WELDABILITY OF HIGH PERFORMANCE STEELS

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Abstract

This paper compares weldability of the traditional steels with 70 and 100 ksi yield strength and High Performance steels (A 709 Grade485 HPS 70W and Grade 785 HPS 100W). The simulative tests used to predict cracking in the weld fusion- and heat affected zones are described. The effects of cooling rate on hydrogen-induced cracking susceptibility and corresponding minimum preheat are discussed. For given levels of diffusible hydrogen and weld deposit strength used, cracking in the weld fusion zone can be avoided by increasing preheat temperatures.

This work includes research results on new combinations of Submerged Arc Welding consumables needed for joining HPS 70W and 100W. Properties of deposits made with electrode wires and fluxes from different suppliers were measured. The weld deposit properties deteriorated as heat input increased. Welding process operational windows were proposed to optimize the weld properties and eliminate hydrogen-induced cracking, findings already included in the Manufacturing Guidelines for HPS steels.

Background

The present study was part of a nationwide effort directed toward finding better steels to cost-effectively build bridges for America's infrastructure. The Office of Naval Research and the American Iron and Steel Institute (AISI) including steel producers such as U. S. Steel, Bethlehem Steel and Lukens Steel, started a cooperative research program to develop High-Performance Steels (HPS) at 70 and 100 ksi yield strengths. Since improved weldability was one of the criteria chosen, welding consumable manufacturers and some bridge fabricators have been involved in the project. LeTourneau University has been involved in simulative weldability testing for hydrogen-induced cracking susceptibility. Because off-the-shelf wire electrode/flux combinations were not originally available for the weathering grades having 70 and 100 ksi minimum yield strength, experimental and commercially available consumables were evaluated.

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To better understand the approach used, a brief review of hydrogen-induced (also called delayed- or cold-cracking) is included here. This type of cracking has been one of the most common discontinuities found in steel weldments and based on a good understanding of the governing factors, several controlling methods have been developed. Such methods focus on a) avoiding susceptible microstructures, b) eliminating sources of diffusible hydrogen, c) reducing restraint and d) avoiding cooling to room temperature where the diffusivity of hydrogen is low (1, 2).

Hydrogen-induced cracking can occur in the weld Heat Affected Zone (HAZ) as well as Fusion Zone (FZ). While the reasons for cracking are the same, the controlling methodology can be different for the HAZ and the FZ. Microstructural control can be easier accomplished in the HAZ because of advances made in modern steelmaking practices (4). Eliminating potential sources of hydrogen from grease, contamination, oxides from the steel base plate is also easier than for the welding consumables. The weld Fusion Zone (FZ), on the other hand, does not undergo thermal-mechanical processing as the base metal, remaining in the welded structure essentially an as-cast and/or reheated condition in multipass welds. Accordingly, the FZ microstructure can only be adjusted by additional alloying by the consumable manufacturer. The final weld properties can also be dependent on the welding technique used (dilution, placement of passes, vaporization of certain elements such as Mn, etc.). Therefore, as the hardenability of the FZ exceeded that of the HAZ in HPS Steels, cracking "migrated" from the HAZ to the FZ.

Preheating for welding remains the most widely method of eliminating hydrogen-induced or cold cracking. The higher the preheat, the less chances for formation of brittle microstructures and more time is allowed for hydrogen to diffuse from the weld. However, preheating is a costly operation to set up, run and supervise. Thus, one of the objectives of developing HPS steels was cost saving by eliminating preheat. Indeed, HAZ cracking has been successfully eliminated in HPS 70W steels without use of preheat by reducing their hardenability, for low levels of diffusible hydrogen and intermediary heat inputs, for plates of up to 2-inch in thickness (5, 6). Accordingly, weldability testing concentrated on finding minimum preheats to avoid cracking in the FZ. Gapped Bead on Plate (G-BOP) testing was found to be the most reliable technique for this purpose. Efforts directed toward improving weld fusion zone (FZ) properties to match the base metal strength and toughness concentrated on using solid wires and neutral or alloyed fluxes, as well as metal-cored wires (6). Resistance to moisture entrapment in the flux was also included in the SAW consumable development effort to minimize hydrogen-induced cracking susceptibility. Experimental research was needed to predict preheat requirements for specific welding consumables to be used for HP steels by the bridge industry. Together with Welding Procedure Qualification testing and destructive testing of experimental girders, a weldability study was needed to write recommended Manufacturing Guidelines for HP steels.

Objectives

The scope of this work was to analyze the results of simulative, small- and full-scale weldability tests used to predict hydrogen-induced cracking susceptibility of HP steels. The correlation between these predictions, other technical literature data and actual bridge fabrication experience were to be addressed. Another scope of this work was to evaluate the effect of heat input on weld deposit mechanical properties for several combinations of SAW welding wires and fluxes.

Methodology

The various testing procedures used in this applied research/ developmental stage of the study are briefly summarized below.

