WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, SEPTEMBER 1974

Sponsored by the American Welding Society and the Welding Research Council

Fracture Control in High Yield Strength Weldments

A fracture mechanics analysis is developed to establish design criteria for flaws in weld metal that is too tough for K_{Ic} tests

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ABSTRACT. This paper draws attention to the factors which affect resistance to brittle fracture in steels and reviews the basic fracture control procedures. It was concluded from a survey of fracture toughness data that the weld metal constitutes the most brittle region of most C-Mn and low alloy steel weldments with yield strengths greater than approximately 500 N/mm² (70,000 lb/in²).

An investigation of the fracture propagation and fracture initiation resistance of the best available SMA, GMA and SA weld metals showed that, for the thicknesses (51 mm : 2 in.), temperatures (−20 to +20 C: −4 to +68 F) and yield strengths (500 to 1,030 N/mm² : 70,000 to 150,000 lb/in.²) of interest, a simple transition temperature approach was unlikely to provide a reliable means of avoiding brittle fracture. It was concluded that in such thicknesses the weld metals fell into that large category of materials which have too much toughness to satisfy the validity requirements for K_{Ic} tests and yet insufficient toughness for design to avoid fracture propagation.

It is demonstrated how yielding fracture mechanics COD relationships may be used to make safe and realistic estimates of the maximum allowable or tolerable crack sizes in weld metals in a range of practical situations. For example, cracks in as-deposited and stress relieved welds in and remote from design stress concentration regions.

Introduction

The increasing use of high strength steels in structures such as pressure vessels, storage tanks and bridges has drawn attention to the fact that fracture toughness tends to decrease with increasing yield strength. This is especially true of the weld zone of high yield strength weldments, where the welding processes place additional limitations on the compositional and structural factors that control the mechanical properties of the weld region. The recognition of this problem area has resulted in considerable research into the combined effects of welding parameters and material compositions. This research has generated data from a range of brittle fracture tests on C-Mn and low alloy steel weldments with yield strengths up to 1,030 N/mm² (150,000 lb/in.²).

The present paper is intended to give a perspective view of fracture toughness data from several parallel investigations. It also draws attention to the limitations which the available properties place on various fracture control procedures and the relevance of fracture mechanics tests.

Design Philosophies

For the majority of steels with yield strength up to 1,030 N/mm² (150,000 lb/in.²) fracture toughness tests may be used to establish a temperature range over which a transition occurs from ductile fracture with large 45 deg shear lips to brittle cleavage fracture with decreasing temperature. For a given material and thickness this transition temperature

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Paper was presented at the 55th AWS Annual Meeting held in Houston, May 6-10, 1974.

range may be raised by such factors as an increase in loading rate and an increase in section thickness (Fig. 1). The lowest transition temperature ranges will be obtained in static or slowly applied load tests which give a measure of resistance to the first significant extension of a pre-existing defect (fracture initiation), whereas the highest transition temperature ranges will be obtained in tests which give a measure of resistance to the continued extension of a crack (propagation).

The distinction between resistance to fracture initiation and resistance to fracture propagation is extremely important in strain rate sensitive materials since, once crack extension occurs, there is a rapid increase of strain rate at the crack tip, with a corresponding reduction in toughness. Thus fracture propagation may continue at lower stresses than those necessary for fracture initiation. This situation, which relates to cleavage fracture, should not be confused with the increase in resistance to fracture propagation which results when the microfracture mode is by void coalescence, which is mentioned later. For cleavage fracture, therefore, tougher and generally more expensive materials are required if design relies solely on a high resistance to fracture propagation.

We can divide brittle fracture tests into two main types: (a) those which are used to assess resistance to fracture initiation, and (b) those which are used to assess resistance to fracture propagation. The choice of which test is most appropriate for use in practice will depend on the philosophy of design to avoid fracture. Practical design philosophies are:

1. Accept that weld cracks will be present and design to avoid fracture *initiation*.
2. Accept that weld cracks will be present and that fracture initiation may occur in an embrittled region and design to avoid fracture *propagation* by using a base metal with sufficient toughness to arrest a crack emerging from such a region.
3. Accept that defects will be present and design to avoid fracture *propagation* in all regions of the structure, e.g., all regions of a welded joint.

For materials that fracture with large 45 deg shear lips at temperatures near the start of the upper shelf of the ductile/brittle transition, the simplest way to implement the philosophies is to ensure that the service temperature range is always above the relevant transition temperature range, as shown schematically in Fig. 2. Under these conditions it may be concluded that the safest philosophy is 3, the next is generally 2 and finally philosophy 1.

However, for materials in which fractures propagate with little or no shear lip at temperatures corresponding to the upper shelf of the transition in initiation resistance, the simple transition temperature approach to fracture control may be unsafe. In such materials the flat part of the fracture surface will be dominated by microvoid coalescence.

The relevance of the three design philosophies and the methods of applying them to high strength weldments are discussed in more detail in the following sections.

Relative Toughness of Weld Regions

Three regions of a weld can be defined for a preliminary assessment of weldment fracture behavior, namely the base metal, the weld HAZ and the weld metal. Brittle fractures in steel weldments invariably start or initiate from defects in the HAZ or weld metal. In mild steels and the lower strength C-Mn steels brittle fractures generally deviate from the weld zone and propagate or arrest in the base metal. It is a reliance on this behavior that is used to justify design philosophy 2. However, for steels with yield strengths in excess of approximately 500 N/mm^2 (70,000 lb/in.^{2}), there is evidence from tests on complete weldments to show that fracture propagation is often confined to the weld metal and in rare instances the weld HAZ. Fracture propagation in weld metal has been observed in wide plate tests. In some initial tests (Ref. 1) notches were sited in grain-coarsened HAZ regions of multipass

