Evaluation of Tubular (Metal-core) GMAW and FCAW Consumables for Welding HPS 70W

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EXECUTIVE SUMMARY

Hydrogen-induced cracking susceptibility of six tubular-wire (GMAW metal-core and flux-core FCAW) consumables from ITW/Hobart and ESAB was evaluated. Gapped Bead-on-Plate (G-BOP) tests were performed to determine susceptibility to cracking, while diffusible hydrogen was measured in the as-received and humidified conditions.

Accelerated exposure to high humidity did not result in a significant increase in diffusible hydrogen levels and corresponding preheats. G-BOP cracking results were consumable-specific and no general preheat recommendations could be made regarding these tubular GMAW and FCAW consumables. It was found that no preheat would be required when using specific consumables at less than 4 ml/100g diffusible hydrogen and heat input above 40 kJ/in.

These recommendations for the tubular consumables are different from those obtained for solid wire GMAW, FCAW and several SAW consumables tested in the past. The reasons for this difference can be related the inherent variability of the gas-shielded arc semi-automatic welding processes. Additional variations in actual heat input can be expected at different droplet transfer modes and use of Pulsed-Wave power sources.

Fabricators will also have to be made aware of the possibility of delayed cracking because of additional variations in diffusible hydrogen due to consumable composition, atmospheric exposure and shielding gas contamination. More work would be needed to clarify the effect of all the above variables on the minimum preheat temperature necessary to avoid cracking.

BACKGROUND

Weldability testing of the High-Performance HP 70W steel has included so far testing for hydrogen-induced cracking susceptibility and weld deposit strength optimization properties. Previous work performed on the subject at LeTourneau University in 1999 was summarized in a 2002 Welding Journal article (Ref. 1). The purpose of that specific work was to evaluate the Fusion Zone hydrogen-induced cracking susceptibility of single-pass weld deposits made using four different welding processes and equivalent diffusible hydrogen levels. The Gapped Bead-on-Plate (G-BOP) test was used to compare Shielded Metal Arc-, Submerged Arc-, Gas Metal Arc- and Flux Cored Arc Welding processes. Equivalent net heat inputs were produced and the weld cross-sectional areas were normalized at different arc energies, including the heat transfer efficiency for each process.

Minimum predicted preheats were different, lower for SAW welds than for the GMAW, FCAW and SMAW welds at similar diffusible hydrogen level and heat input. This difference was attributed to the different solidification microstructures and weld bead geometries. Preheating guidelines based on the SMAW process remained the most conservative, confirming the validity of the past practice of using SMAW to find minimum preheats. It was concluded that preheat values should not be extrapolated from one welding process to another (Ref. 1).

Additionally, variations in heat transfer efficiency of 61-95% can be encountered in GMAW and FCAW depending on the droplet transfer mode and power source characteristics (Ref. 2, 3). Accordingly, net heat inputs and effective cooling rates can be affected, adding to variations in minimum preheat requirements. As modern power supplies become more accepted by all industries, their main feature that allows for greater adaptive control and less dependence on operator skill is the waveform control (Ref. 2). In essence, most standard GMAW power supplies use a rectified "pseudo-DC" current wave, that produces constant welding current for all practical purposes. These traditional and widely used power sources are also called "Continuous Wave" type and can be found in most fabrication shops.

During the past decade, the so-called "Pulsed Wave" power sources have been introduced, mainly to the defense-related industries where high-strength steels and nickel-based superalloys had to be joined with great reliability. These power sources allow for precise and very rapid self-adjustment, of millisecond order of magnitude, of the welding arc to any disturbing input using a combination of feed-back and feed-forward controls. At the same time, because of the high frequency current pulses, sluggish weld pools (in Ni-base alloys) and easily oxidizing pools (Al-alloys) can be welded. Accordingly, these "Pulsed Arc" power sources have typically been more expensive that the "Regular" or "Continuous Wave" power sources. Because of intense competition and advances in electronic materials, however, these new "Pulsed Arc" welding machines are becoming more affordable and can be expected soon to be purchased by other industries such as bridge building because of their exceptional performance, especially in the short-circuiting arc droplet transfer mode.

In anticipation of such developments, a comparison of the two types of power sources was included in the experiment, based on the fact that net heat input differences have been shown between them (Ref. 3). Knowing that net heat input affects cooling rates and can change microstructures/hardness and ultimately cracking behavior, the Pulsed Wave (PW) and Continuous Wave (CW) modes were to be included in the experimental matrix.

Finally, as new matching strength tubular metal-core GMAW and flux-core FCAW consumables have been developed since then and the demand for increased use of these processes in bridge fabrication has increased, there was a need for a new, independent evaluation of these consumables.

OBJECTIVES

The purpose of this work was to determine the minimum preheat required for welding HPS 70W when using gas-shielded arc welding processes and tubular wire electrodes (GMAW and FCAW). The effects of consumable atmospheric exposure, heat input and deposit strength on hydrogen induced cracking were to be evaluated.

METHODOLOGY

Gapped Bead-on-Plate (G-BOP) testing was performed at a range of preheats (70°F, 125°F, and 225°F) and heat inputs to determine cracking susceptibility. The arc energies varied from 20 kJ/in to 90 kJ/in in increments of 10 kJ/in and did not take into account the arc transfer efficiency. For the variable preheats, a constant heat input of 40 kJ/in was used for both GMAW and FCAW, using a normalization procedure based on the weld cross sectional area (Ref. 1). Tests were performed using both continuous wave (CW) and pulsed-wave (PW) arc modes with the GMAW consumables. The FCAW tests were all performed using CW mode.

