**Welding of carbon and low alloy steels and hydrogen causing cracks**

Welding of carbon and low-alloy steels and cracking due to hydrogen

Arc welding is a process in which steel is joined together by the solution-coagulation method. Typically， the process uses a compatible filler material. Before producing a well-bonded joint， the joint surface is heated above the melting temperature to allow complete fusion with the weld metal. Although metallurgical reactions involving melting， solidification and solid state transformation are not uncommon， the observed temperatures and cooling rates are slow.

Reactive gases are also present and can be dissolved in the molten steel. Flux is introduced to alloy with and protect the weld metal. In general， the joint is rigid and inhibits dimensional changes caused by shrinkage and solid state transformation， producing residual stresses of yield strength (YS) magnitude. Because metallurgical changes do not occur under equilibrium conditions and because stresses are high， many reactions may occur in the heat affected zone (HAZ) of the weld metal and steel and may produce defects that weaken its soundness.

Because of the great variability of the welding process， it is difficult to provide much detail about the exact mechanisms involved or the corrections that can be made. In addition， once most problems are identified， then many solutions are obvious. One problem， related to hydrogen (H2)， is not so simple. The issue of hydrogen induced cracking (HIC) is very important as this problem becomes more and more important as more and more high strength， low alloy (HSLA) steels are welded.

Carbon (C) and low-alloy steels are being welded because they have a wide range of applications and good weldability. This usefulness is mainly due to the metallurgical properties of iron (Fe)-based systems. This property includes the ability to undergo anisotropic (microstructural) transformation， which allows the opportunity for hardening and strengthening through martensitic and bainitic transformation or precipitation mechanisms， in addition to the ability to easily alloy with a large number of elements. The weldability of carbon and low-alloy steels can generally be divided into (1) fabricating weldability and (2) using weldability.

Fabrication weldability is due to the possibility of joining C and low-alloy steels by welding without introducing harmful discontinuities. The acceptability of these discontinuities depends on the conditions of the specific welding application. The fabricating weldability of the steel is adequate for non-critical applications. However， the same steel may not be recommended for critical applications or may require special precautions， such as preheating， when welding. Fabrication weldability is mainly concerned with discontinuities such as H2 assisted porosity， sheet tearing， cold cracking， hot cracking and reheat cracking.

Service weldability of C-beams and low-alloy steels means that the finished weldment has sufficient properties to achieve the desired function. An important feature of service weldability is to compare the performance of the HAZ with the performance of the unaffected base steel. The acceptability of weldability in service also depends on the planned application. For applications where corrosion is very important and toughness is of secondary importance， the service weldability of some steels is acceptable. However， in applications where toughness is very important， the same steel is unacceptable. In-service weldability relates to the effect of welding thermal cycling on hot zone properties. In-service weldability often determines the range of heat input allowed for certain steels. Low heat input can introduce undesirable low toughness microstructures and fabrication weldability problems associated with cold cracking. High heat input can introduce rough microstructures with low toughness and low strength. Heat input alone does not control the resulting microstructure and heat affected zone properties， but the resulting thermal cycling controls the microstructure and properties. Therefore， both the heat input and the thickness of the steel are important.

Classification of steels

C-beams and low-alloy steels cover a wide variety of compositions and properties. Steels are often classified according to their C and/or alloying element content. Different classifications have different names， such as normal C steels， C-Mn (manganese) steels， medium C steels， low-alloy steels， high-strength low-alloy (HSLA) steels， and micro-alloy steels. Recently， a new classification of steels has introduced the method of steel processing as a classification factor. These are referred to by various names and are often described as thermomechanically controlled processing (TMCP) steels. The boundaries between all of the above classifications are often scattered， they often overlap， and they are sometimes subjective.

Low carbon steels contain up to about 0.30% C and up to about 1.65% Mn. Most rolled steels used for welding consist of low carbon steels. This category includes steels that vary considerably in weldability. For example， it is possible to weld low carbon steels containing less than 0.15 percent carbon in all welding processes. It is also possible to weld low C steels containing 0.15% to 0.30% C (often called mild steels) up to 25 mm thick. However， thicker mild steel sections may require additional action to weld successfully.

HSLA steels are designed to provide better mechanical properties than conventional C steels. This steel typically has a YS of 290 to 550 N/sqmm and is of the C-Mn type with very small amounts of niobium (Nb) and vanadium (V) added to ensure grain refinement and precipitation hardening. HSLA steels are often identified as microalloyed steels. The weldability of HSLA steels is similar to that of low carbon steels.

