Toughness Properties of HAZ Structures in Structural Steel

Study assesses both crack initiation and crack propagation criteria in relation to fracture safety

BY E. BANKS

Introduction

Except in circumstances where precautions are taken to specify steels of a high toughness, it is considered (Refs. 1, 2) that welded structures rely for fracture safety on initiation rather than propagation resistance. In these circumstances the properties of the welded joint therefore assume more importance than those of the base metal since it is in welded regions that "crack like" defects are generally found. The work in this paper represents an attempt to assess the toughness properties of the subcritical and transformed HAZ for two structural steels of yield strengths 250 MPa (36 ksi) and 350 MPa (50 ksi) which are widely used for welded construction. In the assessment and interpretation of the results, use is made of the fracture mechanics approach.

One of the problems in relating such information to practical welded structures is in the specification of acceptable toughness levels above which brittle fracture should not be a problem. The toughness level specified should be sufficient to allow for the variable and probably somewhat unknown effects of stress concentrators and residual stress. These effects are reproduced in the wide-plate test (Ref. 3) and this is one of the reasons why this form of test is being accepted as capable of demonstrating the suitability of a steel and welding procedure for use at a particular service temperature.

In the Wells' wide-plate test, acceptance is gaged by the development of a particular strain level at a specified temperature. It has been shown (Ref. 4) that the strain developed in the test can be related to the crack opening displacement (COD) developed at the tip of the introduced notch and hence a critical COD can be derived which corresponds to a particular strain level. The possibility of using such a criterion for setting minimum toughness levels is explored in this paper in relation to experience gained in the use of conventional structural steels.

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Materials

The two semikilled grades of steel examined (Materials A and B) were supplied in the "as rolled" condition by BHP Port Kembla Works in the form of plate 25 mm thick × 2 m × 4 m and were of the composition listed in Table 1. Material A was supplied to AS A186 Grade 250 (Ref. 5) which is not impact tested and B was to grade 350LO which has an impact requirement of 27 J (20 ft-lb) at 0 C. The yield strengths of the materials were 250 MPa (36 ksi) and 350 MPa (50 ksi) respectively. Material A is equivalent to ASTM A36 and B equivalent to ASTM A441, however this latter standard does not have impact requirements.

Experimental Details

Base Metals

Fracture toughness (COD) (Ref. 6), Charpy and tensile specimens were machined from base metal for evaluation of properties.

Toughness Assessment of Subcritical HAZ

The Wells' wide-plate (Ref. 3) test in its original form assesses the toughness of the region of a welded joint which is subject to strain aging cycles. In the test (see Fig. 1) a small through thickness notch is cut into the edge of the plate and a butt weld completed so that the notch tip is just outside the transformed HAZ and is subjected to strain-aging cycles during welding. In the current work these conditions were simulated by cutting the small COD samples from large welded plates as shown in Fig. 1. Prior to butt-welding the plates together, small notches 5.0 mm (0.2 in.) deep and 0.15 mm (0.006 in.) wide were cut into the plate with the 90 deg edge preparation; the spacing between the slits was 130 mm (5 in.). The two plates were then welded together. Plate and sample preparation was identical for the three plates AP2, BP5 and BP6 where A or B refers to the base metal. Table 2 details welding procedures which were consistent with procedures recommended to produce strong tough welds (Ref. 7).

COD test specimens 25 mm (1 in.) square were then cut from the welded plates such that the notches in the plate formed the notch in the COD specimen (see Fig. 1.). In the case of plates AP2 and BP6 foil strain gages were attached to the plates prior to cutting but after welding in order to measure the longitudinal residual stress patterns. To avoid any heating of the plates after welding the cutting of samples was carried out under running water. After machining, the COD specimens were

Table 1 — Chemical Composition of Test Materials

	C	Mn	Si	P	S	Ni	Cr	Al	Nb	Cu
Mat. A (Grade 250)	0.16	0.90	0.032	0.005	0.010	0.024	0.008	0.002	<0.001	0.016
Mat. B (Grade 350LO)	0.17	1.38	0.065	0.014	0.015	0.026	0.035	0.005	0.024	0.035

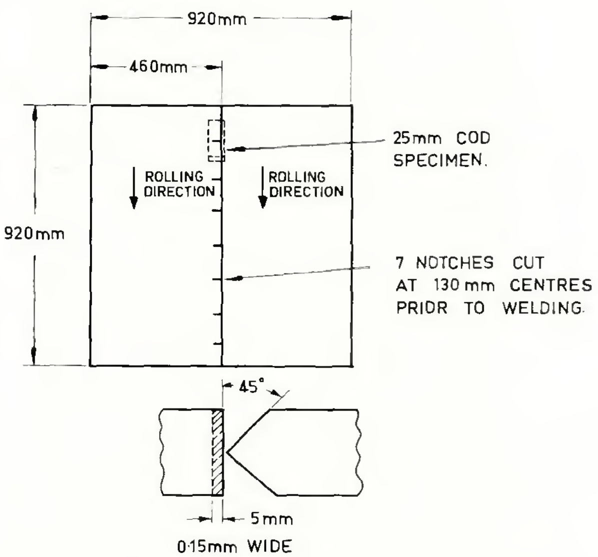

Fig. 1 — Preparation of COD specimens to simulate strain-age, damage at notch tip as produced in a Wells' wideplate test