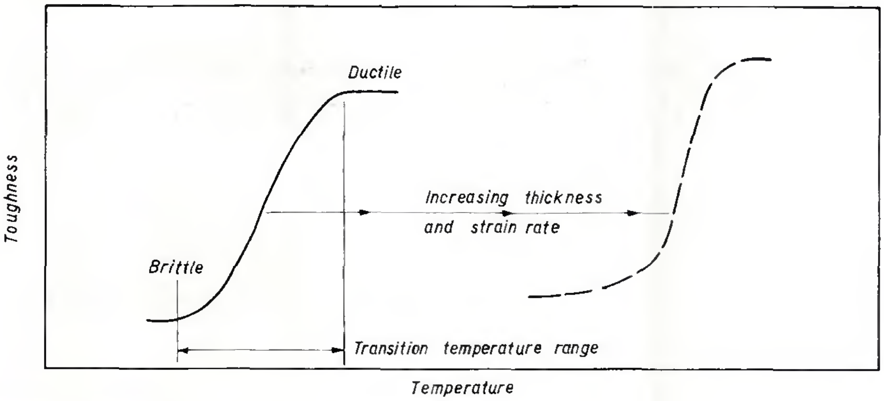


Fig. 1 — Ductile/brittle transitional behavior

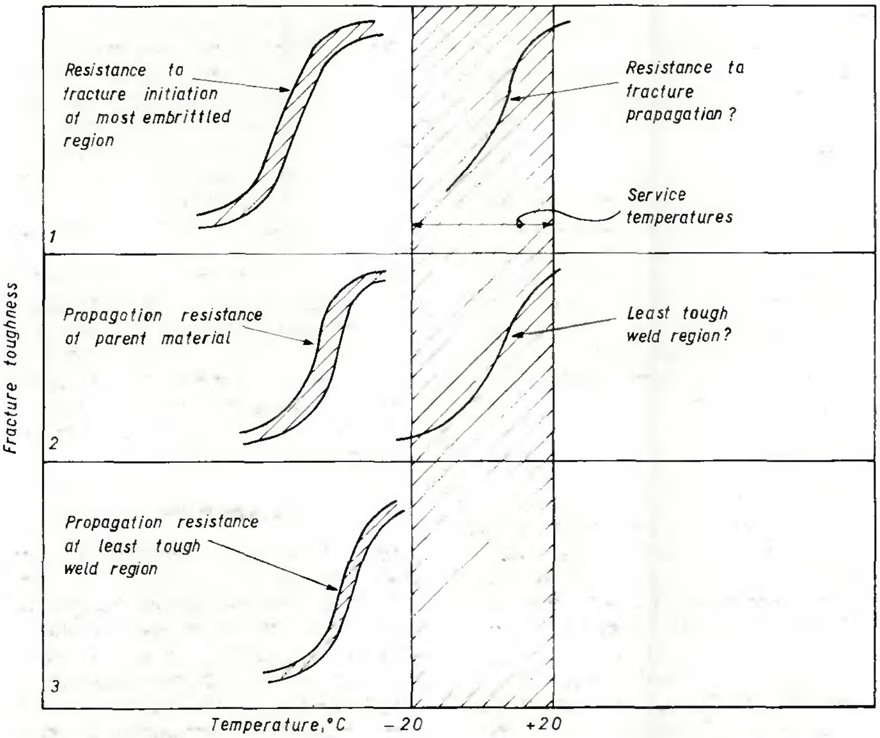


Fig. 2 — Schematic diagram illustrating the transition temperature approach to design philosophies 1, 2 and 3

butt welds, but fracture initation and propagation occurred in the weld metals.

This rather surprising behavior was also observed in Charpy V notch impact tests and full section thickness bend tests in the same program of work (Ref. 1). For example, Fig. 3 shows a macrosection through one half of a broken bend specimen which fractured in the weld metal near the weld fusion boundary even though the notch was located in the base metal outside the visible HAZ. Further examples of fracture initation and propagation in weld metal are given by the wide plate tests that are described later.

American (Ref. 2) and Japanese (Ref. 3) investigators have also observed fracture propagation in the weld zones of high strength steels. Pellini (Ref. 2) publicized an instance where fracture followed the weld zone of a high yield strength test vessel and concluded that "some of the continuing studies of fracture processes should be directed to issues of welds and HAZs; this area has been largely neglected and urgently requires renewed attention."

Shackleton (Ref. 4) has listed numerous investigations in which tests on individual weld regions have shown the weld metal or HAZ to have inferior toughness to the base metal. In general, the weld HAZ toughness is superior to the weld metal toughness when the base metal manufacturer's recommendations are followed with respect to welding preheats, interpass temperatures and postweld heat treatments. Brittle fracture propagation along weld HAZs is made difficult in service by the fact that these regions are generally inclined to the plate surfaces. It is also of relevance to mention that brittle fracture propagation in weld metal near the weld fusion boundary can be easily mistaken for fracture propagation in the HAZ when small shear lips at the fracture edges terminate at the weld edge on the plate surface.

The above discussion leads to the obvious conclusion that the weld metal constitutes the greatest fracture risk in high strength weldments. Furthermore, design to avoid brittle fracture in weld metals will be limited to design philosophies 1 and 3.

Weld Metal Fracture Toughness

For quantitative measurements of fracture toughness that can be used to provide design data (and the transitional behavior of a structure), it is essential to carry out tests on weld metals that are fully representative of the structure concerned. This is important since weld metal fracture toughness is affected by such factors as the base metal composition, the welding process or processes, consumables, preheat and interpass temperatures, heat input, welding sequence, position, number of weld passes, postweld heat treatments and the time lapse between welding and testing. Many of these factors have been discussed in detail in References 5 and 6.

For both metallurgical and mechanical reasons it is important that the test specimens are in full section thickness. Mention was made earlier of the mechanical effect of thickness on fracture toughness (Fig. 1), which is well known. However, the metallurgical reasons for doing full section thickness tests on weld metals are less well known and it may be helpful to mention them. In general, as welds increase in size different positions within the weld metal will experience greater differences in the amounts of dilution from the base metal, the number and rates of heating and cooling cycles, total strain and differences in hydrogen content, etc. These differences result in variations of mechanical properties within the weld metal. For example, in many equal double V multipass butt welds the weld metal at the center of thickness (the weld root) has significantly lower fracture toughness, higher yield strength and hardness than the weld metal near the plate surface.

Figure 4 illustrates some extreme examples of yield strength and frac-

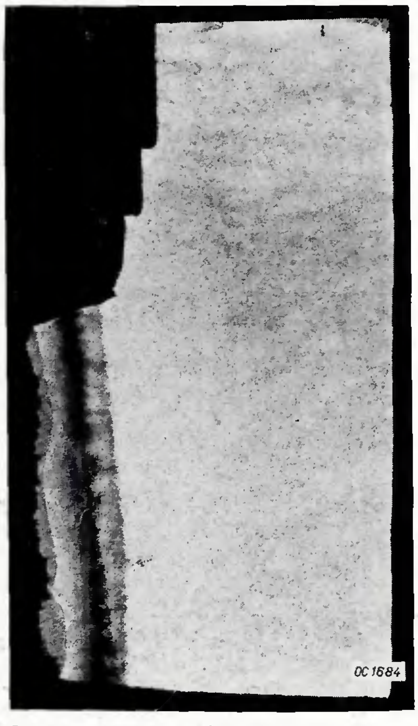


Fig. 3 — Macrosection of fractured bend specimen. The notch tip was located in the base metal but fracture occurred in the weld metal

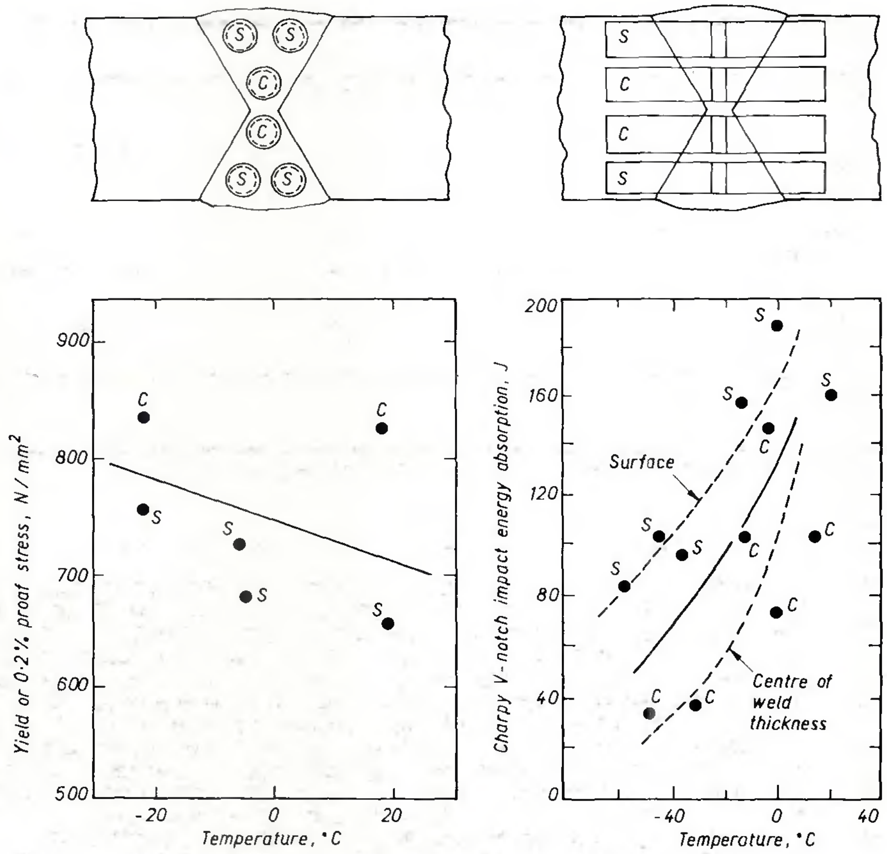


Fig. 4 — Variations of yield strength and toughness with position in thickness

ture toughness variations at different positions in 51 mm (2 in.) thickness butt welds. It will be obvious from Fig. 4 that Charpy V notch impact test specimens and standard 16 mm (0.625 in.) thick DT test (Ref. 7) specimens extracted from one position in a butt weld may lead to completely wrong conclusions about the effective fracture toughness of the total volume of weld metal. This example and other considerations (Ref. 4) of weld metal properties lead to the conclusion that reliable crack propagation data can only be obtained from full section thickness test specimens that contain through-thickness notches in planes parallel to the weld length.