Recently， a new family of HSLA steels has been developed with low C， copper (Cu) bearing age hardening. These steels are not truly low alloy because the total Cu， Ni (nickel) and Cr (chromium) content is typically close to 1%. The weldability of these steels is very good， mainly because of their low C content (less than 0.06%). These steels are usually used in the hardened and aged condition. Because of these two conditions， these steels are sometimes referred to as TMCP steels. Quenched and tempered (Q&T) steels are heat treated to obtain YS of 350 to 1030 N/sqmm. Other examples of these steels include Ni-Cr-Mo (molybdenum) steels. These steels are typically welded without further heat treatment， except for post-weld heat treatment (stress relief) in some special applications. Compared to selected hardened and tempered steels， these HSLA steels have the advantage of reduced weld preheating requirements for copper age hardening. However， these HSLA steels cannot be welded in the same manner as low carbon steels.

Heat treatable low alloy (HTLA) steels are typically re-austenitized， then quenched and tempered after welding. These steels are relatively hardenable steels with a YS above 960 N/sqmm in their quenched and tempered condition. weld metal in the welded or stress relieved condition usually does not develop an acceptable combination of strength and toughness to this level. Therefore， it is necessary to re-austenitize the entire weld after welding， followed by quenching and tempering.

TMCP steels are typically produced using a combination of controlled rolling followed by accelerated cooling or in-line direct quenching. This processing allows the development of a combination of high strength and high toughness while maintaining good weldability. The good weldability is due to the fact that the alloying element content in these steels can be kept very low， with C content typically below 0.06%. The YS levels of these steels may be as high as 700 N/sqmm or more. These steels can usually be welded without preheating. However， in high strength cases， preheating may be required to prevent cracking of the weld metal.

Chromium-molybdenum steels are widely used in high temperature applications. These steels range in chromium content from 0.5% to 9% and molybdenum content from 0.5% to 1.0%. These steels are usually delivered in the "normalized and tempered" or "quenched and tempered" condition. Due to the reasonable hardenability of these steels， appropriate precautions need to be taken to avoid H2 assisted cold cracking (HACC). Service applications often place additional requirements on the welding of these steels. For example， in some industries， these steels need to be creep resistant， with both the weld metal and HAZ providing adequate creep properties. In the corrosive environments of some industries， the maximum heat affected zone hardness needs to be limited to avoid corrosion cracking.

Relative susceptibility of steels to HACC

Graville suggests that susceptibility to HACC can be assessed by calculating the C equivalent (CE) and comparing it to the C content shown in the Graville diagram (Figure 1). steels in zone I have low C and low hardenability and are less susceptible to cracking. Steels in zone III have high C and high hardenability， and all welding conditions produce crack-sensitive microstructures. Therefore， in order to avoid HACC in steels of zone III， it is necessary to use low H2 measures， including preheating and post-weld heat treatment. steels of zone II have a high C level and low hardenability. Therefore， it is possible to avoid crack-sensitive microstructures by limiting the cooling rate of the HAZ. This can be achieved by controlling the heat input and， to a lesser extent， by preheating.

Figure 1 Gravel diagram showing the sensitivity of steel to HACC as a function of C content and CE.

The CE considered in the Graville diagram is CE = % C + (% Mn + % Si)/6 + (% Ni + % Cu)/15 + (% Cr + % Mo + % V)/5. The sensitivity to cold cracking increases gradually as the steel moves from zone I to zone II and then to zone III. The Graville diagram also shows that heat treatable alloy steels， primarily in zone III， require special consideration when welding. CrMo and Q&T steels also require attention， as do some HSLA steels. Mild steels are easy to weld， except in thick sections， for which some precautions need to be taken. tmcp steels were developed specifically to be located in zone I， so their weldability is very good. Figure 1 represents only one aspect of weldability， there are many other issues and for HACC the ideal preference is to use steels that push the composition coverage to the lower left corner of the Graville diagram.

Normal defects associated with arc welding

Porosity is caused by the entrapment of small pockets of gas， particularly H2 and N2 (nitrogen)， which usually have high solubility in liquid rather than solid iron (Fe). During solidification， the gases try to detach themselves from the weld metal. However， due to the high solidification rate， some gases may be entrapped. This entrapment depends both on the rate of gas dissolution and on the solidification rate of the weld metal. If the dissolution rate is high， bubbles have the opportunity to form and escape before the steel solidifies. If the dissolution rate is low， the gas stays in solution， which avoids porosity， but other problems such as H2-induced cracking (HIC) or poor toughness can occur. At moderate rates， the gas can nucleate and become bound by bubbles depending on the amount of gas dissolved in the weld metal and the welding solidification rate. When the gas evolves and solidifies at the same rate， a very severe form of porosity， called wormholes， can occur， resulting in the development of elongated gas pockets to replace the basic spherical bubbles.

