CEPA
FOUNDATION

PREVENTION AND MITIGATION OF HYDROGEN INDUCED CRACKING IN PIPELINE WELDS

Guidance Document

VERSION 1.0 - 2018. 02. 27

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CEPA Foundation

Suite 1100, 505-3rd St. SW
Calgary, Alberta T2P 3E6
Tel: 403.221.8777
Fax: 403.221.8760

i. Executive Summary

Hydrogen-induced cracking (HIC) is among the most common weldability issues encountered in arc welding of carbon steel and low alloy steel materials, including typical pipeline steel materials. HIC is commonly referred to by other names such as hydrogen-assisted cold cracking (HACC), heat-affected zone cracking, under-bead cracking, toe cracking, or simply hydrogen cracking.

The purpose of this guideline is to improve awareness of the phenomenon of hydrogen-induced cracking during pipeline welding and to provide recommendations on its prevention and mitigation.

The HIC prevention and mitigation practices primarily aimed at new pipeline construction mainline welding that are discussed in detail within this guideline are:

- the use of low hydrogen welding processes;
- pre-heating, interpass temperature and other thermal controls;
- improved fitup and reduction of weld stresses, and;
- proper detection using delayed inspection.

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1 Purpose & Scope

The purpose of this guideline is to improve awareness of the phenomenon of hydrogen-induced cracking during pipeline welding and to provide recommendations on its prevention and mitigation. The recommendations provided herein are primarily derived from the combined experience and expertise of seasoned Canadian pipeline operating companies, with references to additional sources and studies where appropriate, but is not intended to supersede applicable code or regulatory requirements.

In an effort to remain concise while addressing the most prevalent hydrogen-induced cracking risks, the scope of this guideline is primarily aimed at new pipeline construction mainline welding using typical North American pipe materials and welding processes. Other topics such as repair welding, tie-in welding, welding of high-strength fittings and welding of vintage pipeline materials are mentioned in brief where appropriate but are not the focus of this guideline and users are advised to seek out additional references on these topics as necessary.

2 Background

2.1 HYDROGEN-INDUCED CRACKING

Hydrogen-induced cracking (HIC) is among the most common weldability issues encountered in arc welding of carbon steel and low alloy steel materials, including typical pipeline steel materials.[1] HIC is commonly referred to by other names such as hydrogen-assisted cold cracking (HACC), heat-affected zone cracking, under-bead cracking, toe cracking, or simply hydrogen cracking.

HIC manifests in pipeline construction welds as cracking in the heat-affected zone (HAZ) or weld metal and can occur during welding operations or shortly after welding is completed. HIC is most commonly observed within a few hours to a few days after completion of welding, though small cracks may initiate sooner but remain undetected until they propagate to a size which is readily detected visually or by non-destructive testing (NDT) methods such as radiographic testing (RT) or ultrasonic testing (UT).

HIC in pipeline welds typically initiates near the weld root, but may also initiate near the toe of the weld cap, elsewhere in the HAZ, at pre-existing defects and occasionally in the weld metal. Cracks are typically oriented parallel to the direction of weld metal deposition, but may also be oriented transverse to the welding direction or at any angle in between depending on the orientation of stresses during and after welding. Cracks are typically surface breaking, but may also be entirely subsurface. Cracks can vary in depth from shallow to partially through-wall but may also propagate through-wall in the presence of high mechanical stresses, from internal pressure during hydrostatic testing or operation, or a combination of the two. Cracks that initiate due to HIC during pipeline construction may propagate in service by other mechanisms at a later date if they are not identified and repaired. An example of a HIC crack originating in the root HAZ of a groove weld is shown in Figure 1.

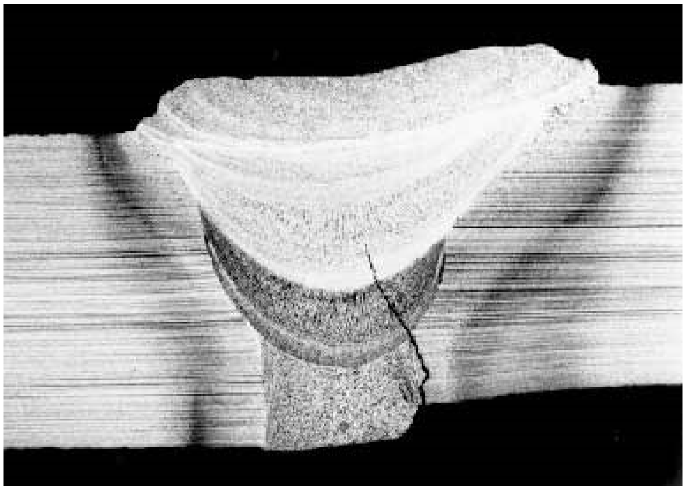

Figure 1 Typical HIC originating in root HAZ and extending into weld metal[2]

2.2 HIC SUSCEPTIBILITY

While the precise mechanism for HIC is not fully understood, susceptibility to HIC is known to depend upon the interaction of the three factors shown in Figure 2.