Four Hobart welding consumables and two ESAB welding consumables were evaluated for welding HPS 70W steel. The tubular-wire consumables were: Metalloy 90 and Metalloy 76 GMAW metal-cored wires, and TM 95-K2 and TM-771 FCAW wires, and ESAB's DS II 101H4M and DS II 80-Ni1H4 FCAW consumables

Diffusible hydrogen tests measurements were performed on selected consumables in the as-received and humidified conditions. The humidification experiment was performed in an enclosure under closed-loop controlled 80°F and 80% relative humidity for 8 days.

RESULTS AND DISCUSSION

The G-BOP test results for the FCAW consumables can be seen in Figures 1 and 4, while GMAW results are shown in Figures 2 and 3, all Continuous Wave (CW) mode. Figure 5 shows the effect of heat input on cracking, while Figure 6 shows pulsed-wave (PW) arc mode effects on the GMAW consumables. Pulsed-wave arc created a deeper penetration and a fingernail type weld bead shape, which increased the stress concentration at the G-BOP test weld root, and resulted in a greater degree of cracking (Figure 7).

Effect of Accelerated Atmospheric Exposure

Extended exposure of the welding wire electrodes to high humidity and high temperature (80% humidity, 80°F for 8 days) did not result in any detectable diffusible hydrogen increase for the consumables tested at random – See Table I. This encouraging result was different from past experience, when the same type of exposure almost doubled the diffusible hydrogen in FCAW electrodes (6.7 to 12.4 ml/100g - Ref. 1).

Effect of Welding Current Mode (Pulsed- vs. Continuous Wave)

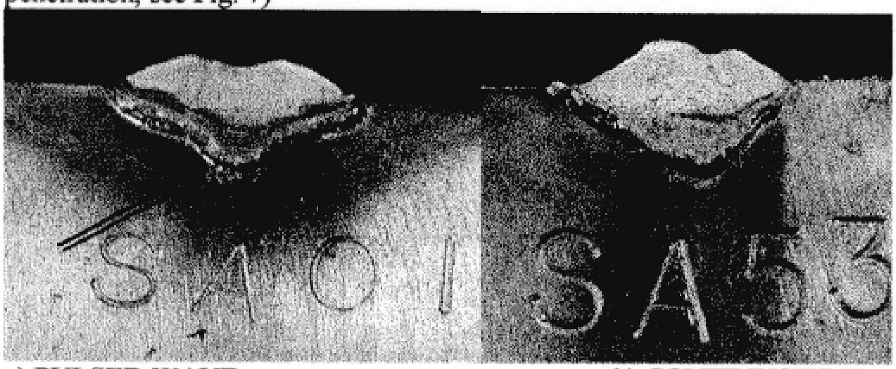
The cooling rates were most likely higher for PW than for the CW mode, due to the lower net heat input. Indeed, for the same setting and readout of current, voltage and travel speed, the PW deposit maximum hardness was 300-350 HV, while the deposit made using the same heat input in CW mode had significantly lower hardness 200-225 HV.

For all other conditions being equal, including the heat transfer efficiency, the only possible explanation for this difference has to do with the actual arc energy at the power source. Indeed, up to 18-39% differences have been measured using calorimetry - Ref. 2 - PW has consistently been lower, i.e. about 61-88% of the heat input in CW.

Accordingly, G-BOP cracking was consistently more accentuated in the PW mode then the CW mode (Fig. 6). This is a worrisome trend, as shop personnel could read the exact same current and voltage values on their digital readouts, incapable of "keeping up" with the 120-250 Hz variation in current typical to PW.

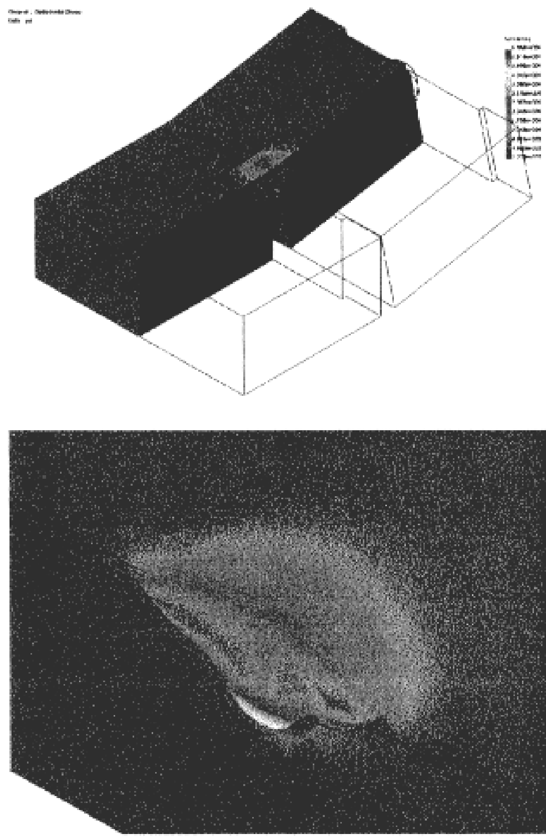
To complicate matters more, the molten droplet transfer mode has also been shown to have an effect on the net heat input in CW mode (Ref. 3). Heat transfer efficiencies varied from 85% in short-circuit transfer to 73% in spray-transfer mode.

