Introduction

Dissolved hydrogen is always introduced into a weld as a result of the welding process if it is introduced in sufficient quantities, it will cause cracking of the joint. The concentration at which cracking occurs depends on a combination of factors which include the inherent susceptibility of the microstructure and the magnitude of the residual welding stresses. The separate and combined role of these factors has been studied extensively. In principle, hydrogen cracking could be avoided if as-welded stress were eliminated. At present, however, there are no practical methods for achieving this. Stresses can be reduced by postweld heat treatment, but cracks can still form during the period between completion of welding and application of stress relief heat treatment.

Similarly, the prevention of hydrogen cracking solely through control of the microstructure is a limited practical option. The microstructure of the weld metal and heat-affected zone is largely dependent on the composition. This composition must clearly be chosen so as to fulfill a broad range of performance requirements based on strength, toughness, creep performance, etc., and not simply for preventing hydrogen cracking.

Welding process parameters such as heat input, travel speed, etc., will have a limited effect in so far as they alter the cooling rate through the transformation range and, in general, increased heat input leads to softer microstructures. However, alteration of process parameters can have a whole range of effects, not least of which, for example, would be an increase in grain size in both weld metal and heat-affected zone resulting from an increased heat input. Thus, while the latter might work in the direction of a softer structure, the resulting grain coarseness might be detrimental in terms of joint performance.

The application of preheat to the joint is beneficial in the same sense that it too alters the nature of the transformation products and promotes softer microstructures. Again, however, this occurs only within the confines of the basic composition being welded.

If the methods referred to above prove inadequate, then a further line of attack is to exercise control over the concentration of hydrogen in the weld. In principle, if this concentration can be kept below the critical level, then cracking will not occur. This leads to two further options. The first of these is to control the entry of hydrogen into the weld in the first instance by applying suitable baking and storage treatments to the consumables used. This is the subject of a separate study some of which has been reported elsewhere. The second is to reduce—by specifying a suitable postweld heat treatment—the concentration of hydrogen present to a safe level; this is the aim of the present work.

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Diffusion Model

To specify a heat treatment for hydrogen removal or to quantify the effect of an existing one, e.g., a stress relief cycle, it is necessary to calculate the concentration profile in the weld as a function of time. Some heat treatments involve lengthy heating and cooling periods. Because of this, much of the diffusional transport can take place under non-isothermal conditions. The diffusion coefficient, \( D \), which is an exponential function of temperature will thus vary with time, \( t \), and direct integration of Fick's law:

\[
\frac{\delta c}{\delta t} = D(t) \cdot \left( \frac{\delta^2 c}{\delta x^2} + \frac{\delta^2 c}{\delta y^2} \right)
\]

where \( c \) is concentration and \( x, y \) are spatial coordinates, but is not possible.

For this reason a parameter, \( T \), has been used and is defined as:

\[
T = \int D \, dt
\]

which on insertion into equation (1) gives:

\[
\frac{\delta c}{\delta t} = D(t) \cdot \left( \frac{\delta^2 c}{\delta x^2} + \frac{\delta^2 c}{\delta y^2} \right)
\]

Equation (3) can be solved analytically or numerically to give the concentration, \( c \), as a function of position \( (x, y) \) and the parameter, \( T \). The solution found must satisfy the boundary and initial conditions imposed by the particular weld being treated. These usually take the form of zero concentration at the surface of the structure at all times and a given distribution of hydrogen at zero time. \( T \) may
be evaluated in a given situation in the following manner.

Any heat treatment schedule can be converted from a temperature/time cycle to a D vs. time curve (Fig. 1) if D is known as a function of temperature. The area under this D/time curve gives a value for T, i.e.,

\[ T = \int \frac{D}{t^2} \, dt \]

If the simpler constant temperature case is considered then,

\[ T = \frac{D_0 \cdot t}{t} \]

where \( D_0 \) is the diffusion coefficient at temperature \( \theta \). Thus, point concentrations and average concentrations can be obtained at any time in the heat treatment cycle, or after any period of time at constant temperature, from the solution to equation (3) obtained analytically or numerically.

In a previous paper, the numerical method of solving equation (3) was introduced based on the finite element technique using a heat conduction computer program. To demonstrate the method it was applied to a fillet weld for which an analytical solution was not available.

