Influence of Welding on Steel Weldment Soundness

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ARC WELDING is a process by which metals are joined by coalescence. In most cases, the process uses a compatible filler metal. Before a well-bonded joint can be produced, the joint surfaces must be heated above their melting temperatures in order to completely fuse with the weld metal. Although the metallurgical reactions that involve melting, solidification, and solid-state transformations may not be unusual, the temperatures and cooling rates observed are severe. Active gases also are present and can dissolve in the fused metal. Fluxes are introduced to alloy with and protect the weld metal. Generally, joints are rigid and will restrain dimensional changes caused by shrinkage and solid-state transformations, producing residual stresses of yield-strength magnitude. Because the metallurgical changes do not occur under equilibrium conditions, and because the stresses are high, many of the reactions can take place in either or both the weld metal and the heat-affected zone (HAZ) of the plate and can produce defects that impair their soundness.

The intent of this article is to point out those defects. However, because of the tremendous variability of the welding processes, it is impossible to provide much detail about the exact mechanisms involved or the corrections that can be made. Furthermore, many corrective measures are self-evident once most defects are explained. One problem, which relates to hydrogen, is not so simple. Because this problem is becoming more relevant as more high-strength, low-alloy (HSLA) steels are being welded, the subject of hydrogen-induced cracking will be emphasized.

Common Defects Associated with Arc Welds

Porosity is caused by the entrapment of small pockets of gas, particularly nitrogen and hydrogen, which typically have a higher solubility in iron than in solid iron. During solidification, gases attempt to leave the weld metal. However, because of high solidification rates, some gas may become trapped. This entrapment depends both on the rate of gas dissolution and on the rate of weld-metal solidification. If the dissolution rate is high, gas bubbles have a chance to develop and escape before the metal solidifies. If the rate is very low the gas may remain in solution, which avoids porosity but allows other problems such as hydrogen-induced cracking or poor toughness. At intermediate rates, the gas can nucleate and, depending on the amount of gas dissolved in the weld metal and the weld-solidification rates, develop bubbles that become trapped. A very severe form of porosity, called worm holes, occurs when the rates of gas evolution and solidification are similar, causing elongated gas pockets to develop instead of essentially spherical bubbles.

Among the possible sources of hydrogen are moisture in fluxes, hydrcarbons in either wire-drawing lubricants or surface contaminants in the joint to be welded, and water leaks in gas-metal arc welding (GMAW) equipment. Nitrogen is gleaned from air that enters the arc regions as a result of poor shielding of the arc. With GMAW, this can happen when the gas flow rates are either so low that crossdrafts displace the shielding or so high that the surrounding atmosphere is aspirated into the shielding gas. With the shielded metal arc welding (SMAW) process, this can happen because welders are not sufficiently skilled or use improper procedures that cause the arc length to be excessive.

Incomplete fusion can take a number of forms, such as inadequate joint penetration (Fig. 1), absence of root fusion, or lack of side-wall fusion (Fig. 2). These defects can be caused by: inadequate energy input to the weld, particularly insufficient current; excessive travel speed, which allows weld metal to flow ahead of the arc; or improper electrode angles or work positions.

Problems with joint penetration and root fusion commonly are due to the use of a joint design that is not proper for the welding process being used or to a disregard for the procedures that are intended to provide adequate penetration of the arc. In most cases, this would mean that the welding current is too low. However, in the case of the gas-shielded welding processes, it could mean that the wrong shield gas is being used. For example, with argon-rich gas mixtures, the penetration pattern is relatively shallow, with the exception of a fairly deep central "finger," which is shown in Fig. 3. Unfortunately, this finger generally is not positioned centrally and, therefore, cannot be relied upon. However, shield gas mixtures that are rich in helium or carbon dioxide are capable of a more uniform and deeper useful penetration pattern. Poor root fusion that occurs when welding from one side requires either a modification in the joint design to allow better penetration or a change to welding from both sides of the plate.