In structures where detailed fracture mechanics analyses are justified for surface and buried cracks it may be necessary to carry out a range of fracture initiation tests to assess weld metal fracture toughness at different positions across the width and depth of a weld. For the majority of service applications, however, a more practical approach is to consider only the region of least fracture toughness. In the majority of equal double V butt welds, the least resistance to fracture initiation will be obtained from tests on full section thickness specimens containing through-thickness notches in planes parallel to the weld length, i.e., specimens of similar design to those recommended for crack propagation tests. The design of fracture initiation test specimens for other types of welds are discussed in more detail in Reference 6.

The above comments give a brief indication of the factors that were considered before starting a large program of tests to assess the fracture toughness of a worldwide selection of commercially available consumables for high strength steels. This program resulted in a selection of twelve process/consumable combinations for base metals with minimum yield strengths of 550 N/mm^2 (80,000 lb/in.^{2} and 690 N/mm^2 (100,000 lb/in.^{2}). The results of fracture propagation tests and fracture initiation tests on the twelve weld metals are discussed below. Relevant details of the base metals, weld metals, welding processes and procedures are summarized in Tables 1 to 5. All the tests were carried out on standard joints made in the flat position.

Propagation Tests

The resistance to fracture propagation in 51 mm (2 in.) thickness was assessed using the dynamic tear test (Ref. 7). Figure 5 illustrates the DT test results for the selected SMA, GMA and SA welds. It can be seen that, for the service temperature range −20 to +20 C (−4 to +68 F), the fracture surface shear lips were always less than 85% of the plate thickness and in one instance, Weld No. 4, the shear lips at −20 C (−4 F) was only

Table 1 — Chemical Analyses of Base Plate Materials

Material	C	Si	Mn	S	P	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	B	Pb	Sn	Co
A 550 N/mm^2 min yield 51 mm thick	0.15	0.25	0.37	0.020	0.012	2.48	1.38	0.27	<0.01	0.18	0.009	<0.01	0.017	<0.001	<0.01	0.02	0.04
B 690 N/mm^2 min yield 51 mm thick	0.15	0.19	0.31	0.009	0.010	2.48	1.24	0.33	0.01	0.14	0.011	<0.01	<0.01	<0.001	<0.01	0.01	0.04

Table 2 — Mechanical Properties of Base Plate Materials

Material	Yield or 0.2% proof stress, N/mm^2			Tensile strength, N/mm^2			Elongation on 51 mm, %			Reduction in area, %			Charpy energy at −84 C, J		
A 550 N/mm^2 min yield	595	653	583	723	767	712	23	25	24	65.3	68.0	69.4	82	72	87
													75	80	69
	578	653	635	713	757	765	26	27	25	71.9	73.5	71.0	105	88	90
B 690 N/mm^2		690			788			26			70		109	125	139
min yield		732			819			27			70		133	155	147

N.B. — 1,000 lb/in.^{2} = 6.9 N/mm^2

Table 3 — Chemical Analyses of Low Dilution Weld Metal Deposits, (wt. %)

Weld metal no.	C	Si	Mn	S	P	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	B	Pb	Sn	Co	O	N
1	0.06	0.45	0.9	0.019	0.028	1.06	0.38	0.24	0.01	0.07	<0.005	0.03	0.007	<0.001	<0.01	<0.01	0.04	0.027	0.008
2	0.06	0.57	1.68	0.02	0.021	2.37	0.09	0.47	0.02	0.04	<0.005	0.02	0.012	<0.001	<0.01	<0.01	0.06	0.028	0.009
3	0.06	0.39	1.45	0.021	0.012	2.13	0.39	0.40	0.03	0.02	<0.005	0.02	0.009	<0.001	<0.01	<0.01	0.05	0.029	0.014
4	0.04	0.25	0.8	0.009	0.013	1.47	0.17	0.41	0.14	0.05	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	0.05	0.039	0.010
5	0.05	0.33	1.12	0.008	0.009	2.03	0.14	0.41	<0.01	0.07	<0.005	0.01	0.008	<0.001	<0.01	<0.01	0.04	0.015	0.014
6	0.05	0.33	0.86	0.007	0.015	1.51	0.26	0.40	0.14	0.06	<0.005	0.01	<0.005	<0.001	<0.01	<0.01	0.05	0.036	0.008
7	0.05	0.38	1.04	0.007	0.018	1.54	0.24	0.40	0.14	0.06	<0.005	<0.01	0.015	<0.001	<0.01	<0.01	0.05	0.030	0.008
8	0.09	0.44	1.45	0.010	0.028	1.99	0.54	0.39	0.02	0.02	<0.005	0.01	0.010	<0.001	<0.01	<0.01	0.04	0.026	0.021
9	0.08	0.30	1.29	0.011	0.008	2.43	0.40	0.47	0.01	0.21	<0.005	0.01	0.010	<0.001	<0.01	<0.01	0.06	0.020	0.007
10	0.09	0.36	1.46	0.006	0.011	2.54	0.16	0.51	0.01	0.05	<0.005	0.01	0.006	<0.001	<0.01	<0.01	0.04	0.013	0.014
12	0.06	0.41	1.32	0.005	0.013	2.46	0.19	0.47	0.01	0.05	<0.005	0.01	0.020	<0.001	<0.01	<0.01	0.06	0.028	0.010
12	0.08	0.35	1.31	0.005	0.012	2.45	0.23	0.46	0.01	0.06	<0.005	0.01	0.01	<0.001	<0.01	<0.01	0.05	0.022	0.007
13	0.07	0.52	0.84	0.014	0.018	1.69	0.30	0.63	0.14	0.05	<0.005	0.07	0.005					0.031	0.007

7% of the plate thickness. Similarly, there was no evidence of upper shelf DT energies at temperatures up to +20 C. Therefore the service temperature range -20 to +20 C was clearly within the fracture propagation resistance transition temperature range for weldments in 51 mm thickness. This led to the conclusion that, following unstable fracture initiation, extensive fracture propagation could occur in the present weld metals if the applied stresses were high enough.

At this point it is worth mentioning that, in relation to the DT test, Pellini et al (Refs. 2,7) have defined a temperature called the fracture transition elastic (FTE), above which stresses greater than yield are required for fracture propagation. The FTE temperature is usually taken as the temperature corresponding to the midpoint of the DT energy transition curve. However, since the upper shelf DT energies were not well defined (Fig. 5), the FTE can only be indexed for Weld No. 8, and then only approximately, as being in the range +5 to +20 C. The applicability of this estimate is confirmed by the fracture propagation behavior of this weld in the wide plate tests at -5 C, which are described in more detail later.

Assuming fracture initiation could occur in the present weld metals, it is difficult, perhaps impossible, at the present time, to predict whether extensive fracture propagation could take place in a complex welded structure.

