The Concept Of Weldability Of Metals

This chapter presents the concept of weldability of metals and factors affecting the same. Different parameters that are used as a measure of weldability have been elaborated. Attempts have been made to describe the relationship between carbon equivalent, hardenability and cracking tendency of weld joints of steel.

Keywords: Weldability, measures of weldability, carbon equivalent, cracking of HAZ, hardenability, austenitic electrode

37.1Understanding weldability

Weldability is considered as ease of accomplishing a satisfactory weld joint and can be in determined from quality of the weld joint, effort and cost required for developing the weld joint. Quality of the weld joint however, can be determined by many factors but the weld must fulfill the service requirements. The characteristics of the metal determining the quality of weld joint includes tendency to cracking, hardening and softening of HAZ, oxidation, evaporation, structural modification and affinity to gases. While efforts required for producing sound weld joint are determined by properties of metal system in consideration namely melting point, thermal expansion coefficient, thermal and electrical conductivity, defects inherent in base metal and surface condition. All the factors adversely affecting the weld quality and increasing the efforts (& skill required) for producing a satisfactory weld joint will in turn be decreasing the weldability of metal.

In view of above, it can be said that weldability of metal is not an intrinsic property as it is influenced by a) all steps related with welding procedure, b) purpose of the weld joints and c) fabrication conditions. Welding of a metal using one process may show poor weldability (like Al welding with SMA welding process) and good weldabilitywhen the same metal is welded with some other welding process (Al welding with TIG/MIG). Similarly, a steel weld joint may perform well under normal atmospheric conditions and the same may exhibit very poor toughness and ductility at very low temperature condition. Steps of the welding procedure namely preparation of surface and edge, preheating, welding process, welding parameters, post weld treatment such as relieving the residual stresses, can influence the weldability of metal appreciably. Therefore, weldability of a metal is considered as a relative term.

37.2 Weldability of steels

To understand the weldability of steel, it important to look into the different phases, phase mixtures and intermetallic generally found in steel besides the changes in phase that can occur during welding due to heating and cooling cycles. All these aspects can be understood by going through following section presenting significance of Fe-C diagram, time-temperature-transformation diagram and continuous cooling transformation diagram.

Fe-C Equilibrium Phase Diagram

Fe-C diagram is also called iron-iron carbide diagram because these are the two main constituents observed at the room temperature in steel while the presence of other phases depends on the type and amount of alloying elements. It shows the various phase transformations as a function of temperature on heating / cooling under equilibrium conditions (Fig. 37.1).

Allotropy and critical temperatures

Change in crystal structure of an element with rise in temperature is termed as allotropy. Iron shows the allotropic behaviour at temperature 910^0C and 1390^0C. Iron changes its crystal structure first from BCC to FCC at 910^0C and then from FCC to BCC at 1390^0C. Therefore, solubility of carbon in iron varies with temperature especially above 910^0C and 1390 ^{0}C.

Isothermal Transformations in Fe-C diagram

Three are main reaction points in Fe-C diagram namely peritectic, eutectoid and eutectic, which are of great academic and practical importance. All three reactions take place at a fixed temperature and composition.

Peritecitc reaction

$$\text{Liquid metal} + \delta\text{-iron (B. C. C.)} \overset{1495\ ^{0}\text{C and } 0.18\%\text{ C}}{\rightleftarrows} \gamma\text{-iron (F. C. C.)}$$

Eutectic reaction

$$\text{Liquid metal} \overset{1130\ ^{0}\text{C and } 4.3\%\text{ C}}{\rightleftarrows} \gamma\text{-iron (F. C. C.)} + Fe_3C$$

Eutectoid reaction

$$\text{Solid } (\gamma\text{-iron}) \underset{}{\overset{727\ ^0\text{C and } 0.8\%\text{ C}}{\rightleftarrows}} \alpha\text{-iron (B. C. C.)} + Fe_3C$$

Proportions of various phases of these transformations can be obtained using lever rule. Fulcrum of the lever depends upon the alloy composition i.e. carbon content. Since these transformations take place at constant temperatures therefore it is easy to find the tie line. Terminal phases (and their compositions) can be obtained using the tie line and alloy compositions.

