

COLD CRACKING OF WELDS

1. PHENOMENA AND TYPES OF CRACKING

From a metallurgical standpoint, weld cracks can be classified in two categories: cold cracks and hot cracks. Differentiating between these cracks requires recognizing where they occur on one hand and when they appear on the other hand.

Hot cracking or solidification cracking appears during the last phase of solidification before the weld metal becomes completely solidified. Cold cracking, also called Hydrogen-induced Cracking (HIC) or delayed cracking, occurs when the metal structure is almost cold. The latter is seen mainly in structural steels (A36, A516, etc.) and low-alloy steels (8620, 4130, 4340, etc.). In fact, this form of cracking appears when the temperature starts to drop from about 190°C (375°F) but the phenomenon often arises at room temperature, and even more, it can take up to 24 hours after complete cooling. It is for this reason that some codes recommend waiting 24 and sometimes up to 48 hours prior to proceeding to the inspection of the welds.

Figure 1 below illustrates, as indicative reference, the temperature ranges related to hot and cold cracking.

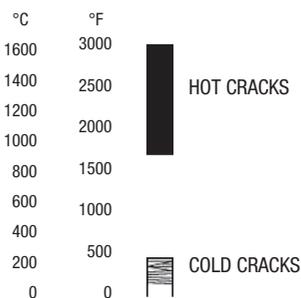


Figure 1 Hot and cold cracking temperature ranges

2. COLD CRACKING MECHANISM

Cold cracking occurs primarily in quench-sensitive areas, either in the weld metal or in the heat-affected zone (HAZ) under or beside the bead. The phenomenon occurs as a result of the coexistence of the following three factors (see figure 2 below):

- Brittle microstructure (martensite);
- Tension stress (shrinkage upon cooling, restraint);
- Diffused hydrogen (H₂) in sufficient concentration.

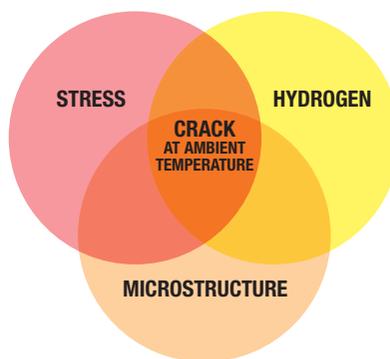


Figure 2 Cold cracking causes

The elimination or the reduction of the effect of one of these factors will therefore noticeably reduce the cold cracking propensity.

3. HYDROGEN SOURCES

The presence of hydrogen in the molten weld pool comes mainly from the following compounds:

- Humidity in the shielding gases, electrode coating (SMAW), flux (SAW), base metal, etc.
- Traces of oil, grease, wax, oxide, rust, etc.

If proper preheating cannot be done, the base metal should at least be heated above the dew point. The dew point indicates the temperature level, at a constant pressure, below which the saturated vapor in the humid air starts to transform to condensate water (liquid water). The dew point increases according to the air temperature and the relative humidity (RH). The example below shows the variation of the dew point for different air temperatures under a constant relative humidity (HR).

- For an air temperature of 10°C (50°F) under RH of 60%, the dew point is 2.6°C (37°F);
- For an air temperature of 20°C (70°F) under RH of 60%, the dew point is 12.1°C (54°F);
- For an air temperature of 30°C (90°F) under RH of 60%, the dew point is 21.4°C (71°F).

If the relative humidity is less important, the dew point will be lower. For example, for a RH of 50% and an air temperature of 20°C, the dew point will be 9.3°C.

4. HYDROGEN BEHAVIOUR

The figure 3 below illustrates the drastic decrease of hydrogen solubility in steel as the temperature drops. Indeed, it is proven that during the last cooling stage, i.e. below 750°C and more particularly below 350°C, the structure becomes less tolerant to hydrogen dissolution. The cooling rate of a hard, constrained structure influences to a large extent its tendency to crack.

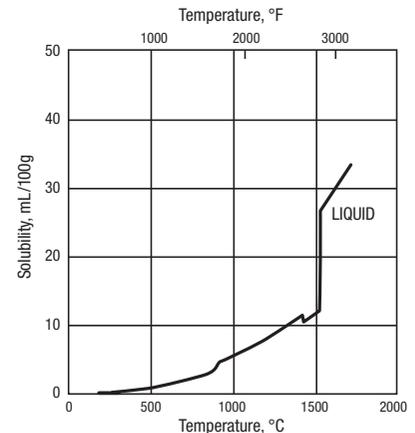


Figure 3 Hydrogen solubility in steel as a function of the temperature

As the temperature decreases, the hydrogen dissolved in the molten metal will react according to the following conditions:

Liquid state: the hydrogen has a high solubility but a low diffusivity. A significant amount of hydrogen gas (H₂) escapes from the weld pool before the solidification process starts.

