Hydrogen Cracking in Weld Metals

The effects of composition, hydrogen content and preheat on weld metal cracking are studied

BY M. McPARLAN AND B. A. GRAVILLE

ABSTRACT. A program to study the effects of composition, hydrogen content and cooling rate on hydrogen cracking in weld metal has been carried out. The G-BOP (gapped bead-on-plate) test was used. The test simply comprises a bead deposited across a gap formed between two blocks. The first phase of work studied the factors that influence the longitudinal stress in the weld metal across the gap in the G-BOP test. It was found that the stress depended on the transformation temperature of the weld metal and on the restraint of the test piece. Lowering the transformation temperature by increasing the alloy content decreased the stress. For very high restraint situations gross yielding of the weld metal would be expected and the stress would not depend on the transformation temperature.

The crack susceptibility of a wide range of weld metals deposited by various processes was examined. The degree of cracking increased with increasing alloy content and hydrogen level. Weld metals with higher alloy level were not affected as much by changes in hydrogen content as lower alloy weld metals. The results have been analyzed on the basis of a simple model where it is assumed that the sole effect of preheat is in allowing hydrogen to diffuse from the weld before it cools to below 50 C. From the measured cooling history of preheated G-BOP tests a diffusion parameter is calculated. Decay of hydrogen content is assumed to be exponential and an equation relating the diffusion parameter to the composition and hydrogen content is established with the constants determined from the experimental results. Good agreement exists between the final equation and experiment and is independent of the welding process when the hydrogen is expressed in terms of fused metal rather than deposited metal.

The form of the equation should allow it to be extended to other welding situations such as multipass welds where a new set of constants would be determined experimentally. Several important practical implications emerge from the study. Because hydrogen appears in a logarithmic term its influence depends on the composition of the weld metal. With higher alloys the effect of changes of hydrogen within the practical range would be small. A high preheat would be necessary in any event and substantial reduction in preheat would need hydrogen levels less than 1 ml/100 g fused metal. For lower alloy levels (e.g. E7018 electrodes) the effect of hydrogen on preheat is marked and considerable benefit is to be obtained by maintaining low hydrogen levels.

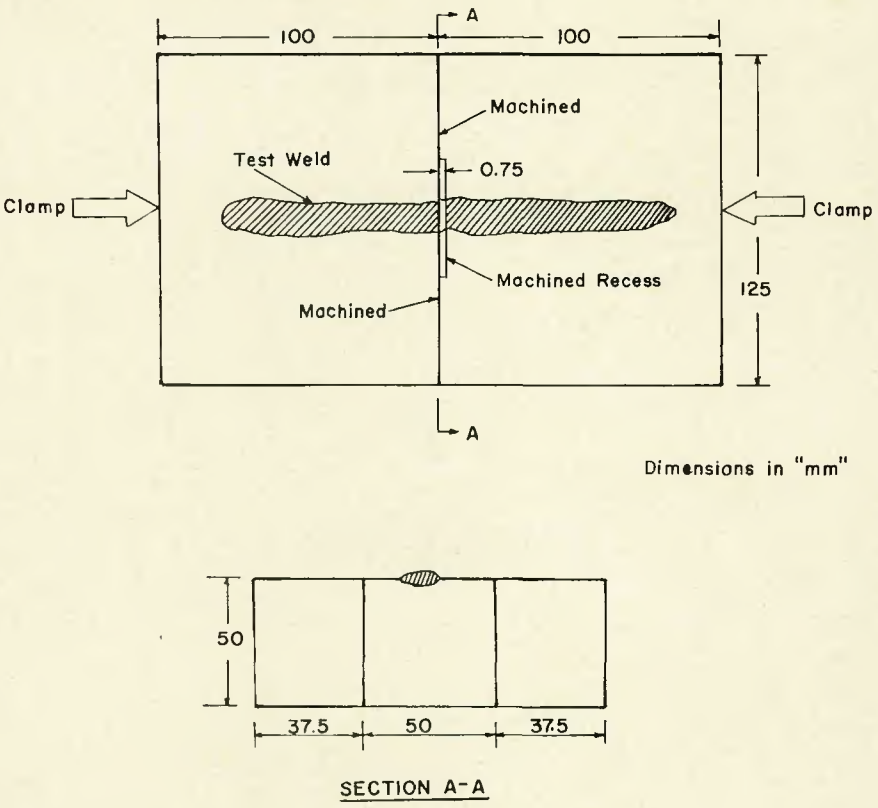

Fig. 1 — Standard G-BOP (gapped bead-on-plate) test

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Introduction

Considerable effort has been spent on studying hydrogen cracking in the heat affected zone (HAZ) of carbon and low alloy steels. Much useful information is now available to aid the welding engineer to select welding procedures to avoid cracking (Refs. 1,2). In practice, however, the welding procedure may be controlled by the need to avoid hydrogen cracking in the weld metal rather than the HAZ. This situation is becoming more apparent as the trend to lower carbon contents in steels reduces the risk of HAZ cracking and the section size of welded structures increases.

Although some studies of weld metal cracking have been published (Refs. 3,4,5) no quantitative data on the effect of the major variables (i.e. hydrogen, composition and stress) have been presented enabling the welding engineer to estimate likely behavior in practice. The purpose of the present investigation was to examine quantitatively the effect of the major variables on hydrogen cracking in the weld metal within the ranges of practical interest. The test techniques developed have proved useful in providing ready means for assessing the susceptibility to cracking of a given electrode.