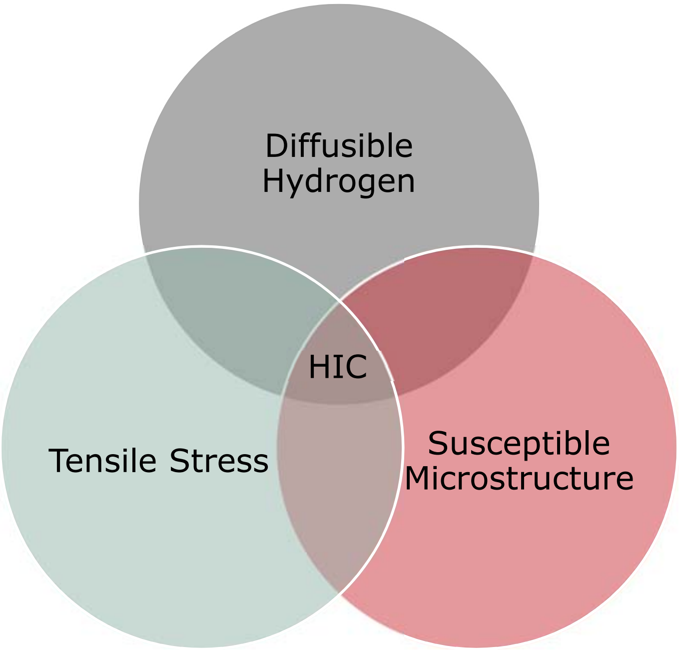

Figure 2 HIC susceptibility factors

The complete elimination of any one of the three factors in Figure 2 effectively eliminates susceptibility to HIC. However, experience has shown it is very difficult to achieve complete elimination of any one HIC susceptibility factor. Instead practical HIC prevention works to address all three susceptibility factors to the extent which is practically achievable and thereby reduce the risk of HIC to an acceptable level. The reduction of diffusible hydrogen in the weld deposit is the most effective and direct means of preventing HIC. By comparison, efforts to reduce tensile stress and susceptible microstructures cannot be achieved with the same level of direct control as hydrogen reduction and may not effectively prevent HIC if diffusible hydrogen is not also controlled.

It is important to note the interrelationships between the three HIC susceptibility factors. Consider diffusible hydrogen for example: if weld tensile stresses are low and the weld does not exhibit microstructures with high susceptibility to HIC, then higher levels of diffusible hydrogen can be tolerated without causing HIC. Conversely, if applied tensile stresses are high or locally intensified and microstructures are particularly susceptible to HIC, then even low concentrations of diffusible hydrogen may be sufficient to cause HIC. These interrelationships between HIC susceptibility factors make it difficult to provide comprehensive guidance or threshold values for all possible combinations of diffusible hydrogen concentration, tensile stress, and microstructure, below which welds might be considered immune to HIC. Furthermore the utility of such universal guidance, if it existed, would be severely limited by the difficulty with which stress intensity and microstructural susceptibility to HIC can be reliably measured, predicted or controlled in production welds. For this reason, the HIC prevention guidance provided in this document focuses primarily on the reduction of diffusible hydrogen levels as much as possible while also taking practical steps to avoid extremes of tensile stress and microstructural susceptibility.

2.2.1 Diffusible Hydrogen

All arc welding processes introduce some monatomic hydrogen into the molten weld metal. Depending on the specific welding process, consumables, conditions, and joint cleanliness the amount of hydrogen introduced into the weld metal can vary widely. While some of this monatomic hydrogen is trapped at various sites within the metal, the majority of it is diffusible and free to move through the surrounding metal even after the weld puddle solidifies. Hydrogen diffuses away from areas of high concentration in the weld metal to surrounding areas of low concentration, traveling through the HAZ and base metal and eventually effusing out of the metal and into the surrounding atmosphere. Hydrogen may also preferentially diffuse to regions of high stress. The speed with which hydrogen diffuses through the metal is highly dependent upon temperature. Welding practices that maintain elevated temperatures in the weld metal, HAZ and base metal throughout welding operations permit hydrogen to diffuse quickly through the material and away from the most HIC susceptible microstructures in the HAZ. If hydrogen is able to sufficiently diffuse away from susceptible microstructures while temperatures are elevated, HIC is much less likely to occur.

2.2.2 Tensile Stress

Tensile stresses in a weld may be due to applied forces or residual stresses from weld metal shrinkage and cooling. Post-weld heat treatment (PWHT) can greatly reduce residual weld stresses, but the majority of pipeline welds are not PWHT for constructability purposes and as such can exhibit particularly high residual stresses. Residual weld stresses can be further exacerbated by designs with excessive weld restraint or by the presence of stress concentrators due to weld geometry, notch-like anomalies and pre-existing defects. Localized stresses at stress concentrators can easily exceed the material yield strength and create ideal sites for initiating HIC.

