

# Hydrogen Content of Single and Multipass Steel Welds

*Tests using covered electrodes were conducted to evaluate the effect of composition and thermal cycling on weld metal hydrogen content*

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**ABSTRACT.** A series of IIW type test welds, as used for the measurement of diffusible hydrogen, have been made with mild steel and matching composition all weld metal center test piece assemblies. A series of multipass welds have been made with different SMA electrode coating types and compositions, and both series have been used to study the influence of composition (E7018, 9018, 12018 and 6013 types) and thermal cycle on diffusible and residual hydrogen contents. The thermal cycle was altered by introducing delays of 5 and 30 minutes before quenching.

Changing the IIW center test piece from mild steel to matching all weld metal did not alter the total diffusible hydrogen content but made some alterations to the "three-day figure," particularly for the E6013 deposit, which was reduced. Increasing the time before quenching the test piece reduced diffusible hydrogen content, as would be expected. The residual hydrogen content was also affected, increasing slightly with alloy content while it was particularly high for the rutile deposit.

For the multipass welds, increasing the alloy content of the EXX18 deposits increased the remaining diffusible hydrogen level as much as 2.5 times, probably caused by a reduced diffusivity and a lowered transformation temperature.

## Introduction

For the majority of practical welding operations, the weld thermal history is significantly different from that adopted in the standard test welds used for diffusible hydrogen measurements made using the IIW recommended standard procedure (Ref. 1). For example, a real weld may experience a faster initial rate of cooling than a test weld, but undergo a longer cooling period, compared to the test weld which is water quenched as quickly as possible after completion of welding. The effect of the cooling cycle upon the ratio of diffusible to residual hydrogen in a weld has been investigated

by Coe and Chano (Ref. 2), who reported that delaying the quench of shielded metal arc (SMA) test welds may increase the proportion of residual to diffusible hydrogen.

Many practical welds are multipass and therefore see significant reheating as part of their overall thermal history; this is also different from that of the standard test welds. It is generally assumed (Ref. 3) that it is the diffusible hydrogen in a weld that causes cracking (if it is present in sufficient concentration) and conversely, that the residual hydrogen, which is trapped, e.g., in molecular or combined form, is innocuous. Ødegård, Evans and Christensen (Ref. 4) found that, with rutile and acid coated SMA electrodes in multipass C-Mn deposits, the proportions of residual to diffusible hydrogen were respectively 90% and 80%.

A study was initiated to investigate: 1) for the standard test welds, the influence of delay periods before quenching on conversion of diffusible to residual hydrogen and 2) for multipass welds, to examine the residual to diffusible hydrogen ratio. For each of these objectives, a further factor, that of consumable composition, was examined by using a series of two C-Mn deposits with and without Ti, and two different levels of alloying in low-alloy deposits. A rutile electrode, was also included since, in the work of Ødegård, et al., it was with a rutile electrode, rather than a basic electrode that apparent conversion of diffusible to residual hydrogen was noticed. The standard test weld uses a mild steel test piece assembly which significantly reduces the alloy content of

the test weld for the alloyed electrode deposits. It was, therefore, decided to use test blocks manufactured from all weld metal multipass deposits as a further variable.

## Experimental Approach

A range of four basic, coated (EXX18) SMA electrodes with increasing alloy content, three of them giving a deposit with ~30 ppm Ti, were produced in the semi-baked condition. These, together with a rutile electrode, were used to make multirun "all weld" deposits in 20 mm thick carbon manganese steel plate similar to that required in ISO 2560-1973. Sufficient welds were made using each electrode type for the following to be provided:

- 1) All weld metal samples analyzed for diffusible and residual hydrogen.
- 2) All weld metal test samples to be used as the test assembly center pieces in standard single run IIW test welds.

Each electrode type was also used to make a series of standard and modified test welds to the IIW procedure. The series of welds made were:

- 1) Standard IIW procedure;
- 2) As 1) but with test piece assembly material made from degassed and matching composition all weld metal samples;
- 3) As 2) but with a delay of five min before quenching;
- 4) As 3) but with 30 min delay.

## Experimental Details

### SMA Welding Consumables

Four experimental electrodes of the following types were prepared:

- 1) An E7018 type giving a deposit with 1.5% Mn, <5 ppm Ti.
- 2) An E7018 type giving a deposit with 1.5% Mn, 30 ppm Ti.
- 3) An E9018 type giving a deposit with 1.5% Mn, 1% Ni, 0.25% Mo, 30 ppm Ti.
- 4) A E12018 type giving a deposit with 1.5% Mn, 3% Ni, 0.4% Mo, 30 ppm Ti.