Experimental

The experimental program was divided into two parts. The first involved a study of the factors which controlled the stress in the test specimen used and the second part was concerned with the effect of composition and hydrogen content on crack susceptibility. In both parts the G-BOP (gapped bead-on-plate) test was used. This test has been described in detail elsewhere (Refs. 6,7) but essentially comprises two blocks, one containing a recess, clamped together to provide a slit over which the test bead is laid (Fig. 1). After allowing a 24 h incubation period the tests are removed from the clamp and the weld over the gap heated with a torch to heat tint any crack that may be present. After cooling the welds are broken open and any cracking appears as a blue thumbnail.

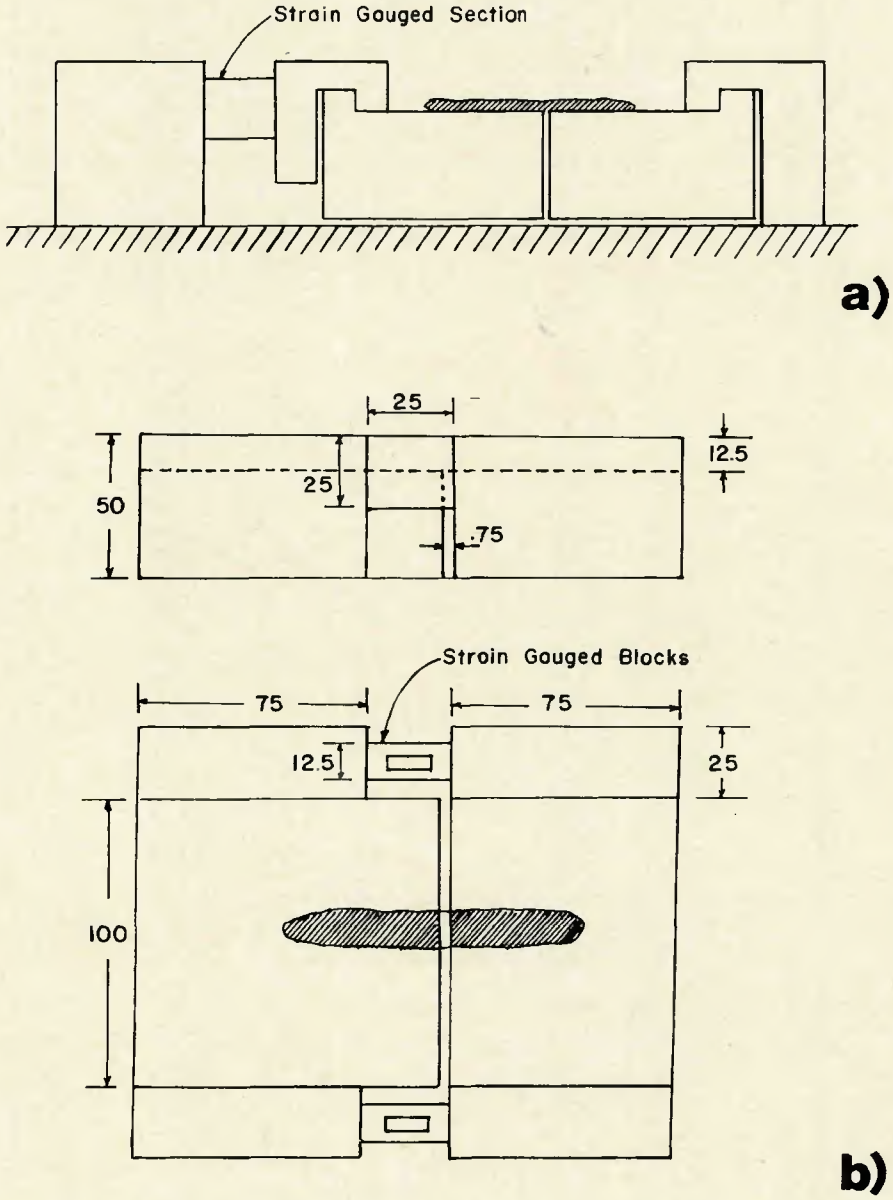

Fig. 2 — G-BOP test instrumented to measure stress (a) restraint K_1 (b) restraint K_2

Stress Measurements

The longitudinal stress across the gap in the G-BOP test was studied using two instrumented versions of the test as shown in Fig. 2. The restraint of the two tests (defined as the longitudinal force required for unit displacement across the gap) was measured and found to be $K_1 = 0.56\times10^5$ N/mm and $K_2 = 1.7\times10^5$ N/mm. The restaint of the standard test shown in Fig. 1 was $K_s = 5\times10^5$ N/mm. A series of tests was carried out using a range of weld metals and welding processes. For each condition two or three replications were carried out. During deposition of the test bead a thermocouple (Pt/Pt-13% Rh) was either plunged into the weld metal or placed adjacent to the weld approximately 5 mm from the gap. Records of load against time and load against temperature were made.

Cracking Tests

The effect of hydrogen, cooling rate and composition on weld metal cracking was studied using the standard G-BOP test. A wide range of weld metals deposited by the shielded metal arc, submerged arc and flux cored processes was examined. Three replications for each condition were made and a standard set of tests for each consumable comprised three tests at each preheat of 20, 50, 100, 150 C totaling 12 tests per set. Higher preheats were used for the more susceptible weld metals. The energy input of the test beads was approximately 1 kJ/mm. After examination of the tests, samples were taken for chemical analysis and hardness measurements were made across the beads.

The hydrogen content of the various consumables was measured under standard conditions using a method essentially the same as that recommended by IIW. The only major difference was that the clamping jig was made of mild steel rather than copper. Estimates of the cooling rate, however, would suggest that an error of less than 5% is incurred. Mercury was used as the confining liquid and

all hydrogen values reported refer to the diffusible amount at room temperature. The cross sectional area of the beads was measured enabling the hydrogen level to be expressed in terms of fused metal as well as deposited metal.

