradient and the type of the alloy columnar or dendritic growth takes place. Usually <001> axis is the favorable direction of growth. The direction of growth is always perpendicular to the weld pool boundary. The alignment of the grains depends on the velocity, thermal conductivity and the size of the component. This is illustrated with the help of sketches in slide 8. A major problem during this stage is the segregation of impurities. During solidification solute atoms are pushed towards the molten metal present along the centerline. This is the region that solidifies at the end. It consists of inclusions and precipitates. The centerline segregation is responsible for the poor toughness of weld joints. Higher the speed higher is the segregation.

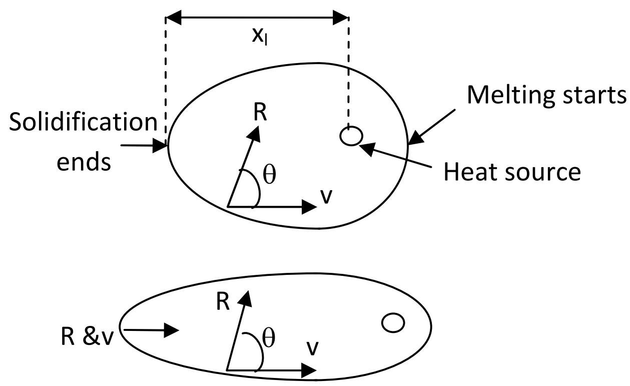


Slide 9

Weld pool structure: The temperature of the solid interface may go beyond its melting point when it comes in contact with the molten pool of weld metal. A thin region of the parent metal may therefore melt and mix with the liquid. This is known as dilution. It helps develop a good contact between base metal and the weld through the formation of a fusion zone. The region that melts and re-solidifies is known as the fusion zone. The subsequent solidification is governed by nucleation and growth. The orientation of the grains that nucleate is exactly same as those at the solid-liquid interface. In welding literature it is known epitaxial growth. The subsequent growth depends on the shape of the solidification front. This is influenced by the solute content in the molten weld metal, the thermal gradient (G) in the weld pool and the rate (R) at which the front moves forward. Slide 9 shows the basic features of the three different types of grain structure that can be seen in weld metal.

It follows from equation 1 that: $G = \frac{\partial T}{\partial x} = \frac{1}{v}\left(\frac{\partial T}{\partial t}\right) = \frac{T_m}{x_l}$ or $\frac{G}{R} = \frac{T_m}{v x_l}$ (2)

Note that T_m denotes the melting point of the metal and x_l is the distance between the heat source and the tail end of the molten weld pool (see fig 1. It shows that R = v). The melting point of a filler alloy is known. It is fixed. As v increases x_l too would increase. Therefore high velocity of the weld pool means lower thermal gradient or G.



$$R = v\cos\theta$$

Fig 1: The shape of the molten weld pool depends on the velocity at which the heat source moves. If the velocity (v) is high the length of the pool is longer. At the far end where solidification ends the rate at which the solidification front moves (R) is equal to the velocity of the heat source because the angle between the two is zero (θ = 0).

The surface of the parent metal must melt and mix with the filler alloy. It is known as the fusion zone. It plays a major role in the development of a good bond between the two. Figure 2 explains why the re-solidification of the fusion zone must take place through epitaxial growth. The thin film subsequently grows into columnar grains or dendrites depending on the thermal gradient (G) and R (the rate at which the solidification front moves). Color has been used to represent the difference in orientation of the grains. The extended part shown by dashed line denotes the fusion zone.

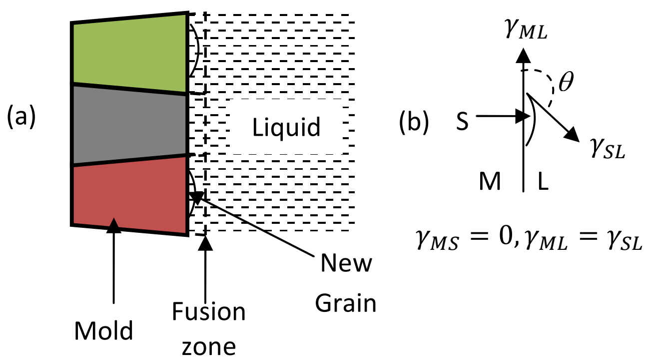


Fig 2: Explains the concept of epitaxial crystal growth. (a) A part of the parent metal that comes in contact with the liquid melts. The new grain that nucleate must have identical orientation. $\therefore\ \gamma_{MS} = 0$ (b) θ = 180°. The other two surface tensions should be equal and opposite. The shape of the new grain is like a thin film.

Apart from G & R the concentration of solute too has a pronounced effect on the microstructure that develops in the weld metal. A set of concentration versus distance and temperature versus distance plots in slide 9 describe three different situations. If thermal gradient at the solid liquid interface is greater than a critical value the interface is planar. This promotes columnar grains. The critical gradient depends on the solute buildup and the corresponding phase diagram. If it is a little lower, the buildup of solute at the interface leads to the formation of a cellular structure. Look at equation 2. It gives a relation between G/R and the melting point. The velocity of the weld pool (v) and x_l (the distance between the heat source and the tail of the weld pool) are constant for a given welding setup. Therefore the only variable (liquidus temperature) which is a function of composition is T_m.