These were dried at 295°C (563°F)

### KEY WORDS

IIW Type Test Welds  
E7018 Electrodes  
E9018 Electrodes  
Diffusible Hydrogen Content  
Multipass Welds  
Rutile Deposits  
Residual Hydrogen Content

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for one h, which was selected to give a standard IIW deposit hydrogen level of 10–15 mL/100 g. A fifth electrode, with a rutile coating *i.e.*, E6013 type, was used in the as-received condition.

### Hydrogen Samples, Multirun Deposits

For each of the basic electrode types given above, and for the rutile electrode, standard, multirun deposits to ISO 2560-1973 were prepared in 20 mm thick plate. The basic electrodes were dried at 295°C (matching that used in the IIW type tests), 350°C (662°F) and 420°C (788°F) for one h to give standard IIW deposit hydrogen levels of 10–15, 5 and 2.5 mL/100 g. Welding was done in the flat position and three beads per layer were deposited. A current of 170 A (DCEP) was used on the 4 mm diameter electrode with an arc energy of 1 kJ/mm. The interpass temperature was standardized at 200°C (392°F). Upon completion of welding, each weld was allowed to cool for 30 min to  $\sim$ 50°C ( $\sim$ 122°F), before being quenched down to  $\sim$ 80°C (112°F). Samples,  $\sim$ 10 x 10 x 40 mm, for hydrogen analysis, were extracted from the center of the weld, keeping the plate cold with solid carbon dioxide during cutting. The samples were kept at low temperature until required for diffusible hydrogen measurement. Some samples were allowed to degas at room temperature for three months before measuring the residual hydrogen content.

### Test Piece Assemblies for IIW Test Welds

Center test piece assemblies were prepared from the multipass weld to the dimensions and surface finish specified in the IIW procedure (Ref. 1). The run on and run off pieces, and center pieces for the standard IIW tests, were prepared from bright mild steel bar stock, specification BS 970: Part 1: 1972: 070M20, and the composition given in Table 1.

### IIW Type Test Welds

For each of the electrode compositions and for each of the five conditions defined previously, duplicate test welds were made. Welding was carried out at a current of 170 A, 22 V DC+ve with a

travel speed such that the 100 mm long test weld took 33 s to deposit, and used typically 125–130 mm of electrode. The humidity at the time of welding was in the range 45%RH at 21°C (69.8°F) to 52% at 22°C (71.6°F). In order to allow consistent drying treatments to be used for each batch of ten welds, sufficient electrodes were dried prior to the welding operation and sealed in glass tubes until required for welding. The welds were made using a SMA deposition machine with an automatic traverse and electrode feed. All welds were made on the same day.

After welding ceased, the welds were removed immediately from the copper welding jig and either water quenched immediately, as required by the standard, or allowed to cool for the requisite time in still air before water quenching. When the welds approached water temperature, they were transferred to carbon dioxide. The five min delay samples had cooled to  $\sim$ 300°C (572°F) and the 30 min delay samples to  $\sim$ 50°C ( $\sim$ 122°F) before quenching. After quenching to the temperature of solid carbon dioxide, the welds were cleaned by wire brushing and stored in liquid nitrogen until required for analysis.

### Analysis for Diffusible and Residual Hydrogen

#### Y-Tube Measurements for Diffusible Hydrogen at Ambient Temperature

The standard and modified IIW test welds were analyzed for room temperature diffusible hydrogen by collecting the evolved hydrogen over mercury in a Y-tube. Measurements of the hydrogen were taken at regular intervals up to 28 days for the basic electrodes and up to 49 days for the rutile electrodes. The samples were then returned to storage in liquid nitrogen to await analysis for residual hydrogen.

#### Oerlikon/Yanaco Diffusible Hydrogen Analyzer at 150°C (302°F)

The samples from the multipass welds were analyzed for diffusible hydrogen at 150°C. A special sample holder contained the samples in individual cells at

150°C. On this occasion, samples were held at temperature for three days. The sampler was then connected to the measuring unit and the hydrogen in each sample cell measured on a calibration obtained by injecting a known volume of hydrogen. After analysis, the samples were sent to TWI to await analysis for residual hydrogen.

