Proceedings of IPC 2000:
International Pipeline Conference
October 1-5, 2000, Calgary, Alberta Canada

IPC00-0029

MULTI-PASS WELD HYDROGEN MANAGEMENT TO PREVENT DELAYED CRACKING

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ABSTRACT

The potential for weld hydrogen cracking, that can also manifest itself as delayed cracking due to formation well after weld deposition, is controlled by three factors: the presence of hydrogen, the susceptibility of the weldment microstructure and tensile stresses. The tensile stresses promoting hydrogen cracking may result from either welding residual stresses or construction or operations based stresses, while the susceptibility of a microstructure is a function of its carbon equivalent and cooling rate. Since all arc welding processes introduce hydrogen into welds to some extent, and in general, base material selection and weld stress levels are not controllable in welding procedure development, the prevention of hydrogen cracking must be accomplished through hydrogen management. This paper describes a means of considering the roles of welding procedure parameters (heat input, preheat, post-heat, inter-pass temperature and time, etc.) in the management of hydrogen in multi-pass welds to preclude delayed cracking. Some results obtained using a multi-pass weld hydrogen and thermal diffusion model are presented to demonstrate the models utility in understanding the effects of welding procedure parameter effects on the risk of delayed cracking.

INTRODUCTION

A significant problem in the welding of steels is delayed or hydrogen induced cold cracking. Cracks of this type, as their name implies, form at low temperatures, generally below 200°C. In most cases they form long after the weld has cooled to ambient temperatures. This delay phenomenon can make it particularly difficult to schedule inspections intended to ensure structural integrity.

Studies related to delayed cracking in weldments (weld metal or HAZ) have demonstrated that delayed cracking will only manifest itself if a critical combination of all three of its necessary conditions are present. These three conditions include the presence of hydrogen, a susceptible microstructure and a tensile stress, as shown in Figure 1. While the removal of any one of these conditions will eliminate the threat of delayed cracking, this approach to delayed cracking control is not generally practical. Therefore, delayed cracking control will be most effectively implemented through the consideration of the relationship between these conditions and to do this one needs to be able to predict welding procedure, environmental and material effects on delayed cracking.

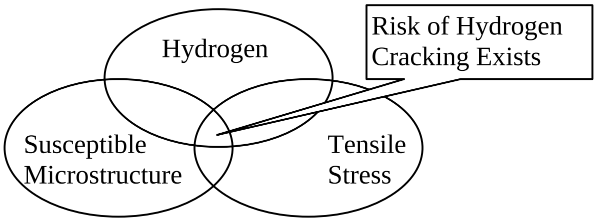


Figure 1: Delayed Cracking Necessary Conditions

Hydrogen Management for Delayed Cracking Control

While weldment microstructure and the tensile stress state (residual stresses in the absence of applied loads) are static after the weld has cooled to the ambient temperature, the concentration and distribution of hydrogen continues to change for a length of time after weld completion. Therefore, to predict the potential for delayed cracking in weldments the initial input of hydrogen and its subsequent diffusion must be adequately managed.

Techniques for the effective control of delayed cracking in fillet or single pass groove welds have been developed based on the reduction of hydrogen input, preheat/heat input consideration and control of the applied stresses. Weldment hydrogen input is controlled through the use of low hydrogen electrodes and practical considerations such as:

- ensuring clean degreased materials surfaces;
- dry electrodes and work environment; and
- specific welding practices such as a longer stick-out or higher heat input to preheat the electrode.

Pre-heating or higher heat inputs may be used to increase the mobility of hydrogen and/or reduce the steel cooling rate to produce a lower hardness (less susceptible microstructure) weld. In addition, the tensile stress state may be controlled by reducing restraint through the consideration of weld sequence, weld under-matching (residual stress limit), reduction in stress concentrations (e.g., undercut, Hi-lo and weld pass profiles) and careful attention to the relative timing of applied loads.