Fracture Initiation Tests

Figure 6 summarizes the results of full section thickness (51 mm) slow bend tests on the same weld metals used for the DT tests. Since the specimens exhibited ductile/brittle transitional behavior over the temperature range of interest, resistance to fracture initiation was characterized by the critical crack tip opening displacements (COD values). The relevance of this parameter is described later. The COD values were obtained from standard fracture mechanics load/linear clip gage records (Ref. 8) using the relationships proposed by Wells (Ref. 9). For the convenience of those who are not familiar with the COD method, Wells' relationships are summarized in the Appendix.

Although the fracture initiation tests (Fig. 6) showed lower transition temperature ranges than the DT tests (Fig. 5), it is clear that it may not be possible to avoid brittle fracture initiation in the present weld metals on a simple transition temperature basis (Fig. 2), since in many instances the service temperature will be below the upper shelves of the ductile/brittle transition temperature ranges. We may conclude that, to avoid fracture initiation in the majority of present weld metals, it will be necessary to know the critical combinations of stress, crack size and fracture toughness, i.e., it will be necessary to carry out fracture mechanics tests and analyses. With this knowledge nondestructive testing and repair welding procedures can be used to ensure

Table 4 — Summary of Tensile and Charpy Data for Weld Metals 1-12

Weld metal no.	Temperature C[a]	Charpy V notch energy J[b]	Yield strength N/mm^2[c]	Tensile strength N/mm^2
1	+20	108	620	710
	- 5	57	620	770
	-20	45	620	780
2	+20	93	760	865
	- 5	72	760	—
	-20	60	760	910
3	+20	80	800	860
	- 5	71	800	855
	-20	58	800	855
4	+20	133	535	660
	- 5	74	610	660
	-20	50	650	700
5	+20	> 170	650	730
	- 5	> 170	650	730
	-20	140	650	780
6	+20	110	690	744
	- 5	66	710	745
	-20	45	720	805
7	+20	80	690	760
	- 5	62	745	839
	-20	50	780	560
8	+20	80	835	900
	- 5	62	840	975
	-20	55	863	1,010
9	+20	140	836	906
	- 5	121	813	905
	-20	112	774	951
10	+20	140	770	860
	- 5	108	810	890
	-20	85	820	880
11	+20	120	775	868
	- 5	100	733	903
	-20	71	786	905
12	+20	150	754	875
	- 5	115	760	882
	-20	88	761	900

(a) 20 C = 68 F; -5 C = 23 F; -20 C = 4 F
(b) 1 ft-lb = 1.36 J
(c) 1000 lb/in.^{2} = 6.9 N/mm^2

Table 5 — Details of Weldments

Weld metal no.	Base metal[a]	Process	Consumables[b]	Arc energy kJ/mm[c]	Current, A	Voltage, V	Welding speed, mm/min	No. of runs[d]
1	A	SMAW	1	2.2	220	22	—	38
2	A	SMAW	2	2.2	180-220	22	—	36
3	A	SMAW	3	2.2	170-220	22	—	37
4	A	GMAW	4	2.2	310	26.5	230	32
5	A	GMAW	5	2.2	310	26.5	230	36
6	A	SAW	6	2.2	350	35	335	30
7	A	SAW	7	2.2	350	35	335	30
8	B	SMAW	8	2.2	200	22	—	35
9	B	GMAW	9	1.8	340	25	292	33
10	B	GMAW	10	1.8	350	25	298	30
11	B	SAW	11	1.2	280	30	419	64
12	B	SAW	12	1.2	280	30	419	67

(a) See Tables 1 and 2 for spec's
(b) See Table 3 for chemical analyses of deposits
(c) Nominal arc energy
(d) Double V, 70 deg included angle, in 51 mm thick plate

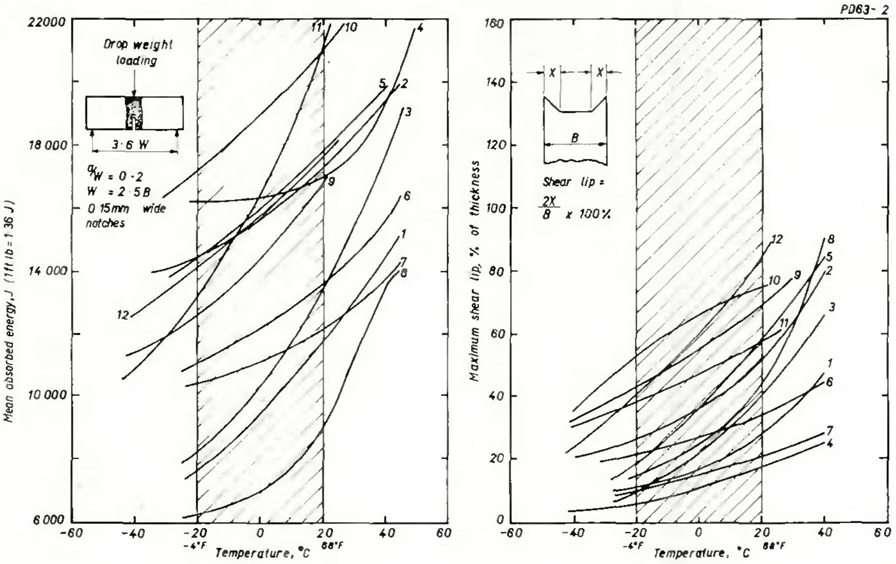


Fig. 5 — Results of DT tests on 51 mm thick SMA, GMA and SA welds

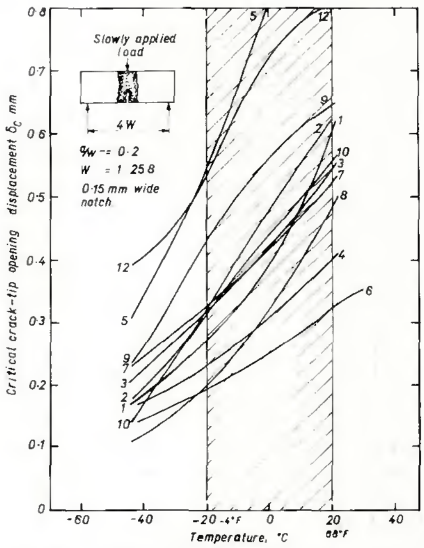


Fig. 6 — COD test results for 51 mm thick SMA, GMA and SA welds (for slowly applied loads)

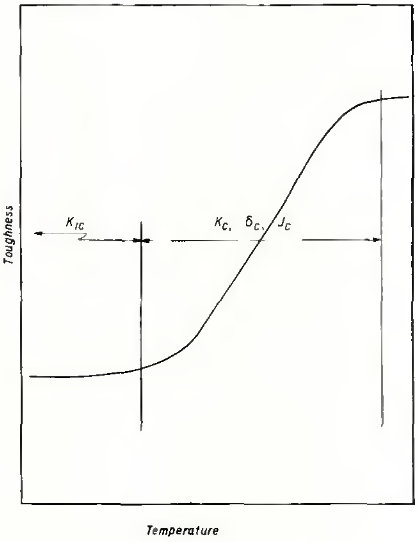


Fig. 7 — Relevance of various fracture toughness parameters to the ductile/brittle transition

that structures contain only subcritical crack sizes, which will ensure a high resistance to fracture initiation.

Fracture Mechanics Tests

At this point it will be helpful to give a short perspective view of the various fracture mechanics tests.