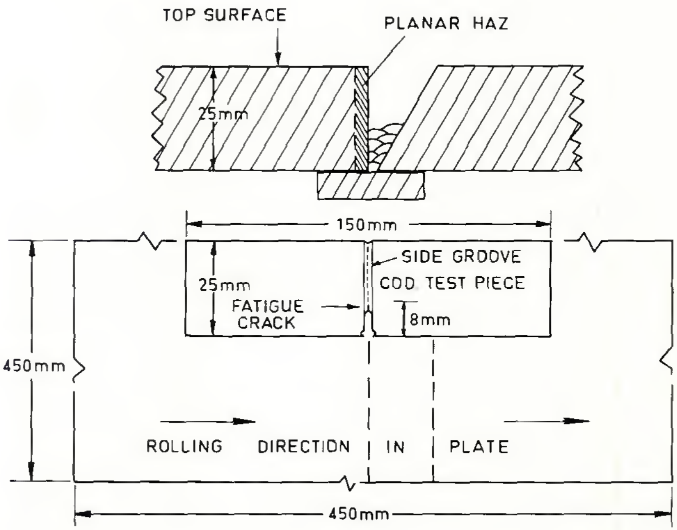

Fig. 2 — Details of weld preparation and COD test pieces from transformed HAZ

tested in three point bending under nominally static conditions in the recommended manner (Ref. 6).

Toughness Assessment of the Transformed HAZ

To examine the effect of heat input on the toughness of the transformed HAZ several plates 450 mm (18 in.) × 225 mm (9 in.) of each steel were butt welded by the submerged arc process with the varying heat input conditions listed in Table 3. One of the problems in evaluating HAZ toughness is ensuring that the introduced notch is accurately located in the relevant zone of the weld. This problem was overcome to a certain extent by using the single bead preparation shown in Fig. 2 which produced a reasonably planar HAZ. Correct location of the notches in the Charpy and COD specimens was ensured by etching the samples prior to the final notching operation. The notches in all specimens were located in the grain coarsened region of the HAZ which was adjacent to the weld metal interface. For the fatigue precracked COD specimens growth of the notch in the desired place was ensured by machining 1 mm (0.040 in.) deep side grooves (see Fig. 2.).

For Material A the effect of a very high heat input level was examined by using the consumable guide electroslag welding process. In this case plate preparation simply consisted of flame cut square edges and the joint opening was set at 25 mm (1 in.). The welding speed was approximately 25 mm/min (1 in./min). Specimen preparation was identical to that described above.

Results

Mechanical Properties

The tensile and Charpy impact properties for the two steels are listed in Table 4. Even though Material A was supplied as a non-impact tested grade it is worthy of note that the properties meet the requirements of

Table 2 — Welded Plate Samples

Plate no.	Material	Welding method	Pre-heat
AP2	A	Manual E7014, 5 mm diam	None
BP5	B	Manual E7018, 5 mm diam	120 C
BP6	B	Sub-arc 3.2 mm diam/wire Heat input, 1.4 kJ/mm	120 C

Table 3 — Welding Conditions

Material	Plate no.	Process	Current, A	Voltage, V	Welding speed, mm/min	Welding speed, in./min	Heat Input, kJ/mm	Heat Input, kJ/in.
A	AP7	Sub-arc	500	30	500	20	1.8	45
A	AP8	"	700	32	250	10	5.4	135
A	AP9	"	500	30	250	10	3.6	90
A	AP4	Consumable guide	550	33	—	—	40	10000
B	BP10	Sub-arc	700	32	250	10	5.4	135
B	BP11	"	500	30	250	10	3.6	90
B	BP12	"	500	30	500	20	1.8	45

Grade 250LO which is 27 J (20 ft-lb) at 0 C.

Toughness of Welded Samples

Subcritical HAZ. Figure 3 shows the residual stress pattern developed in plates AP2 and BP2; the stresses were calculated from the residual strains assuming E= 207 GPa. The stress patterns are similar in both cases with a maximum occurring in the weld metal which overmatches the yield strength of the base metal. For purposes of calculations made later the residual stress patterns are approximately represented by the equation: (1)

$$\sigma_r = 400\left[1-\frac{x}{3.2}+\left(\frac{x}{6.19}\right)^2-\left(\frac{x}{2.45}\right)^3\right] \text{MPa}$$

where σ_r = residual stress (MPa), x = distance from weld center (cm). This equation was chosen as the statistically best fit equation which could be integrated as required later.

In Figs. 4 and 5 the fracture toughness of the subcritical HAZ is compared to that of the base metal for both steels. Even though the welding procedures adopted would be expected to produce tough welds it can be seen that in fact the toughness is reduced in all cases. The reduction at temperatures near 0 C is so low that in fact toughness at 0 C can be expressed in terms of LEFM rather than as a COD value. At this temperature the K_c values of the subcritical HAZ for Materials A and B were 39 MPa$\sqrt{m}$ (36 ksi$\sqrt{in.}$) and 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) respectively. For both materials, the increase in COD transition temperature at the 0.15 mm level is of the order of +50 C.

Also included in Figs. 4 and 5 are toughness values for the stress relieved condition (550 C for 1 h); a marked improvement in fracture initiation resistance can be seen as a result of this treatment.

Transformed HAZ. The COD transition curves for the transformed HAZ structures of Materials A and B are shown in Figs. 6 and 7. A feature immediately obvious is the considerable scatter in the results. This is an inherent feature in HAZ fracture toughness assessment and arises from the fact that all specimens will not have their notches situated in identical locations. In a few of the tests carried out on Material B a double initiation was observed; when this happened the higher COD value at which complete fracture occurred was taken. Another feature of the results which must be noted is that for COD values above 0.4 mm (0.016 in.) appreciable ductile tearing at the notch root was noted and under these circumstances the interpretation of COD is not clear (Ref. 8) and little significance can be attached to the results.

For Material A, heat input levels below 3.6 kJ/mm (90 kJ/in.) produce a HAZ of greater toughness than that of the base material. However, toughness quickly falls away at higher heat input levels, the lowest values being that for the consumable guide weld. On the other hand, Material B shows a lower toughness HAZ for all the conditions studied but as with Material A toughness again decreases with increasing heat input.