G-BOP Testing Procedure for Fusion Zone (FZ) Cracking Susceptibility

Gapped Bead On Plate (GBOP) testing was used to determine the weld metal susceptibility to hydrogen induced cracking of single-pass shielded metal arc welding (SMAW) and submerged arc welding (SAW) deposits. The base metal thickness was 2-inches. Three levels of diffusible hydrogen (2, 4 and 8 ml/ 100g deposited metal) were targeted. The diffusible hydrogen was measured on-site using the mercury method specified in the American Welding Society AWS A 4.3-93 specification. The typical setup for testing is shown in Figure 1a. Two blocks of HP steel were clamped in a fixture and a bead-on-plate weld was deposited over the notch shown. After 48 hours, the weld was "heat tinted" by reheating it using an oxy-fuel torch. In case a hydrogen-induced crack developed, its surface changed color and when breaking the sample, the relative amount could be relative to the weld cross section, Figure 1b.

Y-groove (Tekken) Testing for HAZ Cracking Susceptibility

Figure 2 shows a typical cross section at the fusion line, with the HAZ on one side and the FZ on the other. Y-groove testing for HAZ cracking was performed in accordance with Japanese Industrial Standard JIS Z-3158 (1966) method for 2-inch-thick plate, Figure 3. Note the novel specimen preparation technique of machining the groove and gap from one plate instead of anchor welding two halves together. Using an angled tool to machine the groove and water-jet cutting for the gap, the sample preparation time was cut to 10 percent when compared to welding. Additionally, the sample had no residual stresses to add to the already high restrain provided by the gap. Post-weld evaluation included cross-sectioning, examination for HAZ cracks and Vickers hardness testing in the weld HAZ using 2.5 kg load. The amount of cracking was expressed in its relative length compared to the HAZ total length and given as a percentage varying from zero to 100%.

All Weld Metal Strength Measurements

Several combinations of SAW wire electrode and fluxes were tested. For the 70 ksi target yield strength, two wire types, LA 85 and ENi4 were used, in combination with the standard 800H as well as the modified 800 HP fluxes. The need for these non-conventional wire/flux combinations was the minimum 1% Ni required in the deposit, as well as a minimum 25 ft.lb at -25ºF impact toughness in order to match the base metal properties. For the 100 ksi target yield strength, one solid (SA 120) and one metal-core (MC 120) were used in combination with the 800H flux. Plates 1.0 -inch in thickness were used for SAW welding with a 20 degree included angle, 0.625-inch root gap and a 0.375-inch thick backing bar. The plates were restrained for the entire one-sided welding sequence and a standard bead placement sequence was used. The tensile and Charpy specimens were removed from the all-weld-metal deposit according to Figure 5.1, ANSI/AWS D1.5-98 Welding Code, Structural Steels, for zero dilution with the base metal (in the center of the weld). SAW welding was performed at four distinct arc energies: 40, 70, 100 and 130 kJ/in. Preheat and interpass temperatures for the lower (40 and 70 kJ/in) heat inputs was 200-250ºF, while for the higher heat inputs (100 and 130 kJ/in), the preheat and interpass temperature was maintained at 400-450ºF.

Results and Discussion

G-BOP Test Results

Detailed results of the tests can be found in (4). The main factors affecting the weld deposit hydrogen-induced cracking are discussed below, i.e.: 1) amount of diffusible hydrogen, 2) heat input/cooling rates and 3) welding consumable strength.

1) Diffusible Hydrogen Effect on Minimum Preheat (G-BOP)

Different levels of diffusible hydrogen were obtained using flux humidification experiments. The reason for this intentional increase in diffusible hydrogen was that the original 1.6 ml/100 g of diffusible hydrogen level of the 800H flux was too low to produce sufficient cracking in the G-BOP test for comparison purposes. When plotting selective weld metal cracking results (Figure 4), it became clear that at low levels of diffusible hydrogen (1.7 ml/100g), no preheat would be needed to weld the HP 70W up to two inches in thickness, if single-pass SAW welds would be used. For comparison, the conventional A 709 Grade 70 would have been required by the AWS D1.5-95 code to be preheated to 212°F (10). When diffusible hydrogen exceeded 5.0 ml/100g, a minimum of 125°F preheat was needed to avoid cracking. This result is lower when compared to the D1.5-95 code (i.e. 248°F).

2) *Heat Input (or Cooling Rate) Effect on Minimum Preheat (G-BOP)*

Cooling rates in the weld metal and HAZ are important factors in avoiding cold-cracking. Increased heat input was used instead of preheat to lower the weld metal hardenability and the corresponding increase the diffusivity of hydrogen was investigated. Figure 5 shows the GBOP results for 5 and 7 ml/100g diffusible hydrogen and incrementally increasing heat input for HPS 70W and HPS 100W for different welding consumables. While welding at room temperature and 20 and 30 kJ/in resulted in 95% and 45% cracking, respectively, as the heat input exceeded 40 kJ/in, no more cracking was experienced for the consumables used for the HPS 70W (ENi4/800H and LA85). For the higher strength deposits (MC120 and SA120/800H), as the heat input exceeded 50-60 kJ/in, no cracking was experienced up to 130 kJ/in at 5.8 ml/100g diffusible hydrogen.