2.2.3 Susceptible Microstructures

A variety of microstructural phases and constituents may be present in the weld metal, HAZ and base metal of a welded joint. Even at low magnification variations in microstructure across the weld joint are apparent, as seen in Figure 1. A complete discussion of microstructure types and their relative HIC susceptibility is beyond the scope of this guideline, but several key concepts are presented in the following paragraphs.

Carbon steel microstructure is dependent upon chemical composition as well as thermal and mechanical processing. While pipeline welding does not generally employ mechanical processing methods (i.e. no intentional hot or cold deformation), pipeline welding processes necessarily produce several high-temperature heating and cooling cycles that can cause significant microstructural changes, most notably in the HAZ.

Pipeline weld metal microstructures are primarily derived from the composition of filler metals, fluxes and shielding gases, as applicable. As mentioned previously pipeline welds are generally not subject to PWHT, and the thermal cycling inherent to multi-pass welding has only minor effects on the properties of root, hot and fill pass weld metal. Even when accounting for some base metal dilution, good quality welding consumables are carefully formulated to produce microstructures with low HIC susceptibility when used in accordance with manufacturer specifications.

The HAZ of a welded joint is comprised of base material which is not melted during welding but which is exposed to high enough temperatures to cause microstructural changes including phase changes and changes in grain size. When microstructural phase changes occur, there exists the potential for forming new microstructures with higher HIC susceptibility upon cooling, particularly when parent materials contain higher concentrations of alloying elements and are subjected to rapid cooling rates. For this reason the HAZ generally presents the greatest risk for containing HIC susceptible microstructures.

In the context of a welded joint, “base material” is considered to be parent material that exists outside the HAZ. Although base material will experience elevated temperatures during welding, temperatures are not high enough to cause phase changes or significant grain growth. The result is that base material properties are generally unchanged by the welding process. Good quality base materials are manufactured by forming and heat treating processes that ensure good mechanical properties and generally produce microstructures with low susceptibility to HIC.

3 Prevention of HIC

3.1 LOW-HYDROGEN WELDING PROCESSES

Reduction of diffusible hydrogen is most effective means of preventing HIC. A clear description or definition of "low hydrogen" is not provided in any of the commonly used North American pipeline construction or welding codes, despite common use of terms such as "low-hydrogen welding" and "low-hydrogen electrodes." The American Welding Society (AWS) Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding A-5.1 defines low-hydrogen covered electrodes as those which have a maximum covering moisture content of 0.6% in the as-manufactured or as-conditioned state. In an E7018 electrode welded at 21°C and 60% relative humidity, a covering moisture content of 0.6% equates to approximately 12mL of diffusible hydrogen per 100g of deposited weld metal. However, many E7018 and other low-hydrogen coated electrodes (EXX15, EXX16, EXX18) manufactured today have coating moisture content much lower than 0.6%, which results in diffusible hydrogen levels significantly less than 12mL/100g.[3] By comparison, cellulosic electrodes (EXX10, EXX11) contain 30-50 mL/100g.

For the purposes of this guideline, welding processes which result in diffusible hydrogen levels of 8mL or less per 100g of deposited weld metal are considered "low-hydrogen" and greatly reduce the likelihood of HIC. Several such welding processes are discussed in the sections below, though other welding processes not discussed which produce diffusible hydrogen levels of 8mL/100g or less may also be effective at preventing HIC.

Welding processes and consumables should be selected to achieve the lowest diffusible hydrogen levels reasonably possible.

3.1.1 Gas-Shielded Wire Arc Welding Processes

Solid wire gas-shielded arc welding processes including gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are capable of producing weld deposits with very low diffusible hydrogen levels (much lower than 8mL/100g).[4] While GTAW is not generally used for pipeline field welding, GMAW is widely used for mechanized mainline welding and to a lesser extent for semi-automatic welding.

Gas-shielded flux-cored arc welding (FCAW-G) and metal-cored arc welding (MCAW) processes are also capable of producing weld deposits with diffusible hydrogen levels less than 8mL/100g, with many manufacturers claiming diffusible hydrogen levels of 4mL/100g or less. Recommendations for FCAW-G and MCAW processes include:

- Seamless wires are inherently more resistant to moisture ingress than seamed wires but regardless of wire type all cored wire consumables should be produced, stored and handled in a manner that will ensure low moisture content.
- Manufacturers claimed diffusible hydrogen levels should be based on recommended or typical production welding parameters and verified by manufacturer testing of actual weld deposits.

- Manufacturer’s recommendations should be adhered to during production welding with respect to key parameters such as shielding gas composition, electrical characteristics, and contact tip to work distance, all of which can have significant effects on the diffusible hydrogen content of weld deposits.[5]

- The use of seamless wires and welding automation for FCAW-G and MCAW welding processes is recommended whenever possible to ensure consistently low diffusible hydrogen levels.

Shielding gases for solid wire and cored wire arc welding processes should be free of hydrogen and exhibit low moisture content as evidenced by a dew point of -40°C or lower.