Possible sources of H2 include moisture in the flux， hydrocarbons in the drawing lubricant or surface contaminants in the head to be welded， and water leakage from "gas metal arc welding" (GMAW) equipment. N2 collects from the air entering the arc area due to poor arc shielding. For GMAW， this occurs when the gas flow rate is so low that the cross-flow replaces the shield， or so high that the surrounding atmosphere is drawn into the shield gas. For the "welded metal arc welding" (SMAW) process， this occurs when the welder does not have sufficient skill or uses improper methods that result in an excessively long arc length.

Incomplete fusion can take many forms， such as insufficient penetration of the joint， lack of root fusion， or lack of sidewall fusion. These defects can be caused by (i) insufficient energy input to the weld， primarily insufficient current， (ii) excessive travel speed， which allows the weld metal to flow in front of the arc， or (iii) improper electrode angle or working position.

Difficulties in joint penetration and root fusion are usually due to the use of a joint design that is inappropriate for the welding process being used or neglects the measures required to provide adequate arc penetration. In most cases， this means that the welding current is too low. However， in the case of gas shielded welding processes， this can mean that the wrong shielding gas is being used. For example， with an argon (Ar)-rich gas mixture， the penetration pattern is relatively shallow， except for a fairly deep central "finger". Unfortunately， this finger is usually not in the center and， therefore， cannot be relied upon. However， shielding gas mixtures rich in helium (He) or carbon dioxide (CO2) can produce a more uniform and deeper useful penetration pattern. When welding from one side， poor root fusion can occur， which requires modification of the joint design to allow better penetration or a change to welding from both sides of the steel part.

In most cases， there is a lack of sidewall fusion between the weld metal and the joint when the welder does not use proper measures or control techniques. For the GMAW process， this may be due to the use of inappropriate variations， such as the use of short-circuit transfer when welding heavy sections. Short-circuit transfer is only effective at low energy levels， which makes it very suitable for welding steel sheets or thin plates in all positions. This is because the process is designed to provide little penetration and to freeze the weld metal quickly. For this reason， the weld metal is not melted on the side walls of the joint where the heat is rapidly extracted， i.e. those joints thicker than 6 mm. Both argon jet arc and submerged arc with CO2 protection produce welds that are too large and too fluid to be supported in a vertical or overhead position. However， these processes are very effective for welding in a flat or horizontal position. On the other hand， pulsed arc variations rich in argon gas protection are very effective in all positions， providing both sufficient penetration and control of the weld pool to prevent defects due to poor sidewall fusion.

Thermal cracks， also known as centerline or solidification cracks， are caused by the rejection of low melting point components along the centerline of the constrained weld. They appear immediately after the weld is completed and sometimes during the welding process. If the weld is broken to expose these cracks， they are found to be blue， or heat stained. These cracks are usually caused by sulfur (S) and phosphorus (P) and are more likely to occur in high C alloy steels. In most cases， the underlying steel plate is the source of them. The susceptibility to cracking based on weld composition has been compared with an empirical formula such as UCS = 230 X % C + 190 X % S + 75 X % P + 45 X % Nb - 12.3 X % Si - 5.4 X % Mn - 1. If the UCS value is less than 10， then the susceptibility to cracking is low， while a value above 30 implies that this susceptibility is high， and a value between 10 and 30 implies the need to control the welding technique.

Defects， such as thermal cracking and crater cracking in the weld， are more likely to occur in welding processes or techniques that produce high dilution (i.e.， deep penetration). Another factor that contributes to centerline cracking is the sharp teardrop profile of the weld crater， which is characteristic of high welding speeds. In this case， the weld pits often show shrinkage cracks called pit cracks. Both teardrop-shaped pits and deep penetrations are produced in the "submerged arc welding" (SAW) process and in the GMAW process using CO2 shielding. This problem can also occur in very dimpled fillet welds where the cross section may not be sufficient to withstand the transverse stresses due to weld shrinkage.

