A Model of Hydrogen Absorption during GTA Welding

A model is presented that can be used to estimate the hydrogen concentration in GTA welds

BY J. W. HOOIJMANS AND G. DEN OUDEN

ABSTRACT. This paper proposes a model that predicts the hydrogen absorption in weld metal during GTA welding. The model is based on the assumption that the hydrogen concentration in the weld pool at any moment is the result of two mutually independent processes: inflow of hydrogen and outflow of hydrogen. To test the validity of the model, welding experiments were carried out with pure iron as base material, in which the hydrogen concentration in the weld was measured under different welding conditions. It appears that a considerable amount of the hydrogen absorbed by the liquid weld metal during the welding process leaves the weld metal immediately after extinction of the arc. This hydrogen loss can be determined by numerical calculations using a finite differential program.

It was found that the absorption model is valid in a relatively wide range of experimental conditions and can be used to estimate the initial hydrogen concentration in welds produced under realistic circumstances.

Introduction

One of the most serious problems encountered when welding metals and alloys is the absorption of hydrogen from the surroundings by the weld metal. Once absorbed by the liquid metal of the weld pool, this hydrogen can become partly frozen in during solidification, giving rise to the formation of defects, or to the occurrence of phenomena that generally have a negative influence on the properties of the weld produced.

The most important hydrogen-related weld defect is cold cracking, which under specific conditions can manifest itself when welding ferritic steel (Ref. 1). Favorable conditions for the occurrence of cold cracking, apart from the presence of hydrogen, are a susceptible microstructure (bainite, martensite), the presence of residual stresses and a relatively low temperature (<200°C). Cold cracking can occur in the weld metal and/or in the heat-affected zone of the weld and is often a cause of great concern.

Another hydrogen-related weld defect — which can occur not only in the case of steel welding but also when welding other metals and alloys — is the formation of pores in the weld during the welding process (Ref. 2). Pore formation occurs when more hydrogen is present in the weld pool than corresponds to the solubility in equilibrium with 1 bar molecular hydrogen gas. This will result in the nucleation and growth of bubbles. When the bubbles are caught up by the progressing solidification front, porosity in the weld will result.

In spite of the fact that hydrogen plays an extremely important role during arc welding, limited information is available concerning the hydrogen absorption process. This article deals with the absorption of hydrogen during GTA welding with emphasis on the absorption mechanism. A model of the absorption process is developed and the validity of this model is tested by welding experiments with pure iron.

KEY WORDS

GTA Welding
Weld Metal
Hydrogen Absorption
Hydrogen Inflow
Hydrogen Outflow
Hydrogen Concentration
Modeling

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Modeling of the Hydrogen Absorption Process

An appropriate basis for a fundamental description of the hydrogen absorption mechanism during arc welding is the assumption that the hydrogen concentration in the weld pool at any moment is the result of two mutually independent processes: inflow of hydrogen and outflow of hydrogen. This is schematically illustrated in Fig. 1.

Inflow of hydrogen takes place through the interface between the arc and the liquid metal, the inflow rate being determined by the arc conditions (notably the partial pressure of the hydrogen in the arc and the temperature of the arc). A second source is the hydrogen that enters the weld pool due to melting of the material in front of the weld pool.

Outflow of hydrogen takes place through the entire surface of the liquid metal (including that part of the surface which is covered by the arc), with the outflow rate proportionate to the hydrogen concentration in the liquid metal. In addition to the hydrogen leaving the weld pool through the outer surface, hydrogen also leaves the weld pool during solidification of the liquid metal in which it is dissolved.

On this basis, the time-dependent change of the hydrogen concentration in the liquid weld metal can be described by the equation:

$$\frac{dH}{dt} = W\left(\frac{dc}{dt}\right) = \alpha A - \beta Bc + R_m c_o - \eta R_m c \qquad (1)$$

with H the amount of hydrogen present in the liquid metal (g), t the time (s), W

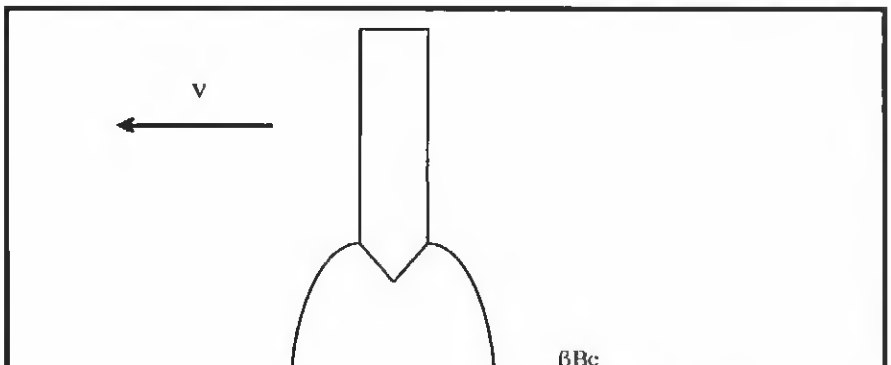

Fig. 1 — Schematic representation of the absorption process.

