Development and Use of the Implant Cracking Test

ABSTRACT. This paper describes a program of work concerned with the development and standardization of the implant cracking test. The results of an investigation are presented in which both this test and the controlled thermal severity (CTS) test were used to assess the relative significance of welding and plate variables on the risk of heat-affected zone cracking in a low alloy steel. The welding and plate variables, investigated at two levels, included weld metal strength, weld metal hydrogen level, arc energy, plate thickness and plate carbon content.

In general, the implant cracking test was more able to determine the relative importance of the variables than the CTS, although the latter did indicate that arc energy was an important factor. The implant cracking test, demonstrated the beneficial effect of low carbon content, plate thickness and weld hydrogen level, and high arc energy on the risk of cracking.

The results indicate that the implant test procedure can be used to provide quantitative data on base metals, welding consumables, and welding procedure variables permitting a rational approach to the prediction of safe welding procedures.

The implant test as used to determine critical stress is judged to be more sensitive than the controlled thermal severity (CTS) test for assessing the effects of variables on risk of cracking

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Introduction

The determination of the effects of welding and plate variables on the risk of heat-affected zone cracking has generally been assessed in the past using weld cracking tests such as the controlled thermal severity (CTS) test. The principal disadvantage of such welding tests is that the applied stress on the heat-affected zone is a variable dependent on weld penetration and root notch geometry, plate thickness and joint restraint. Mechanical tests like the constant load rupture (CLR)[1] and fracture mechanics test,[2] although they have control over the level of stress which is applied, suffer from the disadvantage of employing simulated heat-affected zone microstructures and arbitrary hydrogen concentrations. On the other hand, the implant cracking test, applies a known stress to a real heat-affected zone and can thus assess the susceptibility to heat-affected zone hydrogen cracking by means of a mechanical test parameter. Consequently, the implant cracking test avoids the disadvantages of the above tests yet at the same time incorporates their merits.

In this test a notched, cylindrical implant specimen made from the steel under investigation, is inserted in a hole in a plate so that the notch is located in the heat-affected zone produced by the test weld bead which is made over the end of the specimen. When the weld has cooled to a predetermined temperature, a load is applied to the end of the implant and maintained until either rupture occurs or until it is judged that rupture will no longer take place. The technique consists of the constant load rupture testing of a series of implant specimens, at decreasing loads to establish the critical stress (σ_R) below which cracking does not lead to complete rupture of the specimen. This parameter is

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Table 1—Chemical Analysis of Implant Specimens, %

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
Higher carbon specimens	0.21	0.32	0.15	0.022	0.010	2.67	1.32	0.27	0.02
Lower carbon specimens	0.17	0.38	0.10	0.013	0.010	2.71	1.27	0.30	0.01

taken as a measure of the risk of cracking for the particular combination of welding and plate variables used.

The implant type of welding test was originally used by Granjon[3] to facilitate studies of the initiation and morphology of hydrogen cracking. The test was further developed by Granjon[4] with the object of quantifying the welding behaviour of higher strength steels with a view to recommending welding procedures on the basis of tests carried out on small amounts of steel. The form of test adopted by Granjon was different to that used by Cabelka and Million[5] in that it enabled welds to be made on implant specimens located in plate which was large enough to reproduce the cooling effects that occur in practical welds. Both Cabelka and Million[3] and Granjon[5] studied the applied stress and time to initiate cracking as well as the factors leading to complete rupture.

This paper describes the development and standardization of the implant cracking test at The Welding Institute. It also considers the results of a program of work in which the relative significance of welding and plate variables on the incidence of heat-affected zone cracking was assessed using both the CTS and implant cracking tests. The future application of the implant cracking test and possible modifications are discussed.

Experimental Details

Equipment

Two pieces of equipment were used in making the implant cracking tests. These were the implant testing machine[6] and the equipment for automatic deposition of covered electrodes which are normally used for manual shielded metal arc welding (MSMAW).[7]

The essential features of the implant testing machine are shown in Fig. 1. Here it can be seen that the load is applied through a pneumohydraulically operated lever system, with load measurement by means of strain gauges on the loading bar and with automatic timing of the interval between the application of load and complete rupture of the implant specimen.

The equipment for automatic deposition of covered electrodes is very simple. Its outline is shown in Fig. 2. Here as can be seen, individual electrodes are held in a clamp which is moved vertically at a predetermined constant velocity while the test piece being welded is moved horizontally under the welding head by means of a constant speed tractor. The constant velocity of the electrode is preselected to match the burn-off rate of the electrode by means of a simple voltage control to the drive motor.

Outline Method of Testing

A notched cylindrical specimen, made from the material under test, is inserted, with a sliding fit, into a base block (Fig. 3) so that the notch is located in the heat-affected zone. The test weld bead is deposited on the plate and across the end of the test specimen. Following welding and removal of the slag, the temperature of the surface of the weld bead over the implant specimen is monitored using a contact thermocouple. The thermocouple consists of separate wires making half junctions with the weld bead surface and when the temperature falls to 150 C the pre-set load is automatically applied. The temperature of 150 C was initially chosen to coincide with the technique of Granjon.[5] It was, in addition, considered acceptable on