#### Vacuum Hot Extraction for Residual Hydrogen at 650°C (1202°F)

After analysis for diffusible hydrogen, each sample was analyzed for residual hydrogen at 650°C. Samples were loaded individually into the furnace tube. Evolved hydrogen was transferred to the analysis volume by a mercury diffusion pump and pressure measurements taken using a Baratron pressure gauge. The room temperature degassed multipass samples were treated differently, in that the residual hydrogen was measured initially at 150°C, and then at 650°C.

### Chemical Composition of Multipass Weld Samples

The chemical composition for each of the multipass weld samples are shown in Table 1. Typical mechanical properties are shown in Table 2.

## Results

### IIW Type Test Welds

#### Diffusible Hydrogen Results

The results of the diffusible hydrogen tests are summarized in Table 3. Considering the standard IIW test welds first, the hydrogen levels were all similar for the basic coated electrodes, as would be expected because of their common drying and coating type. The value obtained for the rutile electrode was, as expected, in the range of 25–30 mL/100 g deposited metal. For all electrodes, the amount of hydrogen evolved in three days was in the range of 79–87% of the final diffusible total, *i.e.*, similar to that reported in an inter-laboratory study on 1Cr 0.5Mo basic electrodes (Ref. 5). Although measurements were continued to

Table 1 — Chemical Composition of Multipass Weld Samples, wt-%

Sample	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Ti	Al	B	As	N	O
E7018 0.0465	0.065	0.008	0.014	0.27	1.48	0.04	0.04	0.01	0.0009	0.04	<0.0005	<0.0005	<0.0001	0.0065	0.0063	
E7018 + Ti 0.0454	0.078	0.009	0.016	0.27	1.58	0.03	0.04	0.01	0.0010	0.04	0.029	<0.0005	0.0001	0.0066	0.0068	
E7018 + Ti 0.0459	0.063	0.008	0.014	0.26	1.59	0.97	0.04	0.23	0.0015	0.04	0.031	0.0006	<0.0001	0.0066	0.0071	
E7018 + Ti 0.0472Rutile	0.063	0.009	0.016	0.25	1.51	2.73	0.04	0.32	0.0021	0.04	0.032	0.0018	0.0001	0.0058		
E7018 + Ti 0.0472Rutile	0.063	0.009	0.016	0.25	1.51	2.73	0.04	0.32	0.0021	0.04	0.032	0.0018	0.0001	0.0058		
0.00179	0.0472Rutile	0.072	0.010	0.022	0.44	0.54	0.03	0.03	0.01	0.0190	0.03	0.0150	0.0017	0.0004		
0.00148	0.0085	0.0972Ald Steel Rm*1.12	0.010	0.015	0.21	0.71	0.02	0.02	0.01	<0.005	<0.002	0.01	<0.002	0.003		
<0.0003	0.003	ND	ND													

**Table 2 — Tensile Properties of Multipass Welds**

Sample	Yield Strength N/mm <sup>2</sup>	Tensile Strength N/mm <sup>2</sup>	Elongation %	Reduction of Area %
E7018	454	540	25	76
E7018 + Ti	490	550	30	75
E9018 + Ti	575	639	22	75
E12018 + Ti	730	782	18	69
Rutile	514	564	21	57

**Table 3 — Summary of Hydrogen Measurements in IIW Type Test Welds, mL/100g Deposited Metal**

Sample	28 Day Mean	49 Day Mean	Dif fusible Hydrogen 3 Day/28 Day Ratio	3 Day/49 Day Ratio	Residual Hydrogen	Total Hydrogen	Residual Hydrogen, %
<b>1. Standard IIW</b>							
IIW, E7018	14.2	—	0.84	—	1.14	15.3	7.4
IIW, E7018 + Ti	14.6	—	0.81	—	0.94	15.5	6.0
IIW, E9018 + Ti	14.0	—	0.79	—	0.86	14.9	5.8
IIW, E12018 + Ti	13.8	—	0.87	—	1.09	14.9	7.3
IIW, Rutile	28.6	28.7	0.87	0.87	29.5	58.2	51
<b>2. IIW, + Matching Test Piece</b>							
E7018	13.9	—	0.97	—	1.42	15.3	9.3
E7018 + Ti	14.3	—	0.98	—	0.88	15.2	5.6
E9018 + Ti	15.0	—	0.95	—	1.09	16.1	6.8
E12018 + Ti	13.5	—	0.84	—	1.71	15.2	11.2
IIW, Rutile	24.2	26.1	0.70	0.65	33.3	59.4	56.1
<b>3. As (2) + 5 Minute Delay</b>							
E7018	7.8	—	0.97	—	1.65	9.95	17.4
E7018 + Ti	8.42	—	0.97	—	0.67	9.09	7.3
E9018 + Ti	7.96	—	0.96	—	1.04	9.0	8.7
E12018 + Ti	6.57	—	0.80	—	2.19	8.76	25.0
Rutile	8.41	9.95	0.42	0.36	36.0	46.0	78.3
<b>4. As (2) + 30 Minute Delay</b>							
E7018	5.05	—	0.95	—	1.61	6.66	24
E7018 + Ti	5.17	—	0.95	—	0.74	5.91	12.5
E9018 + Ti	5.65	—	0.96	—	0.99	6.64	14.9
E12018 + Ti	5.14	—	0.70	—	1.88	7.02	26.8
Rutile	4.25	5.44	0.24	0.19	41.1	46.5	88.3