Various hydrogen levels in the same electrode were obtained by exposure in a humidity cabinet containing a dish with a mixture of water and glycerol. Electrodes could be exposed to various humidities for any length of time.

Results and Discussion

Stress Measurements

A typical trace of stress against temperature is shown in Fig. 3 for an alloy electrode (E8018-C2). During transformation of the weld metal an expansion occurs causing a lowering of the stress. After transformation the stress increases with decreasing temperature in an approximately linear form until the final stress. The temperature of transformation can be characterized by the temperature T_t where the extrapolated stress is zero. Weld metals showing a lower value of T_t resulted in a lower final stress across the gap when completely cooled (Fig. 4). Increasing the alloy content of the weld metal resulted in a decrease in the value of T_t and a subsequent lower value of final stress.

As expected, the stress values in the tests with higher restraint K_2 were higher than those in K_1 tests. Typical traces of stress against time for the two sets of tests are shown in Fig. 5. For K_2 tests the stress appears to reach a peak value followed by some relaxation. The relaxation was not associated with cracking and occurred when the specimen was relatively cool. It only occurred in the higher restraint tests where the stresses reached values higher than the general yield stress. Such relaxation may be due to time-dependent plastic flow in a very rigid system although it is possible it results from the measuring technique. When cracking occurred it was usually delayed and took place at the lower stress. Cracking in K_1 tests only occurred in high strength weld metals. The cracking behavior in the K_2 tests was similar to the standard G-BOP test. The effect of composition on peak final stress for the two levels of restraint is shown in Fig. 6, where a conventional carbon equivalent formula is used. Where the yield stress is significantly exceeded the final stress is expected to be controlled by the yield characteristics and not decrease with alloy content as in Fig. 6. Such is the case for the lower alloy levels in the K_2 tests and for a wider range of composition

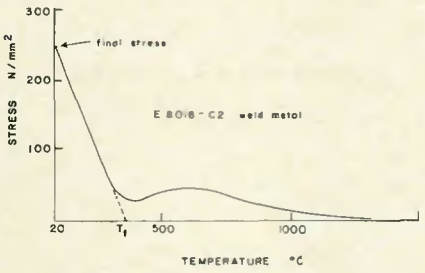

Fig. 3 — Typical curve of stress against temperature in E8018-C2 weld metal using instrumented G-BOP test with restraint K_1

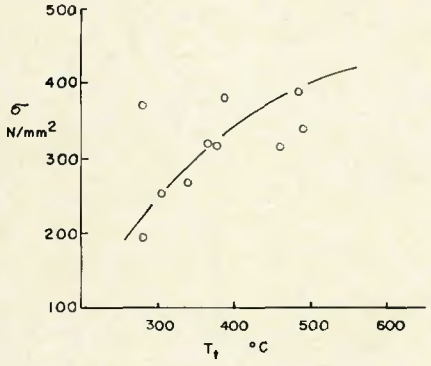

Fig. 4 — Final stress plotted against transformation temperature T_t

in the standard G-BOP where the restraint K_s is higher.

Since the trace of load against temperature in the K_1 tests was approximately linear it is possible to describe the generation of stress in terms of a contracting bar of characteristic length λ. The tension stress σ generated in a bar of cross-section area A and length λ cooling through a range $T_o = T_t - T_{rt}$ and under restraint K will be

$$\sigma = \frac{\alpha E T_o}{1 + \frac{AE}{\lambda K}}$$

where α is the coefficient of linear expansion and E is Young's modulus. It is assumed that no yielding occurs. This can be written in the form

$$\frac{1}{\sigma} = \frac{1}{\alpha E T_o} + \frac{A}{\lambda \alpha T_o K}$$

From the data in Fig. 6, $1/\sigma$ is plotted against 1/K for three different SMAW electrodes. The intercept point is calculated from the measured values of T_o. The values of stress for E8018 and E11018 at K_2 are taken from the curve in Fig. 6 since the compositions of the weld metals for these electrodes were different in the K_1 and K_2 tests. The results in Fig. 7 show good agreement with the expected behavior and enable the stress to be

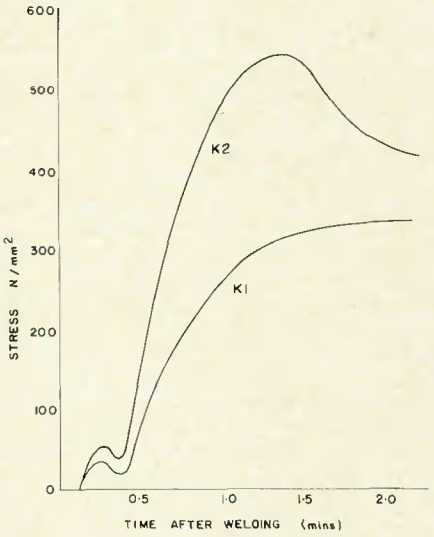

Fig. 5 — Typical record of stress against time for the two levels of restraint K_1 and K_2