The purpose of this paper is to report the application of the technique to several other important weld geometries with the aim of specifying in general terms heat treatments that will reduce hydrogen concentrations in a weld to any desired value. As in the fillet weld case, strict analytical solutions do not exist for these welds.

### Selected Welds and Results

In treating the fillet weld, the weld shape was obtained by tracing the outline of a section from an actual weld. Similar outlines have been produced for four further typical welds: a single-V butt weld, a double-V butt weld, a single-V nozzle weld, and a double-V nozzle weld.

Meshes have been produced, based on these drawings. An example is shown in Fig. 2. Figure 3 shows typical constant concentration contours obtained at selected values of the parameter \( T/L^2 \), where \( L \), a linear dimension of the weld, is defined in the illustra-
tion. The boundary conditions were the same as in the previous work: at \( t = 0 \), a uniform concentration of hydrogen within the weld metal and zero concentration everywhere else, and at \( t > 0 \), zero concentration everywhere outside the structure.

The contours can be produced for any value of \( T/L \) and illustrate the way in which hydrogen diffuses away from the weld area. Using an averaging procedure described in the earlier paper, the fractional average concentration \( \bar{c}/c_0 \) of the weld metal region can be computed, again as a function of \( T/L \). These are plotted in Figs. 4 and 5, and the appropriate curve for the fillet weld is reproduced in Fig. 6.

It has been shown in the previous section how, knowing the temperature history of the weld, a \( T \) value can be obtained. This, together with knowledge of the linear dimensions of the weld, enables \( \bar{c}/c_0 \) values to be read from graphs such as those shown in Figs. 4-6. It should be noted that these curves relate specifically to the actual welds for which the calculations were done.

Strictly, any other example of one of the given weld types which is not geometrically similar will give a slightly different result. However, in practical terms the differences are not likely to be significant; most welds may be approximated by one of those shown in Figs. 4-6. Several practical examples of hydrogen concentration reductions may now be given.

### Stress Relief Heat Treatment

For many welds a postweld tempering and stress relief heat treatment will be specified, and it is instructive to calculate the reduction in hydrogen content due to some of the current specifications. These demand controlled heating and cooling of the weld and associated base material. Moreover, it should be noted that a considerable amount of hydrogen dispersal can occur during these heating up and cooling down periods. For welds in 2\( \frac{1}{4} \)Cr-1Mo and 2\( \frac{1}{2} \)Cr-\( \frac{1}{2} \)Mo-1\( \frac{1}{4} \)W pipework, the following heat treatment is specified: a heating rate < 100 C/h (180 F/h); holding temperature—660-720 C (1,274-1,328 F); holding time—2h/25mm (2 h/1 in.); cooling rate down to 400 C (752 F) < 50 C/h (90 F/h).

For welds in pressure vessels, BS 1515 (1965) sets out the following:

1. Heating Rate: 200 C/h (or 360 F/h) up to 25 mm (1 in.) in thickness; 5080 C (or 9,176 F)/d/h where \( d \), the thickness, is < 100 mm (3\( \frac{3}{4} \) in.); 50 C/h (90 F/h) where \( d > 100 \) mm (3\( \frac{3}{4} \) in.).
3. Holding Time: 1h/25 mm (1 h/1 in.).
4. Cooling Rate to 400 C (752 F): 250 C (450 F)/h up to 25 mm (approx 1 in.); 5080 C (or 9,176 F)/d/h where \( d < 100 \) mm (3\( \frac{3}{4} \) in.); 50 C/h (90 F/h) where \( d > 100 \) mm (3\( \frac{3}{4} \) in.).

In Table 1 the 2\( \frac{1}{4} \)Cr-1Mo/1\( \frac{1}{2} \)Cr-\( \frac{1}{2} \)Mo-1\( \frac{1}{4} \)W cycle has been applied to the butt and fillet welds, and the pressure vessel cycle has been applied to the nozzle welds. The holding times at the top temperature are those required by the specifications, and the relative average concentration of hydrogen remaining as a result of this plus the heating and cooling portions of the cycle are given. Diffusion coefficients have been taken from the review by Coe and are the middle of the range of quoted measured values.

The results illustrate the effect of:
outgassing of the double-V geometries of thin sections and double-V weld metal is used and the "average" examined here arises because less perhaps obvious. The more rapid "L values are defined in Figs. 4-6.