In most cases， this problem can be prevented by keeping the combined S and P levels below 0.06%. However， when welding highly constrained joints with high strength steels， it is generally necessary to keep the combined level below 0.03%. When the steel to be welded contains excess S or P， thermal cracking can be avoided by (i) using a welding method or technique that is not deep， (ii) selecting a sufficiently slow travel speed to prevent the formation of teardrop craters， (iii) providing a convex weld profile， and (iv) filling the crater at the end of each weld.

Sheet tearing occurs in the base steel plate and is usually found below the danger zone when stressed through its thickness. It is associated with strip steels containing thin layers of inclusions that lie beneath the surface of the steel plate. If dirty steel is to be used， then this problem can be prevented by changing the joint design to reduce the strain through the thickness of the steel plate at the weld.

A dark cut is an irregular cut that is usually found in the upper toe of a horizontal fillet weld. The steel base plate of this section of the weld is melted by the arc， but not refilled by the weld metal. In most cases， this defect is caused by improperly selected welding conditions， such as electrode angle， travel speed and welding current. This is more likely to occur when attempting to fillet weld with a weld foot longer than 8 mm. It can also occur in the GMAW process when using an argon shield with an oxygen content of less than 2%. Dark cuts can also occur in welds performed in the vertical position， usually due to excessive braiding.

Overlap， also known as overturning， is usually associated with fillet welding and occurs when the welding current is too low to properly melt the base plate or the travel speed is too low to accept the amount of metal deposited. Improper handling of the electrode during SMAW may also be a factor.

Inclusions are created by slag that is trapped between the welds. The source of inclusions is unmelted flux debris that may be trapped in the joint， or slag that is allowed to flow before the arc and covered by the weld， or solidified slag that is not removed during the welding process， or heavy abrasive debris that is not removed from the joint prior to welding. This problem is most common in the SMAW process as it can be exacerbated by poor welders' control techniques. The presence of inclusions can be expected when welding on high crown or rough welds， as their edges are difficult to clean or penetrate during the welding process. Prevention is achieved by (i) training welders to deposit welds with accurate flat contours， (ii) positioning welds to allow higher energy and more fluid deposition， (iii) preventing rust between welds， and (iv) ensuring that welds are properly treated by cleaning or grinding between welds.

Hydrogen-induced cracking

Hydrogen-induced cracking (HIC) is a phenomenon primarily associated with the welding of low-alloy steels. The factors contributing to HIC are (i) the presence of H2， (ii) high tensile stresses， (iii) susceptible microstructure， (iv) temperatures between approximately 200°C and -100°C， and (v) time. At lower strength levels (~490 N/sqmm)， HIC is typically observed as longitudinal cracks in the HAZ of the base steel， often referred to as subbead cracks. At higher strength levels (~830 N/sq mm and higher)， transverse cracking may also occur in the weld metal.

The often used expression "H2 embrittlement" indicates that H2 destroys the toughness of the weld， but this term is a misnomer. Impact tests on material removed from the area between cracks have shown that the material exhibits a level of toughness comparable to that of a weld without H2， including， of course， the cracks. However， tensile ductility may be reduced because HIC may occur during the tensile test， thereby reducing the cross-sectional area of the test specimen. The resulting defect on the fracture surface is referred to as a "fish eye". Cold cracking is another expression that is used to distinguish these cracks from hot cracks， which are found in weld metal and are produced by the bias of low melting point components during solidification. Delayed cracking is another term being used. It is descriptive because HIC may not occur for days or weeks. When HIC is expected to occur， the weld is often not radiographed for a week or more to allow the crack to develop.

Mechanism

Hydrogen is a common impurity in all arc welding processes. It is present in fluxes where water cannot be avoided， in organic lubricants that fill the wire surface， in debris that collects at the weld joint， and in air where moisture can be drawn into the arc stream. h2 is more soluble in liquid iron than in solid iron， and its solubility in solid iron decreases with increasing temperature. the solubility of h2 in iron is a function of temperature.

At 1500 deg C， the solubility is about 30 ppm (parts per million) above the liquid state， but about 8 ppm in the solid state. at 400 deg C， its solubility drops to less than 1 ppm. the solidification rate of weld metal is very high， so the H2 dissolved in the molten weld metal is retained. Although H2 escapes as a gas， it is often trapped in the form of small bubbles or pores in the weld metal， and large amounts of H2 remain in the solidified weld metal in a supersaturated form. The residue may seem insignificant， but it must be recognized that as little as 1 ppm of H2 can cause cracking problems in high strength steels.