Figures 8 and 9 detail the Charpy energy transition curves for the structures studied above. For Material A the Charpy test rates the toughness of the HAZ in the same order as the COD test results. This however, is not the case for Material B where the Charpy results suggest that the HAZ of this material should be of greater toughness than that of the base metal. This is contrary to the true, more realistic toughness measured by the COD method which shows the HAZ in all cases to be lower in toughness than the base metal.

This difference in behavior between Charpy and COD specimens is somewhat contrary to general experience in which the tests generally rate materials in a similar order. Examination of the fractured Charpy specimens from Material B showed that the fracture path tended to deviate from the HAZ and run into the weld metal or the base metal; such deviations would cause a large contribution to the total energy absorbed. This feature was not prevalent with specimens taken from Material A. The reason for the difference in behavior is not clear but is probably connected with the relative strengths of HAZ, weld metal and base metal.

Metallographic examination of the HAZ structure for both materials showed them to coarsen with heat input, and the extreme example was the consumable guide weld. Because the submerged arc welds were multipass welds, a typical structure cannot be assigned to any weld because subsequent passes refine regions of the HAZ of the earlier passes; consequently, in any weld a range of structures are present, and the COD

Table 4 — Mechanical Properties of Test Materials

Material	Yield point, MPa	Yield point, ksi	Tensile strength, MPa	Tensile strength, ksi	Elongation, %	Charpy Impact @0 C, J	Charpy Impact @0 C, ft-lb	NDT
A	255	37	465	67.5	38	29	21	+ 5 C
B	370	53.6	590	85.6	33	71	52	−10 C

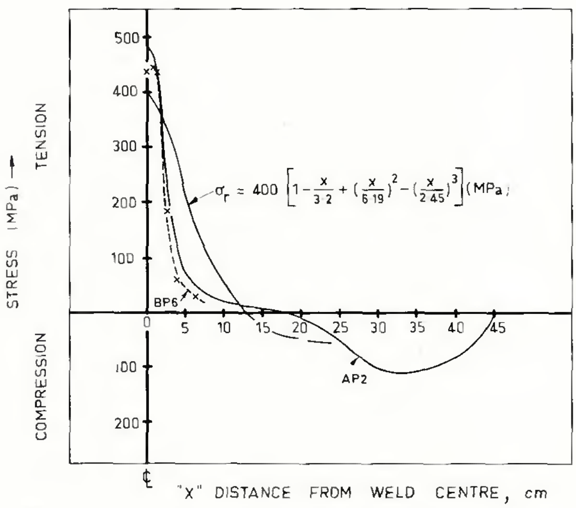

Fig. 3 — Residual stress pattern for AP2 and BP6

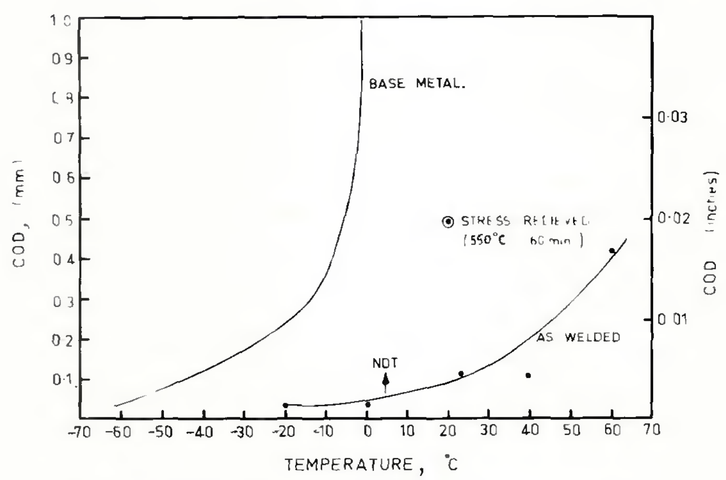

Fig. 4 — Subcritical HAZ toughness of material A

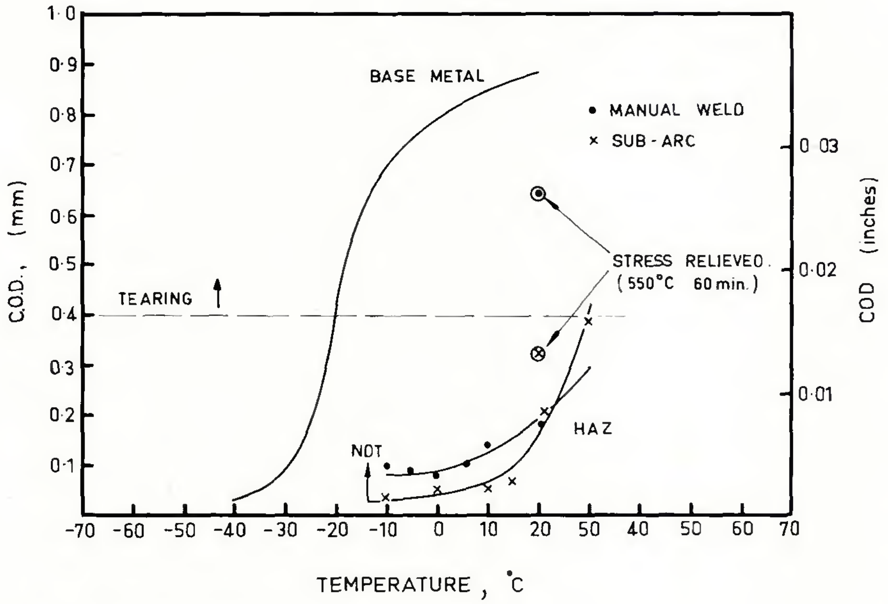

Fig. 5 — Subcritical HAZ toughness of material B

values measured must represent an average value. The structures shown in Figs. 10 and 11 are typical of areas which have not been refined by subsequent passes and demonstrate clearly the effect of heat input in increasing the grain size in the HAZ.