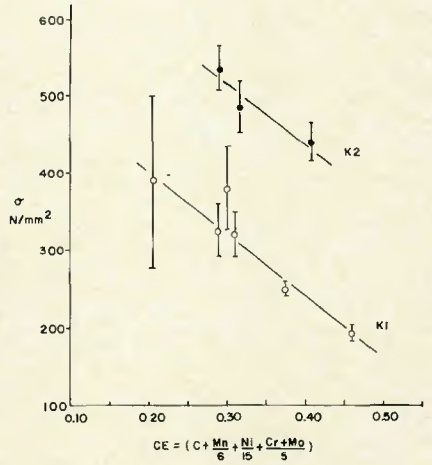

Fig. 6 — Effect of composition on final stress at two levels of restraint

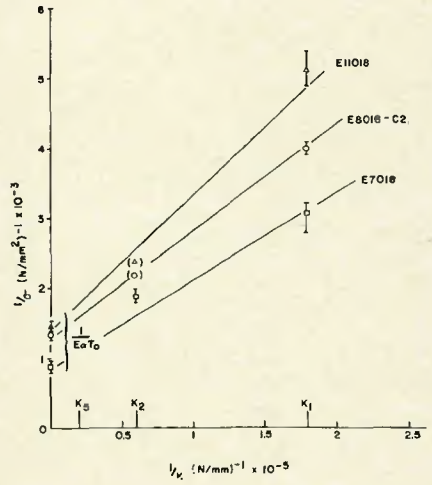

Fig. 7 — Reciprocal stress plotted against reciprocal restraint for three weld metals. The intercept points are taken from the measured values of T_o

estimated for other levels of restraint. The results would be expected to diverge from the straight lines when significant yielding took place. If it is assumed that this occurs at about 500 N/mm^2 then substantial yielding is expected in the standard G-BOP with restraint K_s. It is not expected that the transformation temperature of the weld metal will control the final stress in a standard G-BOP until the carbon equivalent exceeds about 0.60.

The slopes of the three lines in Fig. 7 have been used to evaluate A/λ . If A is assumed to be the real cross-section of the weld the value of λ is approximately the same for all three weld metals and in the range 60-70 mm. Although this value of λ is similar to the length of the real weld or the length of the slit, λ is not necessarily a real dimension and the above analysis is only a representation of the contraction process. The precise mechanism of contraction in the G-BOP test has not been studied.

Cracking Tests

The results of the cracking tests are given in Table 1. The chemical analysis and hydrogen figures are the average of the three replications for each condition. It is noticed that due to the high dilution in the single bead the level of alloys is somewhat lower than normally expected for the electrodes used. Each set of results has been characterized by the critical preheat to just avoid cracking. This has

Table 1 — Summary of Results of Cracking Tests [a] [b]

Filler metal	Composition C	Mn	Si	Ni	Cr	Mo	Code no.	H_2 ml/100 g Used	content metal Fused	Hardness, H_v	Preheat for zero cracking, C
7018	.10	1.29	.45				1	2.1	1.2		<20
	.08	.96	.73				2	3.1	2.1		<20
	.10	.98	.39				3				<20
	.10	1.14	.44				4	3.0	2.1		<20
	.09	1.20	.47				5	4.1	2.5		<20
	.10	1.12	.50				6	4.6	2.7		<20
	.10	1.15	.42				7	4.4	2.8		<20
	.10	1.29	.44				8	3.0	2.1		<20
	.10*	1.0*	.4*				20	4.6	3.3	233	<20
	.13	1.08	.37				24	8.2	4.0	241	50
	.10	.89	.23				25	12.3	5.8	225	80
	.10	1.08	.46				29	12.1	6.1	218	80
7018G	.15	1.33	.33	.03	.03	.04	39	5.4	2.6	230	75
	.14*	1.26*	.3*	.04*	.04*	.05*	40	5.3	2.9		78
	.13	1.27	.30	.04	.06	.08	41	3.5	2.1	270	55
	.05	1.26	.37	.04	.05	.05	42	3.3	1.9	273	60
	.14*	1.26*	.3*	.04*	.04*	.05*	43	5.2	2.9		110
	.14	1.25	.27	.05	.04	.05	44	4.3	2.4	264	50
7018A1	.05	.89	.53			.32	27	7.8	3.4	225	30
6011	.13	.53	.27				21	20.7	8.9	230	100
7024	.10	.94	.59				22	21.0	7.0	220	50
8018-C3	.07	.99	.46	.65*	.05*	.15*	16	2.8	1.4	250	25
	.08	.91	.40	.68	.05	.18	28	7.3	2.9	240	130
8018-C1	.08	1.05	.45	1.36	.06		23	3.5	1.8	255	50
	.08	1.13	.47	1.36	.03		30	8.6	4.5	223	140
11018	.09	1.28	.36	.53	.13	.22	15	3.8	2.0	283	100
8015B2L	.14	1.04	.35		.46	.19	36	5.7	2.0	306	60
	.13	.95	.46		.54	.21	37	20.3	7.7	289	100
	.14	.94	.28		.42	.20	38	32.9	13.7	269	110
9015B3L	.13	1.11	.44		1.01	.37	33	6.8	3.3	337	160
	.14	1.02	.36		.80	.35	34	29.1	18.3	350	160
	.12	.98	.26		.82	.27	35	19.3	11.0	314	160
Sub-arc	.12	.97	.44				13	3.4	1.2	175	<20
	.10	1.24	.49				14	4.4	1.9	233	<20
	.12	.92	.39			.2	19	8.0	3.4	216	<20
	.13	.94	.28			.21	31	8.5	5.3	227	<20
	.15	.92	.34			.15	32	10.6	6.9	229	40
Flux-cored	.10	1.43	.42				9	6.7	3.5	243	50
	.12	1.38	.53				10	5.8	2.8		110
	.11	1.14	.13				11			271	110
	.14	1.27	.55				12	12.3	5.8	257	30
	.09	1.17	.41				17	4.7	2.0	214	<20
	.08	.99	.28				18	1.6	1.0	214	<20
	.09	1.15	.27	.55	.03	.02	26	3.5	1.7	269	40
	.14*	1.27*	.55*				45	7.8	4.3		110
	.15	1.48	.45				46	12.1	6.0*		140
	.13	1.45	.50				47	4.5	2.3*		110
	.12	1.34	.55				48	9.2	5.1		55

(a) Chemical analysis and hydrogen content are averages of three individual measurements.
(b) Each line represnts three tests at each of four preheats.
* Estimated values.

been found by plotting the percentage of cracking against preheat temperature and extrapolating to zero cracking. The mean of the three sets of results for each preheat was used in the plot.