During the cooling interval， atomic H2 diffuses rapidly， some enters the weld HAZ， some escapes into the air， and the rest remains in the weld metal. Under the right conditions， these highly mobile atoms seek out cracks and discontinuities in the metal lattice and concentrate on these points. In conjunction with residual stresses in the lattice， H2 enlarges the discontinuity points and forms microcracks due to external constraints and volume changes caused by solidification and solid state transformation. When the atoms penetrate the crack and are bound as molecules， the local stress is suddenly relieved. The resulting microcracks， with sharp tips， are also associated with high stress concentrations， where more atoms accumulate. These stresses accumulate until they are also released with the extension of the crack. This process of stress accumulation and crack release continues until (i) the cross-sectional area is reduced enough to cause failure， (ii) the amount of H2 escapes enough to reduce its concentration below the level required for cracking to proceed， and (iii) the bead cracking reduces the residual stresses in the weld below the level required for cracking to proceed.

HIC does not occur spontaneously， but in discrete steps. The progression of the steps can be observed acoustically. In small specimens， the progression can also be monitored by measuring the change in resistance. Monitoring describes the change in resistance that occurs after the HIC process starts and the way the HIC progresses step by step until it fails. Monitoring also shows the sensitivity of the HIC to external stress levels. Failure occurs rapidly when the stress on a specimen exceeds its tensile strength (TS)， regardless of the presence of H2. However， when sufficient H2 is present， damage caused by HIC can begin at stresses well below TS. With enough H2 and time， HIC can lead to damage. Typically， the time required to initiate cracking and cause failure increases with decreasing stress.

It is important to know that HIC does not occur below the critical stress. In addition to the applied stress， the amount of H2 dissolved in the steel plays an important role. As the H2 increases， less stress is required to initiate the HIC and the time required for initiation decreases. The interaction of the two variables， stress and H2， shows that both the time to initiate HIC and the critical stress below failure are inversely proportional to the amount of H2 in the steel.

The third variable affecting HIC is the microstructure of the steel (either weld metal or HAZ). Twinning martensite， which occurs in steels with high C content (over 0.3 % C)， is usually very difficult， although the problem can occur in all pin-like microstructures， including bainite. This assumption may be flawed because pin-like microstructures are typically associated with high-strength steels， and the higher stresses are themselves an aggravating factor for HIC. However， steels with relatively tolerant microstructures may show higher critical stresses than stronger steels with sensitive microstructures. Typically， stronger steels are more sensitive to H2 because of the earlier initiation of HIC and lower critical stresses. This difference in behavior has been observed between high-strength martensitic steels and weaker bainitic steels.

Inclusions are also important. the toughness of HSLA steels can be affected by impurities， especially when they are in the form of inclusions. However， since inclusions can act as sinks for H2 atoms， they can also have a beneficial effect. For this reason， some steels of very high purity have been shown to be very sensitive to HIC. It cannot be concluded that in order to develop HIC， the weld needs to have external pressure. The differential shrinkage associated with fusion welding always produces residual stresses in the weld， which， with very few exceptions， are at least equal to the YS of the weakest component in the joint. since most weld metals are stronger than the base material， the residual stresses are close to the YS of the base material. it is often possible to keep residual stresses in critical structures as low as possible by selecting weaker or less well-matched weld metals， making it possible to development to a minimum. For some applications， such as those involving fatigue， a weaker but sound structure may be more suitable than one containing HIC. However， given a sensitive microstructure and sufficient H2， critical stresses can be very low， considerably lower than typical residual stresses. Therefore， if HIC is a problem， in most cases it will occur before the welded structure leaves the fabrication zone.

Another important observation is that the mechanism of HIC is influenced by temperature. At higher temperatures， the diffusion rate of H2 is very high， allowing atoms to concentrate in lattice defects or other sharp discontinuities in the weld. Since the mobility of H2 is essentially zero， HIC is unlikely to occur in welds below -130 degrees Celsius.

Control of HIC

When considering the metallurgical requirements of HIC， it is clear that a number of methods can be used to avoid its occurrence. These requirements include the reduction of residual stresses associated with the welded part. These methods are (i) avoiding pin-like microstructures in the weld metal and HAZ， or at least selecting those that are bainitic rather than martensitic， (ii) reducing the amount of H2 dissolved in the weld metal during the welding operation， or (iii) allowing H2 to be released before it can cause damage. The most suitable of these methods depends on the size of the part to be welded， the mechanical properties required， the foreseen service， the welding process to be used and cost constraints. In most cases， compromises need to be made and a combination of these methods may be the most cost effective.