**Table 1—Relative Average Hydrogen Concentration Remaining as a Result of Stress Relief Heat Treatment**

<table>
<thead>
<tr>
<th>Weld metal hydrogen conc., %</th>
<th>Butt welds&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Fillet welds&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Nozzle welds&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2L = 12.7 mm</td>
<td>2L = 76 mm</td>
<td>2L = 6 mm</td>
<td>2L = 12.7 mm</td>
</tr>
<tr>
<td>50</td>
<td>0.28 (130)</td>
<td>0.14</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
<td>1.3</td>
<td>60</td>
</tr>
<tr>
<td>1</td>
<td>4.2</td>
<td>3.2</td>
<td>151</td>
</tr>
</tbody>
</table>

<sup>a</sup>L values are defined in Figs. 4-6.

<sup>b</sup>Bracketed figures are times at 20 C (68 F), D<sub>i</sub> = 1 × 10<sup>-10</sup> mm<sup>2</sup>s<sup>-1</sup>; D<sub>avg</sub> = 4.5 × 10<sup>-10</sup> mm<sup>2</sup>s<sup>-1</sup>.

1. Section thickness.
2. Double-V vs. single-V weld preparation, thin sections and double-V preparations being the most favorable.

The effect of section thickness is perhaps obvious. The more rapid outgassing of the double-V geometries examined here arises because less weld metal is used and the "average" linear dimension across the weld width is smaller. Transport by diffusion is a process which depends upon the square of these dimensions, and it is clearly advantageous from this point of view to reduce the amount of weld metal used in making the weld.

As stated previously, the reduction in hydrogen concentration necessary to ensure freedom from cracking will depend on the inherent susceptibility of the microstructure and the level of residual stress. The latter will be determined by several factors among which are the degree of restraint applied to the weld by the surrounding material, the temperature interval between end of transformation, and the preheat temperature. High stresses and susceptible microstructures require a lower hydrogen content.

At the present time there is no way of fully quantifying these effects in a real welding situation, and the maximum tolerable hydrogen content must be estimated from experience. There is some evidence<sup>9</sup> that the weld metal concentration immediately after welding is not likely to be > 50% of those values determined for the consumables using the standard test.<sup>11</sup> Since these should lie mainly in the range 10–15 ml H<sub>2</sub>NTP/100g weld metal if welding processes of relatively low hydrogen potential are used, the weld itself may contain 5–7 ml H<sub>2</sub>NTP/100g. Reduction of this content to < 1 ml H<sub>2</sub>NTP/100g should give freedom from cracking in most cases<sup>10</sup> so that a tenfold decrease in weld hydrogen content should suffice.

Table 1 shows that the standard heat treatments achieve reductions to < 10% of the starting concentration in almost every case and should, therefore, subsequently give freedom from hydrogen-induced cracking.

### Effect of Postheat

There are three situations at least in which cracking may still occur:

1. A stress relief heat treatment after welding may not be required by the specification.
2. Where one is specified, there may be a lengthy period at room temperature between the completion of welding and its application.
3. There may be a lapse in preheat during actual welding.

The last of these could allow the weld to cool sufficiently to enter a "crack-sensitive" region while still containing a relatively high concentration of hydrogen. Preheat temperatures generally lie in the range 100–250 C (212–482 F) and cracking has rarely, if ever, been observed in this region, probably because of increased solubility of hydrogen in the metal matrix. It follows, therefore, that as long as the preheat is maintained between completion of welding and heat treatment, and is not allowed to lapse during welding, two of the three possible dangers referred to above may be avoided.

Returning to the first case where no heat treatment is called for, preheat must be maintained for sufficient time after welding to allow a safe concentration of hydrogen to be reached. Example of the time needed at 250 C (482 F) to allow the concentration to reach 50, 10 and 1% of that present initially for the different weld types are given in Table 2. For comparison, the bracketed figures show the time required at 20 C (68 F) which would represent the extreme situation where no postheating was used. The diffusion coefficients, D<sub>i</sub> and D<sub>avg</sub> used in the calculation are again taken from the middle of the range of measured values.

It can be seen from Table 2 that, in order to reduce the hydrogen concentration to a tenth of its original value, a preheat of 250 C (482 F) must be maintained after welding for a period varying from a few hours to at least 2 days, depending mainly on the section thickness 2L.