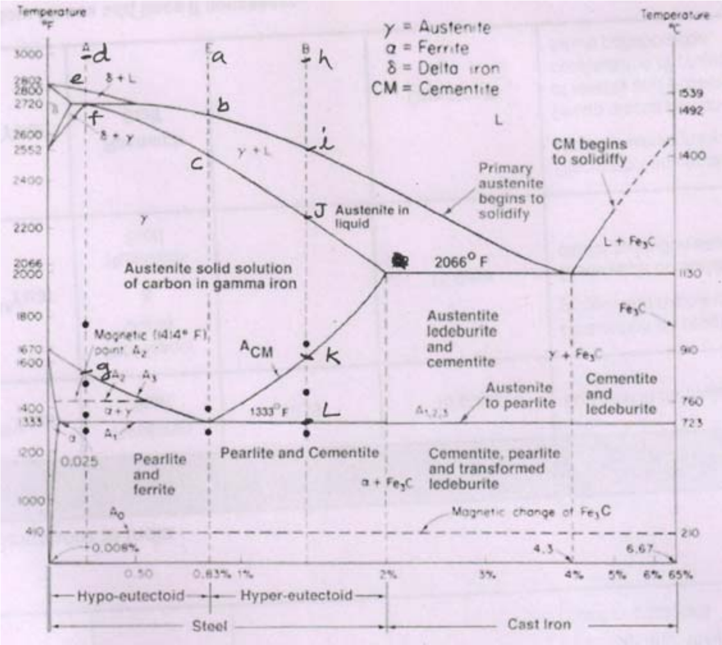


Fig. 37.1 Fe-C diagram (source: Materials Science and Metallurgy, 4th ed., Pollack, Prentice-Hall, 1988)

Phases appearing in Fe-C diagram are ferrite (α-Fe), austenite (γ-Fe), cementite (Fe_3C), δ iron and mixtures of phases such as pearlite (α-Fe + Fe_3C) and ledeburite (γ-Fe + Fe_3C). Pearlite and ledeburite are the result of eutectoid and eutectic reactions respectively. Details of these phases and their mechanical properties are presented in following section.

Ferrite

Ferrite is an interstitial solid solution of carbon in iron having B. C. C. structure. Solubility of carbon in iron having B. C. C. structure at room temperature is about 0.005% while that at eutectoid temperature (727^0C) is 0.025%. Ferrite is a soft, low strength, tough and ductile (50% elongation) phase.

Austenite

Austenite is an interstitial solid solution of carbon in iron having F. C. C. structure. This is not stable below eutectoid temperature (727^0C) in plain Fe-C system as it transforms into pearlite below this temperature. Solubility of carbon in iron having F. C. C. structure at temperature 1330^0C is 2.0% while that at eutectoid temperature (727^0C) is 0.8%. Austenite is a comparatively harder, stronger, tougher but of lower less ductility (%elongation) than the ferrite.

Cementite

Cementite is an inter-metallic compound of iron and carbon i.e. iron carbide (Fe_3C). Cementite contains 6.67% of carbon and has orthorhombic structure. It is the hardest amongst all phases appearing in Fe-C diagram. Its hardness is extremely high while strength is very poor.

Pearlite

Pearliteis a phase mixture of ferrite and cementite and is a result of eutectoid transformation. The pearlite has alternate layers (lamellas) of cementite and ferrite. Strength of pearlite is more than any of the individual phases of which it is made. Mechanical properties i.e. strength, ductility, toughness and hardness of pearlite depends on the inter-lamellar spacing. Thinner plates (layers) of alpha ferrite, Fe_3C results in better mechanical properties.

Ledeburite

Ledeburite is also a phase mixture of austenite and cementite and is formed as a result of eutectic transformation but is observed only above the eutectoid temperature in Fe-C diagram as below this temperature austenite of ledeburitetransforms into pearlite.

Effect of Phases on Mechanical Properties

It is important to note that every phase or phase mixture has its own mechanical properties. Some of the phases are very soft (ferrite) and some are extremely hard (cementite). Therefore, variation in proportions / relative amounts of these phases will affect the mechanical properties of steel as a whole. Increase in carbon content in steel linearly increases proportion of pearlite but at the cost of ferrite. Since ferrite is of low strength, soft and ductile while pearlite is hard, strong and of poor ductility and toughness, hence increase in percentage of pearlite increases strength, hardness and reduces the ductility and toughness of steel as a whole. Cementite appears as an individual phase only above eutectoid composition (steel having carbon > 0.8%). It tends to form a network along the grain boundary of pearlite depending upon carbon content. Complete isolation of pearlite colonies with the cementite (as a result of continuous network of cementite) decreases tensile strength and ductility because mechanical properties of the alloy / steel to a large extent depend upon the properties of phase which is continuous in alloy. Increase in the carbon content above the eutectoid compositions (0.8% C) therefore reduces the strength and ductility because in hypereutectoid steel, network of cementite is formed along the grain boundaries of pearlite and cementite has very low tensile strength (3.0MPa).