As mentioned earlier， the residual stress in a weld is usually equivalent to YS in the weakest material in the joint. in joint configurations where high triaxial stresses are introduced， the residual stress may be significantly higher than YS. although designers rarely use weaker materials in order to reduce residual stresses， it should be recognized that HIC has a significant effect on the fatigue life of a structure. A more acceptable compromise to accommodate weaker steels is to redesign the weldment to include thicker sections. However， other approaches can be taken to take full advantage of the strength of low-alloy steels without creating HIC.

Since there is little possibility of changing the microstructure of the weld metal or heat affected zone， the steel material that is most tolerant of HIC should be selected unless a different steel can be chosen. Another way to reduce residual stresses in the weld is to perform a post-weld heat treatment at a temperature below the critical temperature. Since steel is more fragile at higher temperatures， residual stresses can be greatly reduced by heating the weld to a temperature at which plastic yielding can occur. For steels with a tempered martensitic structure， the most appropriate choice for this heat treatment is at or slightly below the original tempering temperature， typically close to 620 degrees C. This treatment is called stress relief annealing (SRA). For this treatment to be effective， the weldment is kept in a suitably large furnace until the temperature drops below 200 degrees C. Then， to prevent distortion-related difficulties， it is heated and cooled slowly. Considering the temperature and time required for SRA treatment， it is clear that all diffusible H2 in the weld will be released. However， unless the stresses in the weld are to be removed for reasons other than avoiding HIC， SRA may prove to be a very expensive option. Post-heating also has a place in a HIC prevention program. It is not necessary to reheat the weld to temperatures well above 200 degrees Celsius to accelerate the escape of H2 and to avoid the temperature range where HIC may occur. This heat treatment is suitable for welded parts that are small enough to be preheated in the furnace prior to welding and returned to the furnace immediately after welding to allow all the H2 to escape for a period of time. This method is important mainly for very high strength alloy steels， which are very sensitive to H2 related cracking problems.

Similar results can be obtained by slowing down the cooling rate of the weld after welding. This provides more time for H2 to escape before the temperature drops below 200 degrees Celsius. Slowing down the cooling rate also allows the austenite to transform into a softer microstructure that is less sensitive to HIC.

The cooling rate of arc welding is influenced by three main factors， namely (i) the joint temperature before the start of welding， (ii) the arc energy input during the welding process， and (iii) the thickness of the joint. The initial temperature can be the ambient temperature of the area where the steel is stored， or the temperature to which the weld is heated due to previous welding by external methods (interweld temperature)， or the temperature to which the joint was previously heated (preheat temperature). As the preheat temperature increases， the cooling rate decreases. The arc energy input is determined by the amount of electrical energy dissipated by the arc and the speed at which the arc moves along the joint. Higher arc energy input slows down the cooling rate.

The thickness of the joint also affects the cooling rate， since most of the heat entering the joint will enter the body of the weld by conduction. Conduction is at its maximum during three-dimensional cooling. This occurs when the joint is thicker than 25 mm. Conduction is less effective in thinner sections， which means that the weld cooling rate is inversely proportional to thickness. Although the cooling rate in thin sections is also influenced by radiation and convection， the effect is much less pronounced than that of conduction.

The above variables can be incorporated into a single equation that allows calculation of the cooling rate of the weld at a given temperature.CRt = K [(T-To)2 /E] where CRt is the cooling rate at a temperature of T， K is a proportionality constant (including an adjustment for the thickness of the steel if it is less than 25 mm thick)， To is the preheat or intermediate temperature， and E is the arc energy input， calculated by is E= VI/S where V is the arc voltage， I is the welding current， and S is the arc travel speed. By combining the two equations above， a general expression for the cooling rate can be obtained as CRt= K [(T-To)2\*S/VI]. This equation was developed to predict the microstructure of the weld and HAZ， in combination with a continuous cooling transition diagram. This diagram allows to determine the cooling rate above which strong martensite or bainite can be ensured and below which it can be avoided. The same equation can be used to calculate the cooling rate at temperatures critical to the evolution of H2 and the avoidance of HIC.

The adjustment of the welding procedure is done by changing the current or the speed of movement. Voltage is a highly dependent variable determined by (i) the welding process， (ii) the characteristics of the electrode， flux or shielding gas， and (iii) the current. It cannot be considered as a variable that controls the cooling rate of the weld.