In most cases, the lack of side-wall fusion between the weld metal and the joint occurs when proper procedures or manipulative tech-
niques are not being used by welders. With the GMAW process, it can be due to using inappropriate variations, such as short-circuiting transfer, when welding heavy sections. Short-circuiting transfer is effective only at low energy levels, which makes it very suitable for welding sheet or thin plate in all positions. This is because the process is designed to provide little penetration and to quickly freeze weld metal. For that reason, the weld metal may not fuse the side walls of joints from which heat is extracted rapidly, that is, those thicker than 6 mm (¼ in.). Both a spray arc with argon and a buried arc with carbon dioxide shielding will deposit welds that are too massive and fluid to be supported in the vertical or overhead positions. However, these processes are very effective for making welds in flat or horizontal positions. On the other hand, the pulsed-arc variation with argon-rich shielding is very effective in all positions, offering both adequate penetration and control of the weld pool to prevent defects caused by poor side-wall fusion.

Hot cracks, also called centerline or solidification cracks (Fig. 4), are caused by the rejection of low-melting constituents along the centerline of restrained welds. They are called hot cracks because they develop immediately after welds are completed and, sometimes, while the welds are being made. If the welds are broken to expose these cracks, they are found to be blueed, or heat tinted. These defects, which are often caused by sulfur and phosphorus, are more likely to occur in higher-carbon alloys. Nearly always, the base plate is their source. The susceptibility to cracking, based on weld composition, has been compared with empirical equations, such as:

\[
UCS = 230 C + 190 S + 75 P + 45 Nb \\
- 12.3 Si - 5.4 Mn - 1 
\]

(Eq 1)

where the elemental values are given in percent. If the UCS value is less than 10, then the susceptibility to cracking is low, whereas a value higher than 30 means that this susceptibility is high, and a value between 10 and 30 means that the welding procedures become controlling.

Such defects are more likely to occur with low heat input, welding processes or procedures that produce high dilution (that is, deep penetration). Another factor that contributes to centerline cracking is a sharp tear-drop profile of the weld crater, which is characteristic of high welding speeds. In these situations, the weld crater often develops shrinkage cracks, called crater cracks. Both the tear-drop crater and deep penetration are produced with the submerged arc welding (SMAW) process and the GMAW process using carbon dioxide shielding. The problem also may occur in fillet welds that are very concave, because their cross section might not be sufficient to tolerate the transverse stresses that are due to weld shrinkage. In most cases, the problem can be prevented by keeping the combined phosphorus and sulfur levels below 0.06%. However, when welding highly restrained joints using high-strength steels, a combined level below 0.03% might be necessary. When the steels to be welded contain excessive amounts of sulfur or phosphorus, hot cracks can be avoided by:

- Using welding processes or procedures that are not deeply penetrating
- Selecting travel speeds that are sufficiently slow to prevent the formation of tear-drop craters
- Providing convex bead profiles
- Filling the craters at the end of each bead

Lamellar tearing occurs in the base plate when stressed through its thickness and generally is found just below the HAZ (Fig. 5). It is associated with banded steels that contain thin layers of inclusions located beneath the plate surfaces. If the dirty steels must be used, the problem can be prevented by changing the joint design to minimize strain through the thickness of the plate at the weld.

An undercut is an irregular gouge that is generally found in the upper toe of a horizontal fillet weld. The base plate in that section of the weld shown on the left side of Fig. 6 had been melted by the arc, but not refilled by the weld metal. Most often, this defect is caused by improperly selected welding conditions such as the electrode angle, travel speed, and welding current. It is more likely to occur when attempting to make fillet welds with legs that are more than 8 mm (0.31 in.) in length. With the GMAW process, it also can occur when using an argon shield containing less than 2% oxygen. Undercut also can be found in welds made in the vertical position, where it is generally attributed to excessive weaving.

A rollover, also called an overlap (Fig. 6), generally is associated with fillet welds and can be found when either the welding current is too low to properly fuse the base plate or the travel speed is too low to allow the metal being deposited. Poor manipulation of the electrode during the SMAW process also can be a factor.

Inclusions are produced by slag that is trapped between weld passes. They originate as pieces of unfused fluxes that may be trapped in a joint, or as slag that is allowed to flow ahead of the arc and is covered by the weld, or as solidified slag that has not been removed between weld passes, or as heavy mill scale that has not been removed from a joint prior to welding. The problem is most common with the SMAW process because it can be aggravated by poor manipulative techniques on the part of the welder. The presence of inclusions can be anticipated when welding over highly crowned or rough welds because their edges are difficult to clean between passes or to penetrate during welding. Prevention is possible by:

- Training welders to deposit welds that have properly flat profiles
- Positioning welds to allow higher energy and more fluid deposits to be made
- Preventing the development of rust between passes
- Ensuring that the welds are properly conditioned between passes by either cleaning or grinding
Hydrogen-Induced Cracking