Phase Transformation

Steel having 0.8% carbon is known as eutectoid steel. Steels with carbon lesser than 0.8% are known as hypoeutectoid and those having more than 0.8% and less than 2% carbon are called hypereutectoid steels. Fe-C systems having carbon more than 2% are called cast irons. Cast iron having 4.3% carbon is known as eutectic cast iron. Cast irons with carbon less than 4.3 % are known as hypoeutectic and those having more than 4.3% are called hypereutectic cast iron.

STEEL

(a) Eutectoid steel

Transformation of eutectoid steel into various phases on cooling from molten state to the room temperature can be shown by drawing a vertical line through the composition point on E axis (called composition line). No phase transformation occurs until temperature of liquid metal goes down from point ‘a’ to ‘b’ on the liquidus. At the point ‘b’ solidification starts and first of all austenite (with 0.3%C) is formed. Further decrease in temperature results in formation of more and more proportion of austenite whose composition changes along the solidus whereas composition of liquid changes along the liquidus. It shows that carbon content in molten metal increases with the reduction in temperature until it goes down to the point ‘c’. On completion of solidification, steel attains the austenitic state thereafter no phase transformation takes place until it attains eutectoid temperature (723^{0}C). Reduction in temperature decreases the solubility of carbon in austenite. Austenite is supersaturated with carbon as temperature goes below the eutectoid temperature hence austenite rejects the excess carbon leading to the nucleation of cementite along the grain boundary. As rejection of carbon from austenite continues, cementite layer grows toward the center of austenite grain and a very small zone which is depleted of carbon is formed on both the sides of the cementite plate. As concentration of carbon in carbon depleted zone reduces to such an extent when it is enough to dissolve in iron having B. C. C. structure at that temperature austenite transforms into ferrite. Thickness of the cementite or ferrite plates depends on the rate of diffusion and time available for the transformation to take place. As this transformation occurs by nucleation and growth mechanism which is based on diffusion of atoms. Slower the cooling rate, greater is the time available for the transformation and phases to grow hence thicker cementite and ferrite plates are produced. This process continues until whole austenite is transformed into pearlite.

(b) Hypoeutectoid Steel

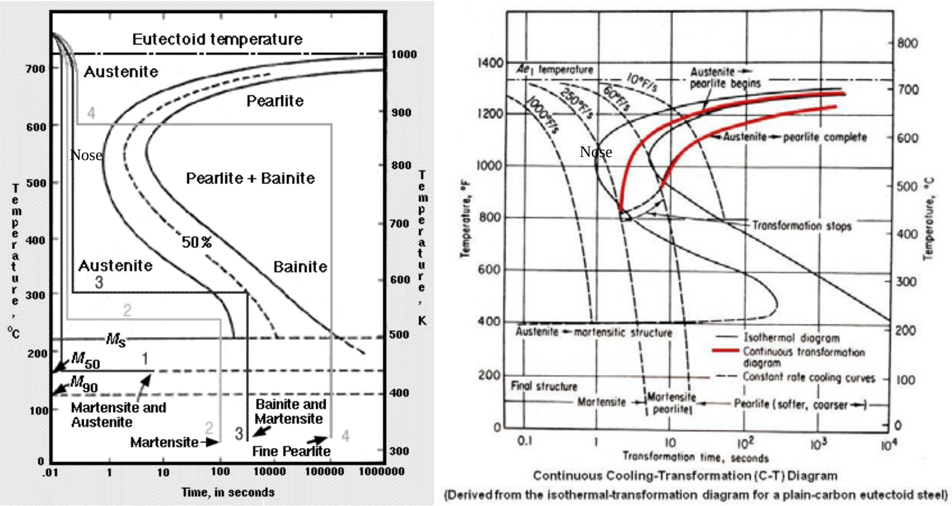
Transformation of 0.18%C steel during the cooling from molten state to the room temperature is shown by vertical line through the composition point. It is observed that no phase transformation takes place until temperature of liquid metal goes down from point ‘d’ to ‘e’ on the liquidus. At the point ‘e’ solidification starts and first of all δ iron (with 0.03%C) is formed. Further, decrease in temperature results in formation of more and more δ iron whose composition changes along the solidus whereas composition of liquid changes along the liquidus. Liquidusshows that carbon content in molten metal increases with the reduction in temperature. At the temperature of 1495^{0}C, liquid metal (with 0.5%C) and solid δ iron (0.1%C) the transformsinto austenite by peritectic reaction. On completion of solidification, steel attains the complete austenitic state thereafter no phase transformation takes place until it attains temperature corresponding to the point ‘g’ (i.e.850^{0}C). At about 850^{0}C, austenite transforms into the ferrite. Further, transformation of austenite into ferrite continues with reduction in temperature until eutectoid temperature is attained. During this transformation, the composition of austenite changes continuously with increase in carbon content in austenite. As eutectoid temperature is attained carbon content in austenite rises to 0.8% i.e. eutectoid composition. At this temperature, austenite of eutectoid composition transforms into pearlite as discussed above. Proeutectoid phase i.e. ferrite, is formed first from austenite in hypoeutectoid steel and subsequently austenite transforms into pearlite. Hence ferrite is found along the grain boundaries of pearlite. Continuity of ferrite network depends upon the carbon content in hypoeutectoid steel. Reduction in carbon content increases the continuity of ferrite network around the pearlite grains. Increase in carbon content reduces the amount of ferrite and increases the amount of pearlite.