While these approaches (total hydrogen, heat and stress control) to delayed cracking control are generally valid for single-pass welds their application in the context of multi-pass welds is more complex. The complexity of the control of delayed cracking in multi-pass welds versus single pass welds is due, in general, to a multi-pass weld's:

- greater volume of deposited weld metal causing larger hydrogen input and concentration (due to lower dilution);
- larger diffusion distances for the hydrogen;
- complex thermal history;
- HAZ reheating and hydrogen recharging;
- complex stress history; and
- potential for multiple welding processes (i.e., GMAW weld with FCAW repair or GTA root and SMAW fill).

For these reasons, the effective control of delayed cracking in multi-pass welds will benefit from the consideration of a hydrogen management approach. In addition to the delayed cracking control techniques described for single pass welds, welding procedure parameters such as inter-pass temperature and time must be considered in multi-pass weld hydrogen management.

To prevent delayed cracking based on a hydrogen management approach, it is necessary to consider the entire welding procedure in some detail:

- thermal history including the effects of any pre- or post-heating, interpass time and temperature, the ambient temperature, welding parameters and environmental factors;
- hydrogen concentration and distribution history which is affected by thermal history, material characteristics and the initial hydrogen content and distribution;
- load history developed from residual stresses, applied loads and local stress concentrations;
- microstructure susceptibility to delayed cracking which will vary with chemical composition.

DELAYED CRACKING RISK MODEL OVERVIEW

The goal in the development of this model was to produce a practical tool for multi-pass weld hydrogen management which could effectively determine the effects of welding procedure parameters on delayed cracking potential. The current delayed cracking risk model (Dinovitzer 1998 [1], Graville 1997 [2]) considers a wide range of welding, environmental and material parameters influencing the risk of delayed cracking. These parameters include:

- Welding Procedure Parameters
  - weld pass deposition timing and heat input;
  - weld pass geometry and hydrogen concentration;.
  - weldment heating temperature, duration and timing
- Environmental Factors
  - ambient temperature and weather;
  - external thermal and hydrogen load history;
  - *applied load history.*
- Material Parameters
  - hydrogen diffusivity;
  - thermal conductivity;
  - *chemical composition.*

The parameters in the above list shown in *italics* are the subject of on-going development work to better incorporate their effects into the delayed cracking risk model.

The numerical models used in the delayed cracking risk assessment approach are based upon a two-dimensional (transverse to the weld axis) representation of the weld. This two-dimensional representation assumes that the flow of hydrogen or heat flow along the weld is small compared to that normal to the weld axis. The thermal and hydrogen diffusion histories are estimated simultaneously based on small incremental time steps using both finite difference and analytic equations.

If a weld with a cross-section such as that shown in Figure 2 is analysed, the thermal histories shown in Figure 3 can be estimated by the delayed cracking model. The single vee butt joint procedures used for demonstration purposes include nine partly overlapping weld passes, of similar size, deposited at 60 second intervals, with heat inputs of 7000 J/s. Each cell in the weld cross-section represents 4 mm^2 (2 mm x 2 mm) of material and is numbered to denote the weld pass deposition sequence. It is noted that this weld might be considered typical of those that are associated with 'heavy-wall' high-pressure, large-diameter Class 2 or 3 pipe segments.

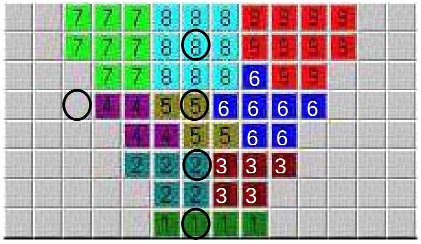


Figure 2: Weld Cross-Section (passes are numbered)