Hydrogen-induced cracking (HIC) is a phenomenon primarily associated with welds in low-alloy steels. Figure 7 depicts a typical crack, which was taken from the HAZ of a weld. The factors that contribute to HIC are the presence of hydrogen, high tensile stress, susceptible microstructures, temperatures between approximately 200 and -100 °C (400 and -150 °F), and time. At lower strength levels (approximately 485 MPa, or 70 ksi) HIC is most often observed as longitudinal cracks in the HAZ of the base metal, often called underbead cracking. At higher strength levels (approximately 830 MPa, or 120 ksi, and higher), transverse cracks can occur in the weld metal as well.

The commonly used expression "hydrogen embrittlement" suggests that hydrogen impairs the toughness of welds, but that designation is a misnomer. Impact tests on material removed from the area between cracks show that the material exhibits levels of toughness equivalent to welds made in the absence of hydrogen and, of course, cracks. However, tensile ductility can be reduced because HIC can occur while the tensile test is in progress, which reduces the cross-sectional area of the test specimens. The resulting defects in the fractured surfaces are called "fisheyes."

Cold cracking is another expression that has been used to differentiate these cracks from the hot cracks that are found in weld metal and are produced by low-melting constituents that segregate during solidification. Delayed cracking is another term that has been used. It is descriptive because HIC might not occur for days or weeks. When HIC is anticipated, welds often are not radiographed for a week or more in order to allow the cracks to develop.

Mechanism. Hydrogen is a ubiquitous contaminant in all arc welding processes. It exists in the water that is unavoidable in fluxes, in the organic lubricants on the surfaces of filler wires, in the debris that collects in weld joints, and in the moisture in air that can be aspirated into the arc stream. Hydrogen has a much higher solubility in molten iron than it does in solid iron, and its solubility decreases with temperature in the solid state as well. The hydrogen solubility in iron as a function of temperature is shown in Fig. 8. The solubility above the liquidus at 1500 °C (2730 °F) is about 30 ppm by weight, but about 8 ppm in the solid state. At 400 °C (750 °F), its solubility drops to less than 1 ppm. The rates of weld-metal solidification are very high and, as a result, the hydrogen that has dissolved in the fused weld metal is retained. Although that which does escape as gas often is trapped in the form of small bubbles or weld-metal porosity, a substantial amount does remain in the solidified weld metal as supersaturated hydrogen. The residue might appear to be insignificant, but it should be recognized that as little as 1 ppm of hydrogen can cause cracking problems in high-strength steels.

During the cooling interval, the atomic hydrogen diffuses rapidly, with some going into the weld HAZ, some escaping to the air, and the rest remaining within the weld metal. Given the right conditions, these highly mobile atoms seek rifts and discontinuities in the metal lattice and concentrate at those points. In concert with the residual stresses in the lattice that are due to external restraint and volume changes caused by solidification and solid-state transformation, the hydrogen enlarges the discontinuities to form microcracks. The localized stresses are relieved abruptly as the atoms penetrate the fissures and become trapped as molecules. The resulting microcracks, which have sharp tips, also are associated with high stress concentrations at which additional atoms collect. Those stresses build up until they, too, are relieved as the crack is extended. This process of stress build up and relief by cracking continues until:

- The cross-sectional area is reduced sufficiently to cause failure.
- Hydrogen escapes in a sufficient amount to lower its concentration below that which is needed for cracking to proceed.
- Underbead cracks have reduced the residual stresses in the weld below that level needed for cracking to proceed.

HIC does not occur spontaneously, but as discrete steps. The stepwise progression can be observed acoustically. In small specimens, its progression also can be monitored by measuring changes in resistance, as shown in Fig. 9. The lower portion of this illustration depicts the changes in resistance that occur after the process of HIC begins, as well as the way in which HIC progresses a step at a time until failure. The upper portion of Fig. 9 illustrates the sensitivity of HIC to the level of external stress. Failure occurs quickly when the stress on a specimen exceeds its tensile strength, whether or not hydrogen is present. However, when enough hydrogen is present, damage that is caused by HIC can be initiated with stresses well below the tensile strength. Given enough hydrogen and time, HIC can cause failure. Note that the time needed for initiating the cracks and leading to failure increases as the stress is reduced.