28 days, evolution was essentially complete after 21 days.

With a matching composition all-weld metal center test piece, the final diffusible hydrogen values were similar to the standard IIW test values, although slightly lower for the rutile electrode. Changes were apparent, however, in the degree of completion of evolution of hydrogen at three days. For the three lower-strength, basic electrodes, the percentage of the final diffusible values evolved at three days increased to 95–98%, while for the E12018 electrode, little change was noticed. For the rutile deposit, a marked decrease from 87% to 65% was observed. Additionally, in contrast to the basic electrodes, evolution was not complete at 28 days and measurement was extended to 49 days, when, although evolution had not ceased, measurement had to stop. During that additional 21 day period, a further 10% of hydrogen had evolved, and hydrogen was still evolving at ~0.5 mL/100 g deposited metal per week.

The introduction of a five min delay before quenching produced a sharp fall in diffusible hydrogen levels, as would be expected. The values obtained were between 49% and 59% of the as-quenched values for the basic electrodes and only 38% for the rutile deposit. The three day diffusible values were similar percentages of the final diffusible values to those obtained for the as-quenched samples for the three lower strength electrodes, but the value for the E12018 electrode appeared slightly lower (80% cf 84%), while the value for the rutile electrode had shown a further marked fall to 36%.

With a 30 min delay time, further reductions had occurred, down to 36–38% for all basic electrodes, while the rutile electrode showed a much greater reduction to only 21%. For the three lower strength basic deposits, the percentages evolved at three days were unchanged at 95–96%. However, the E12018 and rutile deposits showed further reductions compared to the five min delay, down to 70% and 19%, respectively. This implies

that the diffusivity has been reduced in these deposits, markedly so for the rutile electrode, as a result of the slower cool to room temperature, but the mechanism has not been investigated.

#### Residual Hydrogen Results

The results are summarized in Table 3. For the standard IIW deposits using the basic coated electrodes, there was only a slight influence of deposit composition on residual hydrogen level, these being around 1.0 mL/100 g deposited metal. The residual hydrogen level in the rutile deposit was very high and, at 29.5 mL/100 g, deposited metal was virtually the same as the diffusible hydrogen level, and significantly higher than the value of 6.4 mL/100 g deposited metal reported by Ødegård, et al. (Ref. 4).

Introducing the use of the all weld metal center test piece produced little change in the amount of residual hydrogen, although there was a tendency for a

small rise in most cases. With a five min delay before quenching, values were again similar or slightly higher particularly for the E12018 and rutile deposit. Extending the delay time to 30 min again produced little change, except that the residual for the rutile deposit continued to rise slowly to reach a value of 41.1 mL/100 g deposited metal, i.e., an increase of approximately 40% on the standard IIW value and 25% on the all weld metal as-quenched value.

The effect of introducing a delay can also be assessed by considering the residual hydrogen as a percentage of the total hydrogen content. Viewed in this way, the percentage rises with delay time, principally because the diffusible fraction is falling, but also partly because, in the case of the E12018 and more particularly the rutile deposit, the amount of residual hydrogen has actually increased. This indicates that, for these electrode deposits, some additional conversion of diffusible to residual hydrogen is taking place, as a result of the slower cool to room temperature. The mechanism by which a greater proportion of the original hydrogen in the sample becomes "non-diffusible" at room temperature, i.e., "residual", is not clear and needs to be established.