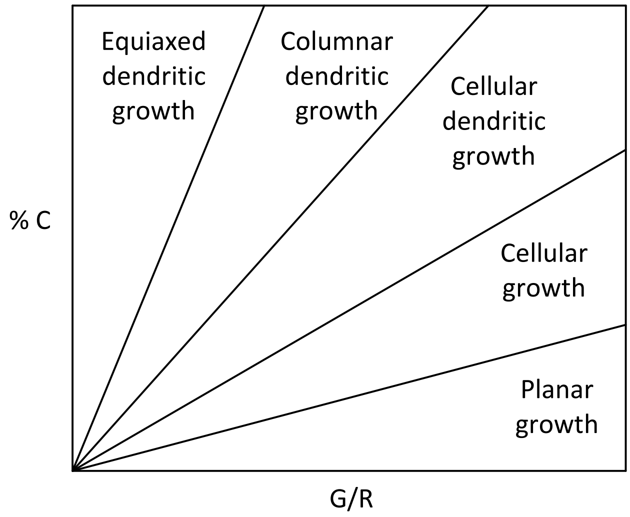


Fig 3: A schematic diagram showing the effect of % concentration and G/R on the nature of the structure that develops in the weld metal.

Figure 3 gives a schematic diagram showing the effect of concentration of solute and the ratio G/R on the nature of structure that evolves within the weld metal. Figure 4 gives main structural features of expected microstructure.

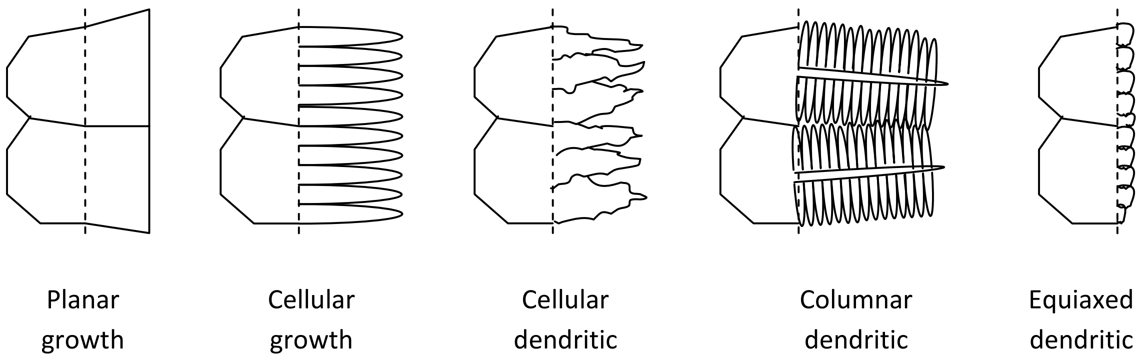


Fig 4: A schematic representation of different types of structure likely to be seen in the weld solidified zone.

Heat affected (HAZ): We have so far talked about the evolution of microstructure within the weld metal. This consists of the solidified filler alloy and the fusion zone. Apart from these there are regions where the temperature can go up significantly. Therefore the microstructure within these is likely to change. The size of such regions is a function of the following factors:

- Peak temperature (T_p)
- Phase diagram
- Transformation kinetics

- Duration (Δt)

The peak temperature in the fusion zone during welding is always higher than the melting point of the parent metal. The heat affected zone extends from the fusion zone to a point in the parent metal where the temperature does not go beyond the re-crystallization temperature of parent metal.

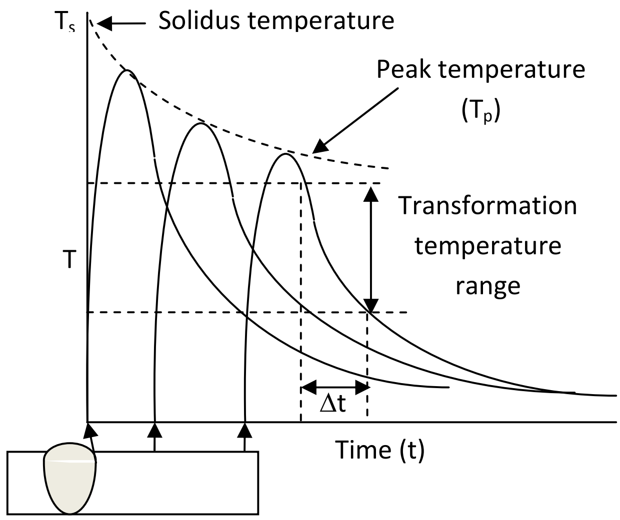
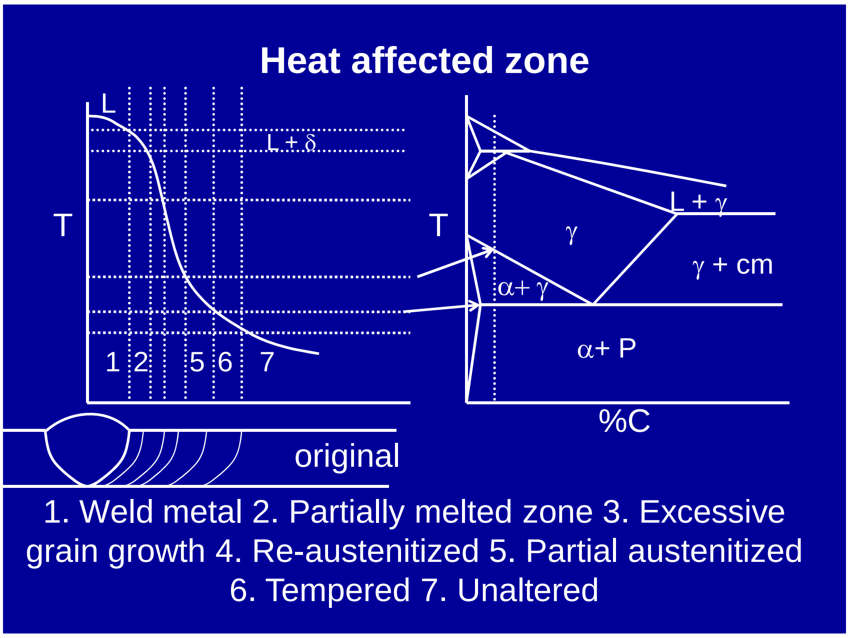