(c) Hypereutectoid steel:

Transformation of hypereutectoid steel is similar to that of hypoeutectoid steel except that proeutectoid phase is cementite instead of ferrite. In this case no phase transformation takes place until temperature of liquid metal goes down from point ‘h’ to ‘I’ on the liquidus. At the point ‘i’ solidification starts and first of all austenite (with 0.8%C) is formed. Further, decrease in temperature results in formation of more and more amount of austenite whose composition changes along the solidus whereas composition of liquid metal goes along the liquidus . It shows that carbon content in molten metal increases with the reduction in temperature until it goes down to the point ‘j’. On completion of solidification, steel attains the austenitic state and thereafter no phase transformation takes place until it attains temperature corresponding to the point ‘k’ (1000^{0}C). At eutectoid temperature, austenite becomes supersaturated with carbon hence austenite rejects the excess carbon which leads to the nucleation of cementite along the grain boundary. Further, decrease in temperature results in formation of more and more cementite from the austenite whose composition changes along the kl. As eutectoid temperature is attained, carbon content in austenite decreases up to the eutectoid composition (0.8%C). At this temperature, austenite of eutectoid composition transforms into pearlite as discussed above. Proeutectoid phase i.e. cementite is formed first from austenite in hypereutectoid steel subsequently austenite transforms pearlite. Hence, cementite is found along the grain boundaries of pearlite.

Time Temperature Transformation (TTT) Diagram

This diagram shows the transformation of meta-stable austenite phase at constant temperature into various phases as a function of time (Fig. 37.2). Therefore, it is also known as isothermal transformation diagram.Transformation of austenite into various phases such as pearlite, bainite and martensite depends on the transformation temperature. Time needed to start the transformation of austenite into pearlite or bainite is called incubation period which is initially low at lower transformation temperature and then increases as transformation temperature increases. TTT Diagram for eutectoid C- steel has C shape due to variation in time needed to start and end the transformation of austenite at different transformation temperature This curve has a nose at about 550^0C. Transformation of austenite into pearlite takes place on exposure at any constant temperature above the nose. It is observed that higher the transformation temperature more is the time required for starting and completing the transformation. Transformation of austenite into pearlite or bainite occurs by nucleation and growth process. Hence, at high temperature high growth rate, low nucleation rate coupled with longer transformation time results in coarse pearlitic structure whereas at low transformation temperatures fine pearlitic structure is produced because of low growth rate, high nucleation rate and short transformation time. High transformation temperature lowers the strength and hardness of steel owing to the coarse pearliticstructure.



Continuous Cooling-Transformation (C-T) Diagram
(Derived from the isothermal-transformation diagram for a plain-carbon eutectoid steel)

Fig. 37.2 Time-temperature-transformation diagram a) isothermal transformation and b) TTT diagram superimposed with different cooling curves

Transformation of austenite at a temperature below the nose of the curve results in bainitic structure. Bainite is a very fine intimate mixture of ferrite and cementite like pearlite. However, pearlite is a mixture of lamellar ferrite and cementite. That is why bainiteoffers much better strength, hardness and toughness than the pearlite. Degree of fineness of bainite also increases with the reduction in transformation temperature like pearlitic transformation. Bainite formed at high temperature is called feathery bainite while that formed at low temperature near the $M_s$temperatureis called acicular bainite.