Most important is the observation that HIC does not occur below a critical stress. In addition to the applied stress, the amount of hydrogen dissolved in the steel also plays an important role. With increasing hydrogen, less stress is needed to initiate HIC, and the times required
Influence of Welding on Steel Weldment Soundness / 111

Fig. 10  Effect of hydrogen and stress on damage caused by HIC. As hydrogen increases, less stress is needed to cause damage by hydrogen-induced cracks.

Fig. 11  Effect of steel strength on susceptibility to HIC damage. Stronger steels can be more sensitive to hydrogen, resulting in lower critical stresses than those exhibited by weaker steels, which are more tolerant.

As mentioned earlier, the residual stresses in welds are generally equivalent to the yield strength of the weakest material in the joint. In joint configurations that introduce high triaxial stresses, the residual stresses can be significantly higher than the yield strengths. Although designers rarely use weaker materials just to reduce residual stresses, they should recognize that HIC can have a significant effect on the fatigue life of a structure. To accommodate weaker steels, a more-acceptable compromise might be to redesign the weldment to incorporate thicker sections. However, other approaches can be taken to gain full advantage of the strengths available in low-alloy steels without incurring HIC.

For the reasons mentioned earlier, the possibility of changing the microstructure of the weld metal or the HAZ is remote, unless given the option of selecting different alloys. In that case, the alloy that is most forgiving of HIC should be chosen.

Another method for reducing the residual stresses in welds is by using a postweld heat treatment at temperatures below the critical temperature. Because steels are weaker at higher temperatures, a significant reduction of residual stresses is possible by heating welds to a temperature at which plastic yielding can occur. For a steel with a tempered martensite structure, the most suitable choice for this heat treatment would be at or just below its original tempering temperature, which is generally close to 620 °C (1150 °F). This treatment is called stress relief annealing (SRA). For this treatment to be effective, the weldment must be placed in a suitably large furnace before its temperature drops below 205 °C (400 °F) and then, to prevent difficulties associated with distortion, heated and cooled slowly. Considering the temperatures and times needed for the SRA treatment, it is obvious that all of the diffusible hydrogen in the weld will escape. However, unless the stresses in a weld must be relieved for reasons other than the avoidance of HIC, SRA can prove to be a very expensive option.

Postheating does have a place in the scheme of preventing HIC. It is not necessary to reheat weldments to temperatures that are much higher than 205 °C (400 °F) in order to accelerate the escape of hydrogen and still avoid the temperature range within which HIC is likely. Such thermal treatments are excellent candidates for welded components that are small enough to be preheated in a furnace prior to welding and returned to the furnace immediately after welding for a period of time that allows all of the hydrogen to escape. This approach is particularly important for very high-strength alloys, such as SAE 4340, that are very sensitive to cracking problems associated with hydrogen. Results are possible by slowing the rates at which welds are allowed to cool after welding. This provides more time for hydrogen to escape before temperatures drop below 205 °C (400 °F). Retarding the cooling rate also allows the transformation of austenite to softer microstructures that are less sensitive to HIC.
412 / Selection of Carbon and Low-Alloy Steels

The cooling rates of arc welds are affected primarily by three factors: the temperature of the joint before welding begins, the arc energy input during welding, and the joint thickness. The initial temperature can be that of the shop in which the steel had been stored, or the temperature to which the weldment had been heated as the result of a previous weld by external methods (the interpass temperature), or the temperature to which the joint had been heated (the preheat temperature). As preheat temperatures are increased, the cooling rates decrease. The arc energy input is defined by the electrical energy dissipated by the arc and the speed at which the arc is moved along the joint. Higher arc energy inputs retard the cooling rate.

The joint thickness also affects cooling rates because of the heat entering the joint is extracted by conduction into the body of the weldment. Conduction is at a maximum with three-dimensional cooling. This occurs when the joint is thicker than about 25 mm (1 in.). Conduction is less effective in thinner sections, that is, the weld cooling rate is inversely proportional to thickness. Although the cooling rates of thin sections are also influenced by radiation and convection, the effect is much less pronounced than that of conduction.