When all the results for each electrode are compared, there are some indications of an effect of deposit composition for the basic electrodes. For example, in Fig. 1, comparison of the E7018 with the E7018-Ti data shows that in all cases the residual hydrogen level is apparently reduced, and at a minimum, by the introduction of ~30ppm Ti into the deposit. Moreover, there is a slight trend through the series E7018 + Ti, E9018 + Ti and E12018 + Ti for the residual hydrogen level to increase with increasing alloy content. Indeed the data for the standard IIW test piece are consistent with the "matching" test piece results in Fig. 1 when it is noted that the IIW results will be for a lower alloy type by virtue of dilution from the mild steel test piece.

#### Multipass Welds

The results of the diffusible hydrogen analysis are summarized in Table 4 and displayed in Fig. 2 for the basic electrodes.

A clear trend is apparent for the diffusible hydrogen remaining in the center of the weld (the location of the test samples) after welding to increase with increasing alloy content. The E12018 + Ti deposit contained 2.5 times the level of diffusible hydrogen found in the E7018 + Ti deposit. There was a consistent trend for the mean value of the E7018 + Ti deposit to be higher than that of the E7018 without Ti, but the difference is negligible.

For all the basic electrode deposits, the level of hydrogen was reduced with the increased drying temperatures which were chosen to give IIW single bead hydrogen levels of approximately 10, 5 and 2.5 mL/100 g deposited metal (equivalent to about 6, 3 and 1.5 mL/100 g fused metal). The residual hydrogen levels are summarized in Table 4. They are all very low, much lower than the values measured in the IIW single bead tests, and show no significant trend with alloy type.

The rutile electrode gave higher values of diffusible hydrogen, as might be expected on the basis of the higher inherent hydrogen level of this coating type. The residual hydrogen level was very much higher and similar to that in

the standard IIW test welds.

Tahle 5 indicates that, for the basic electrodes, essentially no residual hydrogen was released from the room temperature degassed samples at 150°C, indicating that, for multipass basic electrodes, 150°C can safely be used as an elevated temperature, rapid method for diffusible hydrogen analysis, in the same way as demonstrated earlier for IIW welds.

## Discussion

### IIW Type Test Welds

In general, the use of a matching all weld metal center test piece in the IIW type test welds, relative to the standard test procedure, produced little change in either the diffusible or residual hydrogen levels. However, there were probably significant changes in the percentage of hydrogen evolved over three days: slight increases were noticed for the three lower strength deposits, a more definite decrease for the rutile deposit, and little change for the E12018 deposit, suggesting that the actual composition of the test

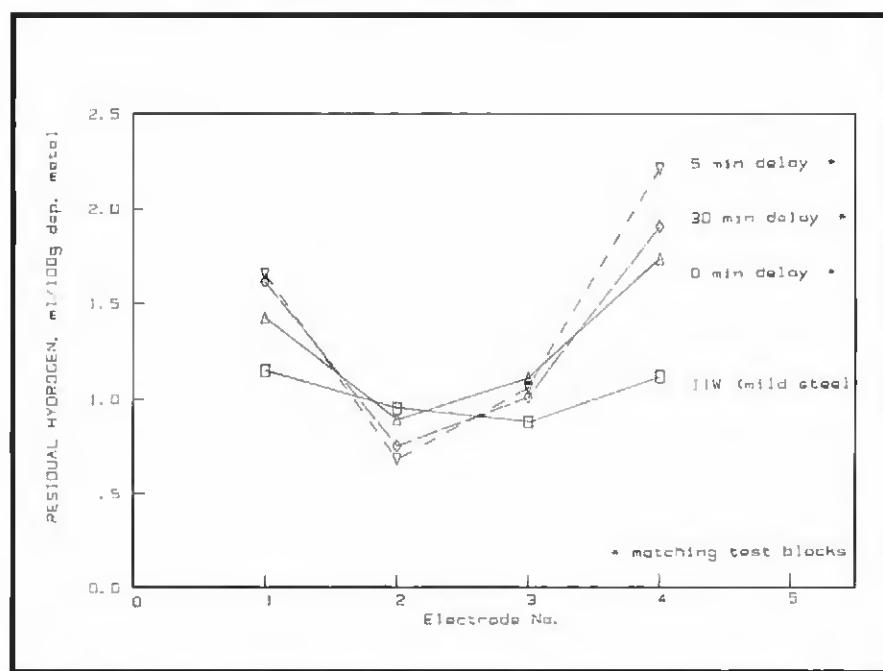


Figure 1 — The influence of electrode type and delay time on residual hydrogen levels.