Transformation of austenite at a temperature below the $M_s$temperatureresults in hard and brittle phase called martensite structure. Martensite is a supersaturated solid solution of carbon in iron having body centered tetragonal (B.C.T) structure. This austenite to martensite transformation is athermal transformation as it takes place by diffusionless process. Rapid quenching/cooling from austenitic temperature to a temperature below the ‘M_s’ prevents any kind of atomic diffusion. Therefore carbon atoms, which are easily accommodated within FCC unit cell (in austenite) at high temperature should be rejected at low temperature because of reduction in solid solubility. But at such a low temperature (below ‘M_s’) diffusion is prevented and that leads to formation of supersaturated solid solution of carbon in iron having BCC structure. This super-saturation of carbon in iron (BCC) causes the distortion of the BCC lattice structure and makes it BCT by increasing the c/a ratio more than 1. Degree of distortion is measured in terms of c/a ratio. This ratio depends up on the carbon content. Increase in carbon content up to 0.8%, increases the c/a ratio. The c/a ratio can be directly related with the increase in hardness, as there is linear relation between the two up to 0.8% carbon content.

Position of transformation lines and nose depends on steel composition, homogeneity of austenite and grain size. For each composition of steel, there will be just one TTT diagram. Steel other than eutectoid composition will have one more line initiating from the nose in TTT diagram corresponding to transformation of austenite into proeutectoid phase. In case of hypoeutectoid steel, first austenite forms ferrite as a proeutectoid phase, subsequently it transforms into pearlite whereas the proeutectoid phase for hypereutectoid steel is cementite.

Addition or reduction in carbon % in steel with respect to eutectoid composition shifts the nose of TTT diagram. For hypoeutectoid steels nose of the curve is shifted towards the left (reduced incubation time) whereas for hypereutectoid steels nose is shifted to right as compared to that for eutectoid steel. Temperature corresponding to start (M_s) and end (M_f) of martensite transformation is found a function of alloy compositions. Addition of alloying elements lowers these temperatures.

Continuous Cooling Transformation (C.C.T.) Diagram

CCT curve shows the transformation of austenite into various phases as a function of time at different cooling rates but not at constant temperature like in TTT diagram. This diagram is similar to that of TTT diagram except that under continuous cooling conditions (when temperature changes continuously) nose of the curve is shifted to right in downward direction and bainite transformation part as obtained in TTT diagram (below the nose) is absent in CCT diagram. Hence, continuous cooling diagram for eutectoid steel has only two lines above M_s,corresponding to the start and end of pearlite transformation (Fig. 37.3). Various linesAB, KN, QR, ZOshowing the reduction in temperature with time representing the different cooling rates called cooling curves. A very low cooling rate ‘AB’ results in the transformation of austenite into coarse pearlite starts at

T_{s1}temperature and ends at T_{s2} temperature. Therefore, transformation takes place over a range of temperature from T_{s1} to T_{s2}. Such low cooling rates are used for annealing of steels which increases the softness. At somewhat higher cooling rate (KN) the transformation of austenite into pearlite starts at T_{s3} temperature and ends at T_{s4} temperature. Therefore, effective transformation takes place over a range of temperature from T_{s3} to T_{s4}. Grain size depends on the transformation temperature. High transformation temperature produces coarse grain. Since the continuous cooling conditions result in transformation over a range of temperature say T_{s1} to T_{s2}hence the grain size also varies accordingly. Therefore, at start of transformation coarser pearlite grains are formed than that at end of transformation. High cooling rate reduces the effective transformation temperature hence fine grain structure is produced. Such cooling rates are used for normalizing of steel. Normalizing increases the strength, hardness and toughness due to finer grain structure.