One additional important welding parameter-related condition often overlooked is the inherent variation in cooling rate with the net heat input typical to each welding process. Thus, a brief overview of the so called "heat transfer efficiency" is needed here. It has been long known that different welding processes have different heat- and melting-efficiencies (Refs. 11,12). The net heat input in any arc welding process can be written as:

$$Qnet = \eta \times Qarc \qquad [cal] \qquad (1)$$

where;
Qnet - net heat input
Qarc - arc energy, kJ/in
η- heat transfer efficiency, a product of the arc efficiency η_{arc} and melting efficiency η_{melt} , always less than 1.0

$$Qarc = (E \times I)/s \times 60 \qquad [J/in] \qquad (2)$$

where:
E - arc voltage, Volts
I - welding current, Amperes
s - travel speed, in/min

Each arc welding process has been found having different energy losses through the arc via radiation, convection, noise, etc. For SAW, η = 0.9-0.95, for GMAW, η = 0.7-0.85, for FCAW, η = 0.7-0.8, and for SMAW, η = 0.65-0.7 (Ref. 10). Because of η~close to 1.0 for SAW, the arc energy Qarc ~ Qnet. For the other welding processes, however, this extrapolation from Qarc to Qnet cannot be made.

Because cooling rates are inversely proportional with arc energy, they will also vary with the welding process chosen for a given arc energy. Therefore, controlling preheat and interpass

temperatures will be more reliable means to avoid hydrogen-induced cracking than adjusting arc energies for welding.

3) Weld Deposit Nominal Strength Effect on Minimum Preheat (G-BOP)

Besides the level of diffusible hydrogen and cooling rate, an important effect on cracking susceptibility was observed as the weld deposit nominal strength level increased. The under-matching ENi4+800H wire electrode/flux combination resulted in the least amount of cracking (Figure 6). For the matching/slightly overmatching consumable combinations, the minimum preheat was 100-150ºF higher than for the undermatching consumable. Additionally, differences were found between the cracking behavior exhibited when using SA 120 (solid) vs. MC 120 (metal-core) wire electrodes. Note that while the yield and tensile strength level of the two combinations was virtually identical (107 ksi yield and 120 ksi tensile strength), the weld metal hardness, microstructure and fractographic features were different. These differences in predicted cracking behavior indicate that even slight compositional and microstructural effects will have to be carefully monitored when using these steels and welding consumables.

Y-groove (Tekken) Testing

Typical HAZ cracking results for low diffusible hydrogen levels, SAW consumables and heat input of 40 kJ/in are listed in Table 1, essentially showing no HAZ cracking except for the SMAW electrode used for control and validation of the testing procedure. One of the possible reasons for the behavior shown was that the minimum heat input could not be lowered to 20 kJ/in because of the SAW weld quality problems. Because no cracking was experienced in the HAZ, the diffusible hydrogen level had to be dramatically increased in order to verify the validity of the test. Welding at the unrealistically high (10.5-11.9 ml/100g) diffusible hydrogen level with SMAW and SAW processes, HAZ cracking was finally induced.

Note that in support of the optimistic prediction of preheats, the HAZ maximum hardness rarely exceeded 390 HV, well below the 420 HV critical hardness predicted for the 100W steel composition (Figure 7). Because the Tekken test has been widely recognized as a highly restrained test (Ref. 5), it is even customary to subtract ~100°F from the minimum preheat predicted by the severely restrained test when applying it to less restrained production conditions. Therefore, no preheat application, if ambient temperature is at least 70°F would be necessary to avoid HAZ cracking at diffusible hydrogen levels below 5 ml/100 when welding at 40 kJ/in and higher heat input. When comparing our results with those calculated using other analytical predictions (Refs. 4-10), it became evident that our predictions appear very optimistic, Table 2. This conclusion is in agreement with the preheat results predicted for the weld metals in # 5.1.1., or 150°F lower than the preheat specified in the D1.5-95 Code.

However, because our hydrogen induced cracking test procedures have repeatedly been proven to be valid, we believe the results show that the HPS 70W and 100W are better steels than those used in the past. Note that the predicting equations (Refs. 6-10) were all developed using typical C-Mn steels having higher carbon content, produced without vacuum degassing, calcium treatment or fine-grain thermal-mechanical processing as the modern HPS 100W. Note that heat input ranges were rarely specified for validity of the literature, another possible source for the discrepancies between predictions.

G-BOP versus Tekken Test Comparison

Overall, the G-BOP and Tekken tests yielded different results for weld deposits having matching strength. Based on the Tekken test which predicts HAZ cracking, it was found that the HP steel needed lower preheat temperatures by 150°F-175°F than presently specified for the conventional ASTM A 709 Grade 100W steel (for up to 2-inch in thickness at diffusible hydrogen levels of less than 5.5 ml/100g and heat input greater than 40 kJ/in). Based on the G-BOP tests, the minimum preheat was only 100°F lower that for the conventional 100 ksi weathering steels. Furthermore, differences in predicted preheat were found based on the wire electrode/ flux combinations (solid- vs. metal-core wire), even for the same deposit strength level.

It is clear that the hydrogen-induced cracking susceptibility in the HAZ was lower than in the weld Fusion Zone (FZ) for matching strength level. Therefore, preheat will be necessary for all conditions investigated. For undermatching deposits on the other hand, the weld fusion zone and HAZ cracking susceptibility were similar, predicting no need for preheat at diffusible hydrogen levels less than 5.5 ml/100g and heat inputs exceeding 40 kJ/in for up to 2-inch thick plate.