As expected the degree of cracking increased with increasing alloy content of the weld metal and increasing hydrogen level. In the more highly alloyed weld metals the degree of cracking was not affected by changes in the hydrogen content as much as in the less alloyed. Exposure of low hydrogen electrodes (e.g. E7018) to high humidity even for relatively short times resulted in a marked increase of hydrogen content and a considerable increase in the degree of cracking. The effect of various exposure conditions on the hydrogen level of one particular E7018 electrode is given in Table 2. The relation between the hydrogen content expressed in terms of fused metal and deposited metal (filler metal used) is shown for most results in Figure 8. A ratio of about 0.5 is evident.

Although there is a rough correlation between composition and hardness the latter was not found to be a particularly useful index of cracking susceptibility. The hardness was not influenced significantly by the level of preheat.

Typical cooling curves for G-BOP tests carried out at various preheats are shown in Fig. 9. Cooling takes place in two definite stages. Within about five minutes the weld itself cools rapidly to the preheat temperature. After this the block cools slowly from the preheat temperature to room temperature. The second stage of cooling follows Newton's cooling law and a plot of log T against time is approximately linear (Fig. 9). The G-BOP test block is designed to be large enough for the heat from the weld to contribute very little to the overall temperature of the block. The cooling history may therefore readily be estimated for any given preheat.

Table 2 — Effect of Electrode Treatment on Hydrogen Content for an E7018 Electrode

Treatment [a]		H_2 content ml/100g metal	
Exposure time	Rel. humidity, %	Used	Fused
None	—	3.0	2.1
3 days	30-40	4.1	2.5
3 h	48	4.4	2.8
4 h	95	8.2	4.0
8 h	95	12.1	6.1
48 h	95	12.3	5.8

(a) All electrodes initially baked 1 h at 350 C

Diffusion Model

In establishing a model for the effect of preheat, hydrogen and chemical composition on cracking it is assumed that the only effect of preheat is in allowing hydrogen to diffuse from the weld before it cools to room temperature. It is assumed that cracking occurs if the average hydrogen concentration remaining in the weld exceeds a critical value dependent on the composition. Any effects of redistribution of hydrogen into 'diffusible' and 'residual' forms as described by Coe and Chano (Ref. 8) have been neglected.

The diffusion of hydrogen from welds has been examined by a number of authors (Refs. 8,9). By making certain assumptions in regard to the geometry of the specimen and the boundary conditions it is possible to arrive at analytical solutions of the diffusion equation. More detailed solutions for complex geometries can be found by numerical methods. The value of such calculations, however, has been limited because in general the critical hydrogen level is not known.

Whatever the precise boundary conditions employed, the mean hydrogen concentration remaining in a solid after time t is expected to be given approximately by

$$\overline{C} = \overline{C}_0 A \exp(-\beta_0 Dt) \quad (1)$$

where $\overline{C}_0$ is the original mean hydrogen concentration, D is the diffusion coefficient and A and β_0 are constants dependent on geometry and boundary conditions. When diffusion takes place in a solid where the uniform temperature is changing, the term Dt can be replaced by

$$\tau = \Sigma_i D_i \Delta t_i$$

where D_i is the diffusion coefficient at temperature T_i where the solid remains for the interval of time Δt_i. The cooling curves for G-BOP tests at various preheat levels have been divided into steps to determine the value of τ when the weld cools below 50 C. (Although cooling time to 100 C is often used to relate to cracking, the tests showed a significant effect of preheats of 50 C on cracking. The value of τ and hence the mean hydrogen level remaining after cooling to 50 C was therefore selected.)

The calculation of τ is shown in Table 3 using values of D_i derived from Coe's work (Ref. 8). Transformation from austenite is assumed to occur in the weld metal at about 500 C and is reflected in the values of D_i. The values of τ will not be greatly influenced by the precise temperature selected. The table shows that

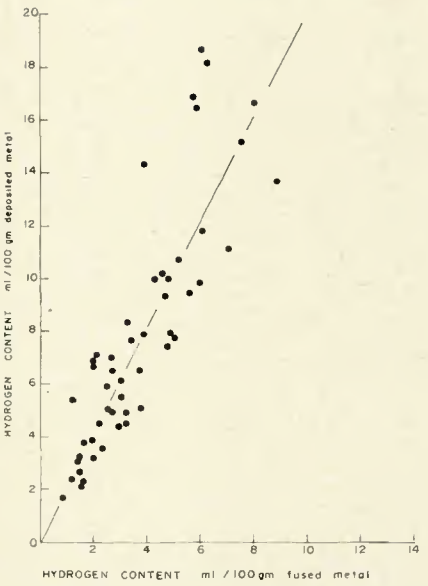

Fig. 8 — Relation between hydrogen content expressed in terms of fused metal and deposited metal