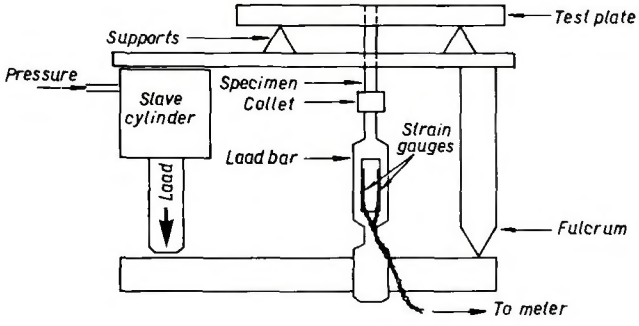

Fig. 1—Diagram showing the essential parts of the implant testing machine

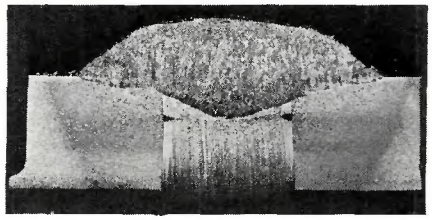

Fig. 3—Transverse section of weld bead on implant specimen showing notch location. Cracking arrested by removal of load. X5 (reduced 50% on reproduction)

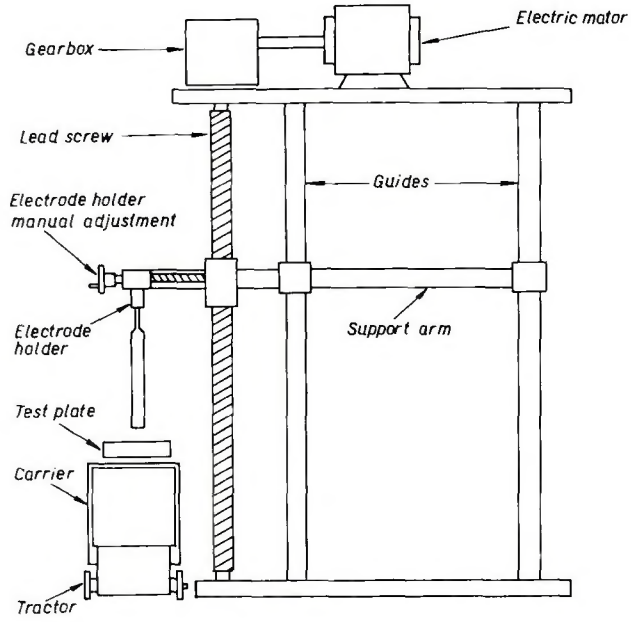

Fig. 2—Diagram showing the essential features of the apparatus for deposition of individual covered electrodes

the basis that it was below the *Mf* of the material being tested, and above the temperature at which cracking generally begins in C:Mn and low alloy steels.

The applied load on the implant specimen is maintained constant until complete rupture has occurred or until it is judged that it will no longer occur owing to the loss of hydrogen from the weld-heat affected zone system. A series of tests are carried out at different applied stress levels to produce a diagram of the form shown in Figs. 4 and 5.

Standardization of Test Method

Throughout the standardization period, a low alloy quenched and tempered steel with a yield stress of 550 N/mm² (35 tonf/in.²) was employed whose composition is shown in Table 1 under the heading "higher carbon." The steel was chosen because of its intermediate susceptibility to hydrogen cracking in practice and because its heat-affected zone microstructure and hardness do not change significantly over a reasonably wide range of cooling rates, thus eliminating any variation in one of the principal factors.

Tests were carried out using MSMAW with Class E11018-M electrodes deposited at a rate corresponding to an arc energy of 1.6 kj/mm (40 kj/in.).

Preliminary experiments to test the loading rig and general operation of the equipment were carried out using 7 mm (0.28 in.) diameter specimens with the notch standardized at 0.5 mm (0.02 in.) depth and consisting of a 45 deg vee with a 0.13 mm (0.005 in.) root radius. Subsequently, the possibility of using a sharper notch was examined with a view to achieving maximum test sensitivity. The depth was maintained at 0.5 mm (0.02 in.), but the root radius was reduced.

At smaller radii it was not possible to maintain a constant radius between specimens and this varied between .013 and .05 mm (0.0005 and 0.002 in.) in different specimens. The tests in Fig. 4 were made with notches within this range and no effect of this variation in notch radius on position in the scatter band was detectable. This variation was therefore considered to be acceptable, and it was decided that all future specimens would have radii in that range. At this stage some specimens of larger diameter were tested [8 mm (0.31 in.)] corresponding more closely with those used by Granjon[4] in a wide range of experiments.

However, with a weld arc energy of 1.6 kj/mm (40 kj/in.) the width of the 8 mm (0.3 in.) diameter specimens approached the width of the weld bead. Under these circumstances, unless a very flat weld penetration profile can be obtained, and in this instance it was not, all of the circumference of the notch cannot be situated in the high temperature heat-affected zone. In fact at the side of the specimen, the notch is more likely to be situated in the lower temperature heat-affected zone. After only a small number of tests it became apparent that the fracture did not follow the notch around the whole circumference but preferred to propagate through the coarse grained heat-affected zone and ignore the notch at the side of the specimen. This type of fracture was associated with increased times to failure, and higher values of σ_R were anticipated in view of the increased fracture area. Therefore, while still depositing the same class E11018-M electrode at an arc energy of 1.6 kj/mm (40 kj/in.) it was decided to keep to the 7 mm (0.28 in.) diameter specimens.

A second series of tests was made to assess the reproducibility of the method, using 0.28 in. (7 mm) diameter specimens with 0.02 in. (0.5 mm) deep notches with root radii in the range 0.0005—0.002 in. (0.013—0.05 mm). These were welded with the same class E11018-M electrodes as in the first series, but dried at 400 C for 1 hr, transferred to and held at 150 C before use. Three batches of tests were made in this series. In two batches the tests were made on different days from electrodes dried and used in exactly the same manner. The third was made with electrodes dried at only approximately 400 C and used after holding at 150 C for between 1 and 24 hr. The small range of scatter in all these tests can be seen from Fig. 4.