Weld Deposit Properties

The all-weld-metal (AWM) properties are shown in Figures 8 and 9. For comparison, relevant results on some of the same wire/flux combinations reported by Lincoln Electric and ESAB were also included in these plots. It can be seen that the weld FZ strength and toughness in the undiluted condition decreased as heat input increased. The average hardness in the FZ confirmed this trend. This loss of properties at high heat inputs, i.e. low cooling rates has been well known (13) and it can mainly be attributed to columnar solidification morphology and formation of coarse pro-eutectoid ferrite at the prior-austenite grain boundaries. Analytical methods used the estimated cooling rate at 1000ºF to calculate the weld deposit strength confirmed the above trend.

By combining the G-BOP, Tekken and all weld metal properties results, minimum preheat recommendations were issued, Tables 3 and 4. Note the heat input limitations for each

HPS type and for different diffusible hydrogen levels. Nevertheless, the HPS steels remained clearly superior to their traditional weathering steel counterparts.

Conclusions

1. HPS steels needed preheat temperatures by 100-175°F lower than presently specified for the conventional steels to avoid heat affected zone cracking for up to 2-inch in thickness
2. Hydrogen-induced cracking susceptibility of the heat affected zone (HAZ) was lower than in the weld fusion zone (FZ) for the same deposit strength and diffusible hydrogen level.
3. The results of simulative tests depended on the arc energy and welding process used. Therefore, future testing should be performed using standard welding conditions.

References

1. Stout, Doty. 1988. Weldability of Steel, University Press, New York
2. Graville, B., 1994. Report on Weldability Tests for Hydrogen Cracking of Higher Strength Steels and Potential for Standardization. *Welding Research Council*
3. Focht, E. et al. 1995 "Development of High Performance Steels for Bridge Construction", CDNSWC Report TR-61-95/16, Naval Surface Warfare Research Center, August 1995.
4. Adonyi, Y. 1998 “Weldability Testing of High Performance 70W and 100W Weathering Steel”, Unpublished report submitted to FHWA/AISI, LeTourneau University.
5. Yurioka, N., 1990. “Weldability of Modern High Strength Steels”, First United States-Japan Symposium on Advances In Welding Metallurgy, pp. 51-64, American Welding Society, 1990.
6. Buchmayr, B., 1989. “HAZ-Calculator; A Software System for Welding Engineers”, International Conference, “Trends in Welding Research”, Gatlinburg, TN.
7. Yurioka, et al. 1988. “Heat Affected Zone Hardness in SAW Weld Metals”. IIW Document IX-1524-88.
8. Beachem, C.D., 1972. “A New Model for Hydrogen-Assisted Cracking”, Metallurgical Transactions, Volume 3, February 1972, pp. 437-451.
9. Suzuki, H, et al. 1983. “Weldability of Modern Steels in Japan”, Transactions of the ISIJ No. 23, pp. 189-204.
10. Ito, Y., Bessyo, K. 1968. “Cracking Parameter of High Strength Steels Related to HAZ Cracking”, JWES Vol. 37 No. 9, pp. 983-991.
11. Inagaki, M. 1986 “Standard for Weldable High Strength Plates and the Weld Metal Cracking Parameter Pcm”, IIW - Doc. IX-1412-86.
12. Dueren, C. 1985. “Equations for the Prediction of Cold-Cracking resistance in Field Welding Large Diameter Pipes”, 3R International 24, pp.3-8, 1985.
13. Quintana, M. 1999, Private communications, The Lincoln Electric Company.

Table 1. Tekken test results, SAW Process, HPS 100W, **40 kJ/in heat input**

Preheat, deg. F	**: 9018M**	**ENi4+800H**	**SA120+800H**			**MC 120+800H**
	~10 ml/ 100g	1.6 ml/100g	1.6 ml/10 0g	~5.5 ml 100g	11.9 ml/ 100g	~5.0 ml/100 g
80	100%	0%	0%	0%	100%	0%
125	70%	0%	0%	0%	70%	0%
225	50%	0%	0%	0%	0%	0%

Table 2 - Minimum **predicted preheat temperatures** for two diffusible hydrogen levels, HPS 100W, as compared with preheat predictions from the open literature.

Weld Zone Assessed	**No.**	**Test Type**	**Diffusible Hydrogen Levels,**	
		Minimum Preheat	**4 ml/100g**	**8 ml/100g**
Fusion Zone (FZ)	**1.**	**GBOP Test, LeTourneau**	70°F	150°F
Heat Affected Zone (HAZ)	**1.**	**Tekken Test, LeTourneau**	70°F	N/A
	2.	**British Standard**	325°F	361°F
	3.	**Inagaki [11]**	348°F	447°F
	4.	**Ito/Bessyo [10]**	327°F	426°F
	5.	**Suzuki [9]**	161°F	167°F