The weld bead shape was also different in PW mode (more D/W finger-like root penetration, see Fig. 7)



a) PULSED WAVE b) CONTINUOUS WAVE

Figure 7. View of typical weld bead appearance after breaking the G-BOP tests, comparing the shape of the PW and CW arc modes, same heat input, 40 kJ/in



a

b

Figure 8. Finite Element Analysis (FEA) representation of the stress developed at the root of the weld during G-BOP testing. Bending loading caused by the asymmetrical residual tensile stress in the weld bead (a) was assumed to be the driving force for this stress (Ref. 4)

Because of the above variability effects, our results could be divided into two groups, 1) general and 2), 3) consumable-specific:

1) In general, GMAW and FCAW hydrogen-induced cracking susceptibility testing using the G-BOP procedure revealed the following:

a) Variability in test results was greater than in any previously tested SAW, FCAW, GMAW or SMAW consumable, probably because:
    i. Net heat input (deposit hardness and bead size) varied with heat transfer efficiency and pulsed-wave vs. continuous-wave mode
    ii. Weld bead geometry varied between solid- and tubular-wire electrodes, all other conditions being equal
    iii. Consumable-related result inconsistencies (why undermatching consumables required higher preheat, why were these tubular wire electrodes so different from previously used solid wires, etc)

2) The following consumables were found to produce crack-free deposits at heat input greater than 40 kJ/in, diffusible hydrogen levels under 4 ml/100g, 2-inch thick HPS 70W plate and <u>NO PREHEAT:</u>

GMAW:
- ITW/Hobart Metalloy 90

FCAW
- ITW/Hobart TM-95K2
- ITW/Hobart TM-771
- ESAB DS II 101-H4Ni
-

3) The following consumables were found to produce crack-free deposits at heat iput greater than 40 kJ/in, diffusible hydrogen levels under 4 ml/100g, 2-inch thick HPS 70W plate and <u>150°F PREHEAT:</u>

GMAW:
- ITW/Hobart Metalloy 76

FCAW
- ESAB DS II 80-H4Ni

CONCLUSIONS

a) Minimum preheat temperatures have been successfully established for each of the six tubular GMAW and FCAW consumables tested. No absolute minimum preheat could be established for a certain group of consumables, as in the past.
b) Difficulties in implementing these recommendations are anticipated due to the large number of process variables (travel speed, shielding gas purity, electrode stickout, droplet transfer mode, power source type, etc)
c) More work will be required to understand the GMAW and FCAW process robustness relative to hydrogen-induced cracking susceptibility. Simulative test results will have to be correlated with small-scale and full-scale testing to confirm the validity of predictions.

REFERENCES

1. Atkins, G., Thiessen, D., Nissley, N., Adonyi, Y "Welding Process Effects in Weldability Testing of Steels", Welding Journal, Research Supplement April 2002
2. Hsu, Soltis, "Heat Input Comparison of SST vs Short-Circuiting in Pulsed- and Continuous-Wave Processes", Lincoln Electric, 2001
3. Bosworth. "Effective Heat Input in Pulsed Current GMAW with solid electrodes"
4. Nissley, N., Olson, T., Adonyi, Y., "Geometry Effects in Weldability Testing of High-Performance Steels", Presentation at the 80th Annual Conference of the American Welding Society, St. Louis, MO, April 1999

TABLE I

Diffusible Hydrogen Data

Consumable	Metalloy 76	Metalloy 90	TM-95K2	TM-771	DS II 80NiH4	DS II 101 H4M
Reported (Hobart, ESAB)	*2.0*	*3.3*	*1.3*	*3.0*	NA 4.0 max	NA
Measured As-received	**4.6**	**4.5**	**1.3**	NA	**6.7**	NA
Measured 80/80 humidified	**4.7**	**NA**	**NA**	**NA**	**6.7**	**NA**