the weight of the liquid metal in the weld pool (g), c the hydrogen concentration in the liquid metal (wt-%), α the absorption coefficient (the amount of hydrogen entering the liquid metal per unit area per unit time, g/m²s), A the interface area between the arc and the liquid metal (m²), β the desorption coefficient (a proportionality factor depending on the temperature of the liquid metal, g/m²s), B the interface area between the liquid metal and the surrounding gas atmosphere (m²), R_m the melting rate (the amount of metal which melts per unit time, g/s) being equal to the solidification rate (the amount of metal which solidifies per unit time), c_0 the original hydrogen concentration in the material (wt-%) and η a constant representing the fraction of the hydrogen that is frozen in during solidification.

The hydrogen entering the weld pool consists of two parts: the hydrogen absorbed under the arc, represented by the term αA, and the hydrogen which enters the weld pool due to the melting of the material, represented by the term R_mc_0.

The hydrogen leaving the weld pool also consists of two parts: the hydrogen disappearing from the weld pool due to solidification, represented by the term ηR_mc, and the hydrogen leaving the material through the upper surface of the weld, represented by the term βBc. Actually, Equation 1 should also contain a term representing the hydrogen leaving the weld pool by diffusion through the fusion boundary to the solid base material. However, this term has been omitted, as it is negligibly small with respect to the term βBc.

The solution of differential Equation 1 can now be written as:

$$c(t) = \left(\frac{\alpha A + R_m c_o}{\beta B + \eta R_m}\right)\left[1 - \exp\left(\frac{-(\beta B + \eta R_m)}{W} t\right)\right] \quad (2)$$

After welding for a sufficiently long time, a steady state is achieved and the hydrogen concentration in the liquid weld metal reaches the steady state value c_e, which can be expressed as

$$c_e = \frac{\alpha A + R_m c_o}{\beta B + \eta R_m} \quad (3)$$

By substitution of:

$$R_m = vs\rho \quad (4)$$

with v the travel speed (m/s), s the surface area of the weld cross section (m²) and ρ the density of the material (g/m³), and taking η = 1 (which is a reasonable approximation as long as hydrogen bubble formation does not occur) and $c_0 = 0$ (c_0 is smaller than 0.00001 wt-%), one finally obtains the equation:

$$c_e = \frac{\alpha A}{\beta B + vs\rho} \quad (5)$$

With the help of Equation 5 it is possible to predict the hydrogen concentration in the liquid metal for any given situation. However, to make this possible the quantities A, B, α, β, v and s should be known. Values of A, B, v and s can be measured directly, whereas values of α and β can be obtained from the results of the stationary arc welding experiments described in a previous paper (Ref. 3).

Experimental Procedure

In the previous section a model was developed that describes the absorption of hydrogen in the liquid weld metal during welding under traveling arc conditions. The basic feature of the model is that, under steady state conditions, the inflow of hydrogen into the liquid metal equals the outflow of hydrogen from the liquid metal. The essential parameters of the model are the absorption coefficient α, the desorption coefficient β, the interface area between the arc and the liquid metal A, the interface area between the liquid metal and the surrounding atmosphere B, the surface area of the weld cross section s and the travel speed v.

In order to evaluate the feasibility of the model, GTA welding experiments were carried out in which the hydrogen absorption was measured under various welding conditions, using technically pure iron as workpiece material. The chemical composition of the iron samples is given in Table 1; the welding conditions used are listed in Table 2.