Another method of retarding the cooling rate， probably the most common， is to control the preheating temperature or interweld temperature of the joint prior to welding. These relatively small changes in temperature can have a strong effect on the cooling rate around 200 degrees Celsius， which is critical to the occurrence of HIC. For example， by increasing the preheat temperature from 20 degrees Celsius to 100 degrees Celsius， the cooling rate at 200 degrees Celsius is reduced by about one-third. By preheating to 150 degrees Celsius， the cooling rate is reduced by a factor of about 10， which is a very important figure when manufacturing high-strength steels with a very low tolerance for HIC.

Preheating is quite expensive. It may affect the microstructure of the weld and may make the working conditions intolerable for the welder. However， preheating is essential to reduce HIC. Preheating affects the low critical stresses in the HAZ of high strength steels when welding with covered electrodes. The ultimate TS of this high strength steel is about 750 N/sqmm. However， failure due to HIC can occur in less than 10 minutes at a stress level of about 490 N/sqmm at 25 degrees C preheat， i.e. room temperature. Failure does not occur at critical stresses below 415 Newtons/square millimeter. By preheating to 120 degrees C， the critical stress increases to 620 N/sq mm， which is about YS for high strength steel， but is still considered unsafe. In order to avoid HIC completely， preheating temperatures above 150 degrees Celsius are required in the conditions used to produce the weld.

There are a number of methods that have been used to select the most appropriate temperature for preheating steel to avoid HIC. some methods rely on empirically derived tables that list the steel and recommended welding measures， both for preheat and postheat. Another method quantitatively relates the cracking tendency to the hardenability of the steel and calculates it on the basis of CE. one equation for CE is: CE = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4.

For applications involving welding with covered electrodes， the recommended preheating temperatures for steels with different CEs show a linear relationship between CE and preheating temperature， although the overall trend shows considerable dispersion. For a quick approximation of the required preheat， a relationship of To = 200 CE can be used， where To is in degrees Celsius. For a scatter band including all data points， a more precise interaction between CE and preheat temperature can be shown by To = 210 CE (+15 to -45). The scatter band of 60 degrees C is quite large， indicating that the upper half can be used to select the appropriate preheat temperature to avoid potential problems. However， if metallurgical softening needs to be avoided， then the most appropriate course of action is to rely on laboratory tests to determine the minimum effective level of preheating. Of course， this determination needs to take into account the energy input， the thickness of the joint and the welding process.

Measurement of H2

Direct measurement of H2 in weld metal is difficult. Unless great care is taken to prevent its escape from the weld before analysis is performed， the amount measured is generally not representative of the amount that could lead to cracking. This means that while waiting for analysis， plan to quickly analyze the sample or subcool it in liquid nitrogen (N2) to stop the diffusion of H2. The technique recommended by the American Welding Society (AWS) is to measure the volume of H2 gas escaping from a test weld approximately 75 mm long. It is collected in an Eudiometer tube (in a mercury or glycerol bath) or in the isolation chamber of a gas chromatograph.

Indirect methods are also used to measure the source of H2. For welding wires used in GMAW and SAW processes， this can be done by measuring the hydrocarbons on their surface. Mass spectrometry can be used for the analysis. For SMAW and SAW processes， it is possible to determine the moisture adsorbed in the solder flux. Typically， this is done by measuring the weight loss after drying at temperatures ranging from 400 degrees Celsius to 425 degrees Celsius. The problem associated with indirect measurements is that the efficiency of H2 transfer from the wire or flux to the weld is difficult to predict. It usually depends on the welding technique. Therefore， empirical results are used to relate the amount of H2 present in the weld material to the HIC in the welded part. For this reason， comparisons between processes become very difficult. However， even measurements of gas evolution can be problematic， as only diffusible H2 is measured. some stays in solution and some is trapped in weld defects or inclusions.

Importance of the welding process

The arc welding process requires a source of filler material， as well as a method of protecting and controlling the arc and deposited metal. In most cases， the filler material is provided in the form of a rod， continuous wire or continuous tube. The surfaces of all these materials are contaminated with residues of H2-rich drawing lubricants. In the GMAW process， shielding gas is used for protection. For cored wire， a combination of shielding gas and flux is used. The submerged arc and covered electrode techniques involve only fluxes. All fluxes are a source of chemically bound or adsorbed water. The amount of H2 dissolved in the solder metal can vary not only between processes， but also from process to process.