3.1.2 Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) electrodes capable of producing weld deposits with diffusible hydrogen not exceeding 8mL/100g or 4mL/100g are widely available in a variety of chemical compositions and tensile strengths. Electrodes with diffusible hydrogen rating less than 4mL/100g are also available. The maximum deposited weld metal diffusible hydrogen in mL/100g is designated by an electrode classification suffix such as “-H8” for 8mL/100g, “-H4” for 4mL/100g, etc. The use of electrodes with a moisture resistant coating is recommended to reduce the likelihood of moisture absorption. Low-hydrogen SMAW electrodes with a moisture-resistant coating are designated by an electrode classification suffix containing the letter “R” such as “-H8R” and “-H4R.” Low-hydrogen SMAW electrodes include the EXX15, EXX16 and EXX18 AWS electrode classifications for uphill vertical weld progression and the EXX45 AWS electrode classifications for downhill vertical weld progression.

Low-hydrogen SMAW electrodes require careful storage and handling practices to ensure that flux coatings do not absorb moisture, which will result in diffusible hydrogen levels higher than the manufacturer’s rating. The following storage and handling practices are recommended unless superseded by manufacturer requirements:

- Electrodes should be shipped and stored in sealed containers.

- Upon removal from sealed containers, electrodes should be used immediately or transferred to an electrode oven continuously operating at a temperature of 120-150°C (250-300°F).

- The use of portable electrode ovens by each welder is recommended for field welding. Electrodes should be taken directly from the portable electrode oven immediately prior to use.

- Electrodes that have been stored outside an electrode oven for longer than 4 hours or otherwise exposed to moisture should be discarded or re-dried.

- Re-drying of electrodes should be carried out at 370-430°C (700-800°F) for 1 hour. Electrodes should not be subjected to more than one re-drying cycle.

- Electrodes which are damaged, soiled or exposed to oil, grease, cleaning fluids or other contaminants should be discarded.

3.1.3 Cellulosic SMAW Electrodes for Root and Hot Pass Welding

Although this guideline recommends the use of low-hydrogen welding processes to prevent HIC, the use of high-hydrogen cellulose-coated SMAW electrodes (AWS EXX10, EXX11) for welding of the root or root and hot passes of one-sided open root butt welds is acknowledged as common practice in pipeline construction. In practice there are few viable alternatives to cellulosic SMAW electrodes for root pass welding in field conditions, with automated short-circuit GMAW being the most common alternative. While it is technically possible to use low-hydrogen SMAW electrodes to deposit the root pass of an open root butt weld this method is seldom employed due to the increased welder skill required and increased risk of root defects.

Weld process modeling and industry experience indicate that hydrogen concentration in the root and HAZ regions of a completed weld made with cellulosic SMAW root and hot passes is comparable to the hydrogen concentration in the root and HAZ region of a completed weld made with low-hydrogen processes for all passes, provided that appropriate preheat is applied and maintained and there is minimal delay between the welding of cellulosic SMAW and low-hydrogen passes.[6] With adequate preheat and interpass temperature controls low-hydrogen fill and cap passes provide sufficient thermal energy to dissipate the increased hydrogen of cellulosic root and hot passes away from crack-susceptible regions in the root and HAZ, and the risk of delayed cracking upon completion of welding is not significantly higher than for a weld produced by low-hydrogen processes only. However, the risk of HIC in the incomplete weld remains elevated during the deposition of cellulosic SMAW passes root and hot passes and particular attention should be paid to minimizing stress and microstructural susceptibility.

3.1.4 Other Sources of Hydrogen

Regardless of the welding process employed, base materials should be clean and dry prior to welding to eliminate potential hydrogen sources such as moisture, grease, paint, and other contaminants.[5,7]

3.2 PRE-HEATING, INTERPASS TEMPERATURE AND OTHER THERMAL CONTROLS

3.2.1 Pre-Heating and Interpass Temperature

The application and maintenance of an elevated pre-heating temperature helps to reduce the likelihood of HIC in the following ways:

- Removes surface moisture from weld area.
- Accelerates diffusion of hydrogen away from susceptible microstructures in the weld and HAZ.

- Slows cooling rate which reduces the likelihood of developing high-hardness microstructures, particularly in the HAZ.
- Reduces residual weld stresses on cooling.

Recommended minimum preheat and interpass temperatures for pipe-to-pipe mainline welds are provided in Table 1. It is recommended that preheat and interpass minimum temperatures be maintained until welding is complete, which may require the application of a heating source between passes.

Table 1 Minimum Preheat and Interpass Temperatures – Mainline Welding

Pipe WT	Welding Process	Minimum Preheating Temperature[1]	Minimum Interpass Temperature[1]
All	Low-Hydrogen All Passes	50°C (122°F)	50°C (122°F)
<12.7 mm (<0.500”)	Cellulosic Root/Hot Low-Hydrogen Fill/Cap	93°C (200°F)	93°C (200°F)[2]
≥12.7 mm (≥0.500”)		121°C (250°F)	121°C (250°F)[2]

Notes:

1. The minimum preheat and interpass temperature may be reduced to 38°C (100°F) when pipe OD is <323.9mm (<NPS 12) and pipe WT is <12.7mm (<0.500”), regardless of welding process.
2. After completion of cellulosic root/hot passes, the minimum interpass temperature may be reduced to 50°C (122°F) for low-hydrogen fill and cap passes.