Table 1 — Chemical Compositions (wt-%) of the Material Used

Element	Pure Iron (Armco)
Cr	0.0179
Ni	0.013
Mo	0.005
C	0.026
P	0.0047
S	0.005
Si	0.0379
Al	0.0398
Ti	0.00107
Mn	0.031
O	0.002
N	0.001
H	0.000009

Table 2 — Welding Conditions Used

Arc Current	100 A
Arc Voltage	13.5 V
Arc Length	3 mm
Test Piece Size	30 x 15 x 10 mm
Polarity	electrode negative
Electrode Diameter	3.2 mm
Electrode Top Angle	60 deg
Shielding Gas Composition	95% argon – 5% hydrogen
Shielding Gas Flow Rate	10 L/min
Travel Speed	3.1 mm/s

The welding setup chosen was identical to that described in the IIW procedure for hydrogen determination (Ref. 4). In this setup the workpiece consists of three parts, with the center one (the test piece) used for the actual hydrogen determination — Fig. 2. Welding was carried out using a DC power source (ESAB DTA300) equipped with high freqoency ignition to

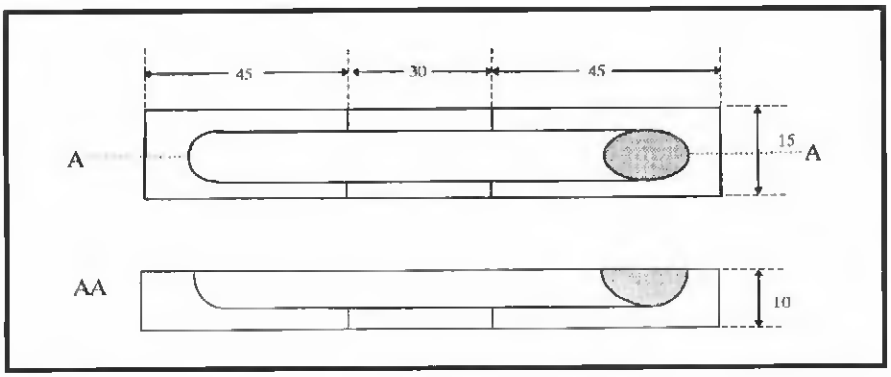

Fig. 2 — Dimensions (mm) of the test pieces used in the experiments.

ignite the arc. Arc voltage and arc current were continuously registered by means of an x-t recorder.

The diffusible hydrogen present in the test pieces after welding was determined using the IIW standard method (Ref. 4). The residual hydrogen was determined using a gas chromatograph of the type Ströhlein M-MAT 251.

Using the setup and following the procedure outlined in the foregoing, the hydrogen absorbed in pure iron during welding was determined as a function of hydrogen content of the shielding gas, arc current, arc voltage (arc length) and travel speed. Some of the results obtained are presented in Fig. 3. In this figure, the measured hydrogen concentration in the weld metal is shown as a function of heat input. The figure shows that the hydrogen concentration in the weld metal increases with heat input.

At this point it should be noted that the steady state value c_e predicted by the model refers to the hydrogen concentration in the liquid metal during welding, which in most cases is not equal to the measured concentration. In fact, a relatively large part of the hydrogen originally present in the weld will be lost in the moment between the extinction of arc and the analysis of the test piece. The amount of hydrogen that leaves the test piece is dependent on the time between arc extinction and analysis and on the diffusion coefficient, which in turn is dependent on the temperature (Ref. 5). This amount can be relatively large, due to the high diffusion rate of hydrogen in metals, especially at high temperature.

To make a comparison possible between the experimental data and the data predicted by the model, it is necessary to calculate the initial hydrogen concentration (the hydrogen concentration in the liquid metal during welding) from the measured hydrogen concentration.