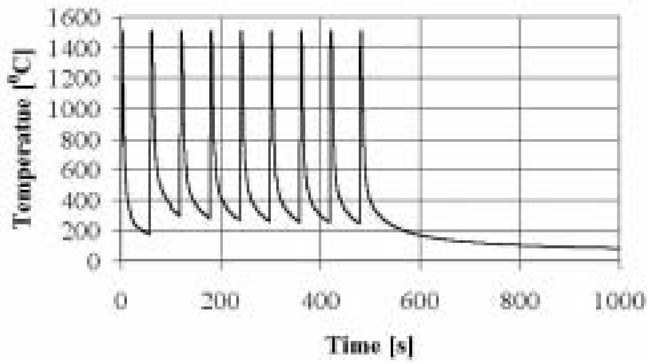
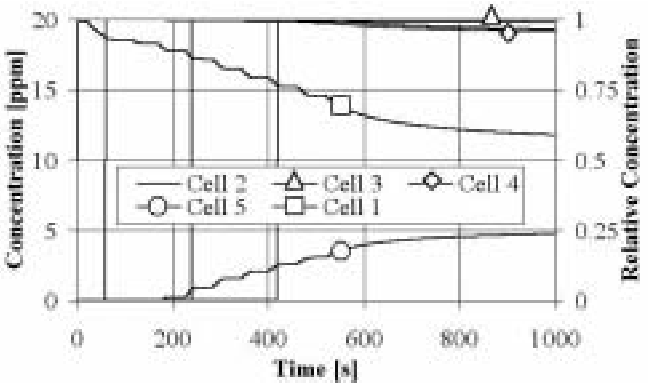
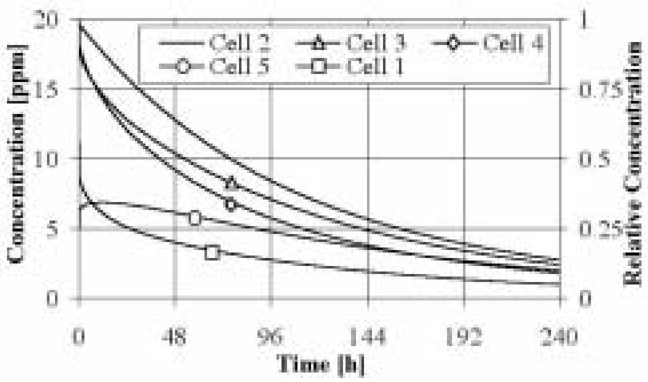


Figure 3: Estimated Thermal Time History of Figure 2

The hydrogen concentration time history for the above welding procedure is developed to identify the local average hydrogen concentration in each cell with time. The hydrogen time history may be considered in ppm or as a fraction of the original average hydrogen concentration. In the example here, it is assumed that cellulosic electrodes are used and an initial hydrogen concentration of 20 ppm is present in each weld pass at deposition. Figure 4 presents the short and long-term hydrogen time histories, estimated by the delayed cracking model, for the five cells circled in Figure 2. Cells 1 through 4 being located on the weld centreline from the root to the cap, respectively and cell 5 is located at mid thickness in the HAZ.



a) Short-term



b) Long-term

Figure 4: Estimated Hydrogen Concentration Time Histories

Figure 4 illustrates the variation in hydrogen concentration with time and location through the cross section of the weld. The results demonstrate that hydrogen diffuses quickest at elevated temperatures and from locations nearest the surface of the weld. The hydrogen concentration in cell 5 increases initially as hydrogen is absorbed from its neighbouring hydrogen rich cells.

Based on the local temperature and hydrogen time histories developed by the delayed cracking model, it is possible to develop a history for the condition of each cell. Example temperature/hydrogen concentration condition histories are plotted as the left hand curves in Figure 5 for cells 1 and 5. The temperature/hydrogen concentration condition curves oscillate, along the horizontal axis, with the heating and cooling process associated with each weld pass deposition. The hydrogen/temperature histories for both reference cells start at the same point, with a zero hydrogen concentration and preheat temperature. They then diverge with the effects of the welding process and would eventually rejoin after all of the hydrogen has diffused out of the weld and it has cooled to ambient temperatures.

In the delayed cracking model the premise for the occurrence of cracking is that the local hydrogen content has reached a critical value. The effect of hydrogen is to embrittle the steel with the degree of embrittlement being a function of temperature. Therefore, the critical hydrogen concentration for a given microstructure would depend on the local tensile stress and temperature. Since the estimation of the absolute residual stress level time history is complex, it is assumed to be constant and the critical hydrogen concentration is estimated as a function of temperature, the right hand curve in Figure 5.