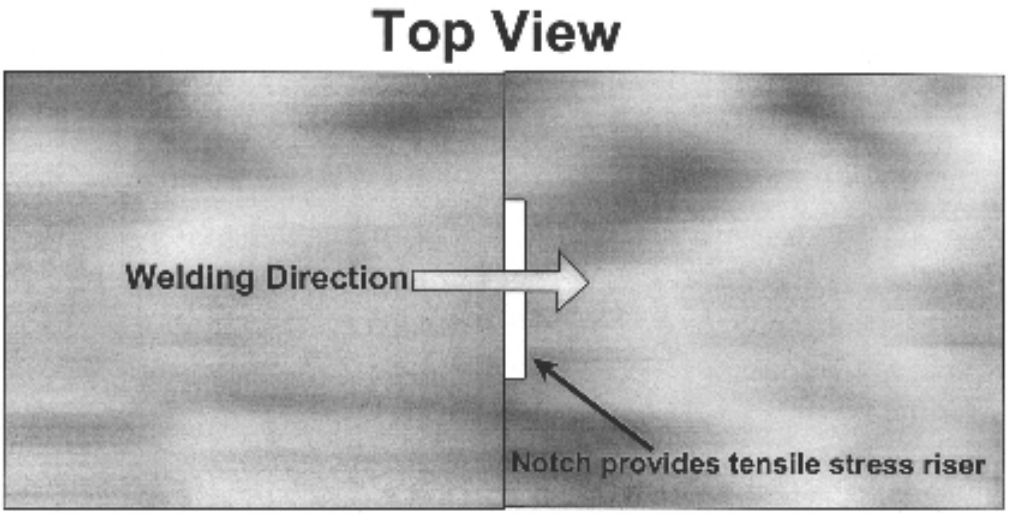
	6.	**Dueren [12]**	181°F	240°F

Table 3. Recommended Minimum Preheat/Interpass Temperatures for up to 2-inch-thick **HPS 70W Plate, 50-90 kJ/in** heat input SAW Welds.

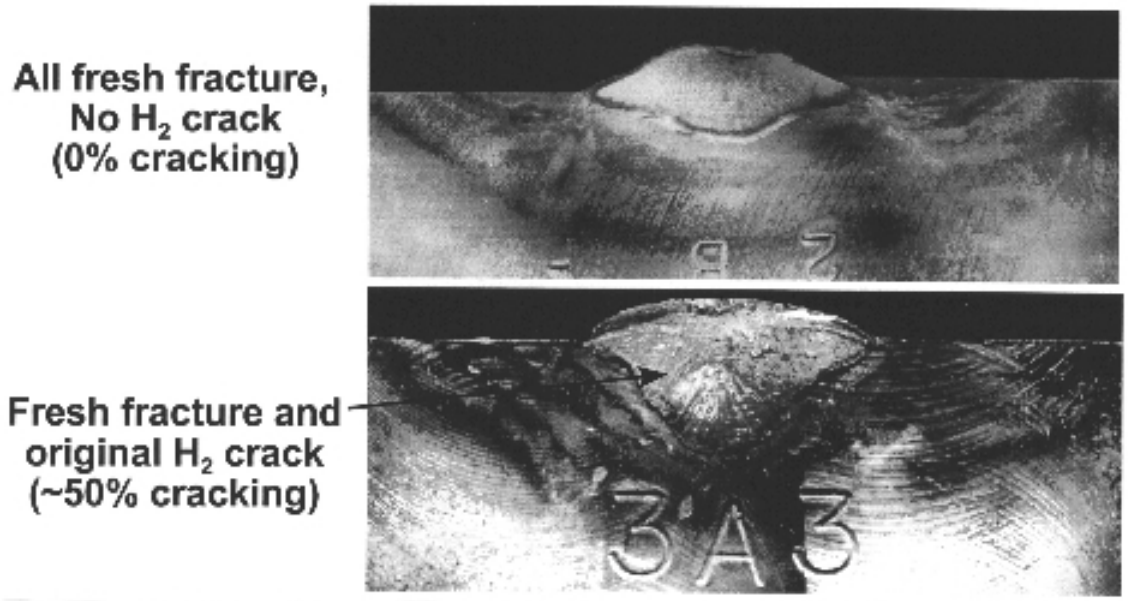
	Diffusible Hydrogen Level		
	H4	**H8**	**H16**
Conventional A 709	**212°F**	**248°F**	**248°F**
High-Performance 70W	**70°F**	**100°F**	**150°F**

Table 4. Recommended Minimum and Maximum Preheat / Interpass Temperatures for up to 2-inch-thick **HPS 100W Plate, 40 - 80 kJ/in** heat input SAW Welds.

	Diffusible Hydrogen Level		
	H4	**H8**	**H16**
Conventional A 709 Grade 100W	**250º/ 400ºF**	**250º/ 400ºF**	**N/A**
High-Performance 100W	**70º/ 250ºF**	**150º/ 400ºF**	**N/A**



a.



b.

Figure 1. Schematic representation of the Gapped-Bead-on-Plate test (a) and post-test fracture appearance used for quantification of cracking (b).