Fig 5: Shows a set of schematic temperature versus time plots at three locations near the fusion zone of a welded structure. T_p, the peak temperature is a function of distance from the fusion zone. The range of temperature is shown by a pair of horizontal lines. The peak temperature may go beyond or lie within this range over a region near the weld. This is known as the heat affected zone because of the structural changes that occurs here.

Figure 5 shows how the temperature at a point in the parent metal is likely to increase initially reach a peak and thereafter decrease. The peak temperature may go as high as the melting point in the fusion zone. Evolution of microstructure in the fusion zone has already been discussed. In this section our focus is on the structural changes occurring in the heat affected zone (HAZ). The peak temperature (T_p) and the duration (Δt) or the time it takes to cool through the critical range of temperature (800°-500°C) determine the type of structure that is expected in the heat affected zone.



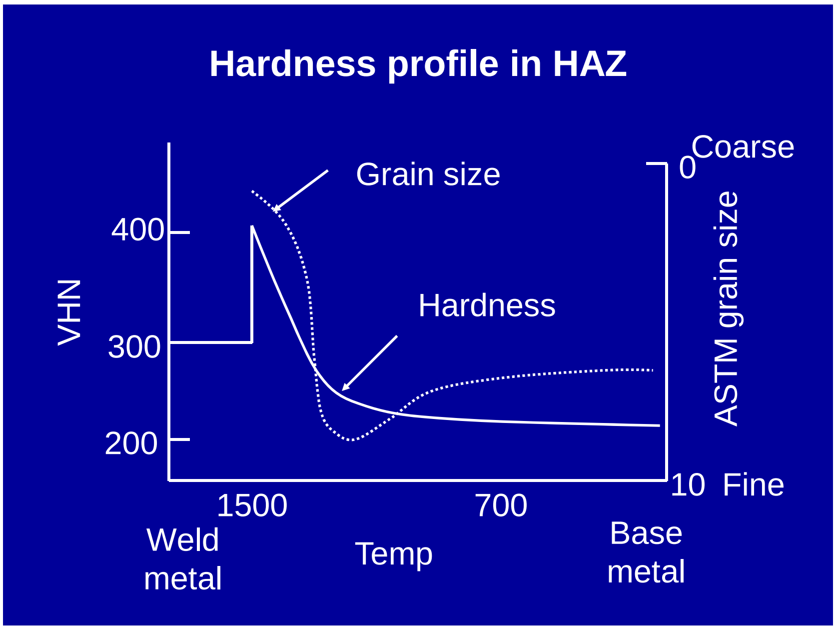
Slide 10

Slide 10 gives T_p versus distance plot and Fe-Fe_3C phase diagram side by side so that it helps appreciate the effect of welding on the structure that evolves within the HAZ. On the basis of the thermal profile the weld joint may be divided into seven distinct zones as indicated in slide 10. The nomenclature itself gives an idea about the main structural features within these zones. Table 1 gives important features of these zones. It also gives the type of failure one might encounter during welding. Solidification cracks are usually found in the weld metal. This is associated with the segregation of low melting constituents within dendritic channels and the thermal stress that develops due to contraction. The partially melted zone is prone to liquation cracking. This too is associated with segregation. However it may occur during subsequent heating (for example during multi-pass welding). The region where the temperature is lower than the melting range but higher than the normal austenitization temperature is susceptible to excessive grain growth. Coarse grain austenite may give rise to a structure consisting of a network of ferrite around martensite particularly in steels having high carbon equivalent. The presence of Nb/V/Ti makes micro-alloyed steel extremely resistant to excessive grain growth. The carbides of Nb, V and Ti are extremely stable even at very high temperatures (~1200°C). Their presence at austenite grain boundary inhibits excessive grain growth. The region where the temperature goes beyond the upper critical temperature would transform into austenite. In the presence of strong carbide formers the austenite grains are relatively fine. Therefore on subsequent cooling it is likely to give a structure consisting of ferrite and pearlite. This zone may be wider in micro-alloyed steel than that in normal plain carbon steel. The austenite that forms in the region where peak-temperature is between A_1 and A_3 has relatively high carbon content. Therefore depending on the cooling rate it may transform into plate martensite. The zone where the temperature does not go beyond the lower critical temperature would depend a lot on its initial structure. The heating to this range of temperature amounts to tempering in the case of air hardening steel. This would promote softening due to coarsening of carbides. In the case of low carbon steel only ferrite grains may re-crystallize. The pearlite may remain unaltered. The temperature in the region beyond this is too low to have a visible change in its microstructure. The temperature may still be high enough to allow the movement of carbon atoms dissolved in ferrite to pin the dislocations. This may lead to strain ageing. Barring this the structure within this remains unaltered.