FCAW G-BOP Results, 40 kJ/in arc energy, as-received condition

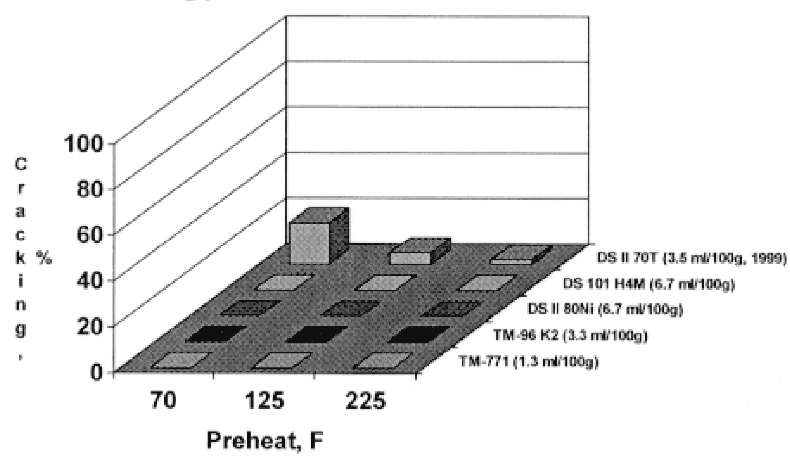


Fig. 1

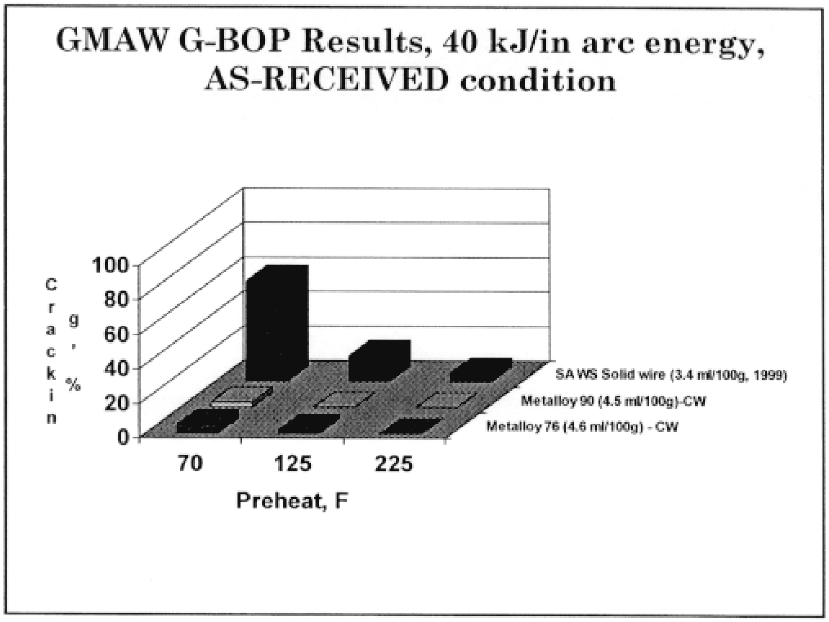

GMAW G-BOP Results, 40 kJ/in arc energy,
AS-RECEIVED condition
Cracking, %
100
80
60
40
20
0
70
125
225
Preheat, F
SA WS Solid wire (3.4 ml/100g, 1999)
Metalloy 90 (4.5 ml/100g)-CW
Metalloy 76 (4.6 ml/100g) - CW

Fig. 2

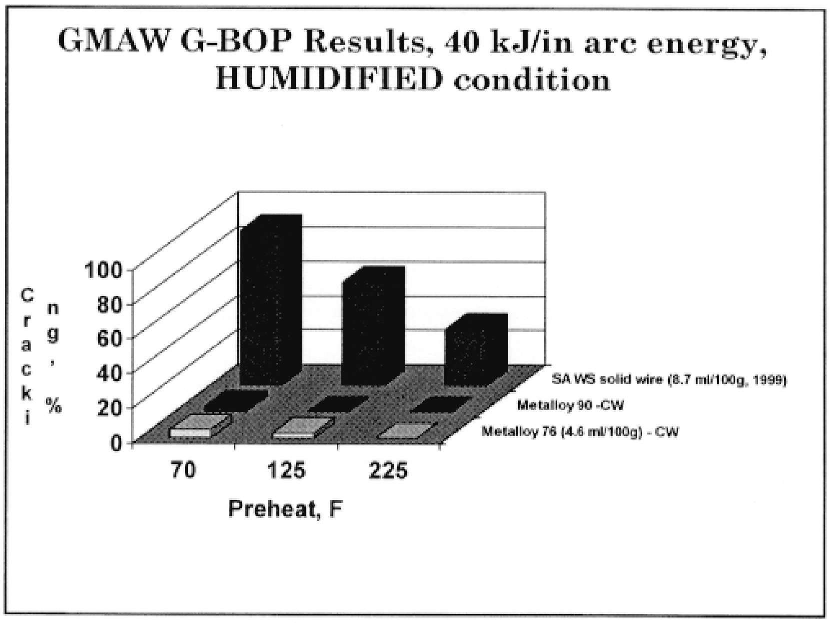

GMAW G-BOP Results, 40 kJ/in arc energy,
HUMIDIFIED condition
Cracking, %
100
80
60
40
20
0
70
125
225
Preheat, F
SA WS solid wire (8.7 ml/100g, 1999)
Metalloy 90 -CW
Metalloy 76 (4.6 ml/100g) - CW

Fig 3

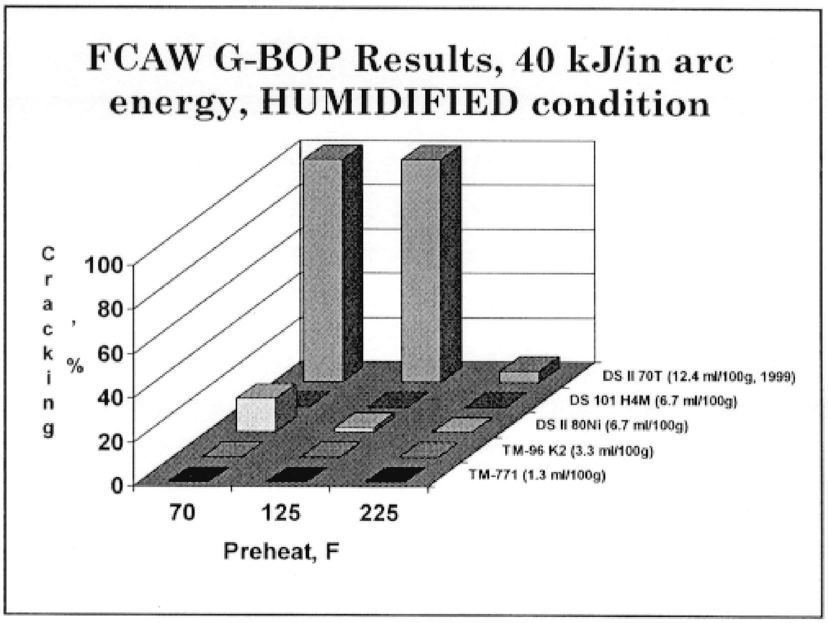

FCAW G-BOP Results, 40 kJ/in arc energy, HUMIDIFIED condition
Cracking, %
100
80
60
40
20
0
70
125
225
Preheat, F
DS II 70T (12.4 ml/100g, 1999)
DS 101 H4M (6.7 ml/100g)
DS II 80Ni (6.7 ml/100g)
TM-96 K2 (3.3 ml/100g)
TM-771 (1.3 ml/100g)