The ferrite/pearlite structures for Material A show the grain size in the HAZ to be considerably larger than that of base metal and yet for heat inputs below 3.6 kJ/mm (90 kJ/in.) the HAZ toughness is greater than the base metal. It is therefore clear that, in these cases, refinement of the structures by preceding welds must have a large influence on the average toughness of the HAZ but, as the heat input is increased, the refinement effect diminishes.

These arguments cannot apply to Material B since in all cases HAZ toughness was lowered. There appear to be several possible causes for this behavior. First, the HAZ struc-

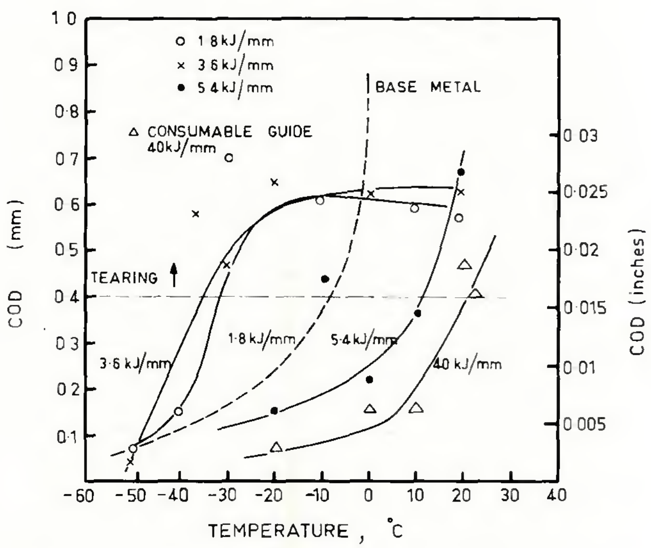

Fig. 6 — HAZ toughness of material A as a function of heat input

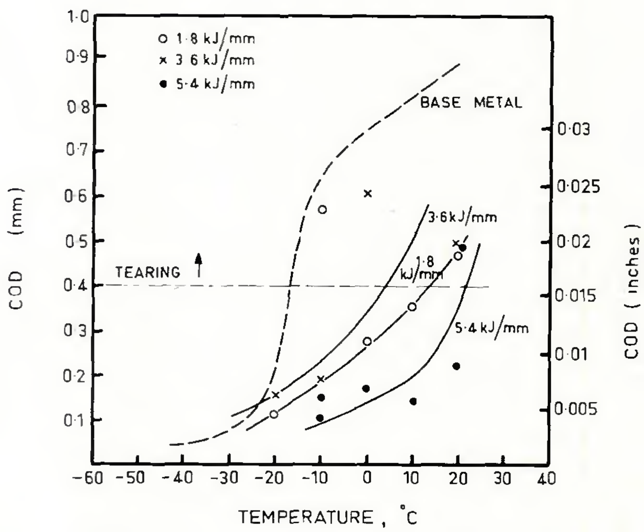

Fig. 7 — HAZ toughness of material B as a function of heat input

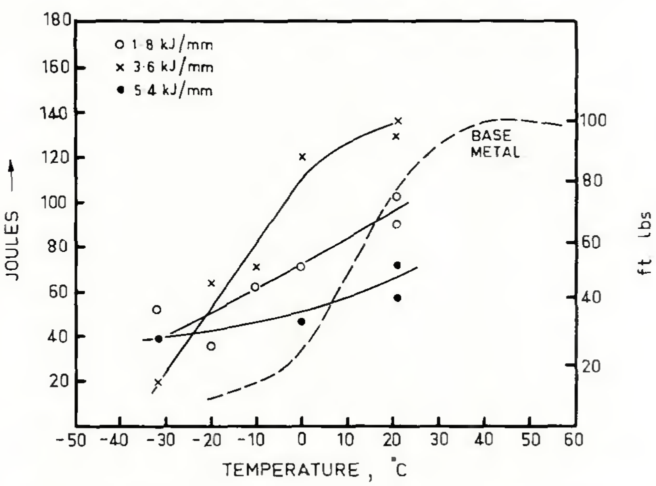

Fig. 8 — Charpy impact transition curves for transformed HAZ structures in material A

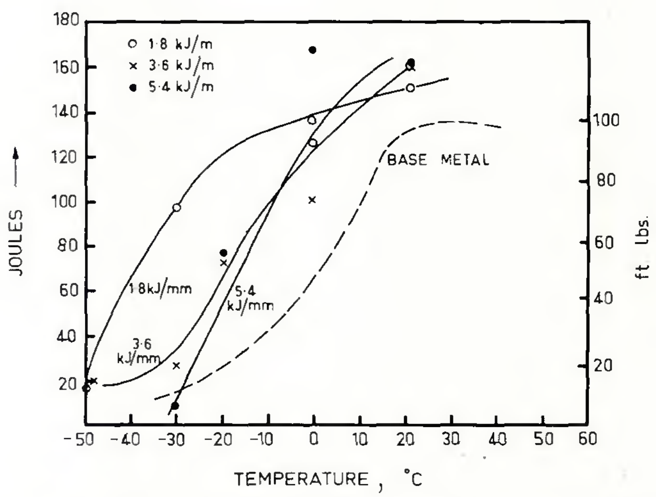

Fig. 9 — Charpy impact transition curves for transformed HAZ structures in material B