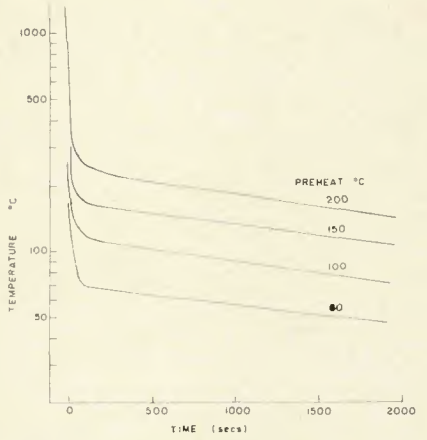

Fig. 9 — Cooling curves in G-BOP tests for various levels of preheat

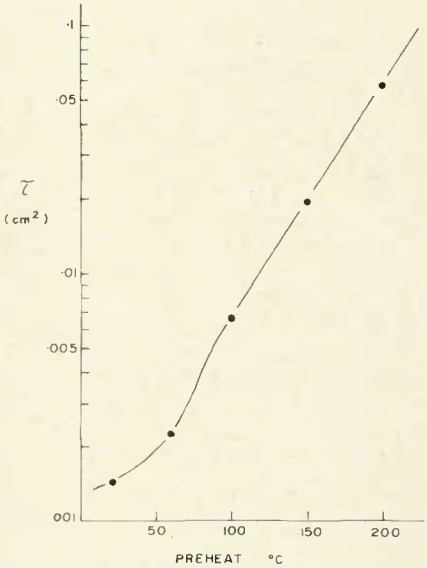

Fig. 10 — Plot of τ (log scale) against preheat temperature for the G-BOP test

Table 3 — Calculation of τ Using Preheats of 20, 60, 100, 150 and 200 C

		20		60		100		150		200	
Temperature range, C	Diffusion coefficient D_i (cm^2s^{-1})	Δt_i, s	$D_i \Delta t_i$, cm^2	Δt_i, s	$D_i \Delta t_i$, cm^2	Δt_i, s	$D_i \Delta t_i$, cm^2	Δt_i, s	$D_i \Delta t_i$, cm^2	Δt_i, s	$D_i \Delta t_i$ cm^2
1500-500	1.3×10^{-4}	3.0	3.9×10^{-4}	3.5	4.6×10^{-4}	6.0	7.8×10^{-4}	7.0	9.1×10^{-4}	10	13.0×10^{-4}
500-450	1.53	0.5	0.75	0.75	1.15	1.3	2.0	1.0	1.53	2	3.1
450-400	1.30	1.0	1.3	0.75	0.98	0.7	0.91	1.5	1.95	3	3.9
400-350	1.07	1.0	1.07	1.0	1.07	1.0	1.07	2.5	2.68	5	5.4
350-300	8.58×10^{-5}	1.5	1.28	1.5	1.28	2.0	1.71	3.0	2.57	14	12.0
300-275	7.55	1.0	0.76	1.0	0.76	1.5	1.13	2.5	1.89	16	12.1
275-250	6.57	1.0	0.66	0.5	0.33	1.5	0.99	4.5	2.95	40	26.2
250-225	4.67	1.0	0.47	1.5	0.70	1.5	0.70	5.0	2.33	190	88.6
225-200	3.09	2.0	0.62	1.5	0.46	3.5	1.08	11.0	3.41	440	136.0
200-175	1.95	2.0	0.39	2.0	0.39	5.0	0.97	29	5.65	520	101.5
175-150	1.16	3	0.35	3	0.35	8	0.93	480	55.7	570	66.1
150-125	6.47×10^{-6}	4	0.26	4.5	0.29	28	1.81	760	49.1	700	45.2
125-100	3.36	7	0.23	8	0.27	546	18.3	900	30.2	900	30.2
100-75	1.5	14	0.21	31	0.47	1140	17.1	1150	17.3	1150	17.3
75-50	6.24×10^{-7}	31	0.19	1539	9.6	1600	10.0	1600	10.0	1600	10.0
$\tau=\Sigma_i D\ \Delta t_i$		14×10^{-4}		23×10^{-4}		67×10^{-4}		196×10^{-4}		571×10^{-4}	

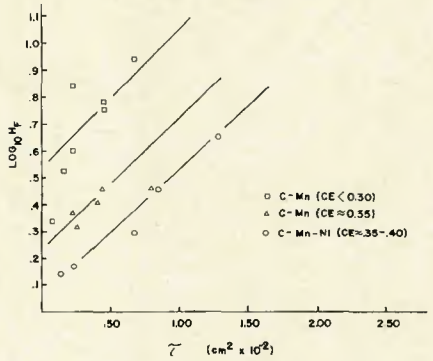

Fig. 11 — Relation between $log_{10}(H_f)$ and τ_c for three groups of weld metals

most of the hydrogen will diffuse out after transformation when the weld cools to the preheat temperature. The relative effect of preheat temperature and time is readily established from the table. A plot of τ against preheat for the specific case of the G-BOP test is shown in Fig. 10.

It may be assumed that the original mean hydrogen concentration $\overline{C}_o$ in a weld is proportional to the measured content determined in a test where cooling conditions are standardized. Further, it may be assumed that the critical mean hydrogen concentration to produce cracking (below 50 C) is a function of chemical composition. If the critical preheat to give zero cracking is that which allows the original hydrogen content to be reduced to the critical value at 50 C then equation (1) may be written in the form

$$\log_{10}(H_f)+f(\text{composition}) = \beta\tau_c \qquad (2)$$

where H_f is the hydrogen content in ml/100 g of fused metal, $\beta = \beta_0/2.3$ and τ_c corresponds to the preheat to give zero cracking. In Fig. 11, log(H_f) is plotted against τ_c for three groups of weld metals where the compositions are similar. Parallel lines have been drawn to fit the three groups although the best fit line for the lowest composition group would be steeper than that drawn. Differences in slope (β) probably reflect differences in the geometry of the beads. For the purpose of establishing a general model a single value of $\beta = 49\ (cm^{-2})$ is taken for the slope. Comparison with the theoretical solution for diffusion from a slab with boundary conditions of zero concentration at both surfaces gives a characteristic half thickness of 0.15 cm which is in good agreement with the mean half thickness of the real weld beads found by dividing the average area by the average bead width.