Table 1: Main structural features of various zones in welded steel

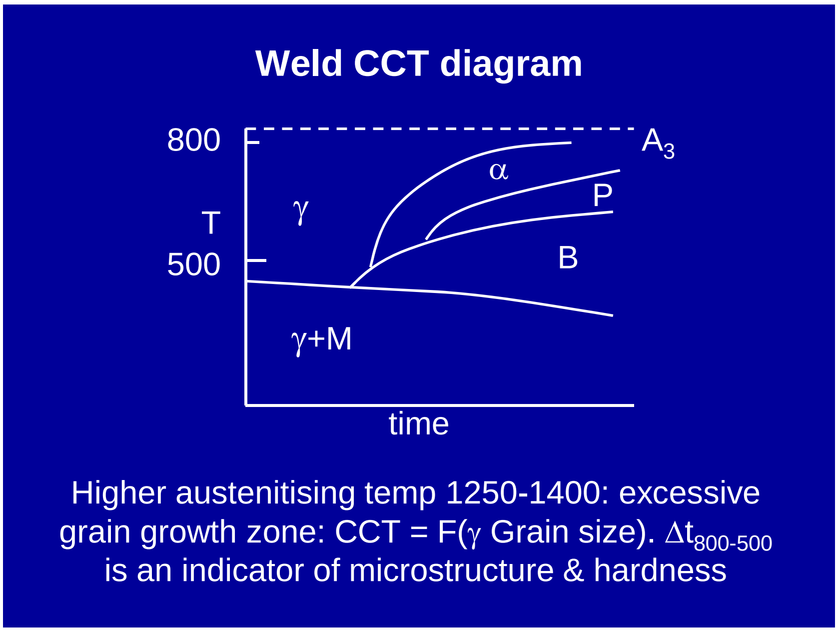
	Zone	Structural feature
1	Weld metal	Cast structure: solidification cracking
2	Partial melting	Coarse grain + cast structure: liquation cracking
3	Excessive grain growth	Pro-eutectoid ferrite network and martensite if C equivalent is high
4	Re-austenitiztion	Fine grain α+P structure: the zone is relatively wide in Nb/V steel
5	Partial austenitization	Depending on Δt_{8-5} α + Pearlite/ Bainite / plate martensite
6	Tempering	Spheroidised carbide (700°-750°C)
7	No apparent change	Prone to stain ageing in presence of residual stresses

The structural change in the HAZ has a pronounced effect on the hardness and mechanical properties of the weld joint. Slide 11 shows with the help of a set of schematic plots the variation in hardness and prior austenitic grain size as a function of distance from the weld parent metal interface. The coarse austenite grains are more likely to give hard martensitic structure. This is the zone having the highest hardness. Grain refinement occurs in the zone where the temperature goes beyond A_3 but remains lower than the temperature at which excessive grain growth takes place. As a result grains within this zone may be finer than that of the parent metal.

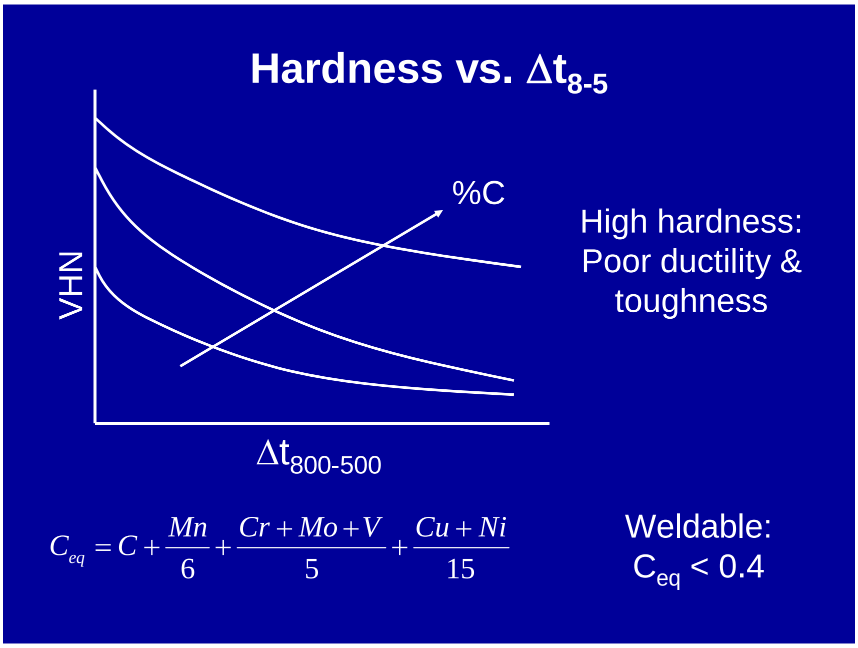


Slide 11

Slide 11 shows that prior austenite grain size may vary from around 2 at the weld interface to around 8 within the re-austenitized zone. CCT diagrams help us predict the evolution of structure in steel. This depends on austenite grain size. Therefore to predict the structure of HAZ it is necessary to have a series of CCT diagrams for a range of prior austenite grain size. Slide 12 gives a schematic (not to scale) CCT diagram of a coarse grain steel. This suggests that the diffusion controlled transformation in steel occurs within 800°-500°C. The time it takes to cool through the range of temperature after it gets heated during welding is an indicator of the structure that would develop within a HAZ. High $\Delta t_{800\text{-}500}$ means soft and coarse structure whereas low $\Delta t_{800\text{-}500}$ means fine and hard structure. The structure of HAZ is therefore determined by both T_p and $\Delta t_{800\text{-}500}$. The former gives an idea about the austenite grain size and suggest which CCT diagram to look for and the latter helps predict the microstructure on the basis of the relevant CCT diagram.