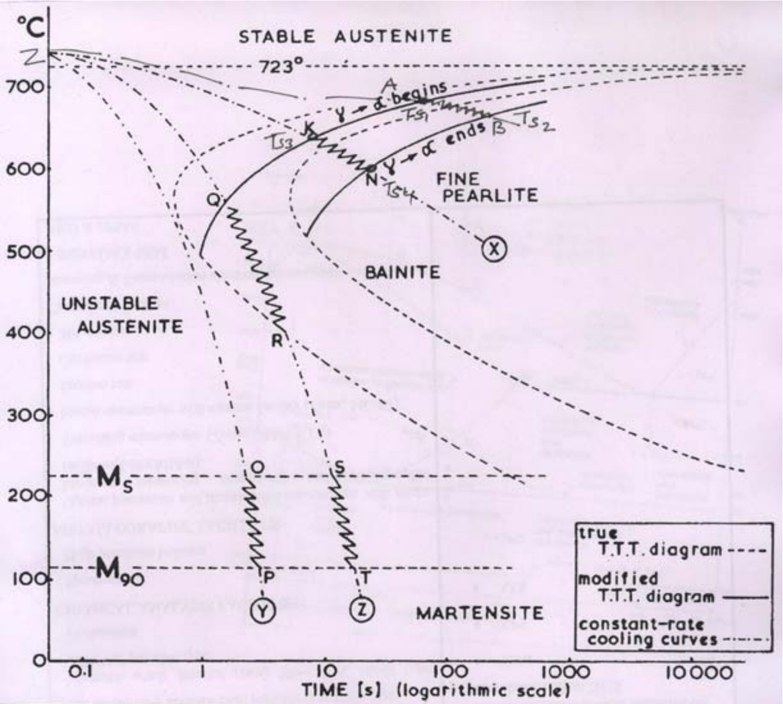


Fig. 37.3 Continuous cooling transformation diagram

Cooling curve 'QR' is tangential to 25% transformation line where 25% austenite has transformed into pearlite and 75% austenite is yet to transform. Thereafter, transformation of austenite stops and no further transformation takesplace until its temperature goes down to M_s. As austenite crosses the $M_s$temperature remaining 75% austenite begins to transform into the martensite. This transformation line is expected to result in about 75% of martensite and approx. 25 % pearlite.

Further, higher cooling rate line ‘ZO’, which is tangential to the nose of the CCT diagram does not cause any transformation of austenite into pearlite. Austenite remains stable until $M_s$temperature is reached. Further reduction in temperature transforms the austenite into the martensite. Moreover, complete transformation of austenite into martensite depends on the quenching temperature. If quenching temperature is below the ‘M_f’ then only whole austenite is expected to transform into the martensite; otherwise some un-transformed austenite is left in steel called retained austenite. Retained austenite is comparatively soft, therefore, its presence reduces the hardness of steel. Amount of retained austenite depends on the quench temperature between $M_s$and M_f. Lower the transformation temperature (between $M_s$and M_f), smaller is the amount of retained austenite in steel. There is non-linear relationship between the amount of austenite transforming into martensite and quenching temperature in range of $M_s$and M_f. Minimum cooling rate that ensures complete transformation of austenite into martensite and avoids the formation of soft phases/phase mixtures (like pearlite) is called critical cooling rate (CCR).

Critical cooling rate depends on the position of the nose, which is governed by the alloy composition, grain size and homogeneity of austenite. To take into account the effect of all alloying elements on the critical cooling rate, carbon equivalent is used.

High carbon equivalent lowers the critical cooling rate hence less drastic cooling is required for hardening. In general, presence of all alloying elements (except Co) shifts the nose of CCT diagram towards right (conversely increases the incubation period to begin transformation) which in turn reduces the critical cooling rate and increases hardenability. Reduction in carbon content increases the critical cooling rate and makes hardening of steel more difficult.

Fine grained austenite starts the transformation earlier so nose of curves is shifted to left (reduces the incubation period for transformation). This increases the critical cooling rate. On the other hand coarse grain structure reduces the critical cooling rate which in turn increases the hardenability. Similarly inhomogeneous austenite (due incomplete transformation/austenitizing during heating) also reduces the transformation time, shifting nose of CCT curve to left and so increases the critical cooling rate.

Weldability of steel and composition

Weldability of steels can be judged by two parameters (a) cleanliness of weld metal and (b) properties of HAZ. Cleanliness of weld metal is related with presence of inclusion in the form of slag or gases whereas HAZ properties are primarily controlled by hardenability of the steel. Proper shielding of arc zone and degassing of molten weld metal can be used to control first factor. Proper shielding can be done by inactive gases released by combustion of electrode coatings in SMA or inert gases (Ar, He, Co_2) in case of TIG, MIG welding. Hardenability of steel is primarily governed by the composition. All the factors increasing the hardenability adversely affect the weldability because steel becomes more hard, brittle and sensitive to fracture/cracking, therefore it needs extra care. So, more the precautions should be taken to produce a sound weld joint.