Of all the arc welding processes that use consumable electrodes， the GMAW process has the lowest amount of H2， the primary source being the residual tensile lubricant on the wire surface. Completely dry wire is unacceptable because it is difficult to feed. For steels with YS less than 520N/sqmm， the amount of residual lubricant is generally not an issue. However， as YS approaches 620 N/sq mm， residual lubricant becomes a potentially significant factor if HIC is to be avoided unless relatively high preheat temperatures can be used. When YS exceeds 830 N/sq mm， residual lubricant should be kept as low as possible.

The importance of residuals is reflected in the effect of H2 on the HIC of welds that have a YS of 930 N/sq mm， which needs to be minimized by controlling the cooling rate. In this case， the cooling rate is determined at 540 degrees Celsius， a temperature close to the temperature at which the weld metal transforms from austenite to martensite. At a relatively fast cooling rate of about 30 degrees C/s， 4 ppm of H2 on the wire surface was shown to have caused HIC. to ensure the absence of HIC， H2 was to be kept below 3 ppm. The H2 tolerance on the wire can be increased to 5 ppm by adjusting the welding technique， the preheat temperature or both in order to retard the cooling rate of 540 degrees C to less than 20 degrees C/sec.

As described in H2 measurements， it is difficult to predict the amount of H2 transferred to the weld from surface contaminants that decompose during the arc (or before reaching the arc)， primarily when measured at single-digit ppm. this level is so low that H2 cannot be measured using gas evolution techniques. the higher tolerance for wire surface contaminants at lower cooling rates may be due to the softer microstructure， but also may be due to the escape of H2. Higher cooling rates are necessary to maintain high strength. Usually， the strength drops abruptly when the cooling rate drops below 10 deg C/s. Obviously， in order to obtain the strongest welds without encountering HIC， it is necessary to minimize the presence of any contaminants containing H2.

Other arc welding processes cannot achieve very low H2 content because they require flux rather than shielding gas. Fluxes can absorb moisture. Moisture in submerged arc flux has a significant effect on the cracking susceptibility of weld metals with a YS of 830 N/sqmm. It has shown that diffusible H2 levels as low as 7 ml/100 g can reduce the critical strength to 105 N/sq mm (1 ppm of H2 content equals 1.11 ml/100 g). Even baking the flux to bring the weld diffusive H2 content below 2 ml/100 g does not eliminate the HIC. the critical stress remains below 415 N/sq mm. it is clear that the welding conditions used for submerged arc welding are unacceptable. Either the steel is unusually sensitive to H2 or the flux used is not sufficiently dry to reduce H2 contamination.

In the SMAW process， similar HIC problems are encountered when the weld strength exceeds 480 N/sqmm. For this reason， low H2 electrodes were specifically developed to minimize， if not prevent， this problem. The formulation of the low H2 electrode coating does not contain any organic materials. This low H2 coating is baked at temperatures in excess of 430 degrees Celsius to reduce residual moisture to a level of approximately 0.1%. This is almost the lowest level practicable， as the absence of moisture in the coating tends to make it brittle. The effect of baking on residual moisture during initial fabrication showed that even with careful control of formulation and baking， the level of moisture covering the electrode coating could not be reduced to a level low enough to prevent HIC in steels with YS above 830 N/sqmm.

Moisture for low H2 electrodes is typically specified at 0.2 %， and this moisture level is expected. This moisture level is expected to be found in the coating of commercial low H2 electrodes immediately after removal from a sealed container. However， the electrode coating will reabsorb moisture if exposed to moist， warm air. The rate of moisture uptake depends on the composition in the coating. In some cases， the reabsorption of moisture can reach levels of more than 1%. For this reason， on hot and humid days， electrodes should be stored in heated ovens and exposed to the shop environment for only short periods of time.

A moisture barrier coating has been developed to counteract the reabsorption problem. Although the coating is quite safe when exposed to relatively cool and moderately humid environments， additional precautions must be taken when welding in tropical conditions. It is possible to salvage electrodes that have become "wet" by re-baking at temperatures close to those used in the manufacturing process. While re-baking can rescue electrodes that have been inadvertently exposed to wet conditions， the process cannot be repeated because the covered electrodes are alloys made from metal powders that may oxidize during the re-baking process. As a result， the resulting alloy is leaner and weaker.

Re-baking causes a loss of Mn and Si content in the weld metal， which leads to a decrease in the weld YS. This occurs in a very controlled re-bake. Unfortunately， the same caution is not always taken in shop atmospheres. the loss of Mn and Si content and mechanical properties can be greatly increased.