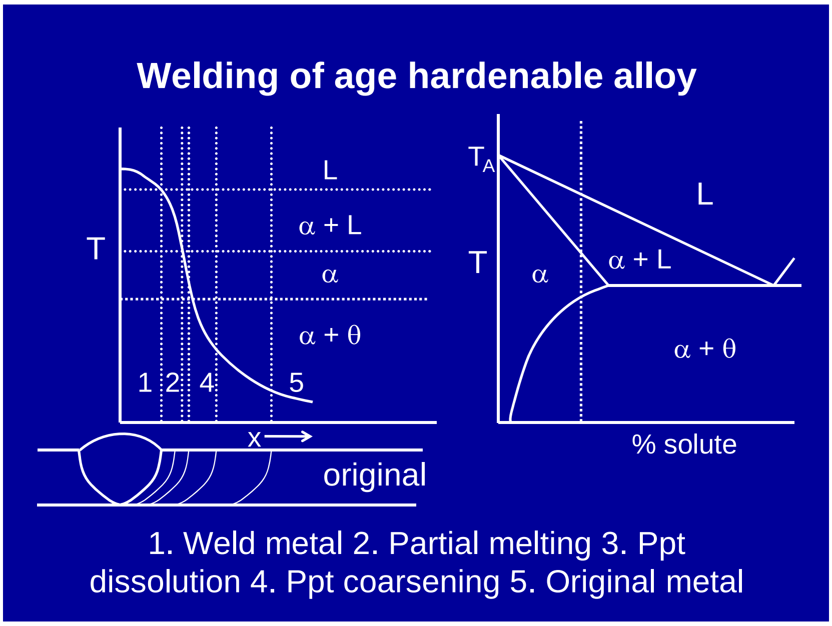
Slide 12



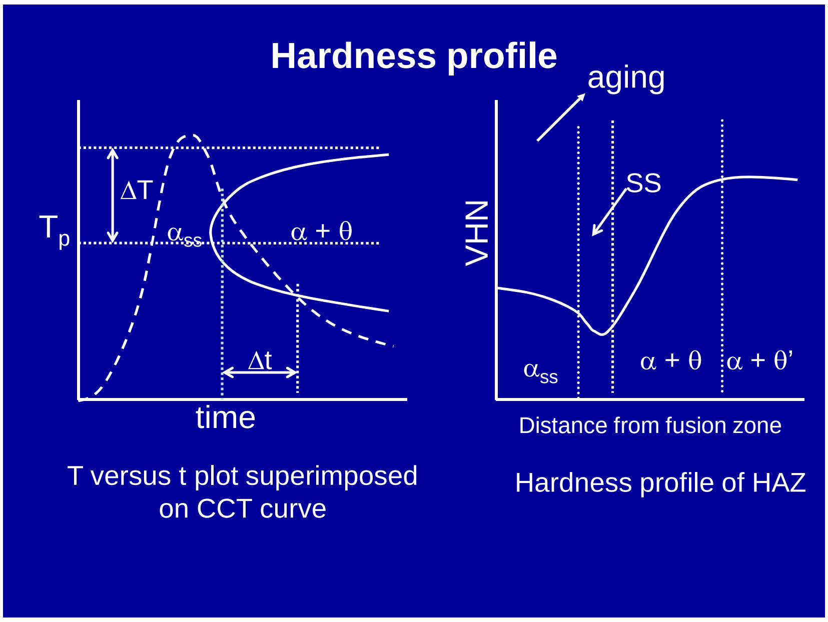
Slide 13

Slide 13 gives a set of hardness (expressed as VHN) versus $\Delta t_{800-500}$ plots for different concentrations of carbon (%C). The lower the magnitude of $\Delta t_{800-500}$ higher is the hardness for a given %C. The hardness increases with %C. Apart from %C the presence of alloy addition also affects the CCT diagrams and hence the harden-ability of steel. The combined effect of all is often expressed in terms of carbon equivalent (C_{eq}). A commonly used expression for C_{eq} is given in slide 13. If carbon equivalent is less than 0.4 a steel is considered to be weldable. If it is higher it may need preheating and post weld heat treatment. Weld metal may pickup gases during welding. Hydrogen being the smallest diffuses fast into the HAZ. This makes the steel particularly those with high carbon equivalent prone to cold cracking. Use of properly baked low hydrogen electrodes and post weld heat treatment may help overcome cold cracking.

HAZ in age harden-able alloy: Here too the temperature could go as high as that of the solidus during welding. Slide 14 presents thermal profile (peak temperature versus distance plot) and the phase diagram of an age harden-able alloy side by side. The temperature of the weld metal and the fusion zone is higher than that of the liquidus. The structure of this zone is likely to be the same as that of a cast metal that solidifies in a metallic mold. We are already familiar with its main features. Besides this the weld joint should consist of (i) a partially melted zone where the temperature goes beyond the solidus but does not exceed the liquidus, (ii) a single phase region where the pre-existing precipitates dissolve into the matrix (iii) a two phase region consisting of soft matrix and precipitates that may have coarsened during welding and (iv) the parent (base) metal where the temperature was not high enough to cause any visible change in its structure. In comparison to that of steel interpretation of structure here is much simpler.



Slide 14



Slide 15

The hardness of the HAZ is likely to be lower than that of the parent metal because of coarsening and dissolution of precipitates. The cooling rate after welding is usually very high. Therefore nucleation of second phase gets suppressed. The region where there is complete dissolution the hardness may be low initially however it may increase later due to ageing. Slide 15 has two plots. The diagram on the left shows how the temperature at a point goes up and then comes down during welding. During the heating the precipitates may dissolve once the peak temperature goes beyond the solvus curve in the phase diagram. If the rate of cooling beyond the peak is higher than a critical rate the precipitation of second phase is completely suppressed. This is illustrated with the help of a C curve shown in this diagram. In this case some amount of precipitate may form. Here too the critical range of temperature (ΔT) and the time (Δt) spent during cooling within this range of temperature would determine the structure that evolves. The second diagram in slide 15 gives the expected hardness profile of the heat affected zone.