The recommended preheat and interpass temperatures provided in Table 1 are intended for modern line pipe materials with specified minimum yield strength (SMYS) of 483 MPa (70 ksi) or less. Additional considerations for higher strength materials, fittings, and vintage materials are briefly discussed in Section 3.2.6.

The use of low-hydrogen welding processes and the minimum preheat temperature listed in Table 1 is recommended for tack welding.

The use of low-hydrogen welding processes and a minimum preheat and interpass temperature of 121°C (250°F) is recommended for mainline repair welding.

3.2.2 Preheat and Interpass Temperature Measurement

Consistent and accurate temperature measurement is essential to the effective of use of preheating and interpass temperature controls as HIC prevention measures. Recommendations for preheat and interpass temperature measurement include:

- Temperatures should be measured at a minimum distance of 50mm from the weld bevel on both sides of joint and should be measured no sooner than 15 seconds after removal of heating source.
- Temperatures should be measured at the top, bottom and sides of the pipe to ensure even preheating. Temperature measurement at the bottom of the pipe is particularly important as this is often the most difficult to reach and subject to the highest stress during root pass welding.
- Temperatures should be measured using temperature indicating crayons or contact pyrometers. The use of infrared pyrometers is not recommended due to poor accuracy and extensive calibration requirements.

3.2.3 Maximum Time Between Weld Passes

Minimizing the delay between weld passes is recommended to facilitate hydrogen diffusion and reduce the likelihood of falling below the recommended minimum interpass temperature. The recommended maximum time between weld passes is 10 minutes between the root and hot pass and 60 minutes between the hot pass and first fill pass.

3.2.4 Travel Speed and Heat Input Considerations for Cellulosic Root and Hot Passes

As discussed in Section 3.1.3 the use of cellulosic SMAW electrodes for root and hot pass welding poses an increased risk of HIC until subsequent deposition low-hydrogen weld passes can provide thermal energy for hydrogen dissipation. The additional risk of HIC during cellulosic root and hot pass welding is primarily addressed by preheating and restricting movement, but control of travel speed and heat input can also prove beneficial. Recommendations regarding travel speed and heat input for cellulosic SMAW root and hot pass welding include:

- For cellulosic root pass welding avoid excessively high travel speeds that may result in low heat inputs. A maximum root pass travel speed of 457mm/min (18”/min) is recommended.
- For cellulosic hot pass welding avoid excessively slow travel speeds or weaving that may result in the deposition of more weld metal than necessary, resulting in increased hydrogen levels in the completed weld. A minimum hot pass travel speed of 330mm/min (13”/min) is recommended.
- For cellulosic root pass welding use the largest diameter possible to increase heat input. A 4.0mm (5/32”) diameter electrode is recommended wherever possible. The use of smaller diameter root pass electrodes may be necessary for narrow root gaps or thin material.

3.2.5 Post-Heating and Slow Cooling

Post-heating of completed welds to dissipate hydrogen (often accompanied by slow cooling under insulating material) can further reduce the risk of HIC in situations where hydrogen diffusion rates are low or diffusible hydrogen levels are high, or when stresses or microstructural susceptibility are high. Examples of situations where post-heating may be considered include low ambient temperature conditions, welding of thin materials with a cellulosic root and hot pass but minimal subsequent low-hydrogen passes, highly restrained welds (such as tie-ins), high-CE materials, and incomplete welds. Specific recommendations for post-heating times and temperatures in all situations are beyond the scope of this guideline but are discussed in other references.[4]

3.2.6 Additional Material Considerations

The majority of modern welded line pipe steels are characterized by a low carbon equivalent and the use of micro-alloying elements and thermo-mechanically controlled processing (TMCP) to produce fine-grained material with high strength and toughness, and good weldability. This type of modern line pipe material provides the context in which the recommendations of Section 3.2.1 through 3.2.4 are provided, though many of the underlying principles may be applied to other carbon steel materials.

TMCP line pipe materials with SMYS greater than 483 MPa (70 ksi) may utilize additional processing steps such as accelerated cooling that can influence as-welded mechanical properties and susceptibility to HIC.[8] Users of these high-strength TMCP line pipe materials should consult the line pipe manufacturer for guidance on weld procedure qualification and field welding practices to ensure acceptable mechanical properties and account for any additional risks of HIC.

Wrought and forged materials such as fittings, valves, or existing (vintage) pipe are fundamentally different from modern TMCP line pipe materials in terms of chemistry, material processing, and microstructural constituents. These materials often have a higher carbon equivalent and higher risk of HIC and may require different welding parameters including higher preheating temperatures, higher heat inputs or post-heating to produce acceptable mechanical properties and prevent HIC. Specific welding recommendations for high-CE wrought, forged and vintage materials are beyond the scope of this guideline but are discussed in other references.[4] Special care should be taken when welding high-CE materials to modern TMCP materials to select welding parameters that will produce acceptable properties in both material types.