Solid state, hot condition (T > 850-900°C): the hydrogen that has not escaped during the liquid state will remain dissolved in the austenite phase. Some of the hydrogen may form gas bubbles during the transition from the liquid state to the solid state. The austenite phase which forms has the ability to dissolve hydrogen without risk of cracking.

Solid state (fast cooling): fast cooling conditions lead to the transformation of the austenite phase to a quenching structure: martensite. In fact, this new structure has a very low solubility for hydrogen, which will then remain in an oversaturated state before starting to diffuse toward the heat-affected zone.

Solid state (slow cooling): slow cooling conditions, due to preheat for instance, promote the formation of a pearlitic structure which is much less susceptible to cracking.

5. ACTING MECHANISM OF HYDROGEN ON CRACKING

The effect of hydrogen on the cracking process is described in the following steps:

- Decomposition of the moisture in the arc column and formation of hydrogen ions (H⁺);
- Dissolution of hydrogen ions (H⁺) in the molten weld pool;
- Accumulation and saturation of the residual hydrogen in the solidified structure of the welded joint. This effect generally occurs when the temperature level is lower than 190°C (375°F). This saturation is promoted by the increase of the cooling speed. The hydrogen is then in a saturated or in an over-saturated state in the weld metal structure depending on the cooling speed, the type of the filler material and the joint thickness.

Very high cooling speeds obviously lead to an oversaturated structure. This effect is accentuated when ferritic or martensitic filler metals are used.

d) Hydrogen starts to diffuse through the cooled structure from the welded joint to the HAZ, since hydrogen has a good coefficient of diffusivity in ferritic and martensitic structures. Moreover, the susceptibility to the formation of a fragile martensitic structure either in the weld metal or in the HAZ depends on the following factors:

- Type of filler metal;
- Base metal;
- Dilution rate;
- Cooling speed.

e) Diffused hydrogen ions continue to accumulate and to gather around stress concentrator zones (metal discontinuities, pores, inclusions, other microscopic defects, etc.) before combining to form gas molecules (H₂). In fact, these stress concentrators serve as crack initiators. Diffusion is a function of time and of the concentration of this diffusive element. Depending on the situation, this diffusion process may last several hours and even up to 24 hours after cooling to room temperature.

f) The hydrogen gas (H₂) reaches a critical concentration and then starts to alter the atomic cohesive force in the metal and to initiate the crack from the pre-existing defects or microcracks. The tensile stress intensity and the form of such micro-defects determine the speed at which the crack propagates in the structure. Figure 4 illustrates the effect of hydrogen at the bottom of a crack in a metal structure.

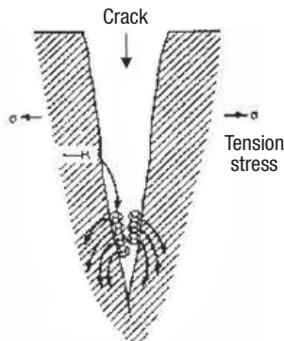


Figure 4 Hydrogen effect at the bottom of a crack

6. CRACKING IN THE WELD METAL VS HAZ

As mentioned above, the effect of hydrogen on cracking usually occurs below 200°C (400°F) in quenched or hardened structures during cooling. This temperature corresponds to an important decrease of hydrogen diffusivity and to the phase transformation austenite-martensite in most carbon and alloy steels. As soon as this transformation begins, the hydrogen already dissolved in the unstable austenite will start to diffuse through the quenched structure (hard martensite) of the weld metal towards the HAZ.

For quench-hardened steels, filler metals are often elaborated so that their carbon content is lower than that of their equivalent base metals in order to obtain a lower Carbon Equivalent index (CE) in the weld metal. Reducing the carbon equivalent index improves weldability and favours the formation of a more crack-resistant structure in the weld metal. However, the heat-affected zone always remains a critical zone for cold cracking. Different observations and reports corroborate this situation.

For some martensitic stainless steel filler metals, the reduction of the carbon content can be offset by the addition of nickel or nickel-nitrogen. Using this approach, the covered electrode E410NiMo was thus developed by modifying the chemistry of its predecessor, the classic E410, to improve the weldability and the toughness of the welded joints. In addition, specialized filler metals such as the electrodes Sodel 333, Sodel 335 or Sodel 3500, among others, have been designed in order to contain some austenite in the as-welded condition, which eliminates the presence of hydrogen in the HAZ and reduces the risk of cold cracking.