Fig 4

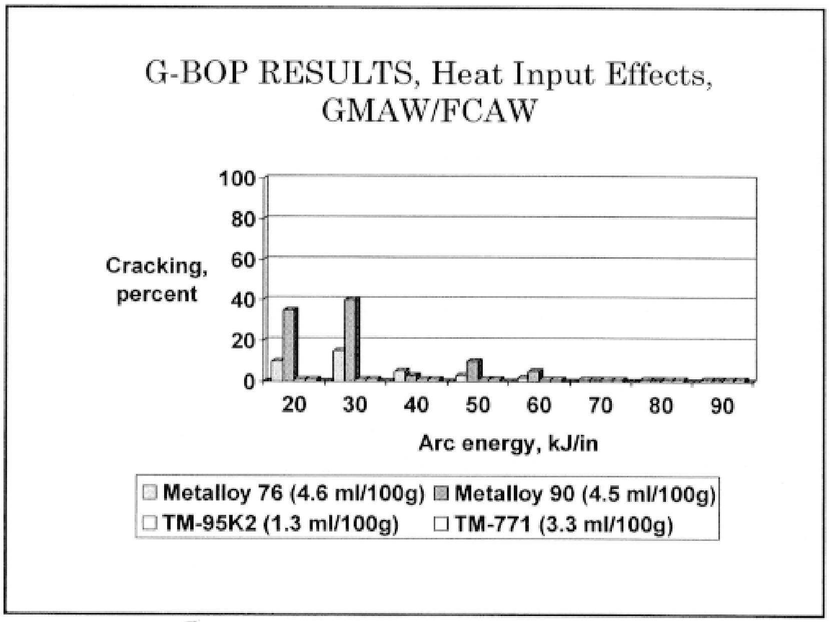

G-BOP RESULTS, Heat Input Effects, GMAW/FCAW
Cracking, percent
100
80
60
40
20
0
20
30
40
50
60
70
80
90
Arc energy, kJ/in
Metalloy 76 (4.6 ml/100g)
Metalloy 90 (4.5 ml/100g)
TM-95K2 (1.3 ml/100g)
TM-771 (3.3 ml/100g)

Fig 5

G-BOP RESULTS, GMAW Metalloy 76, PULSED vs. Continuous Wave

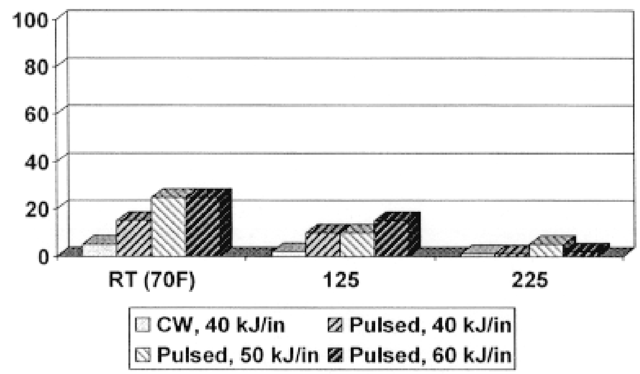


Fig 6.

RECOMMENDED PREHEATS, (up to 2" plate, min. 40 kJ/in heat input)

- **GMAW – METAL-CORE,** 75%Ar+25%CO_2
  - Hobart/ITW, Metalloy 90 (E90C-G) – ***NO PREHEAT***
  - Hobart/ITW, Metalloy 76 (E70C-6M) – ***150°F***
- **FCAW –** 100% CO_2
  - Matching consumables
    - Hobart/ITW, TM-95K2 (E90T5-K2) - ***NO PREHEAT***
    - ESAB, DS II 101H4M - ***NO PREHEAT***
  - Undermatching
    - Hobart, TriMark TM-771 (E71T-12J) - ***NO PREHEAT***
    - ESAB, DS II 80-NiH4* – ***150°F***

* 6.7 ml/100g, not H4

GMAW and FCAW Welding of HPS 70W using Tubular Electrodes

FINAL (AND ULTIMATE?) REPORT

October 23, 2002

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LeTourneau University

Consumables Tested (all tubular, not solid wires)

- **GMAW – METAL-CORE, 75%Ar+25%CO_2**
  - Hobart/ITW, Metalloy 90 (E90C-G) - matching
  - Hobart/ITW, Metalloy 76 (E70C-6M) - undermatch
- **FCAW – 100% CO_2**
  - Matching consumables
    - Hobart/ITW, TM-95K2 (E90T5-K2)
    - ESAB, DS II 101H4M
  - Undermatching
    - Hobart/ITW, TriMark TM-771 (E71T-12J)
    - ESAB, DS II 80-NiH4