Table 4 — Summary of Hydrogen Measurements in Multipass Welds, for Electrodes Dried at 295°C for 1 h

Sample	Diffusible at 150°C	mL/100 g Deposit	Total Hydrogen	Residual Hydrogen %
E7018	1.00	0.07	1.07	6.5
E7018 + Ti	1.14	0.06	1.20	5.0
E9018 + Ti	1.55	0.05	1.60	3.1
E12018 + Ti	2.85	0.12	2.97	4.1
Rutile	4.42	24.6	29.02	84.8

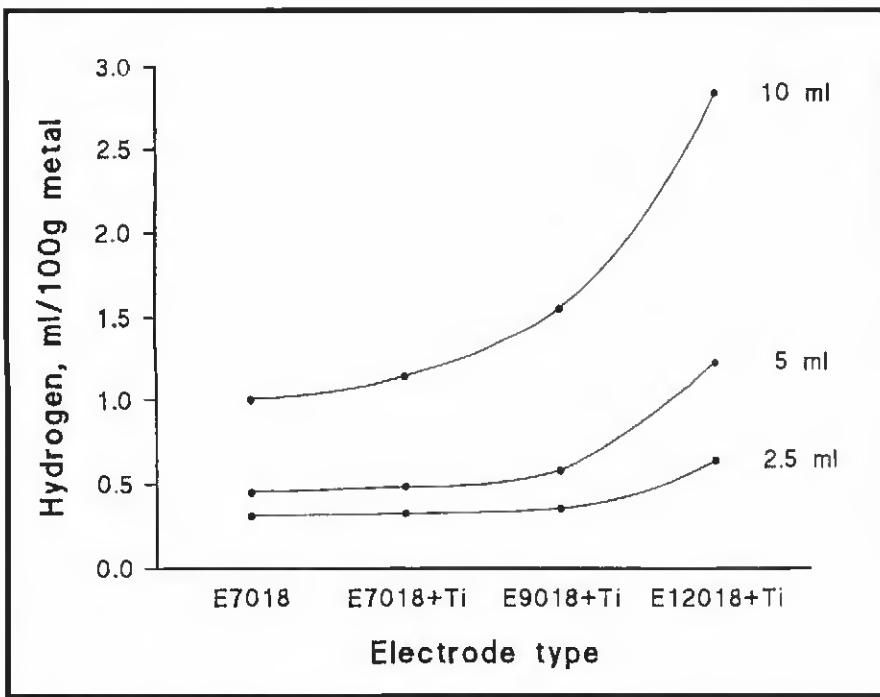


Figure 2 — Diffusible hydrogen in multipass welds, 3 days at 150°C.

piece assemblies may have an influence on the three day hydrogen values, although not necessarily on the total diffusible values. Currently, in standards like ISO 3690 and BS 6693, etc., the composition of the steel is only very loosely defined. The present limited study indicates a need to define a more closely acceptable steel composition, particularly when three day hydrogen figures are being measured. Indeed, it may also be necessary to define the heat treatment, e.g., normalized, to control the microstructure.

Delaying the time before quenching had the obvious effect of reducing the amount of diffusible hydrogen; about 50% was lost during the first five min. For the basic coated electrodes, there was a slight trend for the amount of residual hydrogen to increase as a function of delay time, and this is in contrast to the findings of Coe and Chano (Ref. 2). For their basic electrode, there was no significant trend in the residual hydrogen level with time before quenching.

In the rutile coated electrode, the present results appear to show a more consistent trend for the residual hydrogen

level to increase with delay time before quenching. This suggests that there is some conversion of diffusible-to-residual hydrogen taking place during the slower cool-to-ambient temperature. Although Coe and Chano did not test a rutile coated electrode, they did find that, for cellulosic electrodes, there was an increase in residual hydrogen with delay time before quenching.

For the three lower strength electrodes, introducing a delay before quenching had no effect on the percentage of hydrogen evolved within three days, which remained very high at 95–98%. However, in the case of the E12018 and the rutile deposits, this percentage decreased, particularly for the rutile deposit, suggesting that some temporary trapping was coming increasingly into operation as the delay was extended. In the rutile deposit, this may well have been linked to the trend for an increase in residual hydrogen content. The combination of the reduced rate of evolution, and the conversion to residual hydrogen meant that, for the rutile deposit, the total hydrogen content was unchanged by increasing the delay before quench from

five to 30 min. The nature of the increased trapping is not evident and is presumed to be complex, since it appears to be occurring in two quite different alloy and coating systems.