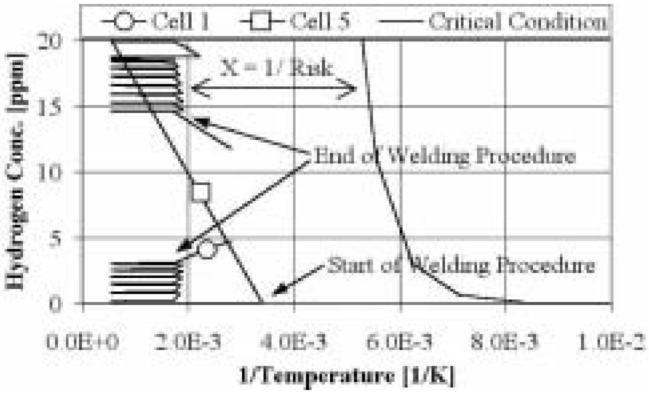


Figure 5: Definition of Delayed Cracking Risk

The critical condition curve, in Figure 5, would belong to a family of curves dependant on local tensile stress for a given material. It is noted that the form of the critical condition curve, in which the critical hydrogen level increases rapidly with increasing temperature, agrees well with experimental data. Cracking would be predicted to occur with the intersection of the left hand (Cell 1 or 5) and right hand (critical condition) curves, if the precise critical curve were known. However, since the precise critical condition curve is not known, the risk of cracking is estimated in terms of the how close the left hand curve approaches the critical condition curve. Thus, the risk of cracking is estimated as 1/X as shown in Figure 5. The exact lateral location of the critical condition curve, that is a function of steel composition and stress level, is currently being studied, however, based on its current definition may still be used to define the risk of delayed cracking on a relative basis.

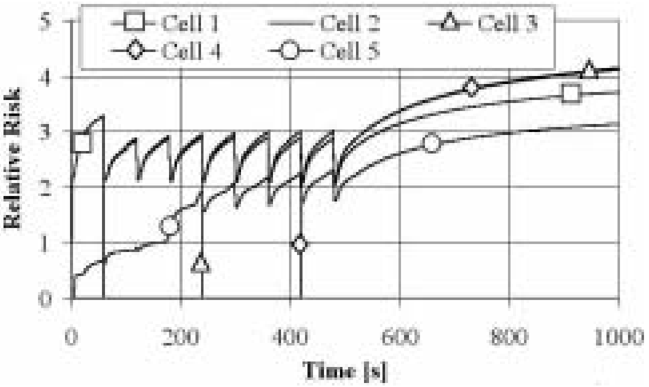
In the delayed cracking model, the risk of cracking is defined as the inverse of the separation of a model cell's temperature and hydrogen concentration state from that of the critical condition. For convenience and graphical representation, the estimated risk value has been limited to a scale from 0 to 5. With this definition the short- and long-term cracking risk histories are developed and are presented in Figure 6 for the five locations of interest in the example weld (see Figure 2). Since the analysis results assume that the five cells have the same local stress and composition, a single critical condition curve may be used to estimate delayed cracking risk.

The model results shown in Figure 6a are presented for the sake of completeness. It is not expected that delayed cracking will occur before the weld cools below 200^{o}C, however, the thermal and hydrogen diffusion histories need to be tracked and thus the risk of cracking is also estimate during the weld cooling process. Figure 6b illustrates that the risk of delayed cracking for cell 3 does not start to decline, assuming a constant tensile stress, until some forty hours after the completion of the weld. In addition, it is noted that the highest risk location for delayed cracking is at the mid thickness location in thicker sections. This result is specific for thick sections in with uniform stress field since no stress concentrations were included in the model definition.

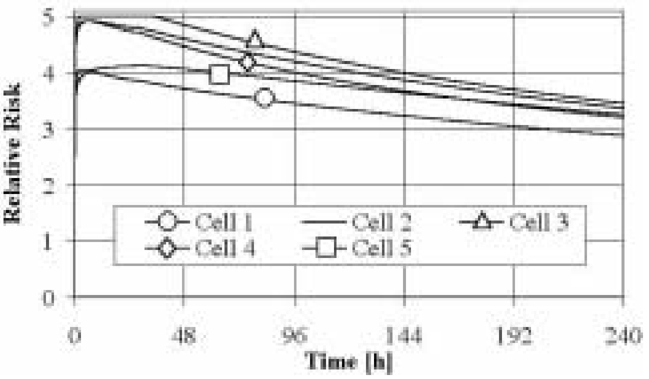
Model Calibration and Validation

The delayed cracking risk model employs a hydrogen diffusivity value estimated from the rate of hydrogen effusion from a weld bead on plate test specimen, prepared in accordance with the standard AWS hydrogen diffusion test (AWS 1993) [3]. The specimens are aged at specific temperatures after which the residual hydrogen is measured to infer the diffusion coefficient at the ageing temperature. The hydrogen diffusion coefficients obtained through this means allow the delayed cracking model to better estimate the hydrogen diffusion process, however, in the absence of this test data the effects of welding procedure parameter modifications on delayed cracking may still be simulated on a relative basis.

