

Table 1 — Composition of Steels (%) and Welding Parameters Used

Element	HSLA 100	ASTM A36
C	0.055	0.051
S	0.012	0.015
P	0.008	0.008
Si	0.31	0.25
Cr	0.06	0.04
Ni	1.59	0.04
Mn	1.96	0.66
Cu	0.62	0.05
Mo	0.45	<0.01
Nb	0.026	<0.01
Ti	0.005	<0.01
Al	0.024	0.01
V	0.007	<0.01
B	0.0008	<0.0005
W	0.014	<0.01
Fe	Base	Base
Pb	0.01	<0.01

Equipment used: Hobart Arcmaster 500/HMC 410 Controller
 GMA heat input: 1.5 kJ/mm, 29 V, 440 A
 Travel speed: 8.5 mm/s
 Single bead on plate
 Welding consumable: 1/8 in. (1.6 mm) low-carbon-steel, metal-cored welding wire (baked in vacuum furnace at 650°C for 1 h and stored at 150°C until use)

standard ST-type connector. The fiber-optic section was then matched to another cable using index-matching optical gel. The gel allowed the light from the photodiode to pass into the section with only a small decrease in power. The bottom of the housing was fitted with a small O-ring to form a seal with the metal surface. Pressure was applied to the sensor using a Plexiglas® plate to hold it in place.

Results and Discussion

Initial experiments were conducted on 51 x 51 x 12.7-mm gas metal arc welded (GMAW) specimens of ASTM A36 steel. The compositions of the steels along with the welding parameters used in this study are presented in Table 1. The sensor was placed directly adjacent to the weld deposit. Using this practice, it was found the amounts of hydrogen diffusing from the base plate were too small for a detectable response. The sensor was therefore modified to sample from the curved surface of the weld deposit using a rubber gasket adapter as shown in Fig. 2.

The experiments were repeated using ASTM A36 steel specimens. The specimens were baked in a vacuum furnace at 650°C for one hour before welding. The specimens were gas metal arc welded with 0.1% H₂/argon, then quenched in ice water and stored in liquid nitrogen (LN₂) until analysis. Data was collected using a general-purpose instrumentation bus (GPIB) interface connected to a laptop computer; measurements were made every minute. The results indicated the

amount of hydrogen diffusing from the weld deposit was more than adequate for detection. A suite of experiments was performed on a specimen that was allowed to remain at room temperature for extended periods of time; measurements were made at one-hour intervals. The specimen was then quenched in LN₂ and the sensor was allowed to recover for three hours in a mixture of 20% oxygen/80% nitrogen. The experiments were repeated up to an interval of five hours after welding. The results are presented in Fig. 3. As shown by the response curves, the hydrogen from the weld deposit was still detectable by the sensor after a period of five hours.

The next set of experiments was designed to gain quantitative measurements from the steel specimens. For these experiments, HSLA 100 steel was gas metal arc welded using levels of 0.1, 0.5, 1.0 and 3.0% hydrogen in argon shielding gas. The specimens were baked in a vacuum furnace at 650°C for one hour before welding. The specimens were analyzed by the standard gas chromatography (GC) method (AWS A4.3-93) to generate and report the results in mL/100 g weld metal. The other set was analyzed using the sensor.

From the sigmoidal shape of the response curves as shown in Fig. 3 it was decided to attempt and correlate the slope of the curve to the initial concentration in the specimen. The steady-state portion of the curve could be assumed to be proportional to the flux of hydrogen from the weld metal. To investigate this possibility, theoretical curves were generated using an

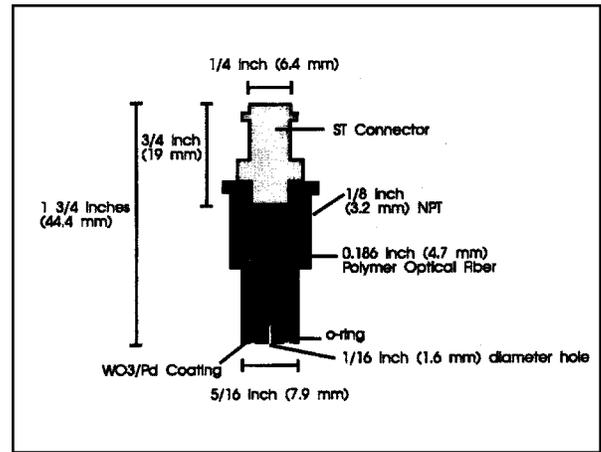


Fig. 1 — Design for prototype diffusible-hydrogen weld sensor.