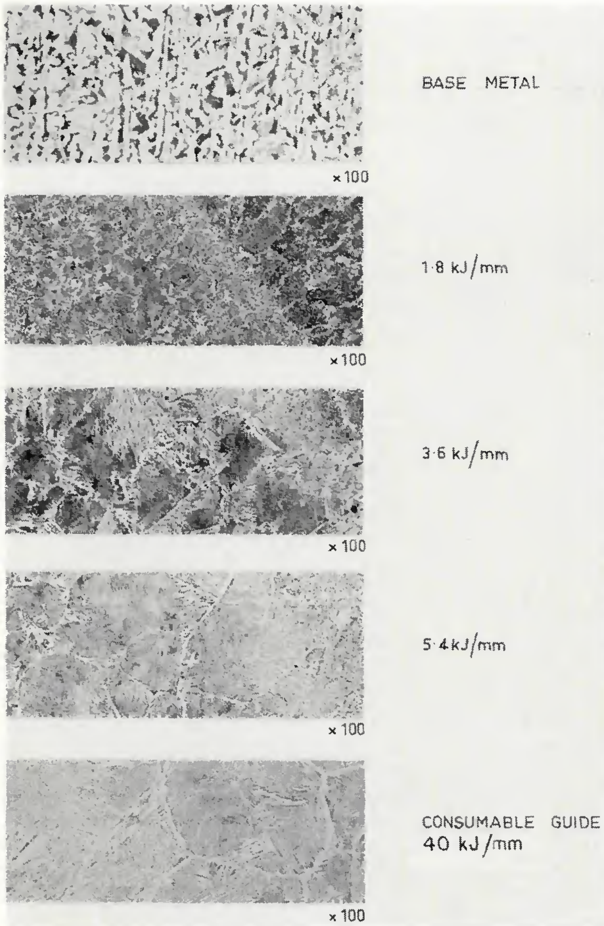

Fig. 10 — Heat affected zone structures as a function of heat input for single pass welds in material A

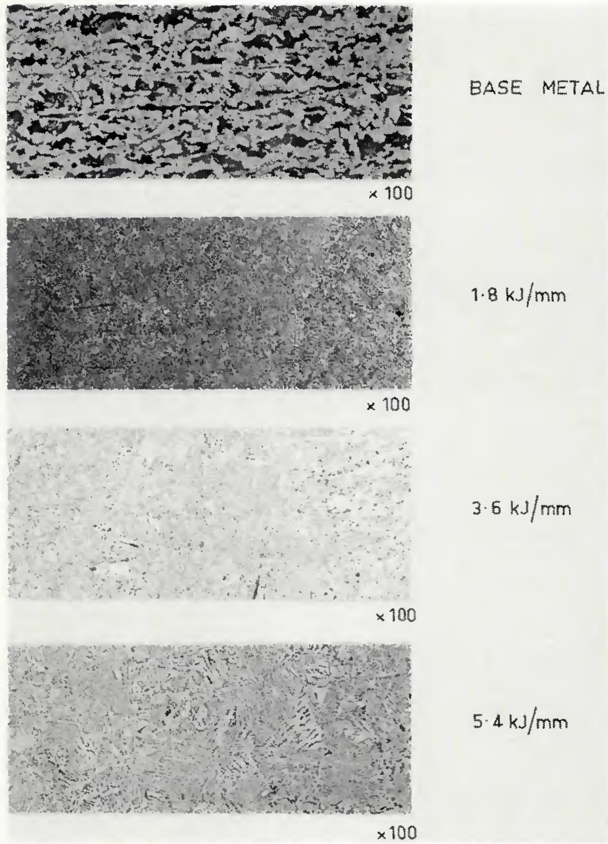

Fig. 11 — Heat affected zone structures as a function of heat input for single pass welds in material B

tures are of an upper bainite type, a structure which is known to be less tough than ferrite/pearlite structures (Ref. 9). This microstructural change from that of Material A is probably due to the influence of the increased Mn and Nb contents (Ref. 10) since the carbon contents are similar. Second, Nb will be taken into solution in the HAZ and subsequent precipitation of fine NbC will also cause degradation of toughness (Ref. 10). Further work is required to define the exact role played by each of these elements.

Discussion

Critical COD Requirements to Avoid Fracture Initiation

In applying the COD approach to toughness assessment problems it is required that all material in a structure should meet some minimum requirement. This will apply to base metal, weld metal and the HAZ. Ideally, the critical COD (δ_c) is selected by deciding upon a defect size which can easily be detected and then deducing a critical COD value. Problems arise when the value of δ_c must be calculated theoretically.

Difficulties of this type have lead to the use of the Wells' wide-plate type of test as a material acceptance standard (Ref. 11). This test on a complete welded joint containing a defect also overcomes difficulties associated with the effects of residual stress and the strain level set for acceptance (0.5% strain over a 5 in. gage length) is sufficient to allow for strain magnification as may be associated with a welded connection; this strain level is claimed to be similar to that associated with a welded nozzle (Ref. 3) in a pressure vessel at the proof stress level.

The strain developed in a large plate containing a notch can be empirically related to the COD developed at the notch tip. Burdekin and Dawes (Ref. 4) have proposed a relationship between COD and developed strain based on measurements made on wide-plate tests containing notches of differing size. Their proposed design curve is shown in Fig. 12.

In using this curve as a means of estimating minimum required COD values for the avoidance of brittle fracture, a value of the ratio e/e_y must be chosen appropriate to the situation under consideration. In their paper Burdekin and Dawes consider values of the ratio appropriate to the specialized field of pressure vessels. In structures such as bridges or buildings applied stresses would not normally exceed $0.67\,\sigma_Y$, however, residual stresses of yield point magnitude would invariably be present and an allowance must be made for these. For a stress concentration factor of 3 and a design stress of $0.67\sigma_Y$ a value for e/e_Y of 2 would be appropriate. To this must be added a value of between 1 and 2 for residual stress, so a value of about 4 will provide an adequate degree of safety. This value is similar to that adopted in many wide-plate tests (Refs. 3, 12).