Addition of all alloying elements (C, Mn, Ni, W, Cr etc.) except cobalt increases the hardenability which in turn decreases the weldability. To find the combined effect of alloying elements on hardenability/weldability, carbon equivalent (CE) is determined. The most of the carbon equivalent (CE) equations used to evaluate weldability depends type of steel i.e. alloy steel or carbon steel.

- Common CE equation for low alloy steel is as under:

$$CE=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15$$

(elements are expressed in weight percent amounts)

- For low carbon steels and micro-alloy steels, CE is obtained using following equation: $CE = C + Si/25 + (Mn+Cr)/16 + (Cr+Ni+Mo)/20 + V/15$

- From the Welding Journal, for low carbon, micro-alloyed steels, Ito-Besseyo carbon equivalent:

$$Ceq = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5*B$$

Since the effect of different alloying elements on hardenability of steel is different therefore, their influence on weldability will also be different. In general, high the CE steel needshigh preheat temperature to produce crack free weld joint. Following point can be kept in mind as broad guidelines for welding steel.

❖ $CE < 0.45$	No preheat required,
❖ $0.45<CE< 0.7$	200-500^{0}C of preheat may be used
❖ $CE > 0.7$	Can not be welded

Thickness of plate to be welded affects the cooling rate which in turn influences the hardening and cracking tendency. To take into account the thickness of plate above criteria is modified to get compensated carbon equivalent (CCE) relation.

$CCE= CE + 0.00425t$

Where t is the thickness of plate in mm

❖ $CCE< 0.4$	No preheat required,
❖ $0.4<CCE< 0.7$	200-500^{0}C of preheat may be used
❖ $CCE> 0.7$	Cannot be welded

From the weldability point of view, steels can be placed in five categories based on chemical composition, mechanical properties, heat treatment conditions, and high temperature properties: a) carbon steel, b) high strength low alloy steel, c) quench and tempered steel, d) heat treatable steel and e) Cr-Mo steel. These steels need to be welded in different forms such as sheets, plates, pipes, forgings etc. In case of steel welding, it is important to consider thickness of base metal as it affects the heat input, cooling rate and restraint conditions during welding.

37.3 Different types of steel and welding

Carbon steel generally welded in as rolled condition (besides annealed and normalized one). The weldablecarbon steel is mostly composed of carbon about 0.25 %, Mn up to 1.65%, Si up to 0.6% with residual amount of S and P below 0.05%. High strength low alloy steel (HSLA) is designed to have yield strength in range of 290-550 MPa using alloying concentration lesser than 1% in total. These can be welded in conditions same as that of carbon steel. Quench and tempered (Q & T) steels can be a carbon steel or HSLA steel category that are generally heat treated to impart yield strength in range of 350 to 1030 MPa. Heat treatable steels generally contain carbon more than carbon steel or HSLA steels, to increase their response to the heat treatment (Kou, S welding metallurgy, John Willey, 2003). However, presence of high carbon in these steels increases the hardenability which in turn decreases the weldability owing to increased embrittlement and cracking tendency of heat affected zone. Further, PWHT of heat treatable steel weld joints is done to enhance their toughness and induce ductility because presence of high carbon in these heat treatable steels. Cr-Mo steels are primarily designed to have high resistance to corrosion, thermal softening and creep at elevated temperature (up to 700 ^{0}C). Therefore, these are commonly used in petrochemical industries and thermal power plants. Weld joints of Cr-Mo steels are generally given PWHT to regain ductility, toughness, and corrosion resistance and reduce the residual stresses.

37.4 **Common problems in steel welding**

37.4.1 **Cracking of HAZ due to hardening**

The cooling rate experienced by the weld metaland HAZ during welding generally exceeds the critical cooling (CCR)which in turn increases the chances martensitic transformation. It is well known from the physical metallurgy of the steels that this transformation increases the hardness and brittleness and generates tensile residual stresses. This combination of high hardness and tensile residual stresses makes the steel prone to the cracking.