A third series of tests was then made using the same size of implant

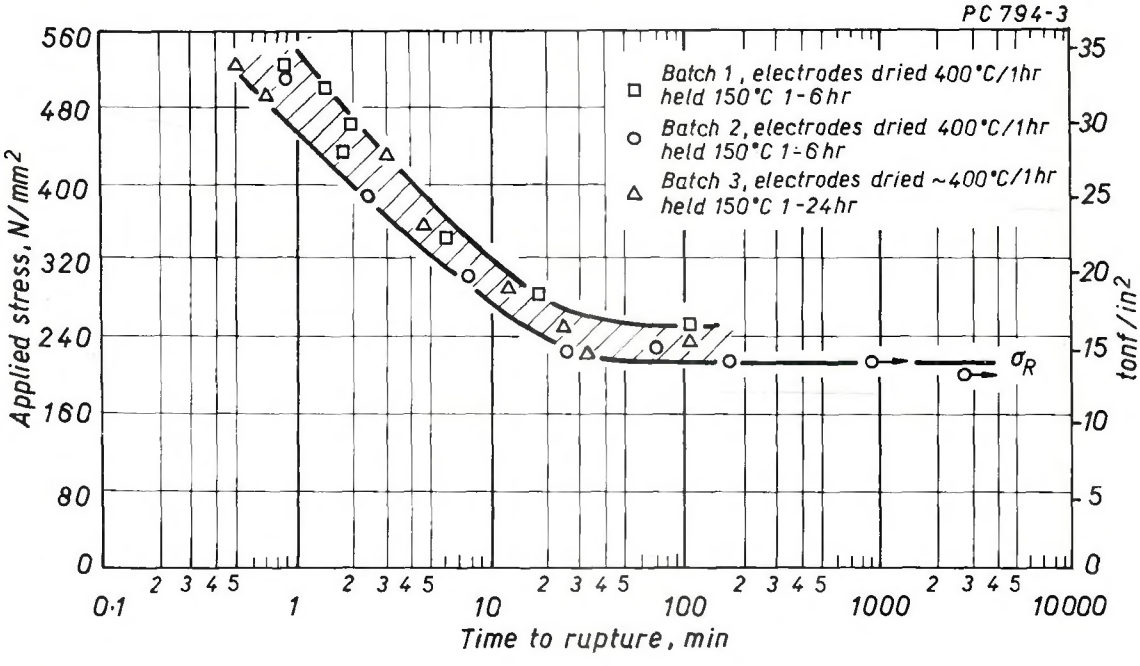

Fig. 4—Graph showing the reproducibility of the implant cracking test with separately dried batches of electrodes

specimen and the same class E11018-M electrodes. In this series, however, the electrodes were used straight from their container without any drying treatment. As can be seen from Table 2, they possessed a higher moisture content in the flux coating and gave a higher weld deposit hydrogen level than did the same electrodes when dried at 400 C for 1 hour.

The results of this series are compared with the previous series in Fig. 5. It is apparent that the increased moisture content and weld deposit hydrogen level and hence the hydrogen concentration in the heat-affected zone have lowered σ_R from 220 N/mm² to 170 N/mm² (14 to 11 tonf/in.²). The increased scatter in this series of tests is attributed to the greater range of weld deposit hydrogen analyses from as received electrodes. This can be seen in Table 2.

Comparison of Implant Cracking Test and Controlled Thermal Severity (CTS) Test

In another program of work,[8] the CTS test was used on the same low alloy quenched and tempered steel to assess the relative importance of welding variables on the preheat temperature to prevent heat-affected zone cracking. The variables investigated were arc energy, weld metal strength (mild steel and low alloy steel under and over matching the base metal, hydrogen potential (welding process), plate thickness, and plate composition.

Each variable was investigated at two levels, and to limit the size of the program a fractional factorial experimental design was used — Table 3. The first series of CTS tests (without preheat), using the electrodes dried in accordance with the particular fabrication procedure (1 hr at 400 C), had such a low incidence of cracking as to indicate that it would be impossible to obtain a statistical interpretation of the results. Further experiments were carried out with the electrodes having a higher moisture content in an attempt to increase the incidence of cracking. More cracking was obtained on completion of the tests under the new conditions. However, interpretation of the results indicated the test method was not sufficiently sensitive to define the relative effects of the variables. At this stage it was decided to re-assess the relative significance of the variables using the implant cracking test.

The standard CTS tests were trithermal and contained a root gap[9] to simulate the fit-up which occurs in practice. The welding conditions, plate composition, and potential and weld deposit hydrogen analysis of the welding consumables are shown in Tables 2–5. In order to allow any possible cracking to develop without interruption from further heating, a period of one week was allowed to elapse between making the first and second test welds. The same period was also allowed between the second test weld and cutting each weld into six sections for examination for cracking.

In the implant testing a full factorial experiment was carried out using MSMAW and the combination of variables in Table 6. One series using pulsed GMAW was tested. Because considerable difficulty was experienced in obtaining a satisfactory penetration profile in the welds made using pulsed GMAW with argon-5% oxygen shielding gas it was necessary to change the gas to argon-20% CO in order to reduce the finger penetration. The MSMAW conditions to give 2.6 kJ/mm (65 kJ/in.) were chosen initially to match those used in the CTS tests. However, the result was a penetration profile which was too deep in relation to its width.

This problem was overcome by dropping the current to 200 amp as used for the 1.6 kJ/mm (40 kJ/in.). This gave a satisfactory profile, but using the appropriate welding speed to give 2.6 kJ/mm (65 kJ/in.). The specific welding conditions used were 200 amp, 20 v, 150 mm/min (6 ipm) for 1.6 kJ/mm (40 kJ/in.) and 200 amp, 20 v (3–7 ipm) 95 mm/min for 2.6 kJ/mm (65 kJ/in).