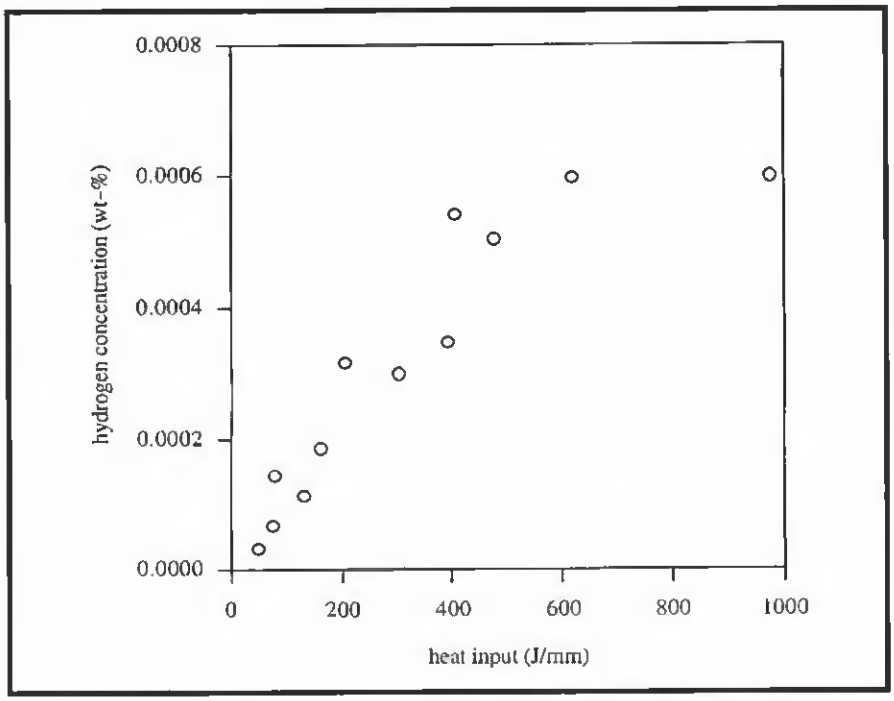

Fig. 3 — Measured hydrogen concentration in the weld as a function of the heat input (shielding gas composition 95% argon–5% hydrogen).

Calculation of the Initial Hydrogen Concentration

Calculation of the initial hydrogen concentration was carried out numerically with the help of a finite differential program, using the measured amount of hydrogen in the test piece as input data. The principle of this calculation method is based on an approach described in a previous paper dealing with arc welding under stationary (nontraveling) arc conditions (Ref. 3). Basis of the calculation is the diffusion of hydrogen through the material, governed by Fick's laws of diffusion.

In order to be able to carry out the calculations, the following assumptions were made:

1) The escape of hydrogen from the test piece during the moment between when the liquid metal solidifies and the test piece is put into water is regarded as a two-dimensional diffusion problem. This can be justified by the fact that the travel speed of the arc is much larger than the rate of hydrogen diffusion. Thus, the test piece can be considered as a series of thin slices within each of which the hydrogen diffuses only in a plane normal to the welding direction. The hydrogen concentration in the total test piece was considered to be the average of the hydrogen concentrations in the different slices of the material.

2) The transverse cross section of the weld has the form of a perfect half ellipse.

3) The diffusion coefficient of hydrogen in the material is constant during cooling. For the calculations, a value of 1×10^{-4} mm²/s is taken, which is approximately the average value of the diffusion coefficient in the cooling range of interest (between the melting point and about 500°C [932°F]) (Refs. 6–8). Justification of this assumption is given below.

4) No bubble formation occurs during the entire welding process.

5) At the moment the weld solidifies, the hydrogen is evenly distributed over the weld (no concentration gradient), while in the surrounding material of the same slice, no hydrogen is present. This is

a reasonable approximation, because the diffusion of hydrogen in the material is slow compared to the travel speed.

6) The hydrogen that reaches the surface of the test piece in atomic form will immediately recombine to molecular hydrogen and disappear into the surrounding atmosphere.

Based on the assumptions formulated above, a finite differential calculation program was developed (Ref. 9). In this approach, the sample is divided in thin slices perpendicular to the welding direction, which in turn are divided in small segments. The change in hydrogen concentration with time is calculated for each of the segments in distinct time steps. The equation used can be written as

$$\frac{c_{i,j,n+1}-c_{i,j,n}}{\delta t} = \frac{D}{(\delta x)^2}\left(c_{i-1,j,n}-2c_{i,j,n}+c_{i+1,j,n}\right) + \frac{D}{(\delta y)^2}\left(c_{i-1,j,n}-2c_{i,j,n}+c_{i+1,j,n}\right) \quad (6)$$

in which c is the concentration, δt the length of the time step, D the diffusion coefficient, δx the segment size in the x-direction, δy the segment size in the y-direction, i the rank number of the segment in the x-direction, j the rank number of the segment in the y-direction and n the rank number of the time step.

The time step and the segment size are limited by the diffusion coefficient. This approach is computationally straightforward, but has a stability restriction that can be expressed by the equation

$$D\left(\frac{1}{(\delta x)^2}+\frac{1}{(\delta y)^2}\right)\delta t \le \frac{1}{2} \quad (7)$$

Using the method described in the foregoing, values of the initial hydrogen concentration were calculated from the measured hydrogen concentration for various situations and experimental conditions. Some of the results obtained are presented in Figs. 4 and 5.