The relevant fracture mechanics toughness parameter for a particular material will depend on the yield strength, temperature, thickness and strain rate of interest. When fracture occurs with small amounts of crack tip plasticity, linear elastic fracture mechanics (LEFM) analyses (Ref. 10) and the critical plane strain stress intensity factor (Ref. 8), K_{Ic}, may be used to calculate critical crack sizes. Alternatively, when there is significant prefracture crack tip plasticity, and it is not possible to make valid measurements of K_{Ic}, critical or non-critical crack sizes may be estimated from the critical non-plane strain stress intensity factor, K_c, the critical crack tip opening displacement, δ_c (Ref. 9), and possibly a critical value of Rice's path independent integral, J_c (Ref. 11). For materials which show ductile/brittle transitions with temperature, Fig. 7 indicates the relevant toughness parameters taking cognizance of thickness and strain rate effects (Fig. 1).

In practice it is convenient to consider the influence of strain rate from two viewpoints:

1. Fracture initiation under slowly applied loading.
2. Fracture initiation under dynamic loading conditions, i.e., conditions when the loading rate is too fast to be considered as slow, but not fast enough to be considered equivalent to that at the tip of a propagating crack.

The term 'loading rate' may be considered the rate of change of stress intensity with respect to time, dk/dt. Slowly applied load tests are those that involve dk/dt values in the order of 35 $Nmm^{-3/2}$ sec^{-1} (1,000 $lb/in.^2\sqrt{in.}/sec$). The initial dk/dt in a DT test may be 10^6 times larger than these values, and it will increase rapidly during the initial stages of unstable crack propagation.

It will be evident that the present investigations of weld metals have examined fracture toughness from extreme viewpoints, namely fracture initiation under slowly applied loads (COD tests) and unstable fracture propagation (DT tests). Furthermore, with respect to slowly loaded structures, it can be concluded that the present weld metals fell into that large category of materials for which the yield strengths, section thicknesses and service temperatures result in too much toughness to satisfy the validity requirements for K_{Ic} tests, and yet insufficient toughness to satisfy the requirements for design to avoid fracture propagation. It is to fill the gap between these extremes of fracture toughness that The Welding Institute have been developing practical forms of yielding fracture mechanics analyses based on Wells' concept of a critical crack tip opening displacement, δ_c (Ref. 12).

Consequently, it was decided to carry out a program of small and large scale tests on some of the present weldments with the following objectives:

1. To assess the accuracy of the COD analyses, and
2. To demonstrate the tolerance of the present weldments to cracks.

The program of tests is described below.

Assessment of COD Approach

This part of the investigation comprised small scale tensile and COD (δ_c) tests, predictions of allowable and critical crack sizes and welded wide plate tension tests on specimens containing the predicted crack sizes.

Relevant Analyses

The COD analyses were based on proposals by Burdekin and Dawes (Ref. 13). These may be used to calculate maximum allowable, or tolerable crack sizes, $\bar{a}_{max}$ values. The calculations are based on a number of simplifying assumptions which are designed to ensure that the $\bar{a}_{max}$ values are always smaller than the critical sizes, $\bar{a}_{crit}$ values. The crack size, $\bar{a}$, is the half length of a through-thickness crack in a semi-infinite plate.

The approach adopted in Reference 13 is based on empirical correlations between the nondimensional COD, Φ, and the ratio of total effective e to e_y, (e/e_y).

$$\Phi = \frac{\delta_c}{2\pi e_y a} \text{ where} \qquad (1)$$

e_y = yield stress/Young's Mod $= \sigma_y/E$

(The relevant yield stress is that of the material in the crack tip region)

Φ= non dimensional crack opening displacement.

The value of Φ depends on the ratio e/e_y, where e = total effective strain = effective applied strain + residual strain.

The design curve, given only in pictorial form in Reference 13, can be replaced by the following equations:

$$\Phi = (e/e_y)^2 \text{ for } e/e_y \leqslant 0.5, \qquad (2)$$

$$\Phi = e/e_y - 0.25 \text{ for } e/e_y \geqslant 0.5 \qquad (3)$$

For a normal design situation, Equations (1) to (3) may be combined and rewritten as (4)

$$\bar{a}_{max} = \frac{\delta_c E \sigma_y}{2\pi\sigma_1^2} \text{ for } \frac{\sigma}{\sigma_y} \leqslant 0.5, \text{ and}$$

$$\bar{a}_{max} = \frac{\delta_c E}{2\pi(\sigma_1 - 0.25\sigma_y)} \qquad (5)$$

for $\frac{\sigma}{\sigma_y} \geqslant 0.5$ and < 1.0

where

σ_1 = effective stress in cracked region

σ = nominal applied stress remote from the cracked region

It is safe to assume values for σ_1 for welded joints as given in Table 6.

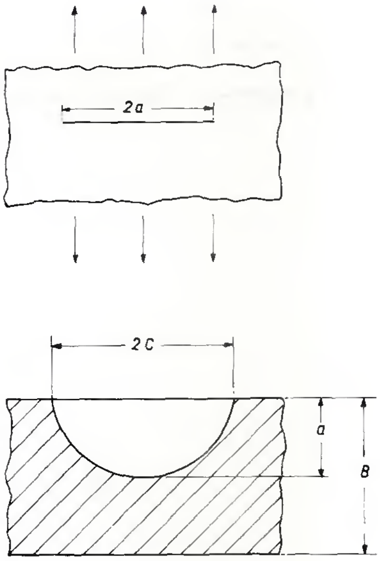
The addition of σ_y to the effective applied stresses in the as-welded condition is to allow for the worst effect of residual stresses. It is not normally possible to establish a meaningful value of σ_y for the HAZ. Since this region is relatively narrow compared to the adjacent base metal and weld metal, deformations in the HAZ are controlled by the adjacent weld region which has the lowest yield strength. Therefore the yield strength of this region should be used for HAZ $\bar{a}_{max}$ calculations.

Using the above assumptions, Equations (4) and (5) can be rewritten for cracks in specific situations. For example, Equation (5) can be rewritten for weld metal cracks in as-deposited main seams as

$$a_{max} = \frac{\delta_{cW} \; E}{2\pi(\sigma + 0.75\,\sigma_{yW})}$$

for $\sigma \leqslant \sigma_{yB}$ and $\leqslant \sigma_{yW}$ and

where the subscripts W and B refer to the weld metal and base metal properties respectively.



Through thickness cracks

Take $\bar{a}_{max} = a$

Surface cracks

i) For $\frac{a}{B} \leqslant 1 - \frac{2\sigma}{\sigma_Y + \sigma_U}$ and $\frac{a}{B} \leqslant 0.7$

Take $a_{max} = \left(\frac{\Phi_o}{M_t M_s}\right)^2 \bar{a}_{max}$

ii) For $\frac{a}{B} \leqslant 1 - \frac{2\sigma}{\sigma_Y + \sigma_U}$ and $\frac{a}{B} > 0.7$

Take $C_{max} = \bar{a}_{max}$

iii) For $\frac{a}{B} > 1 - \frac{2\sigma}{\sigma_Y + \sigma_U}$

Take $C_{max} = 0.7\,\bar{a}_{max}$

NB $\left(\frac{\Phi_o}{M_t M_s}\right)^2$ is obtained from Fig. 9.