Testing procedure was the same as used in the development work on the implant testing. Thus when rupture of the specimen occurred similar specimens were tested at progressively lower stresses until a σ_R stress level was reached, below which failure did not occur. Specimens which had not failed after a maximum of 24 hr were considered as unfailed specimens in the light of the fact that the longest recorded time to failure was less than 6 hr.

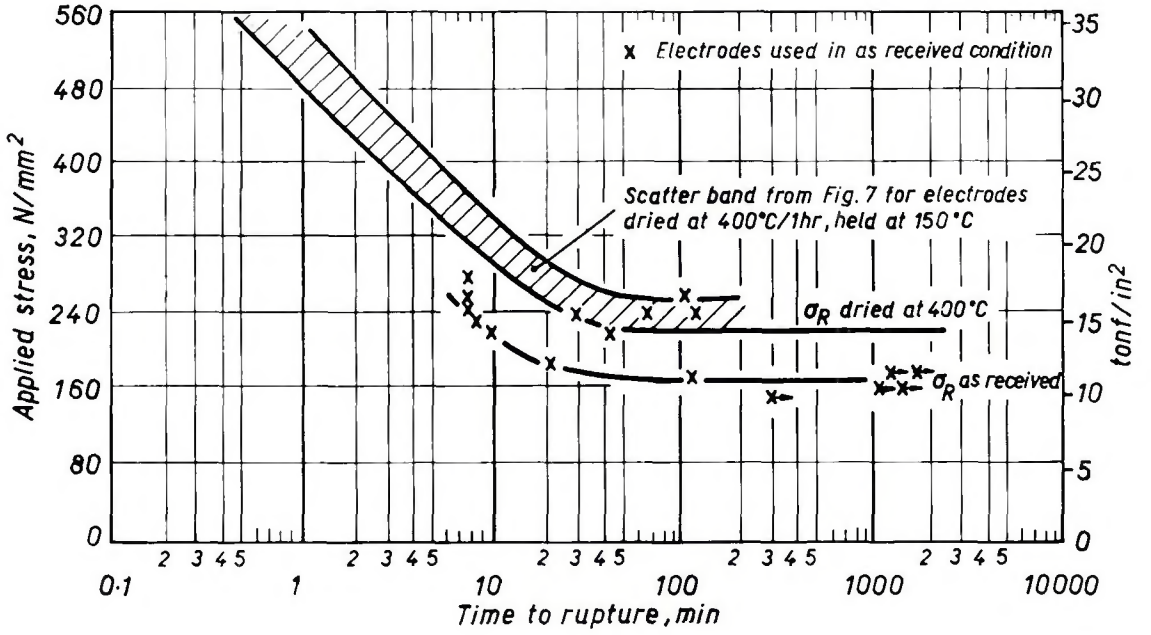

Fig. 5—Graph showing the sensitivity of the test by comparing σ_R values of one type of electrode at two different moisture content levels.

Table 2—Potential and Weld Deposit Hydrogen Analysis of Consumables

Consumable	Potential hydrogen ml H_2/100 g filler metal or % moisture content	Weld deposit hydrogen ml H_2/100 g deposited metal*
Mild steel filler metal 3/64 in. (1.2 mm) As received	3.3 ml	2.3
Low alloy filler metal 3/64 in. (1.2 mm) As received	6.4 ml	3.2
6 swg E11018-M a) As-received	0.19%	10.5
b) Dried 1 hr 400C held 1-2 hr 150C	0.08%	5.5
c) 24 hr at 100% RH, 38C, plus 1 hr 150C, held 1-2 hr 40C	0.40%	11.7

*Chill bead deposit to BS 1719: Part 1 1963 Appendix B.

Table 3—The Combinations of Variables Used in Each CTS Test Series

Series no.	Process (potential hydrogen)	Consumables (weld metal strength)	Plate composition	Thickness mm	Thickness in.	Arc energy kJ/mm	Arc energy kJ/in.
1A	GMAW (low)	Mild steel (low)	Low C (0.15)	25	1	1.6	40
2J	MSMAW* (High)	E9018-M (low)	High C (0.17)	25	1	1.6	40
3B	MSMAW (high)	E9018-M (low)	Low C (0.15)	25	1	2.6	65
4C	MSMAW (high)	E9018-M (low)	Low C (0.17)	51	2	1.6	40
5D	MSMAW (high)	E11018-M (high)	Low C (0.15)	25	1	1.6	40
6K	GMAW (low)	Low alloy (high)	High C (0.17)	25	1	1.6	40
7E	GMAW (low)	Low alloy (high)	Low C (0.15)	25	1	2.6	65
8F	GMAW (low)	Low alloy (high)	Low C (0.17)	51	2	1.6	40
9T	MSMAW (high)	E9018-M (low)	High C (0.21)	51	2	2.6	65
10G	GMAW (low)	Mild steel (low)	Low C (0.17)	51	2	2.6	65
11M	GMAW (Low)	Mild steel (low)	High C (0.11)	51	2	1.6	40
12P	GMAW (low)	Mild steel (low)	High C (0.17)	25	1	2.6	65
13N	GMAW (low)	Low alloy (high)	High C (0.11)	51	2	2.6	65
14S	MSMAW (high)	E11018-M (high)	Low C (0.17)	51	2	2.6	65
15Q	MSMAW (high)	E11018-M (high)	High C (0.21)	51	2	1.6	40
16R	MSMAW (high)	E11018-M (high)	High C (0.17)	25	1	2.6	65

*Manual shielded metal arc welding.