In the case of the 12.7 mm (5 in.) single-V nozzle weld, a 2 day postheating at 250 C (482 F) would lead only to a 75% reduction. However, a weld in this section thickness would almost certainly require stress relief. Consequently, the safe course of action would be to maintain the preheat if possible until stress relief heat treatment was applied. If, for example, it were intended to inspect the weld at ambient temperatures for defects be-
fore heat treatment, then it must be recognized that some risk of hydrogen cracking is incurred due to the difficulty of outgassing a weld of this thickness.

**Discussion**

The heat treatment recommendations outlined above should provide freedom from cracking under most circumstances. However, it is important to re-examine the assumptions on which these are based.

The choice of reduction to an average concentration level 10% of the initial value is made to cover as wide a range of circumstances as possible. It may, for several reasons, be too conservative. In the case of a stress relieved joint, the heat treatment cycle is mandatory and it turns out that the 10% criterion is met anyway. In other cases, comparing the postheating times required by the analysis (Table 2) with industrial practice suggests that the requirement to meet the 10% level would be too stringent in some instances and the times given for the 50% level may be more in line with some of the practical experience.

There are several possible reasons for this. First, if manual metal arc electrodes are baked and stored appropriately, they will generate (under test conditions) nearly 5-7 ml H₂/100 g weld metal than 10-15 ml as assumed. Thus, the starting concentration in the actual weld will be lower, and lower percentage reductions due to postheating will be required. Conversely, of course, poor industrial practice in terms of electrode care might lead to levels > 15 ml and give rise to cracking where it otherwise might not have occurred. Second, aiming for < 1 ml H₂ as a final concentration does not take account of variations in the susceptibility of different microstructures.

Steels vary in their hardenability and transformation products. It is well known that these factors affect the cracking tendency. Some of the softer microstructures will be able to tolerate > 1 ml H₂ without cracking under a given system of residual stresses.

The thickness parameter must be considered. Thickness has a square law effect on hydrogen diffusion, and this has been taken account of in the analysis. However, welds in thick sections take longer to make and this means greater opportunity for hydrogen to escape from the system during welding, resulting in a lower starting concentration. Against this must be set the fact that because thicker welds are more heavily restrained, the residual stresses built up are likely to be greater and, in this respect, will demand a lower final hydrogen concentration to ensure freedom from cracking. The extent to which the first effect helps in achieving a safe level is unknown.

Summarizing, there are several factors to take into account when selecting a postheating schedule for a particular application. In terms of an all-embracing recommendation, aiming for the 10% level should certainly give freedom from cracking in almost every case, but may be too stringent in some circumstances. If the heat treatment required to achieve this level is too lengthy and/or costly, then the other option is to introduce less hydrogen into the weld in the first instance. This may be achieved through the proper baking and storage of electrodes. It may then be sufficient to aim for the 50% level in Table 2.

The results in Tables 1 and 2 have been obtained using literature average values for the diffusion coefficient D₂. If a more accurate value, D₂, is available in a particular case, then a time t₁ read from Table 2 may be corrected to a more accurate value t₂ using the relationship:

\[ D_2 t_2 = D_1 t_1. \]

This arises from the fact that all concentrations are functions of the dimensionless parameter T/L² which at constant temperature is equal to D₂t/L².

Table 1 results are for non-isothermal conditions and although the function is still T/L², it is given by D(t) dt. Thus, to improve accuracy in this case D must now be known over the whole temperature range of the heat treatment cycle. These modifications are unlikely to produce significant differences in the general conclusions.

**Conclusions**

1. Finite element techniques can be applied to real weld shapes to derive hydrogen concentration curves. These then form the basis for an evaluation of postweld heat treatment in terms of hydrogen dispersal from welds.
2. Any chosen level can be reached after welding by maintaining postheating for a period which may be calculated from the finite element results.
3. Hydrogen outgassing in the region of 20°C (68°F) is a lengthy process so that welds requiring stress relief heat treatment will incur some risk of cracking if allowed to cool to ambient between completion of welding and application of the heat treatment.

In general, the mandatory stress relief heat treatments are sufficient to lower hydrogen concentrations to less than 10% of that present initially. Evidence available in the literature suggests that this level will ensure freedom from cracking in most cases.

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**References**