The value of ϕ (see Fig. 12) appropriate to an e/e_Y ratio of 4 can be seen to be 3.75. For a defect of a size similar to that in the wide-plate test δ_c values of 0.08 mm (0.003 in.) and 0.1 mm (0.004 in.) are required for Materials A and B respectively. In view of the approximations made it can be taken that a δ_c value of 0.1 mm (0.004 in.) is necessary for the avoidance of brittle fracture for the two steels under consideration. This value is somewhat less for 25 mm (1 in.) plate than that required by the alternative plane stress criterion suggested by Wells (Ref. 13). By this criterion the δ_c value of Material B would be increased to 0.25 mm (0.01 in.) which is considered by the author to be unrealistically high.

Transformed HAZ. Factors controlling the level of toughness in the

HAZ are heat input, the number of weld passes and the composition of the base metal. The results show clearly the toughness of Material B suffers greater degradation for a given heat input than does the lower strength A and, as outlined earlier, this can probably be related to the influence of Mn and Nb.

Examination of the HAZ toughness levels in Figs. 6 and 7 indicate that for both steels the COD requirement of 0.1 mm (0.004 in.) is met for all heat input levels and temperatures above 0 C. However, at this operating temperature the consumable guide weld in Material A just meets the suggested requirement and careful consideration must be given to structures which are to be welded by this process, subject to tensile load and left in the as-welded condition. A similar situation can exist with Material B at the heat input level of 5.4 kJ/mm (135 kJ/in.). However, before definite heat input levels can be specified further work seems necessary, especially confirmatory full-scale wide-plate testing of welds made under these conditions.

Subcritical HAZ. Sensitivity to strain-age embrittlement is the major factor influencing the toughness of the subcritical HAZ. Semikilled steels must be expected to be sensitive to this form of embrittlement and an increase in the transition temperature observed in Figs. 4 and 5 is expected, both steels showing a similar effect. In fact, as pointed out earlier, at 0 C the fracture toughness values are better represented by a K_c values of 39 MPa$\sqrt{m}$ (36 ksi$\sqrt{in.}$) and 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) for Materials A and B respectively than by COD values.

Examination of the results shows that the initiation resistance of both steels is not at the satisfactory 0.1 mm (0.004 in.) value until above ambient temperature and one must conclude that there must be a chance of a brittle fracture initiation with these steels at normally accepted working temperatures. This contravenes locally gained experience (Ref. 14) which shows that brittle fracture is not a problem with these steels, at least down to 0 C, provided recommended welding procedures are followed (Ref. 7). In fact, on the initiation criterion recommended earlier, minimum working temperatures would be +40 C for Material A and +20 C for Material B when in the as-welded condition. These temperatures, which are well above the base metal NDT values, correspond to Charpy values of 120 J in both cases. They are clearly unrealistically conservative (Ref. 14).

Dynamic fracture toughness measurements have been made on the materials used in the current work (Ref. 15). Dynamic K_{ID} measurements on Material A, using the technique of Shoemaker and Rolfe (Ref. 16), give a value of approximately 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) at 0 C. Similar measurements on Material B were not possible because with an NDT of −10 C valid results could not be obtained at 0 C.

However we can make an estimate for B as follows. Dynamic COD measurements made using root-notch-contraction (Ref. 15) suggest a value of 0.37 mm (0.018 in.) at 0 C. Using the relationship (Ref. 4):

$$\left(\frac{K}{\sigma_{yd}}\right)^2 = \frac{\delta}{e_y} \qquad (2)$$

and assuming σ_{yd} the dynamic yield strength is 50% greater than the static value, this is equivalent for Material B to a K_{ID} value of 220 MPa$\sqrt{m}$ (200 ksi$\sqrt{in.}$). The large increase in toughness of Material B over that of A arises because at 0 C Material B is above the NDT and is in the region where dynamic toughness rises rapidly with temperature.

It can therefore be seen that dynamic fracture toughness values at 0 C, are greater than those of the strain-aged HAZ and the possibility of the arrest of a crack initiated from a small embrittled zone at this temperature must be examined.

To examine crack arrest we consider the behavior of a notch in a plate specimen under an external load. An analysis by Wells (Ref. 17) recognizes the summation of the stress intensity contributions from applied stress K_σ and residual stress K_r as follows:

$$K_{total} = K_\sigma + K_r \qquad (3)$$

$$\text{where } K_\sigma = \sigma\left[W \tan\left(\frac{\pi a}{W}\right)\right]^{1/2} \qquad (4)$$

$$K_r = 2\left(\frac{a}{\pi}\right)^{1/2} \int_0^a \frac{\sigma_r \, dx}{(a^2-x^2)^{1/2}} \qquad (5)$$

and W is the total plate width, a is the half crack length of a central crack, σ externally applied stress, σ_r the residual stress, and x the transverse distance from the weld centerline. Figure 13 shows the evaluation of equation (3) in a plate of similar size to that used in a Wells' wide-plate test for an applied stress of 69 MPa (10 ksi) and the residual stress pattern σ_r represented by equation (1). This figure is instructive in that it clearly shows the large contribution made to K_{total} by the residual stress component and demonstrates the important effect which residual stresses can have in promoting both crack initiation and propagation.