37.4.2 **Cold cracking**

Another important effect of solid state transformation is the cold cracking. It is also termed as delayed/hydrogen induced cracking because these two factors (delay and hydrogen) are basically responsible for cold cracking. Applied/residual tensile stress vs. time relationship for failure by cold cracking is shown in Fig. 37.4. It can be observed that increase in stress decreases the time required for initiation and complete fracture by cold cracking.

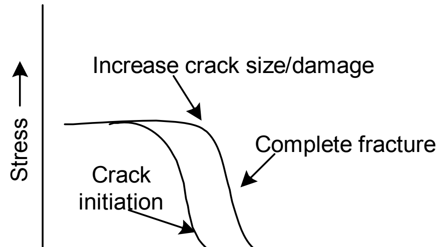


Fig. 37.4 Schematic diagram showing stress vs. time relationship for fracture by cold crack

Origin of this problem lies in the variation of solubility of hydrogen in the steel with the temperature. Reduction in temperature decreases solubility of hydrogen in solid state due to change in crystal structure from F. C. C. to B. C. C. High temperature transformation (like austenite to pearlite or bainite) allows escape of some of excess hydrogen (beyond the solubility) by diffusion. But in case of low temperature transformation (austenite into martensite), when rate of diffusion reduces significantly, hydrogen cannot escape and is trapped in steel as solid solution. Dissolved hydrogen has more damaging effect in presence of martensite and the same has been explained below.

Hydrogen dissolved in atomic state at low temperature tends to diffuse out gradually toward the vacancies and other cavities. At these locations atomic hydrogen converts into diatomic H_2 gas and with time, continued diffusion of hydrogen towards these discontinuities as this gas starts to build up pressure in the cavities (Fig. 37.5). If the pressure exceeds the fracture stress of metal, cavities expands by cracking. Cracking of metal increases the volume which in turn reduces the pressure. Due to continuous diffusion of hydrogen toward the cavities after some time again as pressure exceeds the fracture stress, and crack propagates further. This process of building up on pressure and propagation of cracks is repeated until compete fracture takes place without external load. Since this type cracking and fracture takes place after some time of welding hence it is called delayed cracking. Delay for complete fracture depends on the following factors:

- Hardenability of steel
- Amount of hydrogen dissolved in atomic state

- Magnitude of residual tensile stress

Hardenability of steel affects the critical cooling rate. Steel of high hardenability promotes the martensitic transformation therefore it has high hardness and brittleness. High hardness increases the cracking tendency whereas soft and ductile metals reduce it. Crack tips are blunted in case of ductile metals so they reduce the cracking sensitivity and increases the stress level for fracture. As a result crack propagation rate is reduced in case of ductile and low strength metal. Therefore, steels of low hardenability will therefore minimize the cold/delayed cracking.

Larger the amount of dissolved hydrogen faster will be the delayed/hydrogen induced cracking.

Remedy

- Use of low hydrogen electrodes.
- Preheating of plates to be welded.
- Use of austenitic electrodes.

Use of low hydrogen electrodes will reduce the hydrogen content in weld metal. Preheating of the plate will reduce the cooing rate, which will allow longer time for gases to escape during the liquid to solid state and solid-solid transformation. It may also reduce the cooling rate below the critical cooling rate so that martensitic transformation can be avoided and austenite can be transformed into softer phases and phase mixtures like pearlite, bainite etc. These soft phases further reduce the cracking tendency. Use of austenitic electrode also avoids the martensite formation and provides mainly austenite matrix in weld zone. Austenite is a soft and tough phase having high solubility (%) for hydrogen. All these characteristics of austenite reduce the cold/delayed cracking.

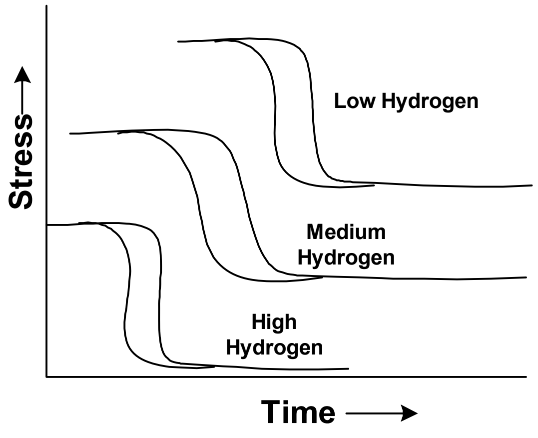


Fig. 37.5 Schematic diagram showing effect of hydrogen concentration on cold cracking at different stress levels

References and books for further reading

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