7. CRACK LOCATIONS

Cold cracks may appear in the weld metal in the HAZ following several directions; the most common ones are shown in the figure 5 below.

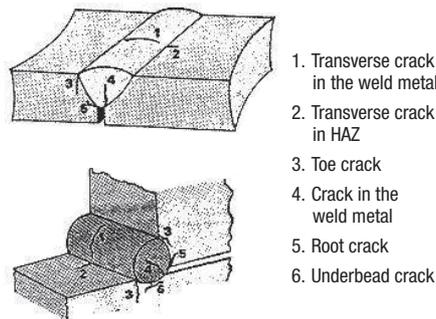


Figure 5. Frequent locations of cold cracks in groove and fillet welds

A typical example of cold cracking in the HAZ of carbon steel is shown in figure 6 below.



Figure 6 Hydrogen-induced cracking in the HAZ of carbon steel, ASM, V.11

8. CARBON EQUIVALENT (CE)

The carbon equivalent index is a concept developed to evaluate the ability to form a hard or fragile structure during welding of steels. Different formulas are used for calculating the carbon equivalent index; the International Institute of Welding (IIW) adopted the simplified formula of Dearden-O'Neill that integrates the equivalent effect of the other alloying elements (Mn, Cr, Mo, V, Ni, Cu) to the carbon. This formula is expressed as follows:

$$CE_{IIW} = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

where the concentration is given in weight percent.

Depending on their carbon content and the resulting carbon equivalent index, steels may be classified into three distinct classes or zones from the standpoint of their cold cracking behavior as shown in the figure 7 below.

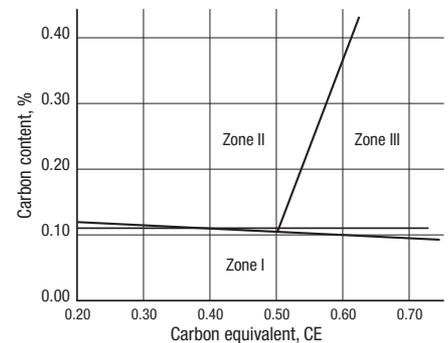


Figure 7 Susceptibility to cold cracking of steels

Zone I includes low carbon steels and low-alloy steels which have a carbon content lower than 0.10%. Regardless of the carbon equivalent, the quenching structure is not hard and, in most cases, it is not crack sensitive.

Zone II includes most carbon steels with a carbon content above 0.10% and also carbon-manganese steels used in the fabrication of pressure vessels, i.e. ASTM A516. Steels of this class with a CE index lower than 0.50% are considered as not prone to cold cracking. However, as the CE index increases with the carbon content, the propensity for cracking in the HAZ becomes likely. It is then mandatory to avoid excessive hardness in the HAZ by achieving controlled cooling on one hand and by using a low-hydrogen filler metal on the other hand.

Zone III includes alloy steels with a carbon content above 0.10% and a correspondingly high carbon equivalent index, such as quenched and tempered structural steels like 100QT (CSA G40.21), ASTM A514, T-1, etc. The formation of a hard martensitic structure is then unavoidable even under controlled cooling. Welding of this type of steels is rather difficult and requires appropriate procedures which mainly take into account the following considerations:

1. Preheating at high temperature with an optimal heat input and, eventually, a Post-Weld Heat Treatment (PWHT) to favour a slow cooling and a softening effect in the martensitic structure.
2. Using low-hydrogen filler metals (basic electrodes) or specialized electrodes.

9. CHOICE OF ELECTRODES AND RECOMMENDATIONS

Basic coated electrodes designated by EXXX-15, -16 or -18 and followed by a suffix HX (ex. X=2, 4), which refers to a low-hydrogen coating electrode, represents the only category of steel electrodes recommended for welding structural steels where the slightest possibility of cracking is not tolerated. In addition, for the weld joint integrity of high strength steels, the diffusible hydrogen content must be as low as possible.

Due to their high susceptibility to moisture absorption, low-hydrogen electrodes (basic coated electrodes) must remain in their hermetically sealed containers until their use. Once these containers are opened, the electrodes must be immediately placed into rod holding ovens at a temperature between 120 and 175°C (250-350°F) until welding starts.

However, if the coated electrodes are exposed to ambient air for more than 2 to 4 hours, they must undergo a re-baking treatment at 425°C (800°F) for 1 to 2 hours to extract all the moisture absorbed by the hygroscopic coating.

NB: H2 or H4 designates a maximum diffusible hydrogen content of 2 or 4 ml/100g in the weld metal.