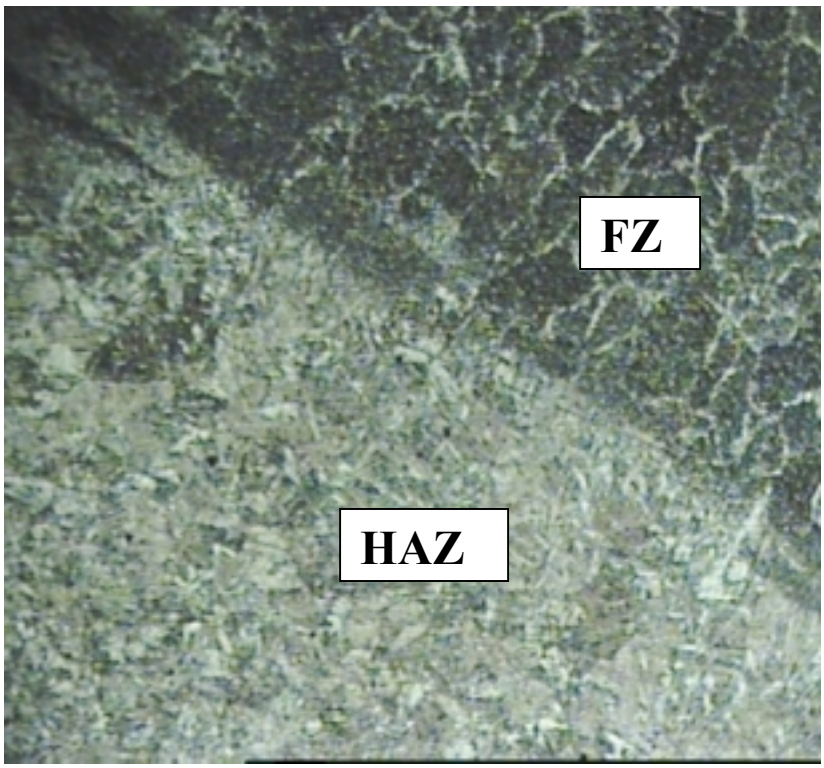


Figure 2. Optical micrograph of a G-BOP weld deposit ENi4 wire, 800H flux, Nital etch, 400 X magnification.

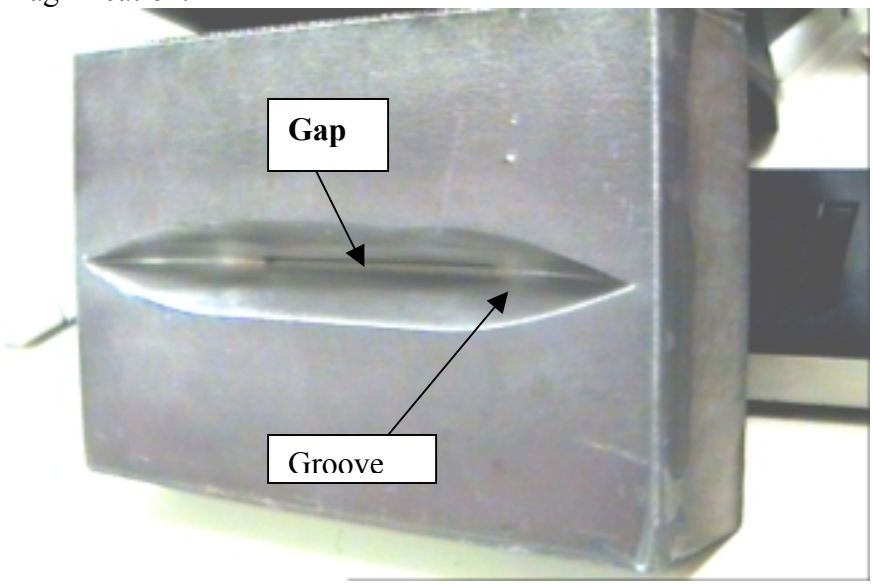


Figure 3. View of the Y-groove (Tekken) test specimen before welding. Note the machined groove and water-jet cut gap over which the test weld is to be deposited.

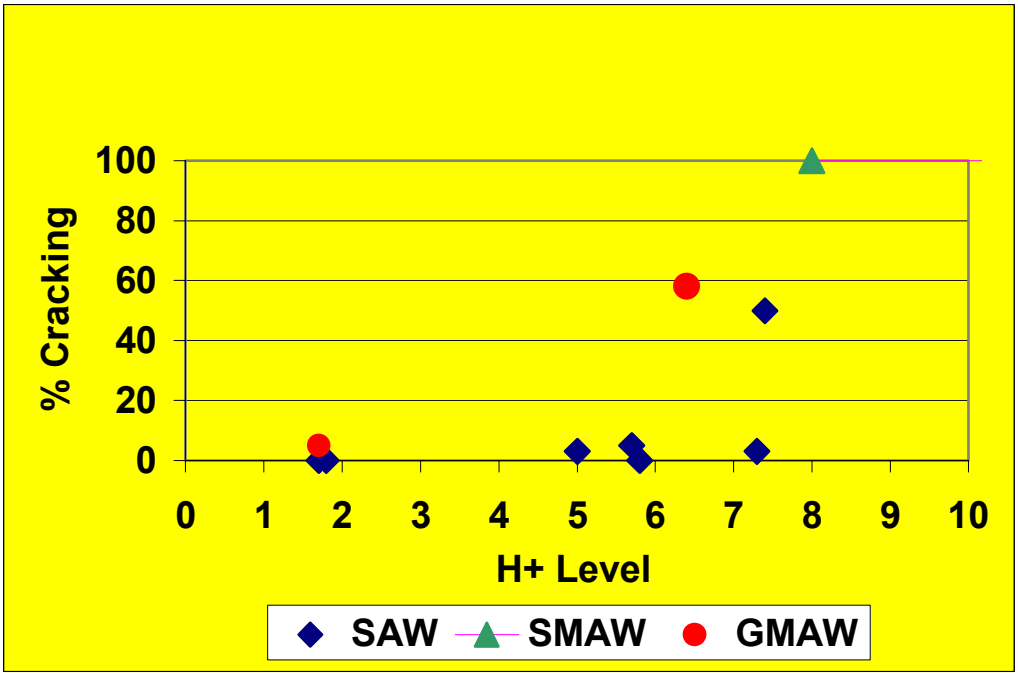


Figure 4. G-BOP cracking results as a function of diffusible hydrogen level.