By evaluation of equation (3) it is possible to calculate the applied stress when fracture initiation will occur in a plate containing a crack-like defect. Initiation will occur when K_{total} is equal to the fracture toughness of the material adjacent to the notch tip. For the strain-aged HAZ in Materials A and B where the toughness is 39 MPa$\sqrt{m}$ (36 ksi$\sqrt{in.}$) and 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) it can be shown that for a through thickness notch 5 mm (0.2 in.) in length (Fig. 1.) initiation will occur at applied stresses of 69 MPa (10 ksi) and 173 MPa (25 ksi) respectively; that is, brittle fracture will occur at 0 C in

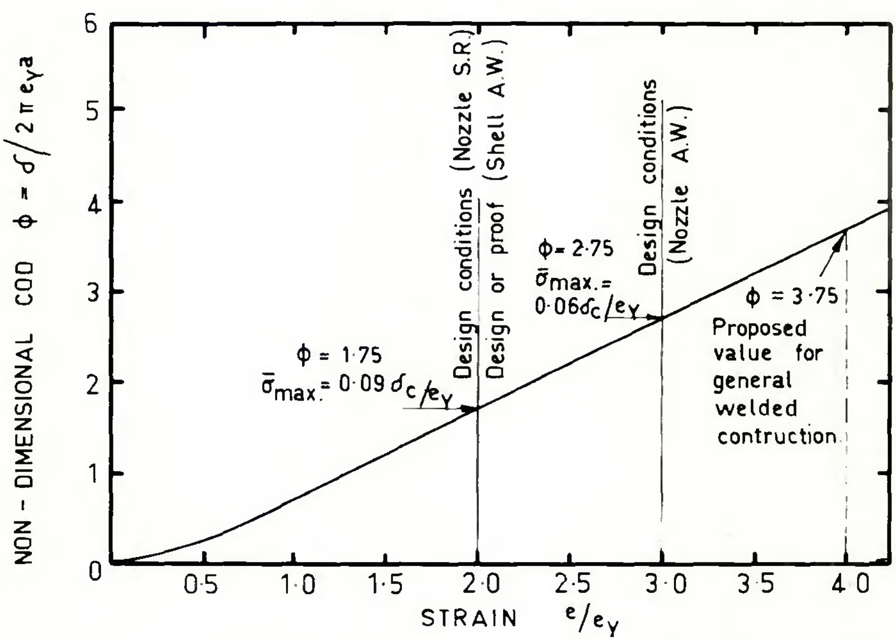

Fig. 12 — Design curve for COD, strain, and crack size relationship proposed by Burdekin and Dawes (Ref. 4)

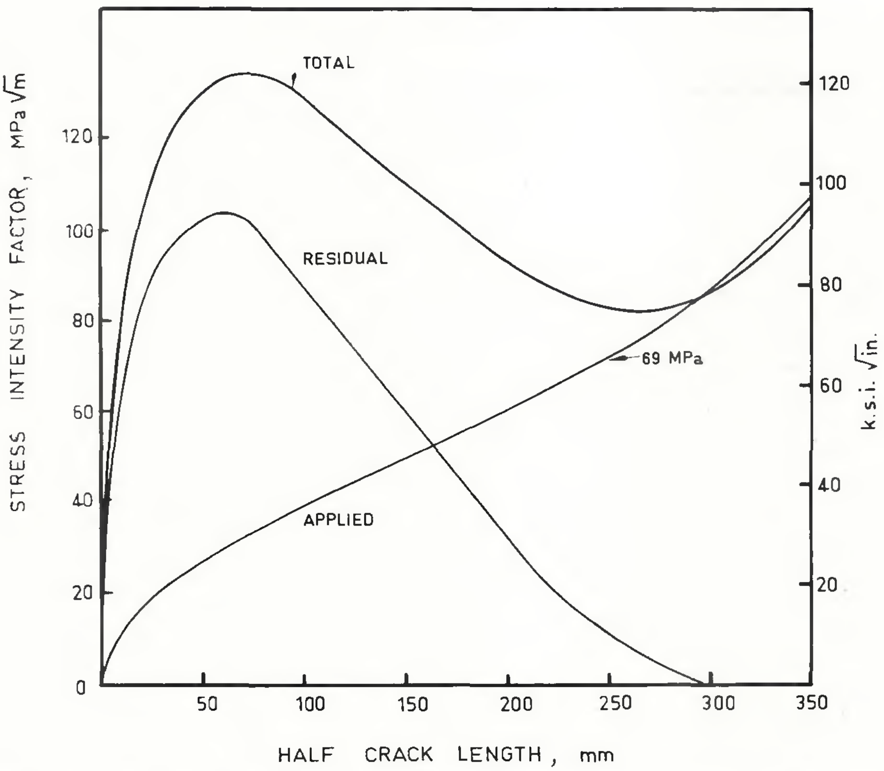

Fig. 13 — Stress intensity values for crack in welded wide plate allowing for effect of residual stress and an applied stress of 69 MPa

both materials.

Of course the strain-aged damaged material will be confined to a volume near the notch tip and an initiated crack will soon run into tougher base metal. Hardness measurements made at the tip of a strain-aged notch indicate the damaged region to be restricted to within 3 mm (0.12 in.). Therefore once the initiated crack has grown to about 11 mm (0.44 in.) in length it will run into base metal, at this point K_{total} has a value of approximately 66 MPa$\sqrt{m}$ (60 ksi$\sqrt{in.}$) for A and 88 MPa$\sqrt{m}$ (80 ksi$\sqrt{in.}$) for B. For Material A, K_{total} is greater than the dynamic fracture toughness of the base metal and propagation of the crack would continue. However, this is not the case with Material B and arrest of the running crack would be anticipated.

It is interesting to speculate whether or not the behavior predicted above provides an adequate guard against brittle fracture. With Material A the case is clear and propagation could ensue; however, if the defect was somewhat smaller than the 5 mm size considered, (of a size similar to that used in the NDT test) which would probably be the case in practice, then arrest could be possible.