Equation (2) is re-arranged to read

$$\beta\tau_c - \log_{10}(H_f) = f(\text{Composition})$$

where a suitable function of composition is to be determined. The mean of all results for each class of electrode was taken, the expression on the left calculated, and a relation with the composition sought. Attempts to find this by multiple regression techniques were not successful because too many of the elements were confounded (e.g. nickel-containing weld metal usually had a low carbon). It was therefore decided to use a conventional carbon equivalent formula to pool the effects of individual elements. A simple linear relation was found to give quite good results, as shown in Fig. 12. The lack of agreement in the case of the E8015-B2L tests probably results from the very high hydrogen levels recorded which may not have been representative of those in the cracking tests. Measurement of the slope in Fig. 12 leads to the relation

$$\beta\tau_c = 3.75(CE-0.40) + \log_{10}(H_f) \qquad (3)$$

where CE = C + Mn/6 + Cr/5 + Mo/5 + Ni/15 (in wt. %). Equation (3) is drawn in Fig. 13 where $\beta\tau$ is plotted on a log scale against 3.75(CE) + log(H_f). The individual test results for shielded metal arc welding are shown plotted and good agreement exists. (Some repeated points have been omitted to avoid congestion in the figure.) Test results for flux cored and submerged arc welding are shown in Fig. 14. General agreement exists although the scatter is greater resulting, perhaps, from the larger scatter in the measurement of hydrogen with these processes. There was a larger number of uncracked tests on the right-hand side of the curve than for SMAW tests, particularly for submerged arc results. The main reasons for the apparent higher susceptibility of some flux-cored weld metals was the moderately higher hydrogen contents and higher alloy content needed for deoxidation. Where these factors were controlled good resistance to cracking was achieved. One flux-cored wire (a seamless type) showed very low hydrogen levels and a cracking resistance better than most E7018 electrodes.

The logarithmic dependence on hydrogen content has some important practical implications. Since it is difficult in practice to achieve hydrogen levels less than 1 ml/100 g of fused metal the log term in equation (3) is not likely to be negative. There is also an upper bound of about 30 ml/100 g set by the solubility of hydrogen in liquid steel. For a weld metal of high susceptibility (e.g. 2½Cr-1Mo) changes in hydrogen content within

the practical range will not have a large effect on the value of τ_c. A large value of τ_c (i.e. high preheat or long postheat) is required in any event and although lowering the hydrogen content (by baking the electrode etc.) is good practice it will not allow a large relaxation in preheat. On the other hand the critical value of τ for a low susceptibility weld metal (such as E7018) is very sensitive to the hydrogen level and considerable benefit may be obtained by lowering it. The relative importance of composition and hydrogen content given by equation (3) may be useful in suggesting safe levels of hydrogen for various weld metal compositions.

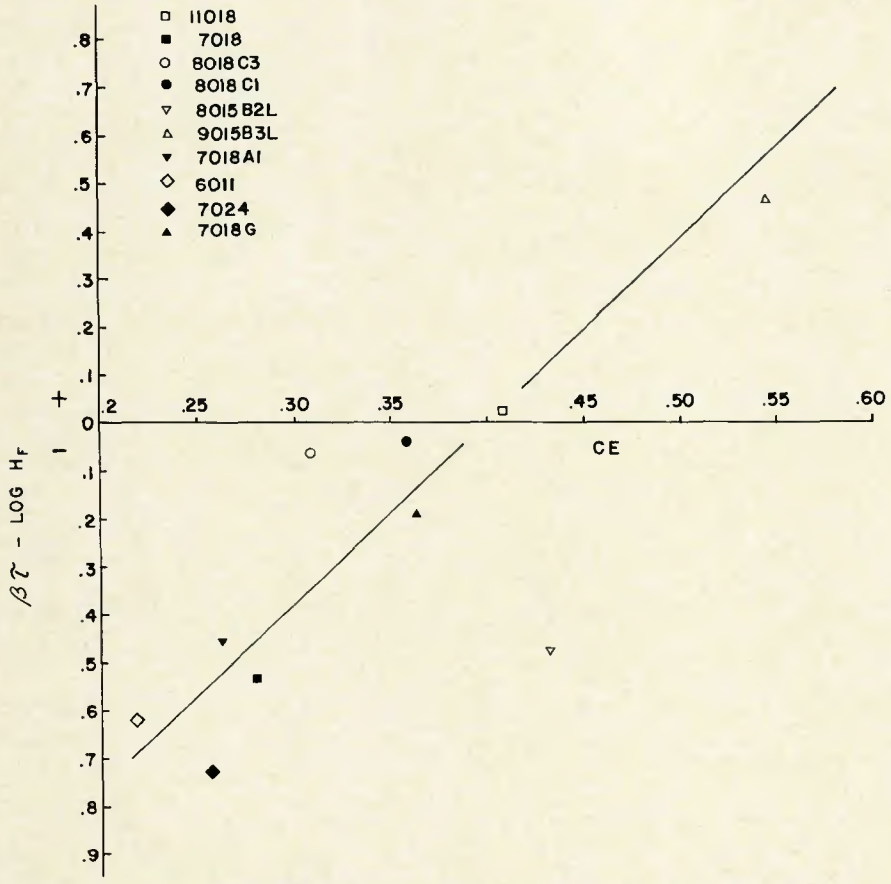

Fig. 12 — Relation between $\beta\tau_c - \log_{10}(H_f)$ and chemical composition expressed as a conventional carbon equipment

It is important to recognize that the preheat levels shown in Fig. 13 apply only to the G-BOP test and not necessarily to any real practical joint. Experience with this test has shown it to be more severe than the average joint met in practice. In extending the present results to practical situations the following points may be considered. The expression $3.75(CE)+\log(H_f)$ representing the susceptibility to cracking of a particular weld metal is expected to be quite general. It represents the relative importance of chemical composition and hydrogen in the cracking process. Since hydrogen appears as a logarithmic term the expression is unchanged as long as H_f is at least proportional to the original hydrogen content in the weld. It is therefore expected to remain valid for any weld including multipass welds if cracking initiates in regions with an as-deposited microstructure. If cracking originates in reheated regions the dependence of susceptibility on chemical composition would change.