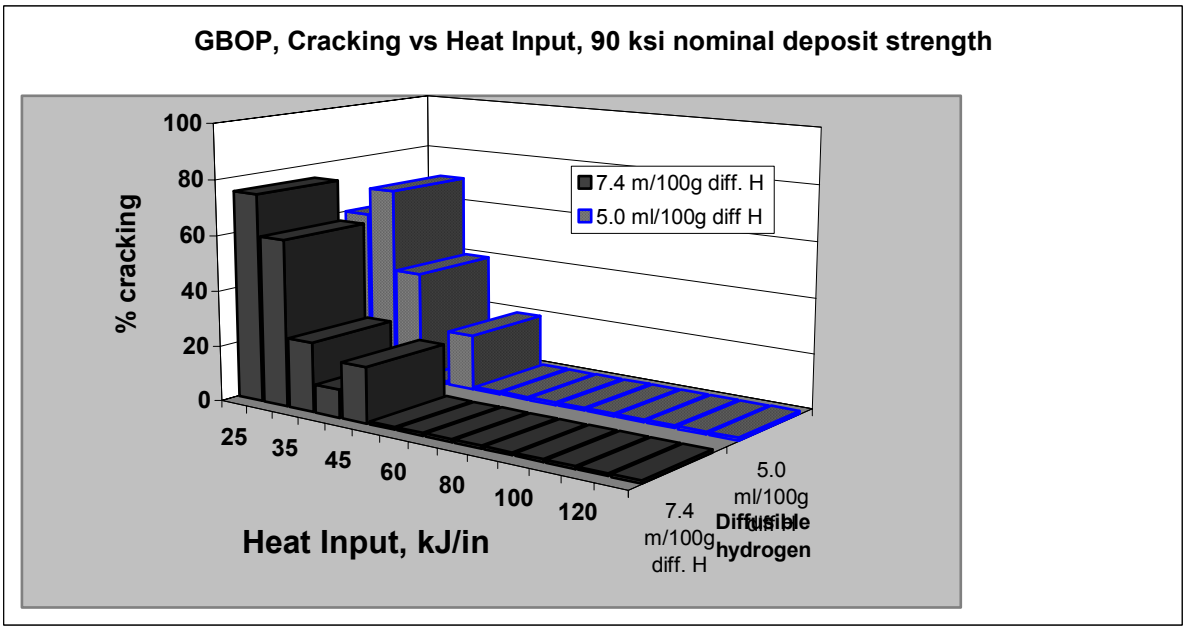


Figure 5. G-BOP cracking results as a function of heat input and SAW deposit nominal yield strength for 5-7 ml/100 d diffusible hydrogen and no preheat.

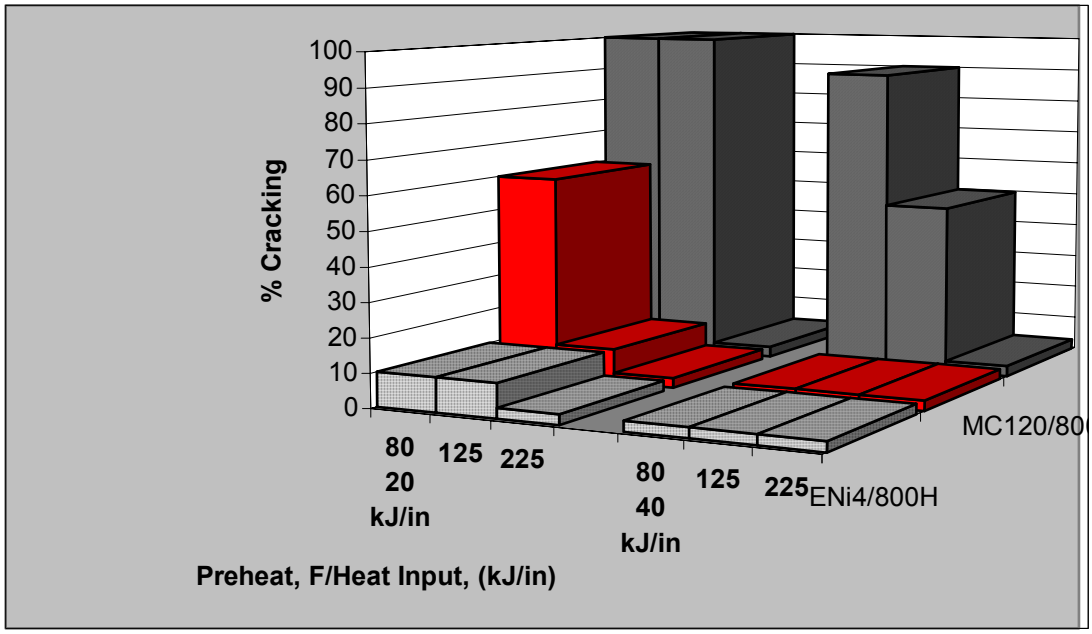


Figure 6. G-BOP test results for two heat inputs and three different SAW consumables