Table 4—Chemical Analysis of Selected CTS Test Plates

Plate thickness mm	Plate thickness in.	Elements, % C	Mn	Si	S	P	Ni	Cr	Mo	Cu
51	2	0.17	0.38	0.10	0.013	0.010	2.71	1.27	0.30	0.01
51	2	0.21	0.32	0.15	0.022	0.010	2.67	1.32	0.27	0.02
25	1	0.15	0.23	0.21	0.011	0.011	2.30	1.14	0.34	0.04
25	1	0.17	0.25	0.20	0.011	0.012	2.28	1.14	0.34	0.04

Table 5—Summary of Welding Conditions

Process	Arc energy kJ/mm	Arc energy kJ/in.	Electrode or filler metal diameter mm	Electrode or filler metal diameter in.	Arc volts,	Current, amps	Travel speed mm/sec	Travel speed ipm	Shielding gas
MSMAW	1.6	40	4.7	3/16	20	200	2.5	6	
MSMAW	2.6	65	6.4	1/4	21	235	2.1	5	
GMAW	1.6	40	1.2	3/64	19	255	3.2	7.5	Argon + 5%O_2
GMAW	2.6	65	1.2	3/64	19	255	1.9	4.5	Argon + 5%O_2
Pulsed GMAW	1.6	40	1.2	3/64	25*	180*	2.9	6.75	Argon + 20%CO_2

*Average RMS meter values. Pulse voltage = 30V.

Table 6—Combination of Variables Used in Implant Testing

Curve no.	Composition, C%	Electrode	Arc energy kJ/mm	Arc energy kJ/in.	Plate thickness mm	Plate thickness in.
1	0.21	E9018-M	1.6	40	51	2
2	0.21	E9018-M	2.6	65	51	2
3	0.21	E11018-M	1.6	40	51	2
4	0.21	E11018-M	2.6	65	51	2
5	0.21	E9018-M	1.6	40	25	1
6	0.21	E9018-M	2.6	65	25	1
7	0.21	E11018-M	1.6	40	25	1
8	0.21	E11018-M	2.6	65	25	1
9	0.17	E9018-M	1.6	40	51	2
10	0.17	E9018-M	2.6	65	51	2
11	0.17	E11018-M	1.6	40	51	2
12	0.17	E11018-M	2.6	65	51	2
13	0.17	E9018-M	1.6	40	25	1
14	0.17	E9018-M	2.6	65	25	1
15	0.17	E11018-M	1.6	40	25	1
16	0.17	E11018-M	2.6	65	25	1
17*	0.21	A632 wire	1.6	40	51	2

*Pulsed GMAW

Results

CTS Tests

For heat-affected zone hydrogen cracking to occur a number of factors have to be concurrently satisfied. They are:

1. Sufficient concentration of hydrogen.
2. Sufficient amount of strain.
3. Susceptible microstructure.
4. Temperature near to ambient.

Any increase in factors 1–3 above will in general increase the risk of heat-affected zone cracking. Similarly the risk of cracking will increase as the weld cools to normal ambient temperature. An additional effect of temperature above normal ambient is to increase the rate of loss of hydrogen from the weld by diffusion. Consequently, the faster the rate of cooling below the transformation temperature range, the more hydrogen will be retained in the weld, and so the risk of cracking will increase. It will be apparent that within each CTS test and implant test series, the combination containing the highest risk of cracking will be the one which incorporates the following features:

1. The highest weld metal hydrogen level.
2. The strongest weld metal (since this will influence the level of strain on the heat-affected zone.[2]
3. The welding conditions, plate thickness and composition which lead to the hardest, most susceptible microstructure, and the fastest low temperature cooling rate.

Based on the above criteria the series of CTS tests made at room temperature have been listed in Table 7 for each process and consumable in order of predicted decreasing risk of heat-affected zone cracking. In assessing the low temperature cooling rate, it was decided to adopt the time to cool from 1000 to 100 C. Appropriate values have been taken from identical tests by Bailey.[10]

It will be seen, from the results of the first series of CTS tests, that it was not possible to determine the relative significance of all the variables investigated because of the large number of tests in which cracking was not observed. Moreover, the results do not entirely agree with the predicted order when assessed on the amount of cracking observed. However, it is considered that the increased incidence of cracking in the

Table 7—Results of CTS Tests Made at 20C Listed in Each Section in Order of Predicted Decreasing Risk of Cracking

Series no.	Cracking*	Composition	Time to cool to 100 C sec	Hardness (HV 2.5)	Plate thickness mm	Plate thickness in.	Energy input kJ/mm	Energy input kJ/in.	N/mm²
			GMAW with low alloy filler metal						
8	29	LC 0.17	48	(424)	51	2	1.6	40	
13	0	HC 0.21	80	(430)	51	2	2.6	65	
6	4	HC 017	100	(434)	25	1	1.6	40	
7	0	LC 0.15	175	(405)	25	1	2.6	65	
			GMAW with mild steel filler metal						
11	0	HC 0.21	48	(435)	51	2	1.6	40	250
10	0	LC 0.17	80	(426)	51	2	2.6	65	
1	0	LC 0.15	100	(412)	25	1	1.6	40	
12	0	HC 0.17	175	(409)	25	1	2.6	65	
			MSMAW with E11019-M electrodes dried 1 hr 400C held 1-2 hr 150C						
15	2	HC 0.21	48	(435)	51	2	2.6	40	220
14	0	LC 0.17	80	(426)	51	2	1.6	65	300
5	17.5	LC 0.15	100	(412)	25	1	1.6	40	320
16	0	HC 0.17	175	(409)	25	1	2.6	65	390
			MSMAW with E9018-M electrodes dried 1 hr held 1-2 hr 150C						
4	6	LC 0.17	48	(424)	51	2	1.6	40	220
9	0	HC 0.21	80	(430)	51	2	2.6	65	240
2	4	HC 0.17	100	(434)	25	1	1.6	40	380
3	0.5	LC 0.15	175	(405)	25	1	2.6	65	420

*Average % of leg length cracked, of all sections.