3.3 FITUP AND REDUCTION OF WELD STRESSES

Avoiding excessive weld stresses during and shortly after welding is an effective way to reduce the likelihood of HIC, particularly when using cellulosic SMAW root pass welding processes. Excessive stresses during welding are primarily attributed to pipe movement or the presence of local geometric stress concentrators due to weld geometry and fitup issues.

3.3.1 Clamping and Pipe Movement – Low-Hydrogen Root Pass Welding

The use of line-up clamps and restriction of pipe movement during welding ensure that the root pass and partially completed welds are not subjected to excessive local stresses which may result in an increased risk of HIC. Recommendations include:

- Internal line-up clamps should not be released until completion of the root pass weld.
- External line-up clamps should not be released until the root pass weld is 50% complete, evenly distributed around the pipe circumference. No pipe movement should occur until completion of the root pass weld.
- Significant pipe movement should not occur until three complete passes or 2/3 of the weld thickness has been deposited, whichever is greater.

3.3.2 Clamping and Pipe Movement – Cellulosic SMAW Root Welding

The use of cellulosic SMAW electrodes increases the risk of HIC during root pass welding and warrants additional measures to prevent excessive stresses. Recommendations include:

- Internal line-up clamps should not be released until completion of the root pass weld and a minimum length of the second pass weld in accordance with Table 2. The minimum length of second pass weld should be deposited in the area of greatest stress, which is often the bottom of the pipe but may also be the top or side in the case of an over-bend or side-bend.
- External line-up clamps should not be released until the root pass is 50% complete, evenly distributed around the pipe circumference. No pipe movement should occur until the root pass weld and a minimum length of the second pass weld in accordance with Table 2.
- Significant pipe movement should not occur until three complete passes or 2/3 of the weld thickness has been deposited, whichever is greater.

Table 2 Cellulosic Root Welding - Minimum Second Pass Length Prior to Clamp Removal

Pipe OD	Minimum Length of Second Pass
610 mm (NPS 24) and greater	250 mm (10 in.)
323.9 mm (NPS 12) to less than 610 mm (NPS 24)	150 mm (6 in.)
Less than 323.9 mm (NPS 12)	Not Required

3.3.3 Fitup

Poor fitup may result in increased stresses due to geometric stress concentrators and may also result in higher restraint and residual stress due to the deposition of additional weld metal. Recommendations to reduce fitup stresses include:

- Pipe should have good end dimension controls to minimize the offset (high-low) of abutting ends at weld joints. For pipes that will be cut into shorter lengths, consider using pipe with dimensional controls for its entire length.
- To minimize the number of challenging weld fitups in the field consider welding pipe pups onto fittings and valves in a controlled shop environment prior to installing them in the field.
- Consider using counter-bored and tapered transition joints instead of back-beveled joints when welding materials of dissimilar thickness, particularly when the difference in thickness exceeds 1.6 mm. The recommended taper angle is between 14° and 30°. The recommended minimum counter-bore length is the lesser of 100 mm or L, as calculated in the following formula:[9,10]

  $$\boldsymbol{L = 0.85\sqrt{Dt}}$$

  where:

  L = minimum counter-bore length

  D = pipe outside diameter

  t = thickness of the thinner material

- Ensure adequate pipe slack for tie-in welds. Where existing piping is buried a good rule of thumb for minimum excavation is 3 m (10 ft.) of excavated pipe length per 25 mm (1 in.) of pipe OD. Where design permits, mitered joints of 3° or less may be used to address pipe alignment issues that cannot be addressed by additional excavation.

3.3.4 Interruptions in Welding

The following recommendations are applicable to welds which are allowed to cool to ambient temperatures prior to the completion of welding:

- Welds requiring elevated preheat and interpass temperatures should not be permitted to cool to ambient temperature until at least 2/3 of the weld thickness is filled. The incomplete weld should include a minimum of two low-hydrogen passes or should be post-heated to the minimum preheating temperature specified in the WPS or 150°C (300°F), whichever is greater, and slow-cooled under a dry insulating blanket. Incomplete welds should be preheated to the specified minimum temperature prior to recommencing welding.

- Consideration should be given to cutting out incomplete welds which do not meet the above recommendations for any reason including unplanned welding interruptions. As a minimum, such welds should be carefully inspected to ensure they are free of cracks.

Tie-in welds should be completed the same day they are started.

3.4 INSPECTION AND QA/QC

Specific QA/QC recommendations are beyond the scope of this guideline. However, the implementation of a suitable inspection plan as part of QA/QC management is recommended to ensure that the recommendations of this guideline are being consistently applied during pipeline construction in the field.

4 Mitigation of HIC

The prevention of HIC is of primary importance, and every effort should be made to prevent conditions that would trigger HIC from occurring in accordance with the recommendations of Section 3. However, in addition to the prevention of HIC, consideration should be given to mitigating the potential consequences of HIC in the event that methods of HIC prevention are not completely successful.