Although there is no effect of cooling conditions on the residual hydrogen level for the basic electrodes, there are indications of some effects of composition on the residual hydrogen level. First, the results suggest that the addition of ~30 ppm Ti to the E7018 electrode reduces the residual hydrogen level. Moreover, there are also indications that increased deposit alloying, with Ni and Mo, may increase the residual hydrogen levels. The precise mechanism by which these changes may occur is not clear, but the Ti may work through modifications of the oxide inclusions. Alternatively, retained austenite may be acting as a trap. Whatever the mechanism, the effect seems to be confined to the single beads, since no trend was apparent in the multi-pass deposits.

In addition to the trends seen in the basic deposits, the results show that the residual hydrogen fraction can vary quite markedly, from ~6% to 50% as the coating type is changed from basic to rutile. There are several compositional differences between the rutile and basic C:Mn deposits and, while they may all in principle exert an influence, possibly the most likely element is the significantly higher oxygen content of the rutile deposit. However, the residual hydrogen levels of Ødegård, *et al.*, (Ref. 4) IIW rutile deposit and those of the IIW cellulosic deposits of Chano and Coe (Ref. 2) were all very much lower than in the present rutile deposits. In general, the deposit oxygen levels will be broadly similar for cellulosic and rutile deposits, and, although Ødegård, *et al.*, and Chano and Coe did not report oxygen content, it seems highly likely that other compositional factors are also important. Further study would be required to provide greater insight into the factors influencing residual hydrogen content. Moreover, on the premise that the risk of hydrogen cracking can be reduced (for a given initial total hydrogen level) by increasing the residual hydrogen fraction, such studies could be of considerable benefit. Many welds are multipass, how-

Table 5 — Residual Hydrogen in Multi Run Deposit Samples Degassed at Room Temperature for Three Months

Sample	At 150°C	Residual Hydrogen, mL/100 g Deposit	
		and then at 650°C	At 650°C only
E7018	<0.01	0.14	0.13
E7018 + Ti	<0.01	0.15	0.13
E9018 + Ti	<0.01	0.11	0.13
E12018 + Ti	0.01	0.20	0.24

ever, and it is, therefore, the diffusible hydrogen within such welds which will more often, especially for weld metal cracking, be of interest. The next section shows that, for the basic consumables, there were significant differences between the residual hydrogen levels in multipass and single pass welds.

### Multipass Welds

Turning now to the multipass welds, one of the most significant findings was the trend among the basic deposits for the amount of diffusible hydrogen remaining to increase with increasing alloy content. It must be assumed that the hydrogen input was the same, since the coating formulations were the same, the electrode drying was the same and the standard IIW test welds showed no evidence of a difference in diffusible hydrogen for the four basic deposits. The finding of a 2.5 fold increase in remaining diffusible hydrogen in a multipass weld strongly suggests that the risk of weld metal hydrogen cracking in a multipass low alloy weld is significantly greater than that of a C-Mn deposit, not only because of the production of a harder microstructure but also because, for the same initial hydrogen level, more diffusible hydrogen will be retained in the joint. In multipass welds, the slower rate of reduction in hydrogen level during welding, parallels the results of the IIW type tests in which the matching all weld metal center test pieces were used. These results, shown in Table 3, indicate that the percentage removal at three days is significantly less for the E12018 than for the other deposits. It is not known whether this arises from the tendency for increased alloying to reduce diffusivity, and/or from the effect of alloying on depressing the transformation temperature, prolonging the time spent in the austenitic range; both would be expected to contribute to the observation.

In the multipass welds, the ratio of the diffusible hydrogen level in the deposits made with the rutile electrodes to that in the comparable basic coated carbon manganese deposits is at least 1:4. Assuming that the basic coated electrodes were used in a coating condition capable of delivering a IIW single bead hydrogen level of around 10 mL/100 g deposited metal, a ratio of about 1:2 is significantly higher than that of the diffusible hydrogen values associated with IIW single beads in these two classes of consumables. This higher ratio in the multipass welds is a further indication of the reduction in evolution rate that occurs in rutile multipass weld metal. In fact, it

would appear to be something that occurs predominantly in rutile weld metal that has been reheated, since the standard IIW single bead tests in Table 3 show a similar three day to 28 day ratio for the rutile and basic coated electrodes. However, as soon as either reheated rutile weld deposits are introduced into the test assembly as in the second series, or when slower cooling takes place as in the third and fourth series, a reduction in the rate of evolution becomes increasingly evident. The apparently slower evolution of hydrogen in the rutile deposits compared to the basic deposits is in line with the data presented by Odegård, Evans and Christensen (Ref. 4), who found an approximate order of magnitude difference in diffusivity between rutile and basic coated multipass deposits.