In Fig. 4 the hydrogen left in the test piece (expressed in terms of the percentage of the hydrogen originally present) is plotted as a function of the diffusion coefficient. The figure shows that the percentage of hydrogen left in the test piece changes only slowly with the diffusion coefficient in the range of interest, which can be considered as a justification of assumption c.

Figure 5 depicts both the calculated initial hydrogen concentration in the sample and the measured values as a function of the hydrogen percentage in the shielding gas. The figure clearly shows that the initial values and the measured values of the hydrogen concentration in the sample differ considerably (more than a factor two) over the entire range of shielding gas composition.

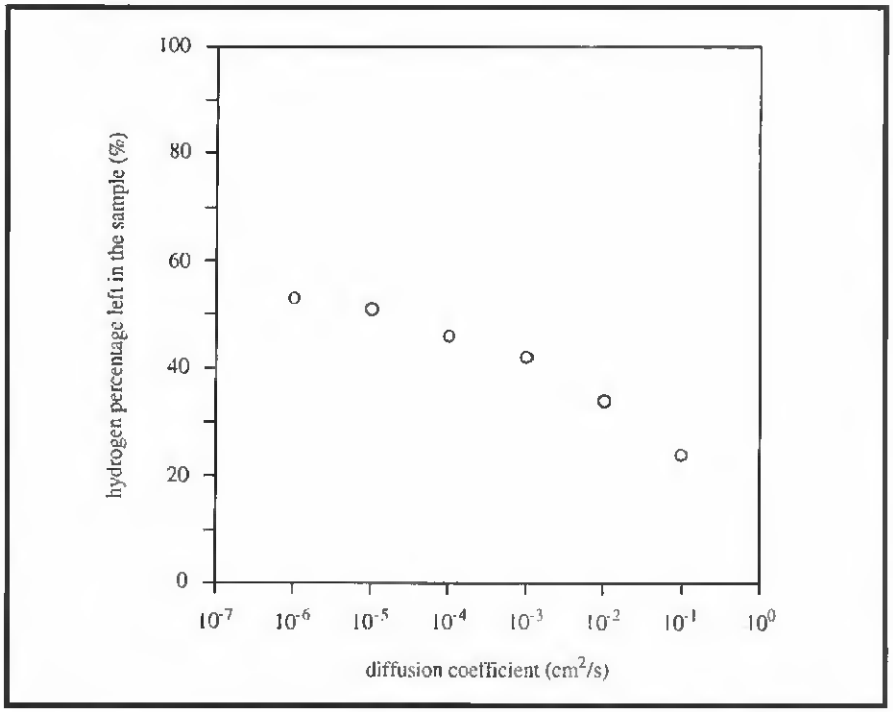

Fig. 4 — Hydrogen left in the test piece (percentage of the hydrogen originally present) after cooling as a function of the diffusion coefficient.

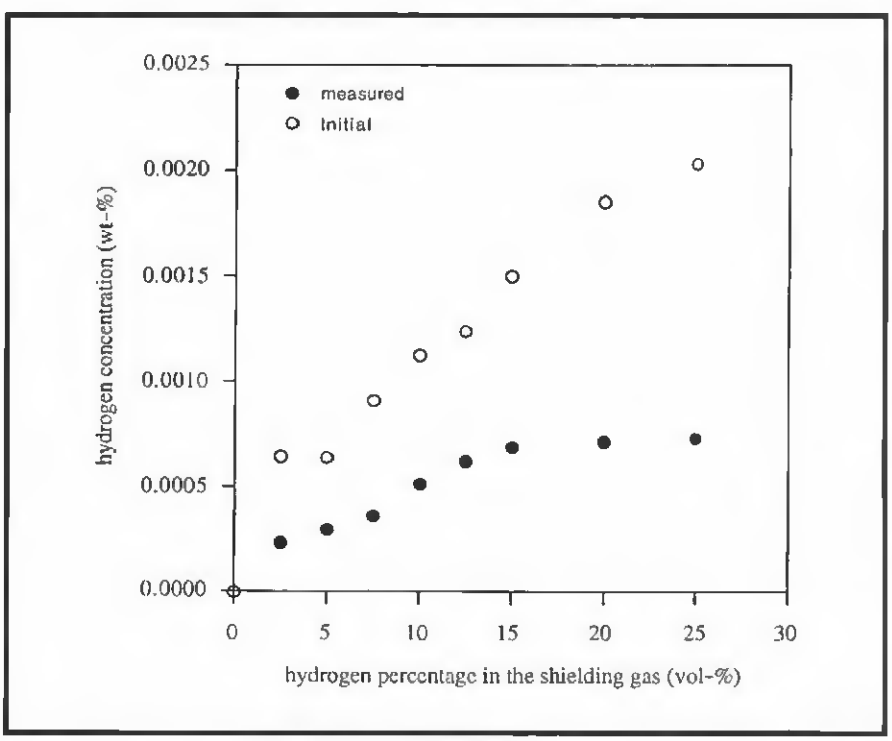

Fig. 5 — Measured and initial hydrogen concentration in the weld as a function of the hydrogen percentage in the shielding gas.