4.1 BACKGROUND – DELAYED INSPECTION

As noted in Section 2.1, a delay is often observed between the completion of welding and the occurrence of HIC. Accordingly, the most common method of mitigating the potential consequences of HIC is to impose a time delay between the completion of welding and non-destructive testing (NDT) of welds. Delayed inspection allows adequate time for any delayed cracking that may occur and ensures cracks are identified during the final inspection process.

Common North American pipeline construction codes and standards do not address delayed inspection for pipeline construction welds, and provide varying guidance on delayed inspection of repair welds or in-service welds made on piping containing service fluids. For example CSA Z662 does not impose a specific delay time for in-service welds but states that a "*time delay of 48h is generally considered suitable for carbon and low-alloy steel materials*", that "*shorter delays might be suitable based upon experience or research*", and that "*longer delays might be necessary for high-grade and thick materials, over-matched weld metal, and very low material temperatures after welding*". Pipeline construction welds are clearly not as susceptible to HIC as in-service welds which are subjected to accelerated cooling, but experience has shown that pipeline construction welds are nevertheless susceptible to HIC and that an inspection delay can provide effective HIC mitigation. However, the absence of specific code requirements or guidance around inspection delay times for pipeline construction welds has resulted in widely varying practices among pipeline operators.

As noted in Section 2.2 several factors influence HIC susceptibility. Numerous studies have investigated the influence of these susceptibility factors and presented various findings regarding the length of time until cracking is observed. Many of these studies have focused on structural materials whose composition and manufacturing are not necessarily representative of modern TMCP line pipe materials, making the findings of such studies difficult to apply directly to typical mainline girth welds. However, in pipeline production welding and inspection activities, the critical question remains: *how long should one wait until NDT inspection is completed?*

The remainder of this section is intended to provide recommended inspection delay times for mainline pipeline welds in consideration of weld diffusible hydrogen levels, material specified minimum yield strength (SMYS), and the HIC prevention recommendations contained in Section 3.

4.2 MINIMUM INSPECTION DELAY TIMES

Table 3 provides recommendations for minimum delay times between completion of welding activities and start of NDT activities for different combinations of welding process and base material. The recommendations provided in Table 3 are derived primarily from the collective experience of seasoned Canadian pipeline operators as well as limited data from applicable studies.[6]

Table 3 Minimum Delay Times for Conducting NDT

Welding Process[1]	Line Pipe Material SMYS	Minimum Delay[2] (hrs)
Any	> 483 MPa (> 70 ksi)	48[3]
Non Low-Hydrogen All Passes	≤ 483 MPa (≤ 70 ksi)	24
Non Low-Hydrogen Root/Hot Passes Low-hydrogen Fill/Cap Passes	≤ 483 MPa (≤ 70 ksi)	8
Low-Hydrogen All Passes	≤ 483 MPa (≤ 70 ksi)	0

Notes:

1. Welding process is considered to be either low-hydrogen or non low-hydrogen, which are defined as:
    a. Low-Hydrogen process: a process that may introduce diffusible hydrogen less than or equal to 8mL / 100g weld metal (e.g. EXX18)
    b. Non Low-Hydrogen process: a process that may introduce diffusible hydrogen exceeding 8mL / 100g weld metal (e.g. EXX10)
2. The delay period begins following the completion of welding.
3. The recommended delay for materials with SMYS >483 MPa (>70 ksi) is based on limited published studies and industry experience which suggest these materials can exhibit increased susceptibility to

HIC as well as greater variability in material properties, as compared to more widely used line pipe materials with lower SMYS. The use of shorter NDT delay times than recommended in Table 3 for these materials may be justified by appropriate studies, material testing, or industry experience.

It is important to note that the recommended delay times of Table 3 are based on the assumption that all critical variables (see Section 3.1 to 3.3) in the welding operation have been controlled and verified, including:

- Appropriate protection of welding zone from ambient conditions (e.g. wind, rain, and snow)
- Storage and handling of electrodes
- Base material preparation and cleaning
- Joint fit up and alignment
- Correct application and maintenance of required preheat and interpass temperatures
- Adherence to welding parameters and heat input limits of applicable welding procedure
- Adequate gas shielding where applicable
- Adequate joint support and restriction of joint movement during and immediately following welding
- Control of cooling rates, especially in ambient temperatures ≤5°C

Where it cannot be confirmed that all critical variables have been adequately controlled prior to, during and following the welding activity, *consideration should be given to extending the delay periods recommended in Table 3 to ensure any HIC is identified.*

It should also be noted that the recommended delay times in Table 3 are intended for pipe-to-pipe welds in typical modern TMCP line pipe materials. Increased NDT delay times may be warranted when welding other materials including high-CE wrought materials such as fittings, flanges and valves, and for tie-ins to vintage piping materials. Specific recommended NDT delay times for materials other than modern TMCP line pipe are beyond the scope of this guideline (see also Section 3.2.6).