Fig. 8 — New definitions of the allowable dominant crack dimensions in terms of $\bar{a}_{max}$

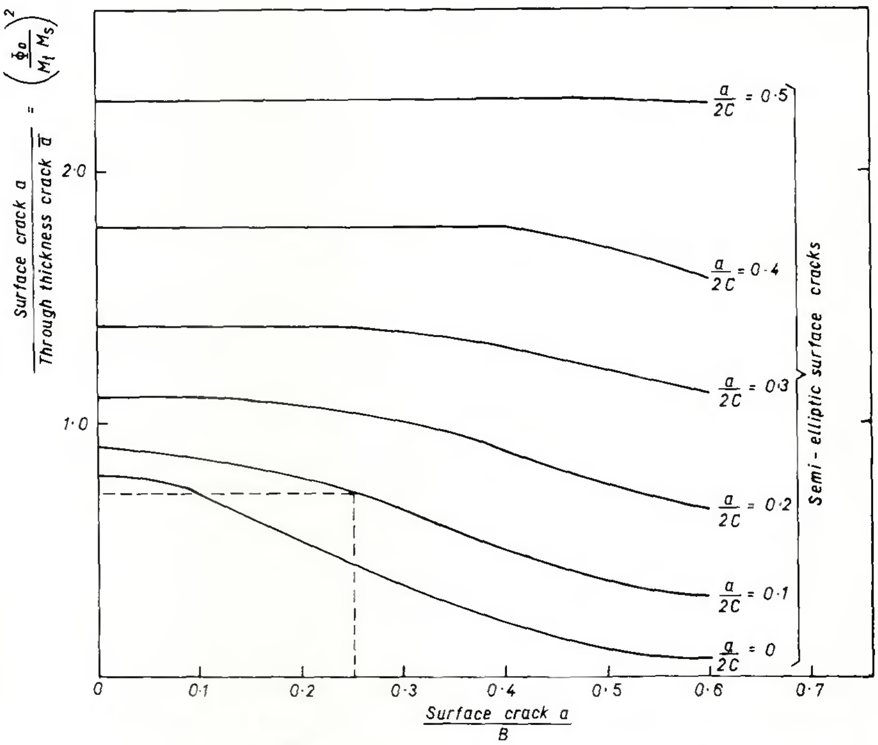


Fig. 9 — Relationships between the half length, $\bar{a}$, of a through-thickness crack and the characterising dimensions of surface cracks

Figures 8 and 9 show how the values of $\bar{a}_{max}$ may be adjusted to give the allowable dominant dimensions of surface cracks. For example, the maximum allowable or tolerable size of a crack in a weld metal with a/2c = 0.1 and a/B = 0.25 would be $a_{max} = 0.7\,\bar{a}_{max}$ for $a/B \leqslant 1 = \sigma/(\sigma_{yW} + \sigma_{uW})$, where σ_{uW} is the weld metal tensile strength.

The above gives a brief description of the relevant COD analyses for the present investigation. However, it should be noted that additional analyses are necessary for buried cracks and cracks in plates subjected to

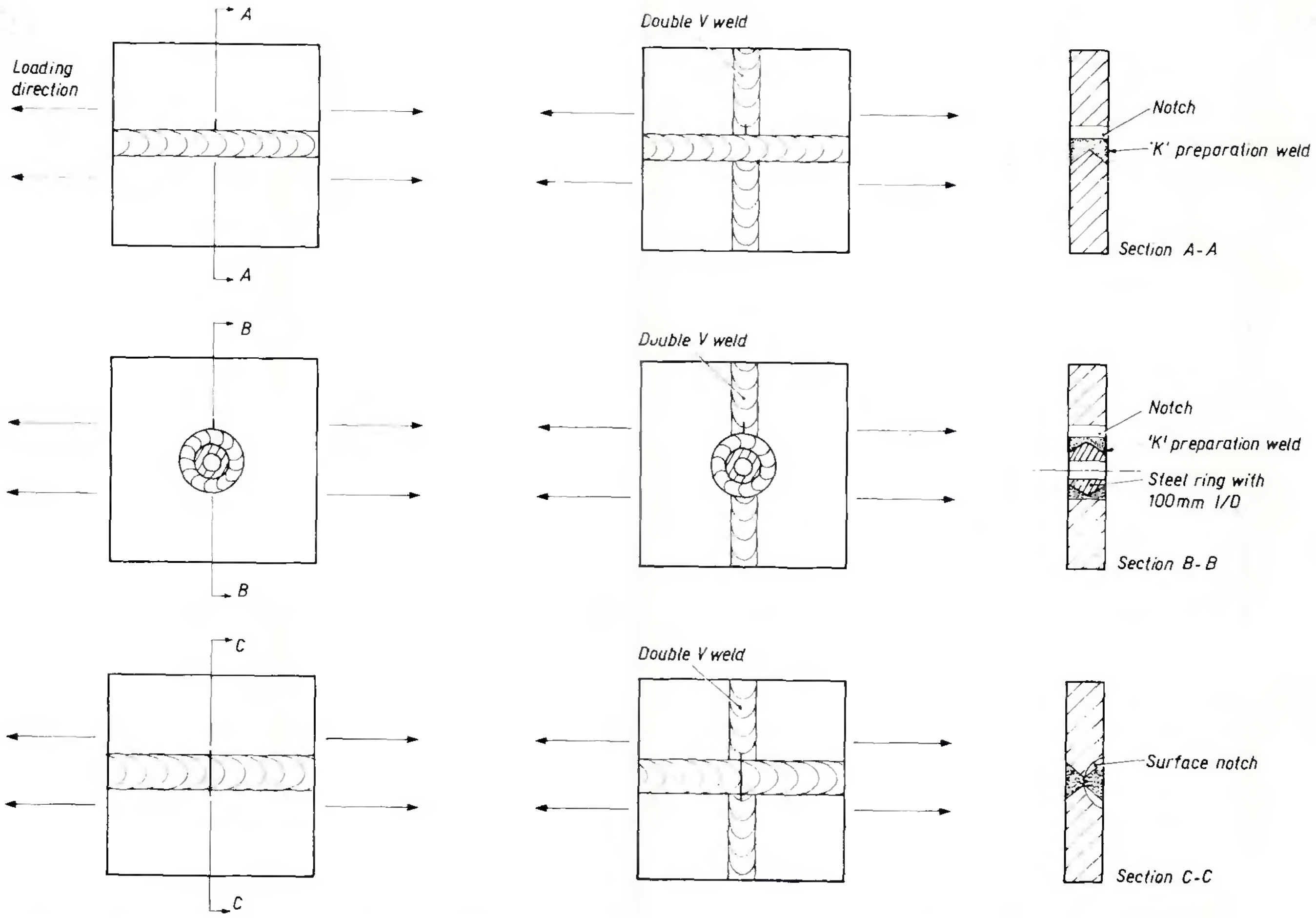


Fig. 10 — Different forms of wide plate test specimen. All specimens approximately 900 × 900 × 51 mm thick

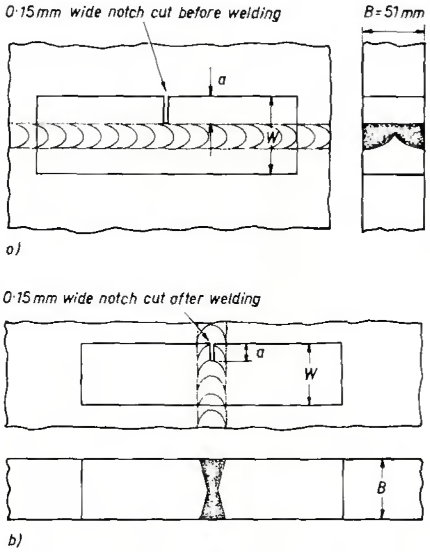


Fig. 11 — Orientation of COD test specimens (relevant to wide plate tests)

bending, combined bending and tension, and some radial cracks at the edges of holes and nozzles, etc. Further guidance on some of these situations may be obtained from Reference 13.

Fracture Tests

Figure 10 illustrates the various forms of wide plate specimen tested in the present program. All the specimens had overall dimensions of approximately 900 × 900 × 51 mm thick (35 × 35 × 2 in. thick). The specimens were designed to assess through-thickness and surface cracks in single and crossing welds in and remote from stress concentration regions.