On the basis of this analysis the suitability of Material A for use at 0 C must be a borderline case and depends critically on the acceptable crack size. With Material B the situation is much clearer and arrest would occur; in fact it can be shown in the case considered that arrest would still occur if the applied stress was equal to the yield stress of the material. If an actual wide-plate test were carried out on Material B at 0 C, the estimate suggests that fracture initiation would occur below general yield and arrest would quickly ensue. Loading could then be continued well past general yield without fracture occurring.

In fact when fracture did occur, COD measurements on base metal (Fig. 5) indicate it would be of a ductile rather than cleavage mode. It is the author's opinion that under these circumstances the material should be considered suitable for use at 0 C. We therefore have the situation where the material would fail from an initiation criterion but would be satisfactory from an arrest point of view.

Although the amount of testing carried out is limited, the results suggest that generally brittle fracture prevention from strain-aged regions is more likely to be obtained by ensuring adequate dynamic toughness of the base metal than by adequate initiation resistance of the subcritical HAZ. There is a considerable amount of circumstantial evidence to substantiate the importance of base metal properties in preventing brittle fracture.

For instance, experience shows that in low alloy steels of the type studied brittle fractures are rare if the Charpy energy value, which is a reflection of the dynamic toughness of base metal (Ref. 18) and not of HAZ toughness, is greater than a value of about 27 J (Refs. 14, 19). These suggestions are of course similar to those put forward by Pellini in his explanation of the NDT concept (Ref. 20).

It can be argued that if brittle fracture prevention from strain-age damage depends on the ability to arrest a small crack then the properties of the transformed HAZ are generally of little consequence. This is not the case because the orientation of possible defects with respect to the welded joint and applied stress must be considered. Defects at or near the HAZ, as may arise from incomplete fusion or hydrogen embrittlement, are usually oriented parallel to the HAZ, and if initiation does occur the fracture can continue to run in the HAZ.

It is therefore still necessary for fracture initiation to be avoided in the transformed HAZ because subsequent arrest in this zone cannot occur unless the applied stress falls. It must be noted that the toughness of the transformed HAZ will be the factor controlling the use of a steel when it is in the stress-relieved condition. The limited number of measurements made (see Figs. 4 and 5) indicate that this treatment essentially removes strain-age embrittlement.

General Discussion

Although only a limited amount of work has been carried out and the conclusions are somewhat tentative, the evidence does point to the fact that fracture safety in a welded construction depends on the transformed HAZ having sufficient initiation resistance as well as the base metal having the capacity to arrest small dynamic flaws.

With the conventional low alloy steels examined in the current work, the transformed HAZ would appear to have inherently a fairly high level of toughness even when welded by high heat input processes. Provided welds are made so that heat input levels are not below the minimum levels recommended to prevent hardened HAZ formation (Ref. 7), toughness levels will be sufficient to prevent brittle fracture initiation in plates of the order of 25 mm (1 in.) in thickness.

This conclusion is in line with Australian experience (Ref. 14). In regions of a plate prepared for welding, such as flame beveled edges, small crack like defects may be present before welding or may form during welding which could be oriented such that they are subject to strain-aging damage. The local toughness at such defects will be severely lowered and it does not appear practical in commercial semikilled steels to reliably prevent fracture initiation by ensuring that these damaged HAZ regions are of some preset toughness. Instead, provided the defect is small, arrest of such cracks will occur provided the base metal meets minimum toughness requirements.

Pellini's work (Ref. 20) and experience indicates that operation at or above NDT is sufficient to ensure the arrest of defects of a size likely to occur when good fabrication practice is used. Australian (Ref. 14) and U.K. experience (Refs. 17, 19) indicates that a Charpy energy criterion of 27 J (20 ft-lb) will be sufficient to avoid brittle fracture for many steels. The NDT temperature for the steels examined was equivalent to a Charpy energy value of 45 J (33 ft-lb) in both materials. Thus, the Charpy energy criterion is less conservative than the NDT criterion.

The most reliable way of ensuring the arrest of defects situated in strain-aged regions appears to be by the specification of dynamic fracture toughness values for the base metal.

Conclusions

1. Charpy specimens extracted from weldments cannot always be relied upon to assess the comparative initiation resistance of differing HAZ structures.

2. As the Mn and/or Nb content of ferrite/pearlite steels is increased, the transformed HAZ toughness shows increased degradation with increased heat input. Further work is required to define the roles played by these two elements. The results show that *a tough base metal provides no guarantee of a tough HAZ* and in fact the reverse is true in some cases.

3. It has been suggested that an initiation criterion of a minimum COD of 0.1 mm (0.004 in.) should be sufficient to avoid fracture initiation in welded structures fabricated from steels with yield points up to 350 MPa (50 ksi). Based on this criterion it has been shown that the steels can be welded with high heat input processes without fear of brittle fracture. At the highest heat input levels studied, toughness values at 0 C in the HAZ were reduced to near the minimum suggested value and in practice care should be exercised when these levels of heat input are used. Procedure trials are recommended.

4. Toughness levels in the subcritical HAZ, as present in the conventional Wells' wide-plate test, are shown to be very low for the steels under consideration. Evidence is presented to show that in such circumstances an initiation criterion is not appropriate for determining material acceptability. Experience indicates that this type of defect will generally be small and it is usually economical to rely on the crack arrest characteristics of the base metal for brittle fracture prevention. The dynamic toughness can be expressed in terms of K_{ID}, NDT or Charpy impact values.

5. When steels are in the stress relieved condition strain-age embrittlement is removed and the initiation resistance of the transformed HAZ will become the critical factor in preventing brittle fracture.

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