Inspection delay times longer than recommended in Table 3 should also be considered where production and inspection schedules permit doing so without impact to overall schedule.

5 History of Revisions

Number	**Date**	**Revision Details**
1.0	2018-02-27	Published

REFERENCES

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[1] N. Bailey, F.R. Coe, T. Gooch, P.H.M Hart, N. Jenkins and R.J. Pargeter. Welding steels without hydrogen cracking, Second Edition (revised). Woodhead Publishing Limited, Cambridge England, 2004.

[2] P.H.M. Hart. Weld Metal Hydrogen Cracking in Pipeline Girth Welds, Proc. 1st International Conference, Wollongong, Australia, 1999.

[3] R. Scott Funderbuck. Selecting Filler Metals: Low Hydrogen. Welding Innovation Vol. XVII, No.1, 2000.

[4] EN 1011-2:2001 Annex C

[5] J.H. Kiefner. Effects of Moisture Contamination and Welding Parameters on Diffusible Hydrogen. Welding Research Supplement. May 1996.

[6] BMT Fleet study on behalf of TransCanada Pipelines Ltd.

[7] Patchett, B. M.; Yarmuch, M. A. R.. Hydrocarbon Contamination and Diffusible Hydrogen Levels in Shileded Metal Arc Weld Deposits. Welding Journal , Vol. 89 Issue 12, December 2010.

[8] Yurioka, N. TMCP steels and their welding. Welding in the World, Vol.35, No 6 pp.375-395, 1995.

[9] Martens, M.; Chen, Y.; Liu, M. Comparitive Integrity Evaluations of Counterbore-Tapered and Back-Beveled Weld Joints. IPC2014-33374. 2014.

[10] Martens, M.; Dekhane, A.; Liu, M. Minimum Counterbore Length and Taper Angle Criteria for Transition Welds.

Appendix A: Productivity and Cost of Low-Hydrogen vs. Cellulosic Welding

A.1 WELDING PRODUCTIVITY – AUTOMATIC AND SEMI-AUTOMAITC LOW-HYDROGEN WELDING VS. ALL-CELLULOSIC SMAW

The information in Table 4 was provided by a CEPA member company to illustrate the productivity of automatic and semi-automatic low-hydrogen pipeline welding processes versus traditional all-cellulosic welding. The superior productivity of automatic and semi-automatic low-hydrogen processes is apparent.

Table 4 Welding Productivity – Automated and Hybrid vs. Cellulosic SMAW

Weld Process	Pipe OD	Pipe WT	Average Welding Time			
			Root Pass	Hot Pass	Fill Pass	Total
Automatic GMAW	1219 mm	15.9 mm	58 sec	1 min 58 sec	6 min 23 sec	28 min
Semi-Auto GMAW/FCAW	1219 mm	15.9 mm	-	-	-	4 hr
Cellulosic SMAW	1219 mm	15.9 mm	-	-	-	6 hr

A.2 WELDING PRODUCTIVITY – DOWN-HAND LOW-HYDROGEN SMAW VS. CELLULOSIC SMAW

Down-hand low-hydrogen SMAW welding is not typically employed for mainline welding due to the availability of higher productivity low-hydrogen processes, but it presents an alternative to cellulosic SMAW (which has increased risk of HIC) and up-hand low-hydrogen SMAW (which is considerably reduced productivity). The information in Table 5 was provided by a CEPA member company to illustrate the productivity of down-hand low-hydrogen SMAW welding versus traditional all-cellulosic welding. A marginally higher welding time was required for the down-hand low-hydrogen SMAW welding with E9045 fill and cap passes as compared to the all-cellulosic welds with E8010 fill and cap passes.

Table 5 Welding Productivity – Down-Hand Low-Hydrogen SMAW vs. Cellulosic SMAW

Pipe OD	Pipe WT	Electrodes	Average Welding Time
610 mm	7.9	E6010/E8010-G	53 min
		E6010/E8010-G/E9045-P2(mod.)	64 min
	8.7	E6010/E8010-G	No Data Provided
		E6010/E8010-G/E9045-P2(mod.)	67 min
	12.7	E6010/E8010-G	86 min
		E6010/E8010-G/E9045-P2(mod.)	97 min

A.3 COST CONSIDERATIONS – LOW-HYDROGEN VS. CELLULOSIC SMAW

In addition to comparable or improved weld productivity, users of low-hydrogen welding processes cite comparable or reduced cost as compared to traditional all-cellulosic SMAW welding. Reported observations from users of low-hydrogen welding processes include:

- Reduced repair rates. Repair welds typically cost 3X a production weld cost once the full cost of rework, inspection and supporting resources are accounted for. Reduced repair rates present a significant savings of low-hydrogen welding processes over cellulosic SMAW welding.
- Reduced or eliminated inspection delays, resulting in increased construction productivity and reduced overall cost.
- Option of leaving partially completed welds overnight without significant risk of HIC, resulting in increased construction productivity and overall cost.