Methodology

- Diffusible hydrogen measured in the as-received and humidified conditions (80% humidity, 80°F, 8 days)
- G-BOP tests performed at 40 kJ/in, and the 20-90 kJ/in heat input range
- Pulsed-Wave vs. Continuous-Wave GMAW experiments performed
- Results compared with previous HPS 70W G-BOP work

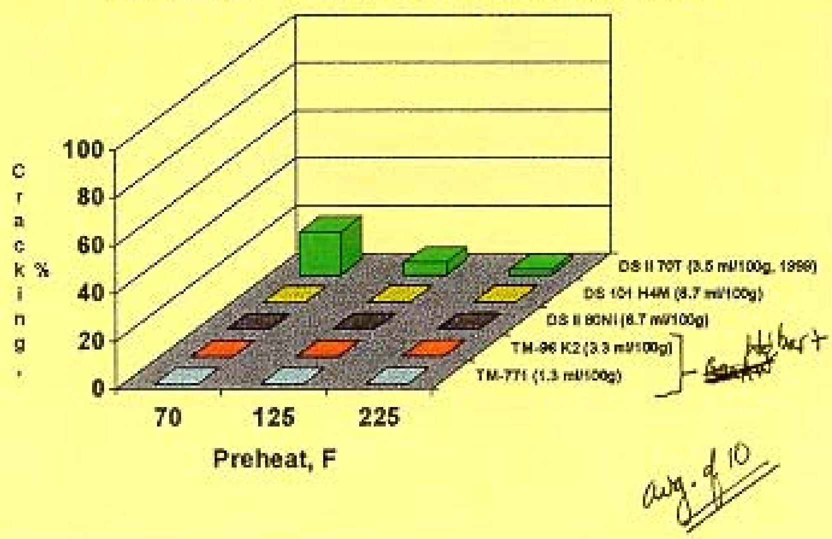
Diffusible Hydrogen Data

Consumable	Metalloy 76	Metalloy 90	TM-95K2	TM-771	DS II 80Ni1H4	DS II 101 H4M
Reported (Hobart, ESAB)	2.0	3.3	1.3	3.0	NA 4.0 max	NA
Measured As-received	4.6	4.5	1.3	NA	6.7	NA
Measured 80/80 humidified	4.7	NA	NA	NA	6.7	NA

RESULTS & DISCUSSION

1. Comparison with past solid-wire GMAW and FCAW results (1999)
2. Diffusible Hydrogen Effects:
    1. Comparison with Manufacturers' Data (H4)
    2. Effect of Accelerated Exposure
    3. Variability (ESO? Welding Parameters?)
3. Heat input effects
    1. Continuous Wave Mode (CW)
    2. Pulsed Wave Mode (PW)
4. Consumable strength effects (under/matching)

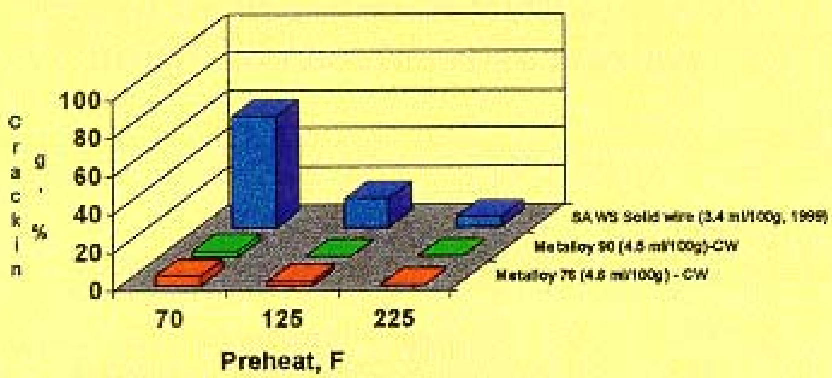
FCAW G-BOP Results, 40 kJ/in arc energy, as-received condition



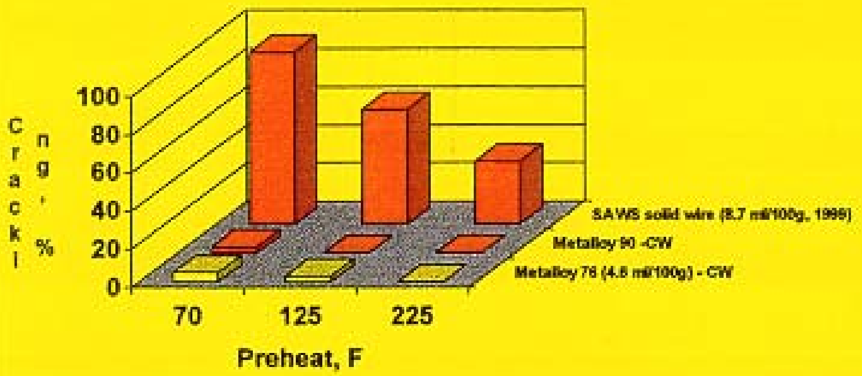
GMAW: Separate G-BOP Testing methodology

- Continuous Wave (CW) STANDARD mode used:
  - New Metal-Cored wire
  - Compared to "Old" (1999) solid wire weld data
- Pulsed Wave (PW) mode used:
  - New Metal-Cored wires only
- Determined the effects of heat input, CW vs. PW arc mode and atmospheric exposure on minimum preheat