While these comments concerning the rutile coated electrode may be of only minor practical significance relative to the use of this class of electrode, which is well known to be of a high hydrogen type and therefore to require significant precautions for the avoidance of hydrogen cracking, it remains to be seen whether the same phenomenon would apply to rutile flux cored wire consumables. If that were the case, the point may be of greater practical significance, since this latter type of consumable is generally within the low hydrogen category and therefore the same comment as made earlier (concerning of the effect of increased alloying leading to an increased risk of weld metal hydrogen cracking) may also apply to rutile flux cored wires. Such a point would need to be established, however, by examining and comparing diffusible hydrogen levels in multipass welds made with basic and rutile flux cored consumables.

### Summary and Conclusions

A series of IIW type test welds with mild steel and matching composition all weld metal center test piece assemblies, and a series of multipass welds, have been made with different SMA electrode coating types and compositions, to study the influence of composition and thermal cycle on diffusible and residual hydrogen contents. The following conclusions have been drawn from the work:

1. Changing the IIW test assembly center piece from a mild steel sample to a matching all weld metal sample did not significantly affect the total diffusible hydrogen content measured. However, for the E7018 and E9018 consumables studied, the percentage of hydrogen evolved at three days was increased (from 79–87% to 95–98%), while, for the rutile

deposit, it was decreased (87–65%). No major changes were observed in the residual hydrogen content.

2. Overall, the residual hydrogen levels varied markedly from as little as 0.05 mL in the basic electrode multipass deposits to 41 mL/100 g deposited metal for the rutile, delayed quench IIW test welds. Within the basic deposits, the residual hydrogen levels appeared to reduce slightly with the addition of ~30 ppm Ti to the E7018 electrode, while the addition of up to 2.7%Ni and 0.3%Mo appeared to slightly increase the residual hydrogen content.

3. Since the composition of the test piece assembly appears to influence the percentage of hydrogen evolved at three days, the analysis and specification of the test piece assembly material should be more closely defined than is currently specified, when a three-day figure is required.

4. Increasing the time before quenching the test piece in the IIW type tests reduced the diffusible hydrogen content, as would be anticipated. Residual hydrogen in the basic electrode deposits appeared to be at a minimum for electrode two and then increased with alloy content. For the rutile deposit there was significant conversion of diffusible hydrogen to residual hydrogen. While the rate of evolution of diffusible hydrogen was unaffected for the lower strength basic deposits, it was reduced in the E12018 deposit and particularly so in the rutile deposits.

5. In the multipass welds, it was shown that, increasing the alloy content of basic deposits increased the remaining diffusible hydrogen level, by as much as 2.5 times. The precise reason for this is not known, but is probably associated with a reduced diffusivity and perhaps also a depression of the transformation temperature.

6. The observation of an increased diffusible hydrogen content in alloyed deposits strongly suggests that, for a given initial hydrogen level of a consumable, as characterized by the IIW single bead test, the risk of weld metal hydrogen cracking will rise with increased deposit alloy content, even more than would be expected from just the effect of alloy content increasing the hardness.

7. The diffusible hydrogen content in the multipass rutile deposit was significantly higher than expected, based on a pro rata comparison of initial (IIW single bead) hydrogen level with the basic carbon manganese deposits. This result indicates the need to establish whether the same trend is true for rutile and basic flux cored deposits, since this would indicate whether the

comment in conclusion 5 above would also be applicable to rutile flux cored wires.

8. The mild steel rutile deposit produced a significantly higher residual content (~25 times) than the basic deposits. Although a major factor causing this is believed to be the higher weld oxygen content, it is also considered that other compositional factors must be included and would be worthy of identification.

9. Diffusible hydrogen from multipass basic electrode deposits may be measured using 150°C as an elevated temperature technique.

#### Acknowledgments

The authors are grateful to Oerlikon Welding, Ltd. for supplying the electrodes and the multipass weld material and diffusible hydrogen data. They also would like to thank the members of the Sponsor Group, namely L'Air Liquide, MoD, ESAB U.K. Ltd., Framatome, General Dynamics Corporation (Electric Boat Division) and Smitweld for their kind permission to publish. They are also grateful to other members of the TWI staff for their assistance at all stages, and to Mr D. H. Parker for his diligent analytical work.

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