The variables described above can be incorporated into a single equation that allows calculation to be made of the rate at which welds cool at a specific temperature:

\[ CR_T = C \frac{(T - T_o)^3}{E} \]  \hspace{1cm} (Eq 2)

where \( CR_T \) is the cooling rate at temperature \( T \), a constant of proportionality (including an adjustment for plate thickness, if it is thinner than 25 mm, or 1 in.), \( T_o \) is the preheat or interpass temperature, \( E \) is the arc energy input, which is calculated as:

\[ E = \frac{VI}{S} \]  \hspace{1cm} (Eq 3)

where \( V \) is the arc voltage, \( I \) is the welding current, and \( S \) is the arc travel speed. By combining the above two equations, a general expression for cooling rate is obtained:

\[ CR_T = C \frac{(T - T_o)^3}{VI} \]  \hspace{1cm} (Eq 4)

This equation was developed for the purpose of predicting weld and HAZ microstructures in conjunction with continuous-cooling transformation diagrams. These diagrams allow the determination of the cooling rates above which strong martensites or bainites are ensured or below which they can be avoided. The same equation can be used to calculate the cooling rates at temperatures critical to the evolution of hydrogen and the avoidance of HIC.

The adjustment of welding procedures is accomplished by varying the current or the travel speed. Voltage is a strongly dependent variable that is determined by the welding process; the characteristics of the electrodes, fluxes, or shielding gases; and the current. It should not be viewed as a variable with which to control weld cooling rates.

The other method of retarding cooling rates, which is probably the most common method, is to control the preheat or interpass temperature of the joint prior to welding. Relatively small changes in those temperatures can exert strong effects on cooling rates at temperatures around 205 °C (400 °F), which is critical with regard to the onset of HIC. For example, by increasing the preheat temperature from 20 to 95 °C (70 to 200 °F), the cooling rate at 205 °C (400 °F) is reduced by approximately one third. By preheating to 150 °C (300 °F), the cooling rate is reduced by a factor of approximately ten, which is a very significant amount when fabricating high-strength steels that have little tolerance to HIC.

Unfortunately, preheating is expensive, it can affect the weld microstructures, and it can make working conditions unbearable for welders. Nevertheless, as Fig. 12 shows, a preheat is important for reducing HIC. The data plotted in Fig. 12 clearly show how a preheat affects the lower critical stress in the HAZ of HY-80 steel when welded with an E11018-M covered electrode. The ultimate tensile stress of this heat of HY-80 is approximately 760 MPa (110 ksi). However, with a 25 °C (78 °F) preheat, that is, room temperature, failure was caused by HIC in less than 10 min, at a stress level of only 480 MPa (70 ksi). The lower critical stress below which failure did not occur was only 415 MPa (60 ksi). By preheating to a temperature of 120 °C (250 °F), the critical stress was increased to 620 MPa (90 ksi), which is approximately the yield strength of the HY-80 steel, but still considered unsafe. To avoid HIC entirely, under the conditions used to produce the welds shown, the preheat temperature would need to exceed 150 °C (300 °F).

A number of approaches can be used to select the most appropriate temperature for preheating a steel to avoid HIC. Some approaches rely on empirically derived tables that list the steels and recommended welding procedures, including those for preheat and postheat. Another relates cracking tendencies quantitatively to the hardenability of the alloy steel, calculating it on the basis of the carbon equivalence. One such formula for carbon equivalence is given as:

\[ CE = C + \frac{Mn}{6} + \frac{Ni}{40} + \frac{(Cr + Mo)}{3} \]  \hspace{1cm} (Eq 5)

For applications that involve welds made with covered electrodes, the recommended preheat temperatures for steels having different carbon equivalencies are plotted in Fig. 13. Although considerable scatter is seen, the overall trend demonstrates a linear relationship between the carbon equivalence and the preheat temperature. For a quick approximation of the required preheat, the following relationship can be used:

\[ T_o = 200 \frac{CE}{6} \]  \hspace{1cm} (Eq 6)

where \( T_o \) is in °C.

To include the scatter band that incorporates all of the data points, a more-precise interaction between the carbon equivalence and the preheat temperature can be shown as:

\[ T_o = 210 \frac{CE}{6} + 15/-45 \]  \hspace{1cm} (Eq 7)

The scatter band of 60 °C (108 °F) is quite large, which suggests that the upper portion be used for selecting suitable preheat temperatures with which to avoid potential problems. However, if metallurgical softening needs to be avoided, then the most appropriate course of action would be to rely on laboratory trials for determining the minimum effective level of preheat. Of course, such a determination would require that the energy input, the thickness of the joint, and the welding process also be considered.
Measurement of Hydrogen. Direct measurements of hydrogen in weld metal are difficult. Unless great care is taken to stop its escape from a weld before an analysis can be made, the amount found will not be representative of that which might have caused a crack to develop. This means that specimens must be designed to be analyzed quickly or supercooled in liquid nitrogen to stop the diffusion of hydrogen while awaiting analysis. The procedure recommended by the American Welding Society (AWS A4.3-86) measures the volume of hydrogen gas that escapes from a test weld approximately 75 mm (3 in.) in length. It is collected in either a cuidrometer tube (in a mercury or glycerine bath) or in the isolation chamber of a gas chromatograph.