Residual stress:

Stresses can develop in a fusion weld joint because of post solidification thermal contraction of the weld metal. As a rough approximation the magnitude of stress is given by $E\alpha\Delta T$ where E is the elastic modulus, α is the coefficient of linear expansion and ΔT is the temperature difference between the weld metal and HAZ soon after solidification. If the stress is greater than the fracture strength of the region it leads to cracking. If it is greater than its yield strength it would lead to distortion. Since the stress that develops gets relaxed by plastic deformation the highest residual stress that could exit in a weld joint is the yield strength of the material.

The stress field that exists is always under equilibrium. It means that if the stress is tensile in certain location of the weld joint there must be similar compressive stress in a region a little away from it. Weld distortion can be controlled by decreasing temperature difference (ΔT) by preheating or by adopting appropriate weld procedure (Look at fig 6). The total heat input too affects the extent of distortion. It also depends on welding method that is adopted. Excessive heat input as in the case of gas welding causes greater damage to the work piece resulting in a weaker joint and higher distortion. Use of intense LASER or sharply focused electron beam can melt the material instantaneously giving little time for the heat to dissipate to the neighboring region by conduction thereby resulting in a high quality joint with minimum distortion. Figure 7 gives total heat input as a function of power density of three different welding techniques.

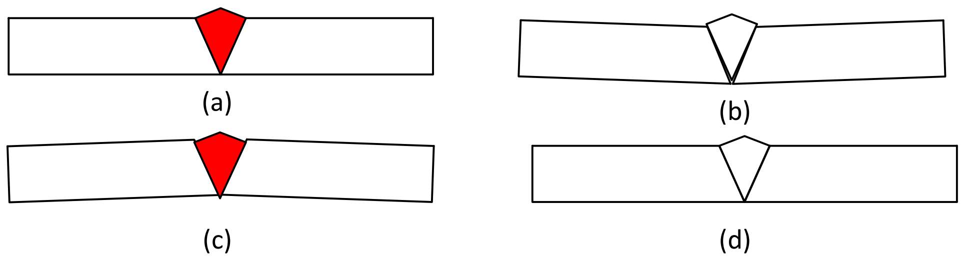


Fig 6: Shows how distortion can be minimized by proper placement of the two parts being joined. If the two parts are kept as shown in (a) during welding it results in joint having distortion (b). If these are aligned as in (c) during welding, subsequent contraction makes the plates straight.

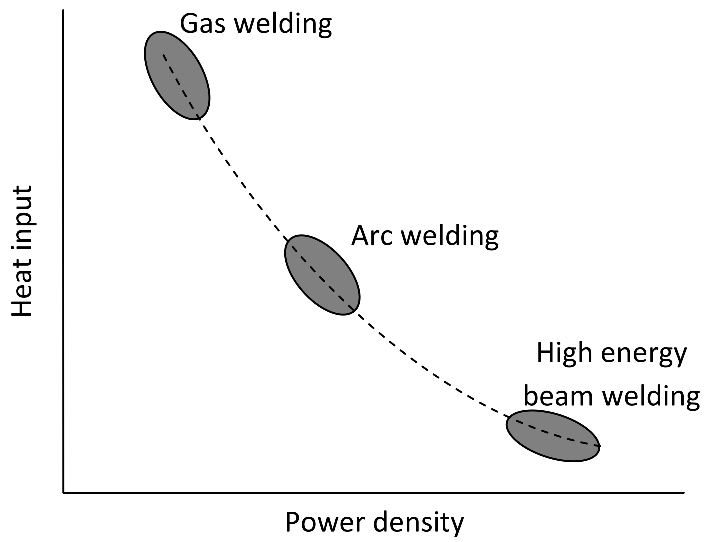


Fig 7: Total heat input as a function of power density of the heat source used during welding. Intense heat source (focused LASER or electron beam) although comes at a cost but ensures higher weld speed, increased penetration, less distortion and better weld quality.

Cold cracking susceptibility:

This is a problem associated with the presence of hydrogen in molten weld pool from where it could diffuse into the heat affected zone (HAZ) of the welded joint. The presence of dissolved hydrogen in HAZ makes it susceptible to delayed cracking after it cools down. It is also known as under bead cracking. Considerable efforts have gone in to find out the factors that determine susceptibility of steel to cold cracking. Both % C and the presence of alloying elements have been found to be the two most important factors. The former determines the hardness of steel whereas the latter determines the size of the heat affected zone (HAZ) having poor resistance to crack growth.