The delayed cracking model as a whole has been experimentally validated based on comparisons made with slow bend (Graville 1995) [4] and constant deflection tests (Graville & Pussegoda 1997) [5]. The slow bend test applies an increasing deflection (strain or load) to a notched weld after a given weld aging time (which results in a predicted hydrogen distribution) to determine the critical stress and hydrogen condition for the given microstructure. The constant deflection tests apply a known deflection (load or stress state) to a notched weld metal or HAZ, as appropriate, while the hydrogen diffuses and redistributes over time to develop the critical stress and hydrogen condition to promote cracking. The results of these tests suggest that the type of local hydrogen modelling approach used here, despite its simplifying assumptions, provide a practical tool for addressing delay cracking problems in multi-pass welds.



a) Short-term



b) Long-term

Figure 6: Estimated Delayed Cracking Risk Time History

EFFECTS OF WELDING PROCEDURE

The delayed cracking risk model described in the previous sections has been used to investigate the effect of welding parameter modifications on the risk of cracking for specific material and environmental conditions. Multi-pass welding procedures have been modified or assessed to:

- reduce hydrogen cracking risk (reduce repair costs);
- estimate and minimize weld final inspection time (minimize inspection delay / improve productivity);
- minimize return to service time (shorter down-time); and
- develop a better understanding of the variables influencing the delayed cracking phenomena.

Due to the large number of parameters that may be studied, it is difficult to demonstrate the effect of all welding parameters on delayed cracking risk. For this reason, a few examples have been chosen for a heavy wall pipeline girth weld procedure outlined in Figure 7.

The weld described in Figure 7 represents a twelve pass single vee girth weld procedure for a pipe with a 22 mm thick wall, which will be used as the basis of discussion of the effects of welding procedure parameters.

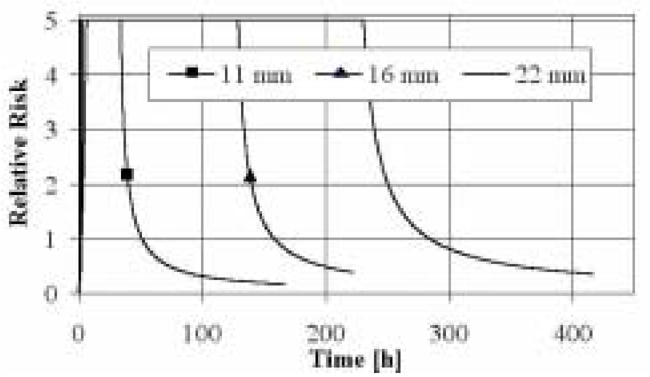


Figure 7: Wall Thickness Cracking Risk Relationship

Material thickness, an essential variable for a welding procedure can have a significant effect on the risk of delayed cracking and the location of the cold cracks. The thickness of the pipe wall is varied in Figure 8 to demonstrate its effect on cracking risk.

Figure 8 illustrates the relationship between section thickness and delayed cracking risk for three similar welding procedures developed for 11, 16 and 22mm thick pipe walls. In all cases, the delayed cracking risk is reported for a mid thickness location similar to the encircled cell in the weld pass geometry of Figure 7. The longer duration of high delayed cracking risk for thicker sections is as anticipated, due to the greater diffusion distance of the hydrogen present at the weldment mid-thickness location. Since it would be unreasonable to require final inspection to be delayed for a period of about ten days, hydrogen management considerations could be used to resolve this problem. A possible welding procedure improvement that has been demonstrated is the maintenance of a certain minimum inter-pass temperature and an increase in the inter-pass time.