Comparison Between Model and Experiment

To test the validity of the model, values of the initial hydrogen concentration c_i as calculated from the measured values, can now be compared with the

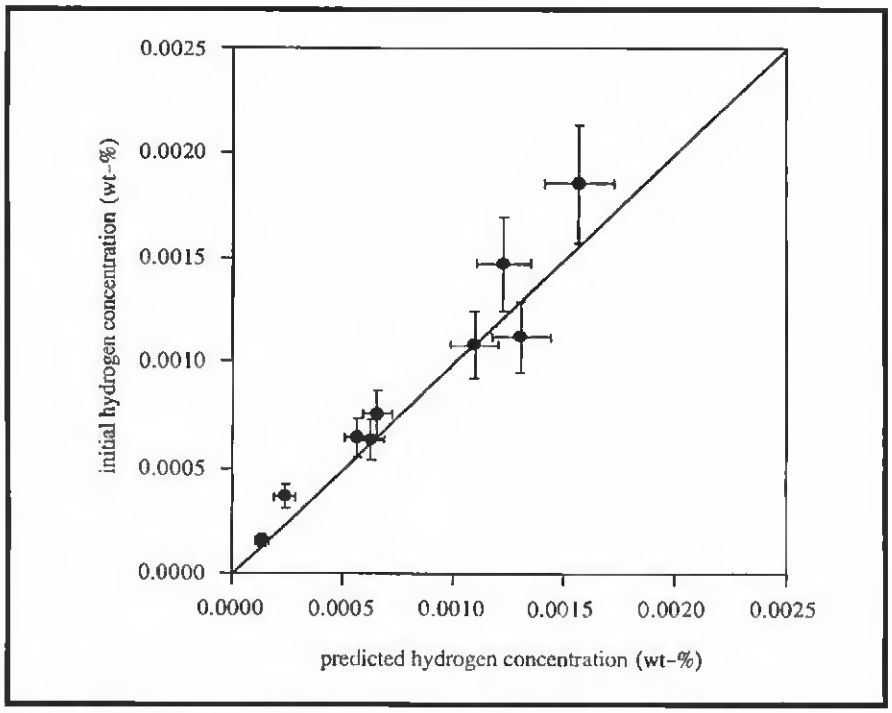

Fig. 6 — Plot of initial hydrogen concentration vs. hydrogen concentration predicted by the model.

model values c_e obtained with the help of Equation 5, using the values of α and β obtained from the results of stationary arc welding experiments (Ref. 3).

This was done for a number of different experimental conditions, *i.e.*, the standard conditions listed in Table 2 with different values of

1) The hydrogen percentage in the shielding gas (5, 10 and 20 vol-%)

2) The arc current (100, 200 and 300 A)

3) The arc length (1.5, 3 and 6 mm)

4) The travel speed (3, 7 and 18 mm/s).

The results are presented in Fig. 6 in the form of a c_i vs. c_e plot. The figure shows that reasonable agreement exists between the initial hydrogen concentration and the hydrogen concentration predicted by the model. Apparently, the model is valid in a relatively wide range of experimental conditions and can be used to estimate the initial hydrogen concentration in welds produced under realistic circumstances.

Conclusions

The results of the experiments lead to the following conclusions:

1) During GTA welding, large amounts of hydrogen can be absorbed by the weld metal.

2) A large part of the hydrogen absorbed by the weld metal during welding leaves the weld immediately after extinction of the arc.

3) The initial hydrogen concentration in the weld pool can be determined from the measured hydrogen concentration by numerical calculations using a finite differential program.

4) The hydrogen absorption process can be described in terms of a model based on the assumption that the hydrogen concentration in the weld pool at any moment is the result of two mutually independent processes: inflow of hydrogen and outflow of hydrogen.

5) The absorption model is valid in a relatively wide range of process parameters and can be used to estimate the hydrogen level in welds produced under realistic welding conditions.

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