Indirect methods also have been used for measuring the sources of the hydrogen. For wires used in the GMAW and SAW processes, this can be done by measuring the hydrocarbons on their surface. Mass spectrometry can be used for analysis. For the SMAW and SAW processes, the moisture adsorbed in the fluxes can be determined. Often, this is done by measuring weight loss after drying at high temperatures of approximately 400 to 425 °C (750 to 800 °F). The problem with indirect measurements is that the efficiency of transfer of the hydrogen to the weld from the wires or fluxes is difficult to predict. It can be very dependent on the welding procedures. Therefore, empirical results are used to relate the amount of hydrogen present in the welding materials to the HIC in the weldment. For this reason, a comparison among processes becomes very difficult. However, even the measurements of gas evolution can be faulted, because only the diffusible hydrogen is measured. Some remains in solution and some is trapped within weld defects or inclusions.

Importance of Welding Processes. The arc welding processes require a source of filler metal and methods for protecting and controlling the arc and the deposited metal. In almost all cases, the filler metals are provided in the form of rods, continuous wires, or continuous tubes. The surfaces of all of these materials are contaminated with residues of hydrogen-rich drawing lubricants. In the GMAW process, a shield gas is used for protection. For cored wires, a combination of shield gases and fluxes are used. The submerged-arc and covered-electrode methods involve only fluxes. All of the fluxes are sources of chemically combined or adsorbed water. The quantity of hydrogen dissolved in weld metal can vary, not only between but within processes. Some indication of the variability to be expected is shown in Table 1.

Table 1 Effect of welding processes and electrodes on hydrogen levels in welds

<table>
<thead>
<tr>
<th>Type of electrode</th>
<th>Diffusible H₂, ml/lb 100 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMAW solid wire</td>
<td>0–10</td>
</tr>
<tr>
<td>Basic SMAW electrode</td>
<td>3–20</td>
</tr>
<tr>
<td>Acid SMAW electrode</td>
<td>20–40</td>
</tr>
<tr>
<td>SAW solid wire and flux</td>
<td>4–20</td>
</tr>
<tr>
<td>GMAW cored wire</td>
<td>3–30</td>
</tr>
</tbody>
</table>

Fig. 13 Effect of carbon equivalent on preheat requirements. Amount of preheat needed to prevent HIC is proportional to the carbon equivalent of the steel being welded.

Fig. 14 Influence of hydrogen present on a wire surface and weld-metal cooling rate on HIC. Data are based on GMAW weld metal with yield strength of 930 MPa (135 ksi).

Fig. 15 Effect of cooling rate on strength of HSLA steel weld metal. Tensile yield strength of HSLA steel weld metal is affected by the cooling rate at which it transforms. Data are based on AX-40 CMAW and E11018 SMAW filler metals.

Fig. 16 Influence of hydrogen present on a wire surface and weld-metal cooling rate on HIC. Data are based on GMAW weld metal with yield strength of 930 MPa (135 ksi).
The importance of such residues is shown in Fig. 14, which summarizes the effects of hydrogen on HIC in welds that have a yield strength of 930 MPa (135 ksi) and shows how it can be minimized by controlling cooling rates. In this case, the cooling rates indicated were determined at 540 °C (1000 °F), a temperature close to that at which the weld metal transforms from austenite to martensite. The closed circles indicate the presence of HIC in the welds, whereas the open circles indicate sound welds. At the relatively rapid cooling rates of 28 °C/s (50 °F/s), 4 ppm of hydrogen on the wire surface is shown to have caused HIC. To be securely free of HIC, the hydrogen had to be maintained at levels below 3 ppm. By adjusting the welding procedures, preheat temperatures, or both, in order to retard the cooling rate at 540 °C (1000 °F) to less than 20 °C/s (35 °F/s), the tolerance for hydrogen on the wire was increased to 5 ppm.