Weld Pass and Joint Geometry

10	10	10	10	10	10	10	10	10,11	11	11	11	11	11	11	11,12	12	12	12	12	12	12	12	12
10	10	10	10	10	10	10	10	10,11	11	11	11	11	11	11	11,12	12	12	12	12	12	12	12	12
10	7,10	7,10	7,10	7,10	7,10	7,10	7,8	8,11	8,11	8,11	8,11	8,11	8,11	8,11	8,11	9,12	9,12	9,12	9,12	9,12	9,12	9,12	12
	7	7	7	7	7	7	7	7,8	8	8	**8**	8	8	8	8,9	9	9	9	9	9	9	9	
	7	7	7	7	7	7	7	7	7,8	8	8	8	8	8,9	8,9	9	9	9	9	9	9	9	
		7	6,7	6,7	6,7	6,7	6,7	6,7	8,6	8,6	8,6	8,6	8,6	8,6	6,9	6,9	6,9	6,9	6,9	6,9	9		
			6	6	6	6	6	6	6	6	**6**	6	6	6	6	6	6	6	6	6			
			5	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5,6	5			
			5	5	5	5	5	4,5	4,5	4,5	**4,5**	4,5	4,5	4,5	4,5	5	5	5	5	5			
				4	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4				
				4	4	4	4	4	4	4	**4**	4	4	4	4	4	4	4	4				
					4	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4					
					3	3	3	3	3	3	3	3	3	3	3	3	3	3					
					3	3	3	3	3	3	3	3	3	3	3	3	3	3					
						3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	3						
							2	2	2	2	2	2	2	2	2	2							
							2	2	2	2	2	2	2	2	2	2							
								2	1,2	1,2	**1,2**	1,2	1,2	1,2	2								
									1	1	1	1	1	1									
									1	1	1	1	1	1									
										1	1	1	1										
										1	1	1	1										

▨ Base Material □ Joint Opening

Welding Procedure Parameters

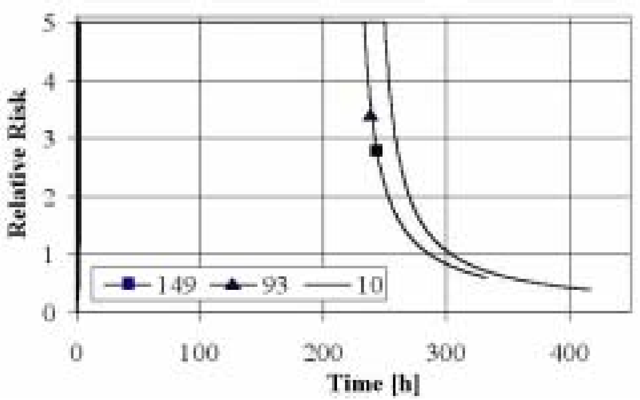
Pass		Energy [j/mm]	Start Time [s]	Pass		Energy [j/mm]	Start Time [s]
1	Root	794	0	7	Split Fill 1	941	7020
2	Hot	1059	900	8	Split Fill 2	941	7740
3	Fill 1	1569	1800	9	Split Fill 3	941	8460
4	Fill 2	1569	3300	10	Cap 1	784	9060
5	Fill 3	1569	4800	11	Cap 2	784	9660
6	Fill 4	1569	6300	12	Cap 3	784	10260

Ambient Temperature = 10 °C Preheat = 93 °C

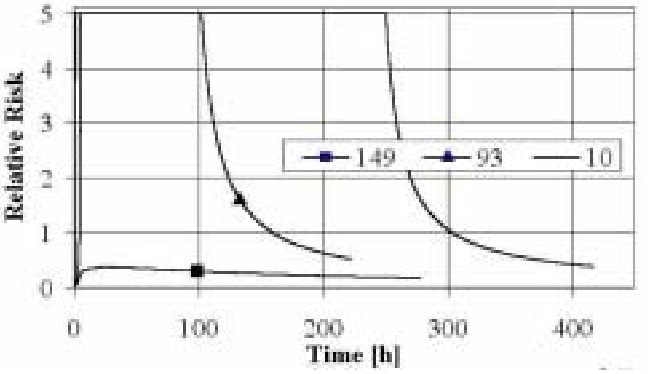
Figure 7: Girth Weld Procedure Data

Figure 9 demonstrates the effect of different preheat temperatures (149, 93, 10^0C) and preheat maintenance on delayed cracking risk for the example welding procedure outlined in Figure 7. The results in Figure 9a suggest that there is only a marginal benefit to applying preheat if it is not maintained through to weld completion. When the welding preheat is maintained till the end, thereby ensuring a certain minimum inter-pass temperature (as shown in Figure 9b), the benefits are significant.