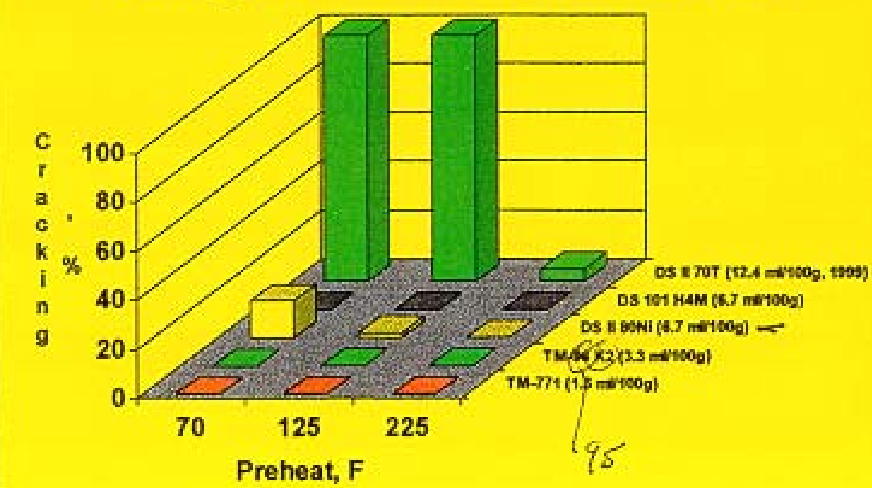
GMAW G-BOP Results, 40 kJ/in arc energy, AS-RECEIVED condition

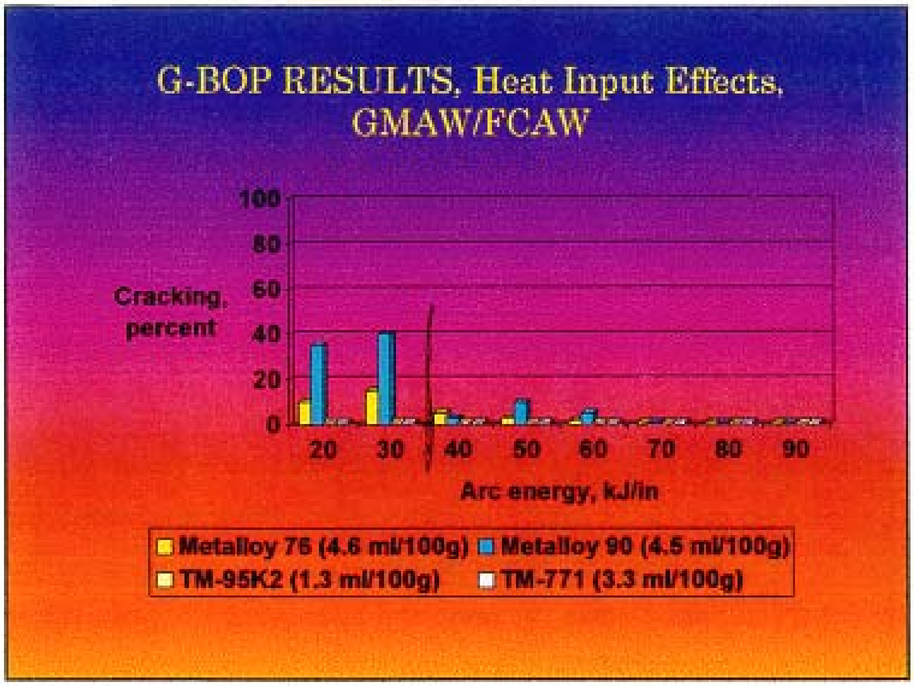


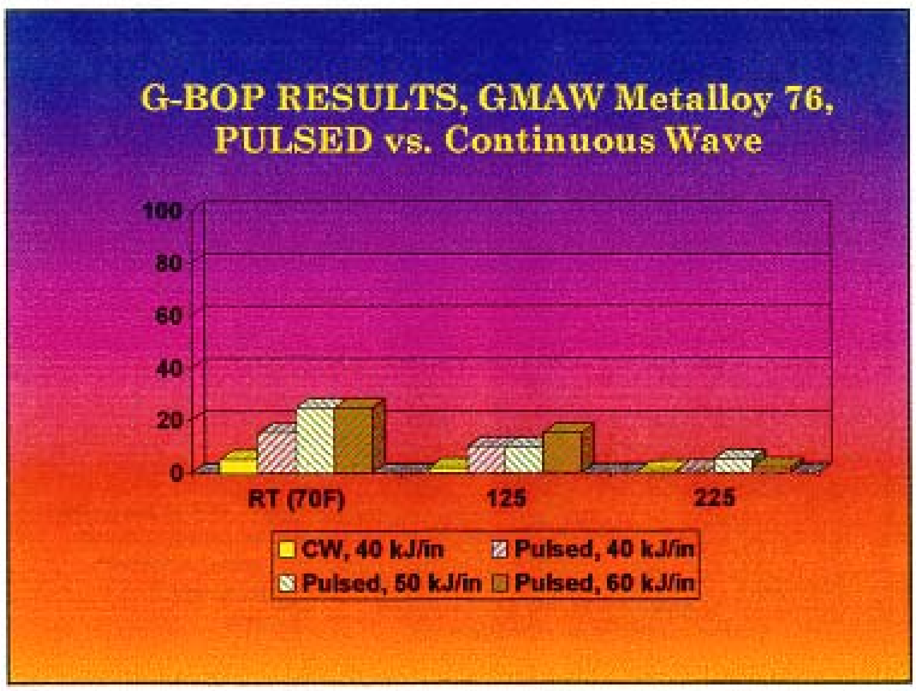
GMAW G-BOP Results, 40 kJ/in arc energy, HUMIDIFIED condition