As mentioned earlier in the discussion of hydrogen measurements, it is difficult to predict the amount of hydrogen that will transfer to a weld from surface contaminants that are decomposed in the arc (or before reaching the arc), particularly when the levels are measured in single-digit parts per million. These levels are so low as to preclude the use of gas-evolution techniques to measure the hydrogen.

The higher tolerance for wire surface contaminants at lower cooling rates may be due as much to softer microstructures as it is to the escape of hydrogen. The effect of cooling rate on the tensile yield strength of these alloys is illustrated in Fig. 15. To retain high strengths, the higher cooling rates are essential. In this example, a very abrupt drop in strength is shown as the cooling rate drops below 10 °C/s (20 °F/s). Obviously, to obtain the strongest possible welds without encountering HIC, it is necessary to minimize the presence of any contaminants that contain hydrogen.

The attainment of such low levels of hydrogen is not possible with any of the other arc welding processes, because they require fluxes instead of shield gases for protection. Fluxes can absorb water. The data in Fig. 16 summarize the importance of moisture in a submerged arc flux on the cracking sensitivity of a Soviet weld metal that has a yield strength of 830 MPa (120 ksi). It demonstrates that diffusible hydrogen levels as low as 7 mL/100 g can drop the critical strength to 105 MPa (15 ksi). (Note that a hydrogen content of 1 ppm is equivalent to 1.11 mL/100 g.) Even baking the flux to reduce the weld-diffusible hydrogen below 2 mL/100 g did not eliminate HIC. The critical stress remained below 415 MPa (60 ksi). It is evident that the welding conditions used for these submerged arc welds were not acceptable. Either this steel is unusually sensitive to hydrogen or the flux used is not capable of being dried sufficiently to reduce hydrogen contamination.

Similar HIC problems are encountered in the SMAW process when weld strengths exceed 480 MPa (70 ksi). For this reason, low-hydrogen electrodes were developed specifically to minimize, if not prevent, these problems. Low-hydrogen electrode coatings are formulated without any organic materials, such as the cellulose that characterizes the EXX10 classes. These low-hydrogen coatings are baked at temperatures exceeding 425 °C (800 °F) to reduce residual moisture to a level of approximately 0.1 wt%. This is the lowest practical level, because the absence of moisture in a coating tends to make it brittle. The effect of baking on the residual moisture during initial manufacture is shown in Fig. 17. Even with careful control of formulations and baking, the moisture level of covered-electrode coatings cannot be reduced to levels sufficiently low to prevent HIC in steels having yield strengths higher than 830 MPa (120 ksi).

The moisture in low-hydrogen electrodes generally is specified as 0.2% max. This moisture level is what is expected to be found in coatings of commercial low-hydrogen electrodes, immediately after being removed from hermetically sealed containers. However, if exposed to humid, warm air, these electrode coatings will re-
absorb moisture, as shown in Fig. 18. The rate of moisture pickup depends on the constituents in the coating. In some cases, reabsorbed moisture can reach levels exceeding 1%. For this reason, electrodes must be stored in heated ovens on hot and humid days and exposed to shop environments for only short times.

Moisture-resistant coatings have been developed to counter the reabsorption problem. Their rates of reabsorption are typical of the lower curve shown in Fig. 13. Although they are quite safe when exposed to the relatively cool and moderately humid environment indicated, extra precautions are essential when welding in tropical conditions.

It is possible to salvage electrodes that have become "wet" by rebaking them at temperatures that approach those used during their manufacture. Typical results are shown in Fig. 19. Drying times of about 1 hour are needed to recondition typical electrodes at approximately 400 to 425 °C (750 to 800 °F). Although rebaking can salvage electrodes that are inadvertently exposed to moist conditions, it should not be repeated. Covered electrodes are alloyed with metal powders that can be oxidized during rebaking operations. Therefore, the resulting alloys are leaner and weaker, as seen in Table 2.

Rebaking caused a loss in both manganese and silicon in the weld metal, resulting in a drop in the weld yield strength. These data were obtained after very controlled rebaking. Unfortunately, the same care is not always taken in shop environments. Significantly greater losses in the manganese and silicon contents, as well as mechanical properties, can be expected.

<table>
<thead>
<tr>
<th>Number of bake cycles</th>
<th>Composition, wt%</th>
<th>Yield strength</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>1</td>
<td>0.069</td>
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