All changes that affect the diffusion of hydrogen are included in the terms β and τ in the vertical axis of Fig. 13. β includes all geometrical factors such as size and shape of the weld and boundary conditions. τ includes the cooling history of the weld, in particular the cooling time through the lower temperature ranges. Changes in stress in the weld or in stress concentrations from which cracks might initiate would be expected to shift the curve of Fig. 13 in the horizontal direction. It is therefore possible that

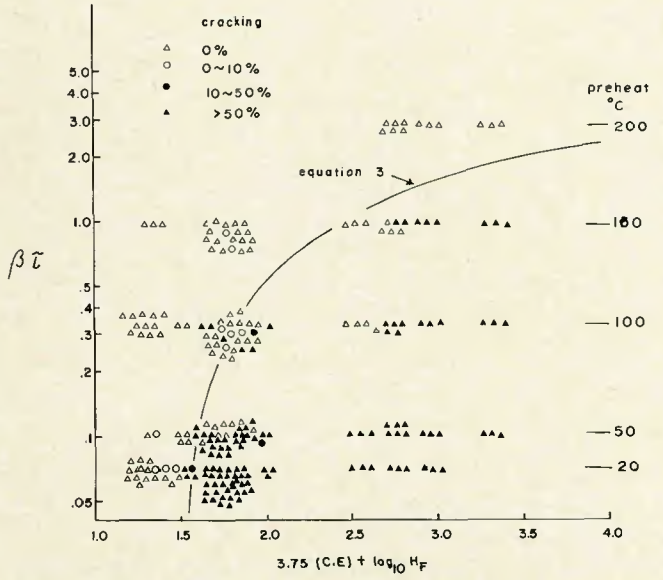

Fig. 13 — Results of cracking tests for SMAW plotted as $\beta\tau$ (log scale) against susceptibility parameter $3.75(CE)+\log_{10}(H_f)$

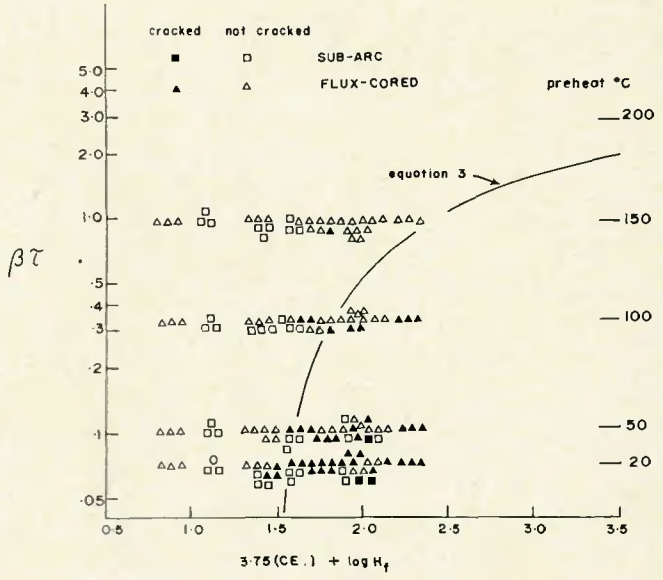

Fig. 14 — Similar plot to Fig. 13 for flux cored and submerged arc results

the form of Fig. 13 can be extended to many types of welds of practical interest without changing its shape. This is only possible, however, where it can be assumed that the main effect of preheat is in diffusing hydrogen. This may not be true for very high preheats that could cause microstructural changes or for high alloy weld metals that would show a reduction in stress at high generally applied preheats.

Several problems are raised by the present study that would warrant further work. The use of electrodes of immediate commercial interest precluded a statistical analysis of the effects of various alloying additions on susceptibility to cracking. It was necessary therefore to use a conventional carbon equivalent formula for chemical effects. A more detailed study of the effects of alloy additions would be useful, in particular the influence of minor additions from the base plate due to dilution.

It should also be noted that the effect of chemical composition on susceptibility has been studied for a specific heat input and hence microstructure. Although this is believed to be the most useful for SMA welding where small beads are likely to be used the effect of changes in microstructure for the same compositions is worthy of further study.

To enable the results to be of more use in practice a study of the effects of weld geometry is required. Of special interest would be multipass welds, and some preliminary work has shown the G-BOP type of test to be suitable for this. In addition, the significance of the redistribution of hydrogen as 'diffusible' and 'residual' is not understood.

Conclusions

A study of hydrogen cracking in weld metals has led to several conclusions. The longitudinal stress in the G-BOP test is dependent on the restraint and the transformation temperature of the weld metal. Except in high restraint cases a reduction in the transformation temperature due to an increase in alloy content results in a decrease in longitudinal stress. In high restraint cases the final stress is determined by the yield characteristics. The final stress in the standard G-BOP is not likely to be influenced by the transformation characteristics if the carbon equivalent is less than about 0.60.

The effect of hydrogen level on the preheat to avoid cracking in the G-BOP test can be explained in terms of the diffusion of hydrogen. A model is developed in which the effects of composition and hydrogen level are included, the hydrogen level appearing as a logarithmic term. The model agrees very well with the experimental data. The preheat to avoid cracking in a higher alloy weld metal is less sensitive to changes in hydrogen content within the practical range than a less alloyed weld metal.

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