FCAW G-BOP Results, 40 kJ/in arc energy, HUMIDIFIED condition



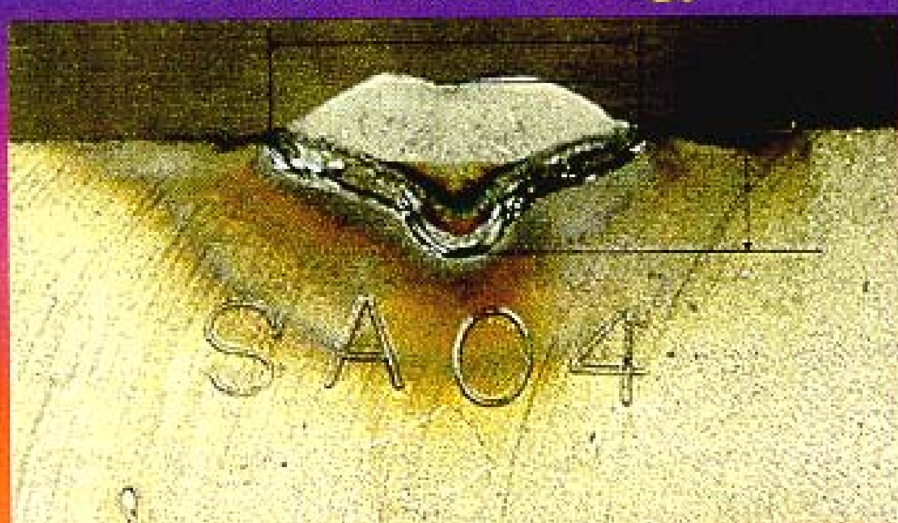

G-BOP RESULTS, Heat Input Effects, GMAW/FCAW
100
80
60
40
20
0
Cracking, percent
20
30
40
50
60
70
80
90
Arc energy, kJ/in
Metalloy 76 (4.6 ml/100g)
Metalloy 90 (4.5 ml/100g)
TM-95K2 (1.3 ml/100g)
TM-771 (3.3 ml/100g)


G-BOP RESULTS, GMAW Metalloy 76, PULSED vs. Continuous Wave
100
80
60
40
20
0
RT (70F)
125
225
CW, 40 kJ/in
Pulsed, 40 kJ/in
Pulsed, 50 kJ/in
Pulsed, 60 kJ/in

G-BOP RESULT VARIABILITY

- Consumable manufacturer technique:
  - FCAW diffusible H varied between 1.3 to 12.4 ml/100g
  - GMAW diffusible H varied between 3.5 to 6.7 ml/100g
- Welding parameters used
  - Net heat input variations +/- 3 kJ/in for 40 kJ/in
  - Depth/width shape variations from solid vs. tubular wire as well as PW vs. CW
- Welding setup (robot vs. carriage) difference
- Different operators
- Tubular electrode deposition rate/bead shape

Bead Shape, Pulsed GMAW, 40 kJ/in arc energy



RECOMMENDED PREHEATS, (up to 2" plate, min. 40 kJ/in heat input)

- GMAW – METAL-CORE, 75%Ar+25%CO_2
  - Hobart/ITW, Metalloy 90 (E90C-G) – *NO PREHEAT*
  - Hobart/ITW, Metalloy 76 (E70C-6M) – *150°F*
- FCAW – 100% CO_2
  - Matching consumables
    - Hobart/ITW, TM-95K2 (E90T5-K2) - *NO PREHEAT*
    - ESAB, DS II 101H4M - *NO PREHEAT*
  - Undermatching
    - Hobart, TriMark TM-771 (E71T-12J) - *NO PREHEAT*
    - ESAB, DS II 80-NiH4* – *150°F*

* 6.7 ml/100g, not H4

Areas of Concerns over IMPLEMENTATION

- Difficulty in imposing Arc energy > 40 kJ/in (most commonly used GMAW/FCAW parameters are in the 25-30 kJ/in range) + mostly SEMIAUTOMATIC applications => no control over travel speed
- Practically impossible to account for additional reduction in net heat input due to heat transfer efficiency variations (60-90 % from PW spray transfer to short-circuit CW mode)
- More possibilities for H contamination than in SAW – moisture in shielding gas, tubular electrode propensity for moisture pickup –

CONCLUSIONS

- No UNIQUE minimum preheats could be recommended for either GMAW or FCAW welding (results were consumable-specific)
- Pulsed GMAW should be avoided until more information is developed
- More research is needed to validate preheat predictions and clarify reasons for variability in G-BOP results
  - lower strength consumables - more cracking?
  - measured diffusible H higher than expected?
  - lack of correlation with 1999 data?

PROPOSED FUTURE WORK

- GMAW:
  - Develop heat transfer efficiency database using solid wire and calorimetric D/A system
    - CW short-circuit, SST and spray droplet transfer
    - PW spray transfer mode
  - Repeat on tubular wires and perform G-BOPs
- FCAW:
  - Repeat G-BOP tests on H4 consumables from other heats at H4 level (ESAB/ITW) and different manufacturers (Lincoln/others?)