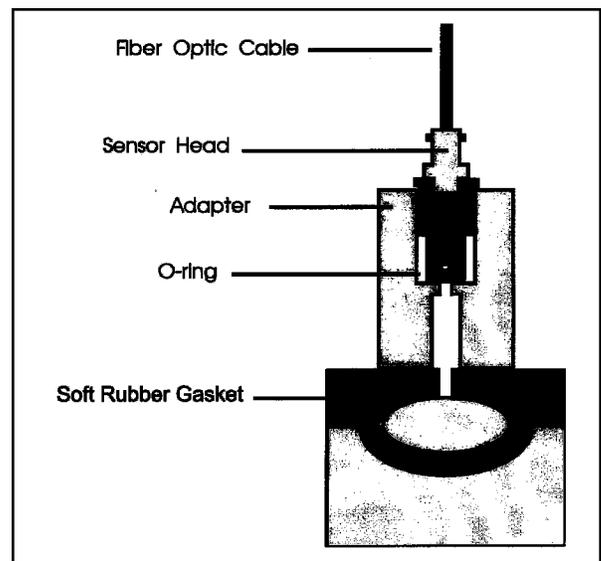


Fig. 2 — Design for prototype diffusible-hydrogen weld sensor with soft rubber gasket.

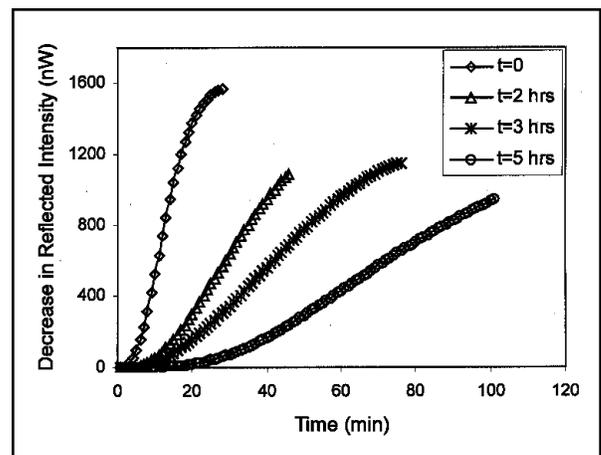


Fig. 3 — Hydrogen response data as a function of time after quenching for gas metal arc welded ASTM A36 steel (0.1% H₂/Ar shielding gas) using prototype diffusible-hydrogen sensor with soft rubber gasket.

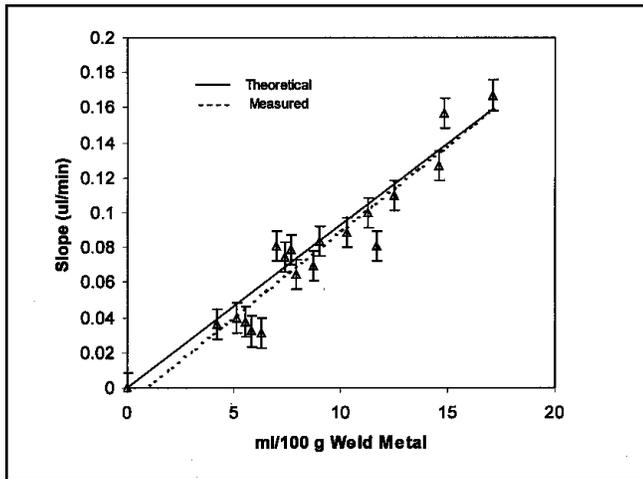


Fig. 7 — Comparison of experimental and theoretical data for fiber-optic, diffusible hydrogen sensor (gas metal arc welded HSLA 100 steel; $D_{\text{eff}} = 7.5 \times 10^{-5} \text{ cm}^2/\text{s}$; $r = 0.970$).