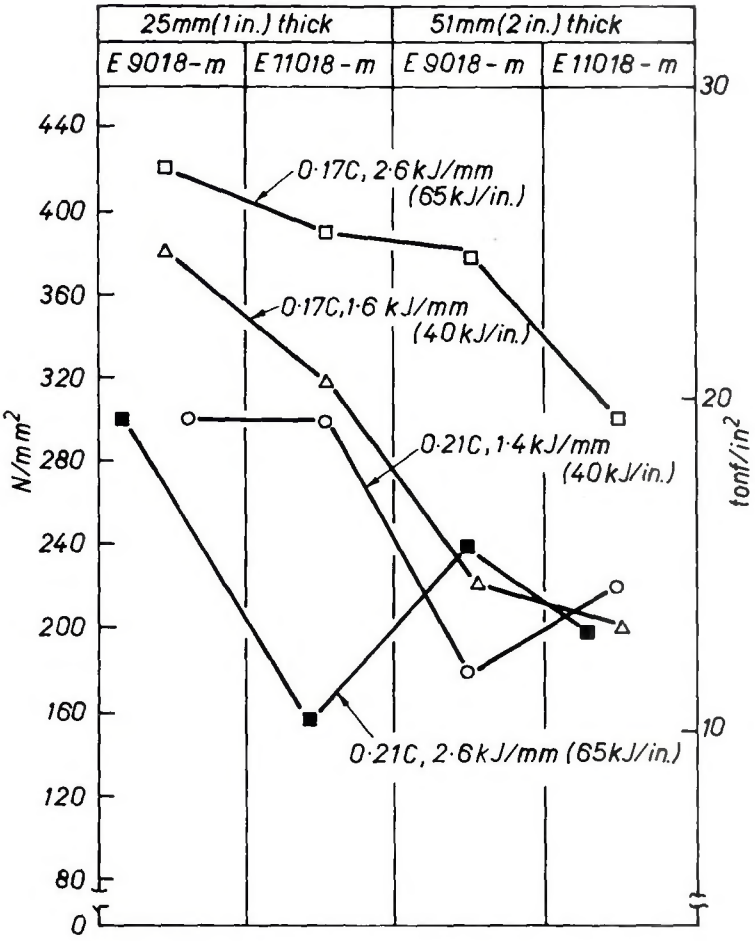

Fig. 6— σ_R results of implant tests on low alloy steel showing the effect of welding and plate variables

series welded with the low alloy filler metal compared to that welded with the mild steel filler metal is due to the combined effects of the increased yield strength of the low alloy filler metal weld deposit and its slightly higher hydrogen level.

The reason for the apparently lower risk of cracking of the 51 mm 2.6 kJ/mm combination, compared to the 25 mm 1.6 kJ/in. combination is not known for certain. However, for this series of tests despite the apparent anomaly, the beneficial effect on the risk of heat-affected zone cracking of raising the arc energy is clear. Only in one out of eight CTS tests made at 2.6 kJ/mm (65 kJ/in.) was cracking observed, while six out of eight made at 1.6 kJ/mm (40 kJ/in.) were cracked.

The results of the tests made with moistened electrodes are summarized in Table 8. Unlike some of the earlier tests made with electrodes dried at high temperature, these results do conform to the predicted pattern of risk of cracking. However, it is clear from Table 8 that for the series 2, 4, 5, 9, 14 and 15 there is only a small range of the critical levels of preheat temperature to prevent cracking (155–170 C). Thus it was again not possible to assess the results to determine the relative effects of the variables.

Table 8—CTS Test Results With Humidified Electrodes

Series no.	Preheat temperature to prevent cracking, °C	Variables: Composition	(Hardness HV2.5) average	Plate thickness mm	Plate thickness in.	Arc energy input kJ/mm	Arc energy input kJ/in.
		E11019-M electrodes					
15	160	0.21	(435)	51	2	1.6	40
14	160	0.17	(426)	51	2	2.6	65
5	155	0.15	(412)	25	1	1.6	40
16	130	0.17	(409)	25	1	2.6	65
		E9018-M electrodes					
4	170	0.17	(424)	51	2	1.6	40
9	160	0.21	(430)	51	2	2.6	65
2	160	0.17	(434)	25	1	1.6	40
3	100	0.15	(405)	25	1	2.6	65

Implant Weld Tests

The results of the implant tests are summarized in Fig. 6 where the σ_R value for each series has been plotted. In considering the results it has been assumed that the higher the value of σ_R the lower the risk of cracking On this basis the effects of the variables are individually considered below.

Effects of Thickness. For the low carbon steel, Fig. 6 shows that there is a marked effect of thickness since, in all cases, increasing the thickness increases the risk of cracking. For the higher carbon steel there is again a similar marked effect in all except one case. This exception is for 2.6 kJ/mm (65 kJ/in.) and E11018-M electrodes where there is a slight decrease in the risk of cracking in going from 25 to 51 mm (1 in. to 2 in.) plate.

Effect of Electrode Type. For the low carbon material, Fig. 6 shows a consistent trend in that for all cases changing from E9018-M to E11018-M increased the risk of cracking. For high carbon material, in three cases there was either no change or an increase in the risk of cracking. However, in the fourth case, 1.6 kJ/mm (40 kJ/in.) and 51 mm (1 in.) plate, the change of electrode decreased the risk of cracking. The effect of increasing the risk of cracking by changing from low to high strength weld metal was not apparent from the CTS test results.