The single weld wide plate specimens containing through-thickness notches (top left in Fig. 10) were fabricated by cutting the plates in half, and preparing the cut edges for rejoining the plate halves with a 'K' weld. Before making the weld a through-thickness 0.15 mm (0.006 in.) wide notch was cut into the vertical size of the 'K' preparation as indicated in Fig. 10. When the longitudinal weld was made, a sharp natural weld defect occurred at the notch tip in the longitudinal weld. The cross welded specimens were prepared in a manner similar to the single weld specimens, except that the transverse weld was made first on a double V butt weld preparation. The procedure for the surface notches comprising welding up one side of a double V weld, making a 0.15 mm wide sawcut to the required depth in this weld, back grinding to reveal the bottom of the sawcut and welding over this to complete the second side of the double V weld. Similar procedures were also used to prepare surface and through-thickness notches in a region of stress concentration, i.e., close to a hole.

It may be noted that the size and design of the wide plate test specimens allowed an assessment of resistance to fracture initiation in cracked welds, which in the as-welded specimens contained yield magnitude residual stresses. In the single weld specimens only the notch tip was in weld metal, whereas in the cross welded specimen the whole of the notch was in weld metal.

As mentioned earlier, the sizes of the notches in the wide plate specimens were estimated from the results of the tensile tests and full thickness COD tests. The results of these tests are summarized in Table 7. Figure 11 shows how the COD specimens were extracted from 'K' and double V butt welds to simulate exactly the notch tip conditions in the wide plate test specimens.

Fig. 12 — Wide plate specimen ready for assembly into the 9,000,000 lb tension test rig

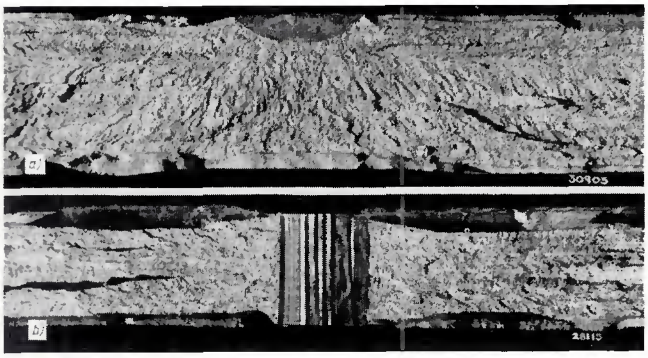


Fig. 13 — Typical wide plate test fracture surfaces: (a) fracture at surface notch; (b) fracture at a through-thickness notch

All the tests were carried out at -5 C (23 F). This is a common winter temperature in many countries, including the U.K., and is approximately equal to the lowest temperature for structures submerged in sea water.

Figure 12 shows one of the wide plate test specimens ready for assembly into a 40 MN (9,000,000 lb) tension test rig.

Fracture initiation in the majority of the specimens occurred at less than the base metal and weld metal yield strengths. In the single weld specimens the fracture propagated through the ligament of weld metal ahead of the notch tip and arrested in the base metal, whereas in the cross welded specimens fracture propagation took place through the center of the crossing weld. As mentioned earlier this behavior was expected in the case of Weld Metal 8 since the DT tests indicated that -5 C was below the FTE temperature. Figure 13 illustrates the fracture appearance of two cross welded specimens. An examination of all the fracture surfaces showed that in some instances weld metal hydrogen cracks had increased the initial crack sizes.

Finally, it should be noted that *unstable* fracture initiation and propagation in Weld Metals 2 and 8 occurred by a process of microvoid coalescence, whereas the unstable fractures in Weld Metal 13 occurred by cleavage predominantly.

Table 6 — Assumed Values for Effective Stress in Cracked Region

Crack location	Condition	Assumption for σ_t
Main seams remote from stress concentration regions	Stress relieved[a] As-welded	σ $\sigma + \sigma_Y$
In regions of stress concentration	Stress relieved[a] As-welded	$\sigma \times$ SCF[b] $(\sigma \times \text{SCF}) + \sigma_Y$

(a) Note it is assumed here that the stress relieving treatment is such as to remove all residual stresses. In many practical instances this will not be so and due allowance should be made for any stress remaining after treatment

(b) SCF = stress concentration factor

Table 7 — Mechanical Properties Relevant to Wide Plate Tests at -5 C (+23 F)

		Weld metal			Base metal		
Number of tests	Condition[a]	Weld metal No.[b]	σ_{yW} N/mm²	δ_{cW} mm	Identification[c]	σ_{yB} N/mm²	$\frac{\sigma_{yW}}{\sigma_{yB}}$
2	A-W	2	788	0.33	Similar to A	584	1.35
2	A-W	2	788	0.33	Similar to A. but reheat treated	850	0.93
2	A-W	13	704	0.07	Similar to A	584	1.21
2	A-W	13	704	0.07	Similar to A, but reheat treated	850	0.83
12	A-W	8	962	0.25	Similar to A, but reheat treated	796	1.21
2	S-R	13	809	0.025	Similar to A	570	1.41

(a) A-W = as-welded; S-r = stress relieved

(b) See Tables 3 and 4

(c) See Tables 1 and 2

Relevance of Analysis

The accuracy of the COD analyses was assessed by substituting the values of δ_{cW} and σ_{yW} from the small scale tests (Table 7) and the wide plate fracture stresses, into Equations (4) and (5) and comparing the calculated values of $\bar{a}_{max}$, a_{max} or C_{max} with the actual or critical crack sizes in the wide plate test specimens. These comparisons are illustrated in Fig. 14. The safety of the COD analyses is demonstrated by the fact that the maximum allowable or tolerable crack sizes were always smaller than the actual or critical crack sizes in the wide plate test specimens. Also, Fig. 14 shows a trend of increasing values of $\bar{a}_{max}$ with increasing $\bar{a}_{crit}$, which confirms that the COD approach characterizes the fracture behavior in the wide plate tests. The present results suggest that it would be generally safe to assume that the critical crack sizes were double the maximum allowable crack sizes.

Summary and Conclusions

A systematic investigation has been made of various fracture control procedures for SMA, GMA and SA weld metals with yield strengths in the range 500-1,030 N/mm² (70,000 to 150,000 lb/in.²). The investigation included fracture propagation tests (DT tests) and fracture initiation tests (K_{Ic}/COD/wide plate tests). The tests were carried out over a range of ambient temperatures on 51 mm (2 in.) section thickness weld deposits.

It was shown that for the thicknesses, temperatures and yield strengths of interest a simple transition temperature approach was unlikely to provide a reliable means of avoiding brittle fracture. For the ambient temperature range -20 to +20 C (-4 to +68 F) the majority of the weld metals had too much toughness for a design to be based on the results of linear elastic fracture mechanics tests and insufficient toughness for design to avoid fracture propagation. Therefore, it was concluded that the majority of weld