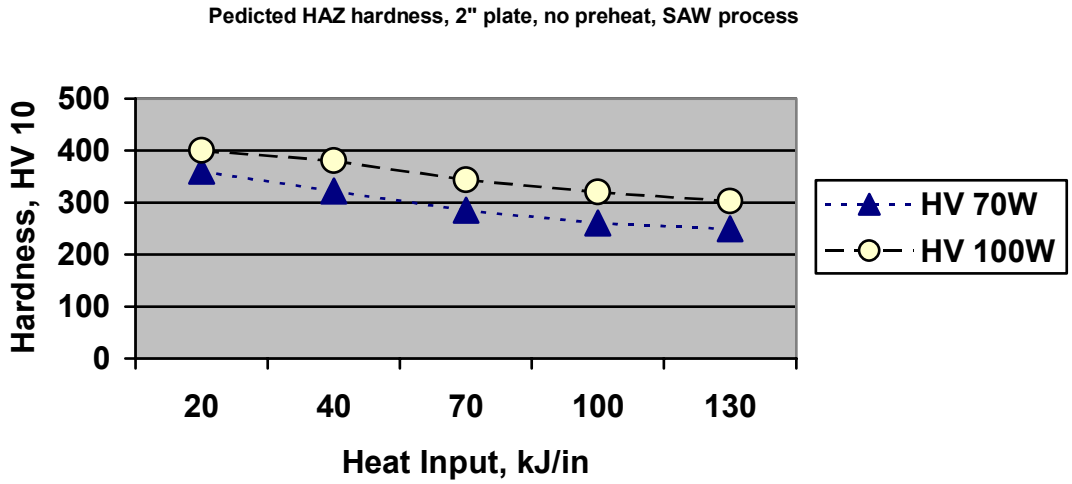


Figure 7. HAZ hardness variation with heat input, HAZ Calculator (5)

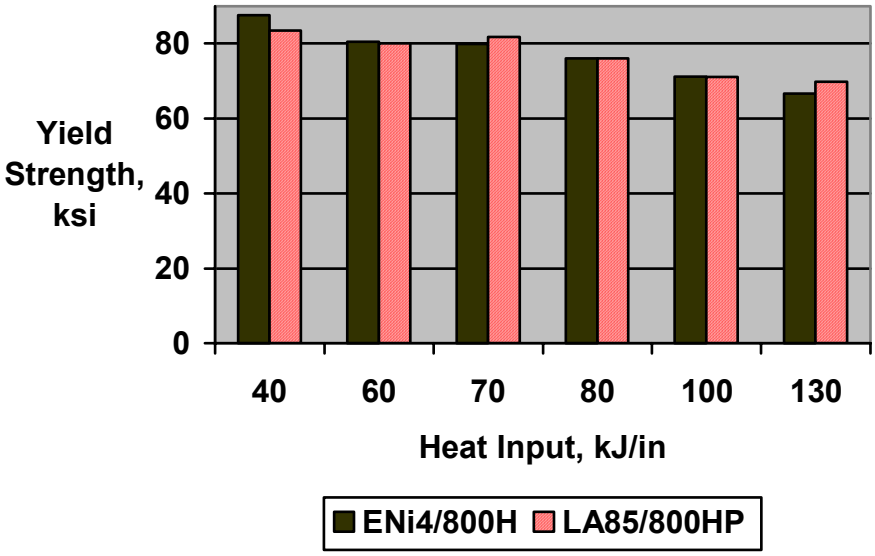


Figure 8. All-Weld-Metal Yield Strength variation with heat input, HPS 70W, SAW Welding process, Single-wire, DCEP.

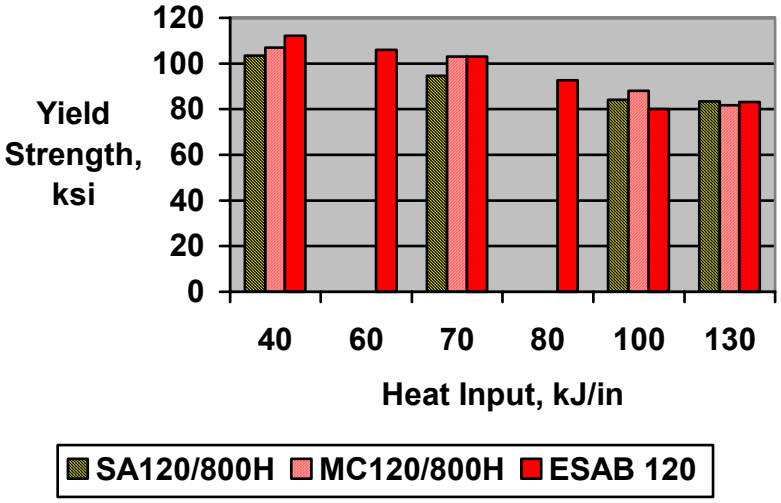


Figure 9. All-Weld-Metal yield strength variation with heat input, HPS 100W

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