It has been argued[2] that changing from an under-matching electrode to an over-matching electrode (in terms of yield stress) in a CTS test, increases the effective stress on the heat-affected zone (i.e., the risk of heat-affected zone cracking is increased). On the other hand, the same argument cannot be immediately applied to implant testing where the effective acting stress is controlled by the notch shape, the cross-section area and the applied

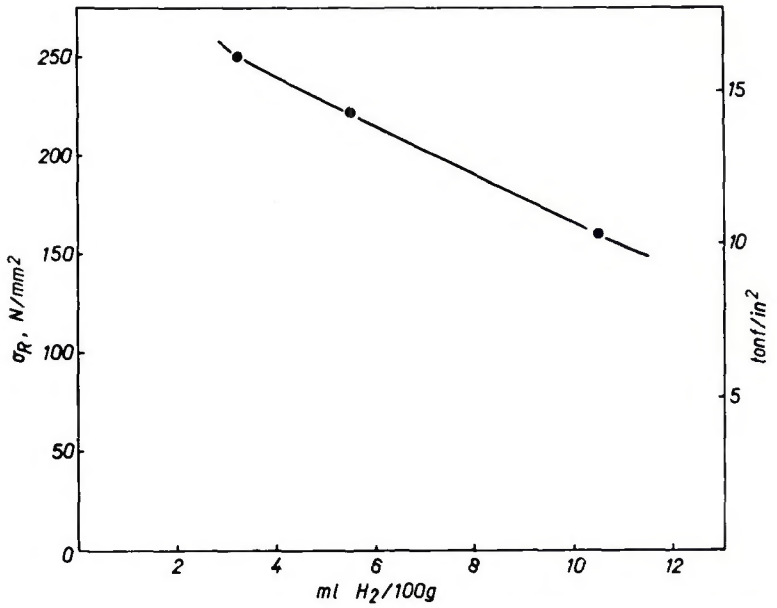

Fig. 7—Graph showing the effect of weld metal hydrogen level on the risk of cracking

load. However, estimates of the plastic zone size around the notch tip indicate that it will not be confined to the heat-affected zone and will embrace some weld metal. Hence, raising the strength of the weld metal will tend to restrict the development of the plastic zone in the heat-affected zone. Also, this will increase the degree of triaxiality and thus increase the risk of cracking.

It is possible that the increased risk of cracking in welds made with E11018-M electrodes could have been due to an increased concentration of hydrogen in the heat-affected zone. This could have arisen in two ways. First, the hydrogen potential of the E11018-M electrodes might have been higher than the E9018-M electrodes (the latter were not analyzed) and this would have led to an increased level in the heat-affected zone. Second, because the E9018-M electrodes are less highly alloyed than the E11018-M electrodes, the transformation temperature would be higher than for E11018-M electrodes. Hence, there would have been a longer period of time during which the E9018-M weld metal was ferritic, but the heat-affected zone still austenitic. At this point, hydrogen could escape more rapidly (because of its higher diffusivity in ferrite) from the weld metal into the heat-affected zone or into the atmosphere.

Because of the lower diffusivity of hydrogen in austenite, the most noticeable difference in hydrogen concentrations (when the weld has cooled to the cracking temperature range — say, to less than 150 C), would be in the weld deposit and not in the heat-affected zone. Thus, if the hydrogen potential of the two electrodes was the same, then for the above reasons the reservoir of hydrogen available to produce delayed cracking would be less for weld metal deposited from E9018-M electrodes than from E11018-M electrodes. It is not possible to state which and to what extent the three effects, (triaxiality, different hydrogen potentials, and different weld hydrogen levels at ambient temperatures) are responsible for the increased risk of hydrogen cracking of the welds made with the E11018-M electrodes.

The σ_R for the pulsed GMAW involving the low alloy filler metal, 51 mm (2 in.) plate, high carbon steel for the implants and an arc energy of 1.6 kJ/mm (40 kJ/in.) was 250 N/mm² (16 tonf/in.²). This should be compared with σ_R of the MSMAW involving the same variables which was 220 N/mm² (14 tonf/in.²). Since GMAW gave 3.2 ml and the MSMAW 5.5 ml hydrogen / 100 g deposited weld metal, the difference in σ_R reflects the change in weld metal hydrogen content. In fact, the difference of 30 N/mm² (2 tonf/in.²) for an increase of 2.3 ml of hydrogen corresponds well with the results obtained in the development work on similar material and consumables, where an increase of 5 ml hydrogen/100 g lowered the σ_R by 50 N/mm² (3.2 tonf/in.²).

Carbon Content. At an arc energy of 2.6 kJ/in.), increasing the carbon content markedly increased the risk of cracking in all cases. At an arc energy of 40 kJ/in. (1.6 kJ/mm), in all cases but one there was a similar trend, although the increase was smaller. The exception was for 2 in. (51 mm) plate and E11018-M electrodes where there was a slight decrease in the risk of cracking.

Arc Energy. For low carbon 25 and 51 mm (1 and 2 in.) plate there was a consistent trend in that increasing the arc energy from 1.6 to 2.6 kJ/mm (40 to 65 kJ/in.) reduced the risk of cracking in all cases. For the high carbon material and E9018-M electrodes with 25 mm (1 in.) plate, raising the arc energy produced no change in the risk of cracking whereas with 51 mm (2 in.) plate the risk of cracking was reduced. However, in the remaining two cases of high carbon material, E11018-M electrodes with 25 and 51 mm (1 and 2 in.) plate, raising the arc energy rather surprisingly increased the risk of cracking. This effect of reducing the cooling rate yet increasing the risk of cracking has been observed before.[11]

Hydrogen Level. In Fig 7 are plotted the σ_R values as a function of weld metal hydrogen levels for the welding condition of 1.6 kJ/mm (40 kJ/in.) on 51 mm (2 in.) thick plate. This shows a marked trend to a lower risk of cracking as the initial hydrogen level decreases. This was not apparent in the CTS test results with GMAW and MSMAW with baked electrodes, although the CTS tests did indicate a higher risk of cracking when the electrodes with a higher moisture content were used.