A comparison of Figures 9a and b suggests that the risk of cracking for the specified welding procedure can be effectively eliminated by maintaining a minimum inter-pass temperature of 149^0C. With a pre-heat and minimum inter-pass temperature of 93^0C, final inspection for delayed cracking would need to be completed four days after welding to ensure that no cracking occurred, if the welding procedure were performed as outlined in Figure 7. This inspection delay can be reduced to a more acceptable duration by increasing the inter-pass time.



a) Preheat not maintained beyond first weld pass



b) Preheat maintained until end of welding

Figure 9: Effect of Preheat Temperature and Maintenance

The simple trends demonstrated in the above examples illustrate some of the capabilities of the delayed cracking model and its use in hydrogen management. It is noted however, that the effects of other factors on the risk of cracking can be considered by the delayed cracking model and these include:

- tensile stress due to either residual stress effects or applied loads (handling) - the relative timing of lifting stresses can promote cracking and should therefore be timed to occur after hydrogen concentrations are significantly reduced;
- material characteristics such as hydrogen diffusivity or microstructure susceptibility, typically quantified in terms of carbon equivalent, can influence the risk of delayed cracking,
- effect of pass sequence and offset in thin wall sections (local strain behaviour);
- low ambient temperatures or wind speeds causing more rapid cooling will increase the risk of delayed cracking (Glover & Graville 1999) [6]; and
- environmental effects such as heat sources or sinks and hydrogen sources (i.e. sour service).

These factors should also be considered in the development of welding procedures for specific applications or environments to prevent delayed cracking. No matter what the approach, as long as the conditions are understood, then the relevant welding procedure can be developed to control the risk of cracking. Based on the application of the delayed cracking risk model (Glover & Graville 1999 [6], Dinovitzer 1998 [1]) it has been noted that:

- for mainline manual welds using cellulosic electrodes, there is a significant increase in cracking risk and delay time when ambient temperatures are low or wind speeds are high;
- procedures, both mainline and repair, that increase root pass strain at low ambient temperatures, can increase delayed cracking risk even in nominally low hydrogen welds; and
- for mainline construction using manual welding processes the peak in cracking risk, assuming no change in applied loads, occurs within a few hours of welding and is thus within typical inspection time frames.

CONCLUDING REMARKS

A tool for evaluating the risk delayed cracking in multi-pass welds has been developed. The model is capable of capturing the effects of all of the significant welding procedure parameters, environmental effects and material properties. Based on this information, weld temperature and hydrogen concentration histories may be developed by the hydrogen model. Using a definition of the critical temperature and hydrogen state for cracking, the risk of hydrogen cracking may be developed.

Based on the results of the delayed cracking model it has been shown that the risk of delayed cracking:

- can increase with section thickness
- can be controlled by considering inter-pass time and temperature control in a welding procedure; and
- is useful technique for evaluating welding procedures.

The Future for the Delayed Cracking Model

It has been demonstrated that the delayed cracking model agrees well with experimental results and is well suited to welding procedure development and modification to prevent delayed cracking. While the model has been used to solve a range of practical welding problems, many challenges lie ahead in both the further development of the model and in consolidation of its results for codification and practical widespread application.

In terms of model development, the following issues are being dealt with to improve the model's predictive capabilities:

- consideration of an applied load schedule to incorporate loads due to the construction process in the risk of delayed cracking;
- the development of a more detailed chemical composition based cracking microstructure susceptibility effect on the critical hydrogen concentration and temperature condition for cracking; and
- the inclusion of a more localised approach to residual stress and local weld pass stress concentrations (e.g., weld pass profile, Hi-lo or undercut) in the delayed cracking model.

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