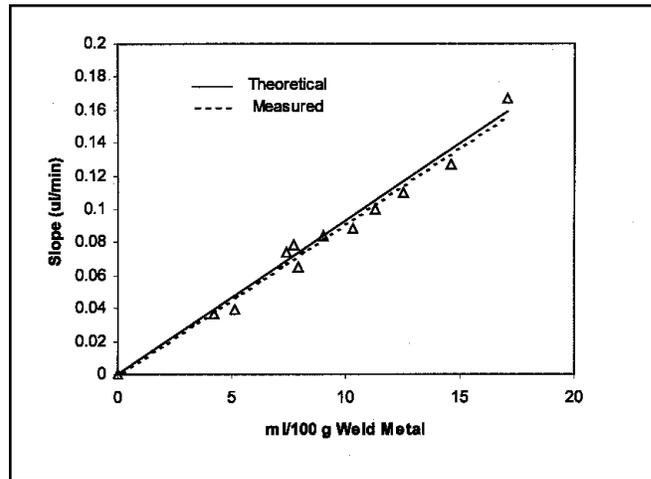


Fig. 8 — Comparison of experimental and theoretical data for fiber-optic diffusible-hydrogen sensor (gas metal arc welded HSLA 100 steel; $D_{\text{eff}} = 7.5 \times 10^{-5} \text{ cm}^2/\text{s}$; $r = 0.989$).

tremely rapid, with results obtained within ½ hour. The test may be performed on the actual welds on the structure, as opposed to a laboratory sample. The sensor is extremely sensitive and can analyze samples hours after welding. The equipment used is relatively inexpensive, and can be designed for use by trained welding personnel. It is anticipated that further refinement of the sensor design will provide the welding industry with a powerful tool for control of hydrogen damage in welded structures, especially those structures manufactured from high-strength alloys, where such control is most critical.

Conclusions

- 1) An optoelectronic diffusible-hydrogen sensor has been developed. The sensor generates results quickly, and allows analysis of an actual welded structure as opposed to a laboratory specimen.
- 2) The sensor has been calibrated to yield quantitative results for HSLA 100 steel in mL/100 g weld metal as a function of hydrogen diffusion rates from the sample surface. A resulting effective diffusion coefficient of $7.5 \times 10^{-5} \text{ cm}^2/\text{s}$ provides a good fit to measured data.

Acknowledgments

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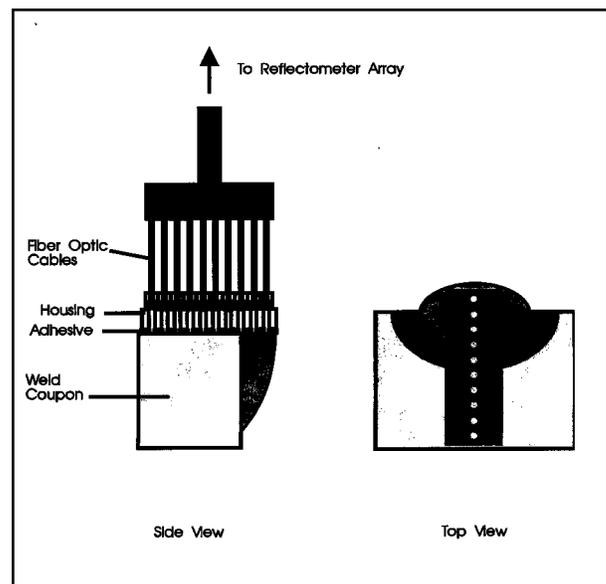


Fig. 9 — Design for fiber-optic, diffusible-hydrogen sensor array.