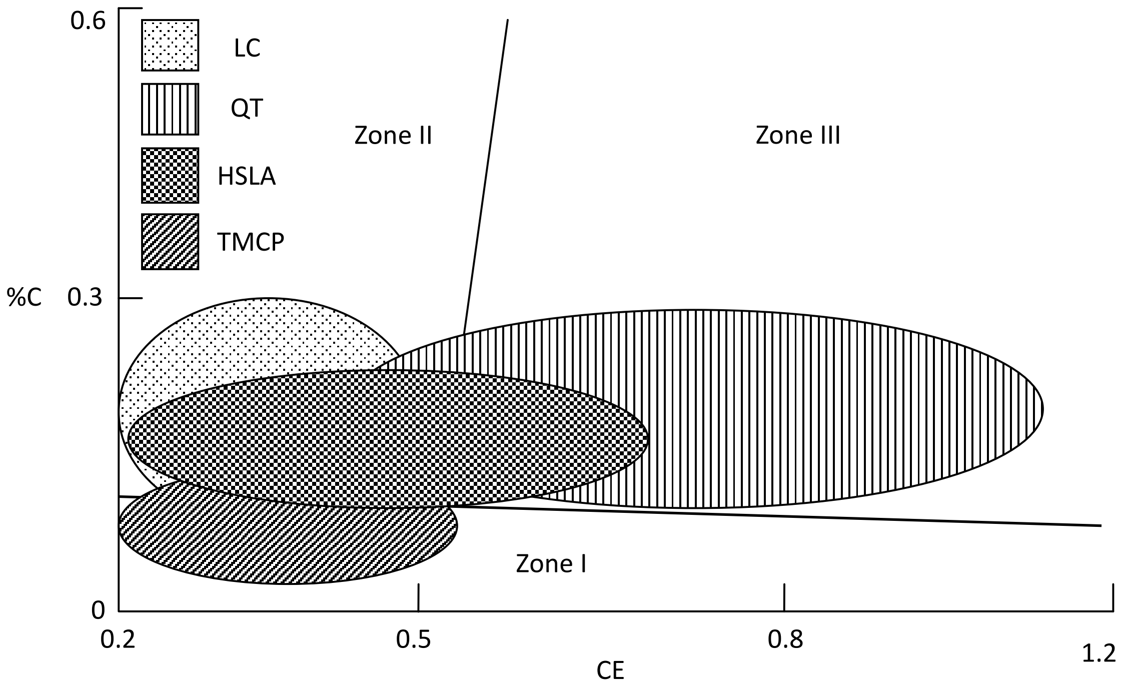


Fig 8: A schematic representation of Graville diagram showing locations of four common grades of steel in a %C - CE space. LC denotes low carbon steel, QT denotes quenched and tempered steel, HSLA denotes high strength low alloy steel, and TMCP denotes steel made by thermo-mechanical - controlled processing route. CE = %C + (%Mn + %Si)/6 + (%Ni + %Cu)/15 +(%Cr +%Mo + %V)/5

Susceptibility of steel to such cracking is best described by Graville diagram (Weldability of HSLA: micro-alloyed steel, Int. Conf. Proc. ASM Nov 1976). Figure 8 shows how the susceptibility of steel to cold cracking can be classified into three zones. Steel whose composition falls within zone I is not susceptible to cold cracking. Steel lying within zone III is most difficult to weld (See fig 8). It is extremely susceptible to cold cracking. It needs low hydrogen electrode, preheating and post weld heat treatment. Steel lying in zone II is moderately susceptible to cold cracking. Use of low hydrogen electrode often may be enough. In case of thicker plates preheating may be necessary. Diagram also includes the range of %C & CE for four different grades of steel. TMCP steel having low carbon and fine grain structure is least susceptible to cold cracking whereas QT steels are most susceptible to such cracking.

Summary

In this module we have looked at different methods of joining and the mechanism of bond formation. However the main focus was on the structural changes that occur during welding where the temperature is high enough to melt the surface of the metal being joined. This helps proper mixing of the filler metal and the fusion zone. This is why the strength of welded joint is much higher than that of the solder. Welding is done with the help of a filler alloy having nearly the same composition as that of the parent metal. However, this is not so in the case of brazing or soldering. The melting point of solder alloy is much lower than that of the brazing alloy. Therefore the strength of solder joint is lower than that of the brazing joint. Usually the strength of brazing joint is lower than that of welding. Some idea about the heat transfer during welding is important. The basic concept has been described. This helps us appreciate the effect of various weld parameters on the shape of the weld pool and the subsequent structure that develops. Apart from the weld pool the region surrounding it is also exposed to significant thermal exposure. Therefore it undergoes structural changes. The basic concepts of physical metallurgy could be applied to predict the structure and properties of different regions of a weld joint. The structural evolution in steel is certainly more complex than that in other alloys. Why it is so is evident from the illustrations included in this module. The main focus however has been on fusion welding. This is where you are likely to have a wide variation in the microstructure and properties of the metals being joined. Apart from this there are several other joining processes. Solid state joining processes such as friction or friction stir welding has recently gained considerable popularity. Both use the heat that is generated at the interface due to friction either between a rotating and a stationary part (friction welding) or between a rotating cylindrical tool and two rigidly clamped parts touching each other (friction stir welding). The rotating tool has a probe that ploughs through the adjoining regions as it moves along the interface. The heat that is produced is not high enough for fusion but is sufficient to join the two parts. Severe plastic deformation at the interface is responsible for the development of a good bond between the two. The plastic deformation and the heat that is generated at the interface would alter the microstructure of the work piece. In most cases there will be three distinct zones: thermally affected zone, thermo-mechanically affected zone and dynamically re-crystallized zone. In the thermally affected zone there is no change in the grain structure although it may soften a little. In the thermo-mechanically zones the grains get severely twisted or deformed whereas all the old grains in the dynamically re-crystallized zone by numerous tiny grains. This zone is commonly known as nugget. The basic physical concepts given in this module would help you interpret such structural changes.