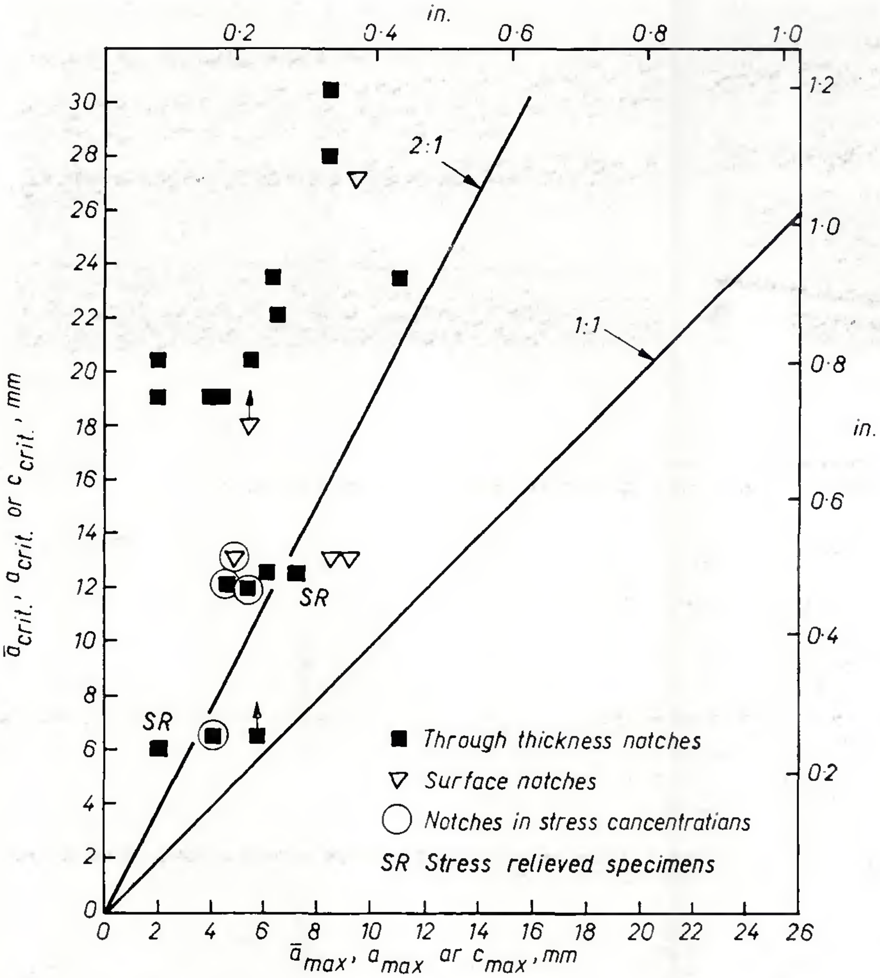


Fig. 14 — Comparison of critical and allowable crack sizes

metals fell into that large category of materials for which a yielding fracture mechanics analysis is justified.

It was shown how simple COD relationships may be used to make safe and realistic estimates of the maximum allowable or tolerable crack sizes for cracks of different shape in as-deposited and stress relieved weld metals. These included weld metals which under and overmatched the base metal in yield strength, and also weld metals in regions of design stress concentration. The wide plate tests suggest that it would generally be safe to assume that the critical crack sizes were double the calculated maximum allowable crack sizes.

Acknowledgements

The author is indebted to Dr. R. Weck, Director General of The Welding Institute for permission to present this paper. He wishes to thank his colleagues for helpful discussions and also Mr. B. A. Wakefield and his staff for their help with the experiments.

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Authors — a reminder

Abstracts with application forms (see page 411, June) for papers to be presented at the 1975 Brazing and Soldering Conference in Cleveland, must be mailed by September 15, 1974.

APPENDIX - CALCULATION OF CRACK TIP COD FROM CLIP GAUGE OPENING DISPLACEMENT

Using the dimensions illustrated, the Wells relationships(9) may be re-arranged to give

$$\delta_c = \frac{V_c - V^1}{1 + 2.22\left(\frac{a+z}{W-a}\right)} \quad \text{for } V_c \geqslant 2V^1$$

and

$$\delta_c = \frac{0.25\,\frac{V_c^{\,2}}{V_1}}{1 + 2.22\left(\frac{a+z}{W-a}\right)} \quad \text{for } V_c < 2V^1$$

Where $V^1 = \dfrac{\Upsilon\,\sigma_Y\,W\,(1 - \nu^2)}{E}$

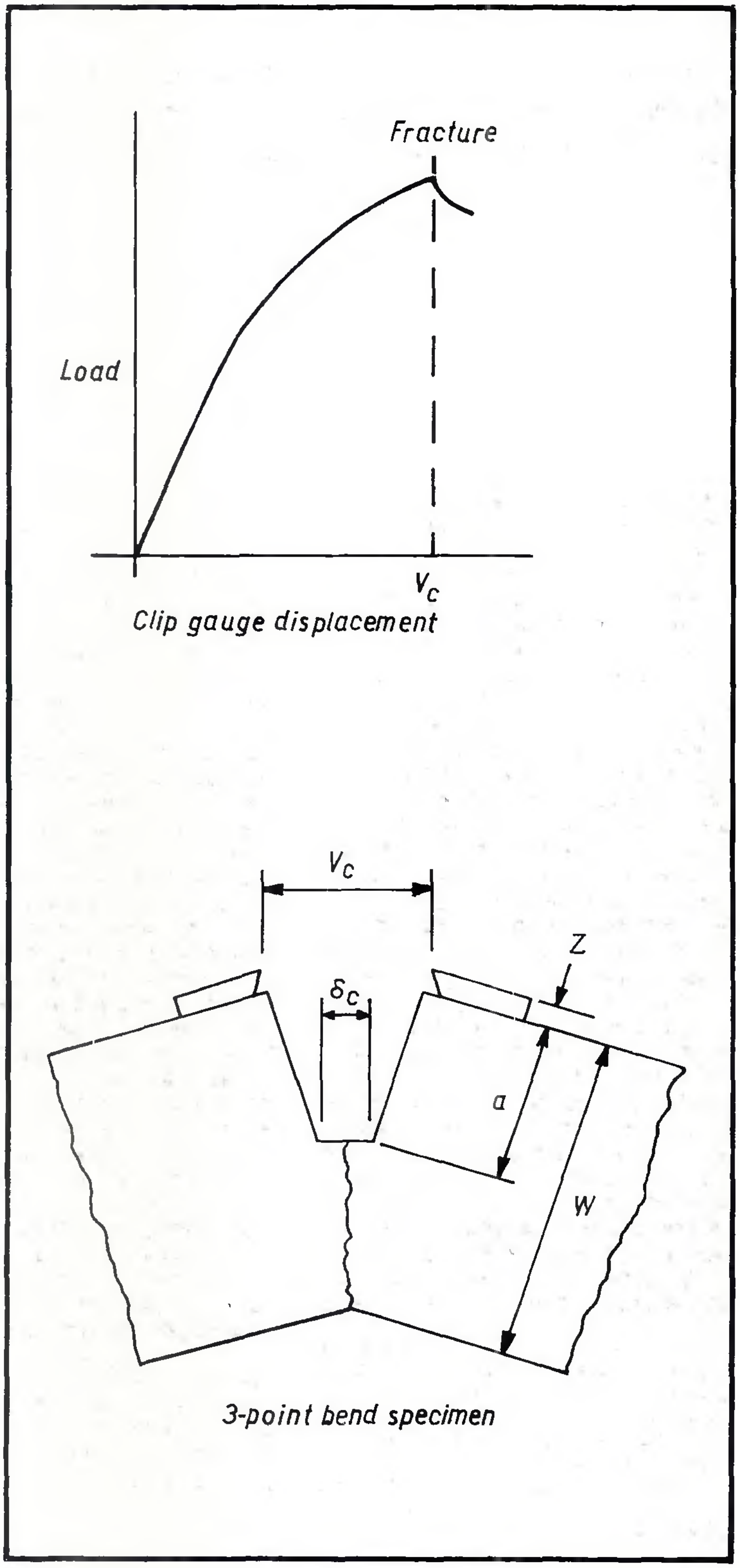
and $\Upsilon = f\left(\frac{a}{W}\right)$

σ_Y = yield stress

ν = Poisson's ratio

E = Young's Modulus

$\frac{a}{W}$	Υ
0.2	0.7
0.3	1.03
0.4	1.35
0.5	1.54
0.6	1.72



3-point bend specimen