Discussion

Comparison of the implant cracking test and CTS test results indicates that the former is a very capable method of determining the relative significance of welding and plate variables on the risk of cracking; it is certainly more discriminating than the CTS test. Probably the main reason for this is associated with the fact that the initial stress concentration and applied stress are constant in the implant cracking test. With the CTS, even at constant plate thickness, the applied stress on the heat-affected zone would be expected to vary with weld bead size, and the stress concentration at the root of the weld is likely to vary even at the same weld bead size.

In addition, current methods of assessing CTS test results depend on either determining whether cracking has occurred or estimating the extent of cracking — but both of these are assessed by sectioning and examining the weld. Inherent in most practical techniques of sectioning is

the possibility of missing some cracking. This is because experience has already shown that the observation of the percentage of the leg length which is cracked can vary between 0 and 15% in a distance corresponding to the width of a saw cut. This is not to say that the CTS test and other weld cracking tests do not give a true indication of the risk of cracking for the particular combination of joint geometry, plate and welding variables.

Provided sufficient tests are conducted to minimize the error involved in assessing the results of the tests, there is no doubt that they give a true indication of the risk of cracking. In fact Winn[12] has shown that the preheat temperatures to prevent cracking determined from the CTS tests are in line with his own experience on similar steels. What the results of the work described above do indicate is that (for the purpose of investigating the effects of plate and welding variables on the risk of cracking) the implant cracking test is superior to the CTS test because of the greater degree of control the operator has over one of the principal factors.

The implant cracking test results indicated that within the range of plate and welding variables investigated there was a wide range of risk of cracking, as represented by σ_R which varied from 160–420 N/mm^2 (10.5–27 tonf/in.^{2}). The results also showed that, for the lower carbon material, decreasing the arc energy, increasing the plate thickness and changing from E9018-M electrodes to E11018-M electrodes all increased the risk of cracking. For the higher carbon material similar trends were evident, but they were not so marked. However, statistical interpretation of all the implant tests results (analysis of variance) showed that the only significant variables were carbon content and plate thickness and these at the 10% level of confidence. For lower carbon material an additional significant variable (at the 10% level) was arc energy. A regression analysis of all the variables gave the following equation:

$$\sigma_R = 923\text{-}2250\ (C\%) - 0.28\ (YS\ of\ weld\ metal) + 40\ (arc\ energy) - 3.1\ (plate\ thickness)$$

This indicates that increasing the carbon content has a greater effect on the risk of cracking than the other variables. In terms of equivalence of the variables the equation indicates that an increase in carbon content of 0.05% is equivalent in its effect on σ_R to an increase of 400 N/mm^2 in the weld metal yield stress, or an increase in plate thickness of 36 mm, or a decrease in arc energy of 2.8 kJ/mm.

All the work in the implant cracking test described in this paper has been concerned with determining $\bar{\sigma}_R$ the critical stress below which cracking does not lead to complete rupture of the specimen. The development work showed that when determining σ_R it was important to be able to locate all the plane of the notch in the high temperature region of the heat-affected zone. In an attempt to overcome such difficulties and to increase the sensitivity of the test, consideration is being given to the possibility of using the minimum stress for crack initiation (σ_C) instead of rupture (σ_R) as the criterion of failure. If such a criterion is adopted, it is no longer important to locate all of the plane of the notch in the same region of the heat-affected zone. Under these circumstances the penetration profile of the weld bead is not important, and the implant cracking test can be used to assess all arc welding processes. Development work is currently in hand to determine the best method to use for detecting crack initiation. Techniques such as ultrasonic examination, stress wave emission, and metallographic examination are being considered.

The results presented in this paper have already indicated the potential of the technique for assessing the relative effects of welding and plate variables. Programs of work at present in operation are also using the technique for comparing the susceptibility to heat-affected zone cracking of C:Mn structural and micro-alloyed steels. This is being done in the first instance by comparing the curves of σ_R (or σ_C) against a cooling parameter and the hardness of the heat-affected zone. These curves can be determined for a range of weld metal hydrogen levels. It will then be possible, after establishing correlations with other tests, to predict from these diagrams the critical hardness to prevent hydrogen cracking for a particular joint type and weld metal hydrogen level. These critical hardnesses may then be used in conjunction with the diagram devised by Bailay[13,14] for predicting safe welding procedures.

Conclusion

Comparison of the results of the CTS test and implant cracking test obtained in a program to assess the relative significance of welding and plate variables on the risk of cracking in a low alloy steel has demonstrated the advantages of the implant cracking test for this application. The increased sensitivity of the implant cracking test is believed to be primarily due to having direct control, and reproducibility, over the level of stress applied to the heat-affected zone.

On the basis of the σ_R values the implant test was able to indicate that increasing the carbon content from 0.17 to 0.21% markedly increased the risk of cracking at an arc energy of 2.6 kJ/mm (65 kJ/in.) and to a lesser extent an arc energy of 1.6 kJ/mm (40 kJ/in.). The results also showed that decreasing the arc energy, increasing the plate thickness and changing from E9018-M to E11018-M electrodes all increased the risk of cracking. Moreover, results showed that the risk of cracking was more marked for the low carbon than for the high carbon material. A regression analysis of the results indicated that increasing the carbon content had a greater effect on the risk of cracking than any of the other variables. The CTS test results, however, were only able to indicate that decreasing the arc energy decreased the risk of cracking.

When the implant cracking test results are assessed on the basis of a rupture criterion it is important to ensure that all of the plane of the notch is situated in the same region of the heat-affected zone. This is particularly difficult to achieve when the welding conditions result in a deep penetration profile. To overcome this difficulty it is considered necessary to use a crack initiation criterion in which case the above requirement for the location of the plane of the notch would not apply.

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