Exercise:

1. Why there is excessive grain growth in the heat affected zone of a welded structure even if it is made of micro alloyed steel?
2. Most structural steels have some amount Mn primarily to take care of the hot shortness problem because of residual sulfur in steel. Some amount of Si is also present. It is added to remove dissolved oxygen in steel. ASTM A516 Grade 60 is a common grade of

steel used for the construction of welded vessels. It has 021C, 0.66Mn, 0.45Si, S <0.035, P < 0.035. Examine if it is suitable for construction of welded pressure vessel.

3. What are the precautions that need to be taken to weld creep resistant steel tubes having 0.15C, o.5Mn, 0.54Si, 2.25Cr, 1.0Mo (this corresponds to ASTM T 22 grade steel)?
4. There is no chance of forming martensite in heat affected zone while welding austenitic steel. Should therefore all grades of austenitic steels be easily weldable? Give reasons for your answer.
5. Derive an expression for the time it takes to reach maximum temperature at a distance r from the heat source during arc welding of a thick plate. Estimate maximum temperature at a point 5mm away from the heat source during welding of carbon steel. Material and process parameters are as follows: thermal conductivity = 50W/m/K, density = 7850kg/m3, specific heat = 0.45kJ/kgK, initial temperature of the plate = 300K, weld current = 150 A, voltage = 20volts, welding speed = 2.5mm/s, heat lost = 0.4.
6. Use the data given in problem 5 to estimate the distance at which temperature would reach 1500^{o}K (the melting point of the steel).

Answers:

1. Micro-alloy elements are present in steel as carbo-nitrides. These are effective in pinning grain boundaries during normal thermo-mechanical processing. However during welding temperature near fusion zone goes beyond their solvus temperature. Absence of precipitates to pin austenite boundaries in this region leads to excessive grain growth.

2. Medium carbon steels are more prone to heat affect zone related problem. Although % C is 0.21 its carbon equivalent = 0.21+0.66/6 = 0.33. This too is less than 0.4% C. Therefore it can be welded without any special precaution. There is little chance of formation of hard and brittle martensite from where crack could initiate. Experience shows that failures often do not take place in the main welds of a structure rather it initiates from points where a small weld bead may have been placed to attach ancillary equipments temporarily during fabrication.

3. Carbon equivalent for this steel = 0.15 + 0.54/6 + (2.25+1.0)/5 = 0.89. In this case martensite is likely to form unless special precautions are taken to preheat the tubes before
welding. This would help reduce cooling rate encountered in the HAZ during welding. In many cases post weld heat treatment is also required. Note that most steel specifications allow a range of composition. To decide whether any special precaution is necessary carbon equivalent should be estimated using the maximum permissible alloy content.

4. Totally different kinds of problem are faced during welding of austenitic steel. One is related to solidification shrinkage which is much more than in ferritic steel. This is overcome by suitable control of the composition of weld consumables so that on solidification it has some amount of delta ferrite. Ferrite meters, a non destructive testing tool to detect if there is some delta ferrite. The second problem is associated with the precipitation of $Cr_{23}C_6$ at grain boundaries in the heat affected zone. The carbides have very high amount of chromium. Whenever such precipitates are formed chromium content of the surrounding matrix drops below the minimum amount needed to form protective oxide layer. These regions become prone to corrosive attack. Often it leads to inter granular failure. This phenomenon is known as sensitization. Stainless characteristics of sensitized steel can be restored by giving post weld annealing by heating to 950˚C followed by rapid cooling to suppress carbide precipitation. Alternatively select special low carbon austentic steels or those having additional alloy elements like Nb. This is a strong carbide forming element. It does not allow any carbon to be present in the matrix to form $Cr_{23}C_6$.

5. Temperature at distance r from a moving point heat source is given by the following expression: $T = T_0 + \frac{q}{2\pi\lambda vt} exp\left(-\frac{r^2}{\alpha t}\right)$ where T is temperature, t is time, α is thermal diffusivity, v is welding speed, λ is thermal conductivity, T_0 is initial temperature of the plate, q =εiV where i = current, V = voltage, ε = efficiency, $\alpha = \lambda/(\rho c)$ where ρ = density and c = specific heat. To find out time at which T reaches maximum at a given point r equate: $\frac{dT}{dt} = 0 = \frac{dln(T-T_0)}{dt}$. Since $ln(T - T_0) = ln\left(\frac{q}{2\pi\lambda v}\right) - ln(t) - \frac{r^2}{\alpha t}$ or $\frac{1}{(T-T_0)}\frac{dT}{dt} = \left(\frac{r^2}{\alpha t^2} - \frac{1}{t}\right) = 0 \therefore t_{max} = \frac{r^2}{\alpha}$ On substituting this in the expression for T: $T_{max} = T_0 + \frac{q}{2\pi\lambda vet_{max}}$ On substituting numerical values one directly gets both t_{max} and T_{max}. $t_{max} = \frac{r^2}{\lambda}\rho c = \frac{(0.005)^2}{50} \times 7850 \times 450 = 1.77\ second$ and $T_{max} = T_0 + \frac{q}{2\pi\lambda evt_{max}} = 300 + \frac{0.6\times150\times20}{2\pi\times50\times0.0025\times1.8\times2.718} = 777^0K.$

6. The expression for T_{max} can be rewritten as $T_{max} = T_0 + \frac{\varepsilon iV\alpha}{2\pi\lambda evr^2}\ or\ r^2 = \varepsilon iv\alpha/\{2\pi\lambda ev(T_{max} - T_0)\}$ = $(0.6 \times 150 \times 20 \times 1.42 \times 10^{-5})/(2\pi \times 50 \times 2.718 \times 0.0025 \times 1200) = 0.00316m$