Welding Research

Sponsored by the Welding Research Council

WRC

SUPPLEMENT TO THE WELDING JOURNAL, DECEMBER 1972

Procedures for Evaluation of Fracture Toughness of Heat-Affected Zones

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A good quality weld requires adequate fracture toughness of base metal, weld metal, and heat-affected zone (HAZ). Reliable methods are available for the first two but the HAZ evaluation has posed particular experimental problems which are dealt with in this paper.

Introduction

Welded structures must be viewed essentially as three-component composites of weld metal, plate and heat-affected zone (HAZ). Inadequate toughness in any one is a threat to structural integrity.

In carbon steel weldments the fracture situation is generally a plate problem in the main. The protective geometric aspects of U- or Vee-groove geometries and the toughness levels in welds deposited with modest control generally eliminate the HAZ and weld metal as common paths of major failure. However flaws in either area are capable of extension to the plate. Therefore the key to catastrophic fracture control has centered on the use of steel of sufficiently low transition temperature. The World War II ship failure problem is an excellent case for reference.

In weldments of quenched and tempered steels, the potential for extended fractures not only in plate but also in either HAZ or weld metal must be considered. The steels in this group, because of differences in alloy content and kind differ widely in plate toughness characteristics and in sensitivity to HAZ damage in welding. At the same time the higher strength requirements for weld metals for these steels pose considerations in respect to toughness which become more acute as advanced strengths or more economic compositions or both are sought.

The control of fracture via the plate transition temperature while possible for carbon steel weldments is insufficient for quenched and tempered steel weldments. Evaluative methods for the quenched and tempered (Q+T) steel must take into account the susceptibility of all weldment components to fracture. Two approaches are possible. Testing weldments in composite specimen procedures such as the Explosion Bulge or Delta allows identification of the most fracture prone elements. Procedures to test the toughness of the weld, plate and HAZ represent a second approach.

The Drop-Weight (DW) and Dynamic Tear (DT) tests have been used widely to characterize plate and weld metal toughness separately and quantitatively. From tests using these two specimens, data are presented in this report to demonstrate the applicability of these two procedures to the HAZ as well. Results of composite specimen tests and single component tests will be shown to be in agreement when applied to several steels. Consequently the understanding of results of composite specimens tests is enhanced and their applicability better defined. At the same time the

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successful characterization of HAZ toughness by the DW and DT procedures provides quantitative reference data for use in the Fracture Analysis and Ratio Analysis Diagrams.

The Weldability Problem in Relation to Fracture Toughness in Carbon Steels

The ship failures in World War II typified the weldability problem in carbon steel structures. The intensive investigation of these failures revealed that the fracture problem was essentially a plate metal problem, that is, high plate transition temperatures, since they were the path for extended failures. Adequate toughness in the weld metal was possible through use of commercial filler materials deposited under modest control. Sufficient compensation for metallurgical damage via the protective geometric aspects of joints with U- or Vee-groove configurations was effective in minimizing extended fractures in the HAZ.

However flaws in either the weld metal or heat-affected zone could and did act as sources for fractures which were transmitted to and extended in the plate. As a consequence a two-pronged attack was brought to bear on the carbon steel fracture problem — one, to produce plate with lower transition temperatures, the other to identify and eliminate creation of flaws in welding.

In the effort, a host of tests was developed. In the context of the problem, all were called weldability tests. Some were designed to measure plate toughness more satisfactorily or completely than possible by the Charpy test; these were regarded as service tests. Others generally termed fabrication tests were designed to measure susceptibility of the base plate to heat-affected zone cracking. One was the bead on plate cracking test in which a weld bead was deposited on the plate material and then examined for evidence of cracking in the HAZ under the natural shrinkage stresses generated by weld cooling.

A second procedure was the "clip test" in which a piece of plate or "clip" was welded with a single fillet weld to form a Tee-joint with the material being examined. Testing consisted of striking the clip, which was the vertical bar of the Tee-joint, with a sledge to determine whether in breaking it away, fracture took place in the brittle coarse-grained HAZ of the subject material.

Another approach to determine susceptibility of either weld metal or HAZ to cracking in fabrication was the Lehigh Restraint[1] Specimen. In this test, a weld deposited in a double-U-joint was restrained from shrinking in cooling. Variable restraint allowed definition of a threshold value above which cooling cracks would form. Either weld metal or HAZ could fail depending on the materials and welding conditions.

Consideration of the HAZ as an area of potential difficulty led to various researches. Doan, Stout, Tor and Frye[2] proposed a systematic approach to controlling hardness and brittleness in the coarse-grain heat-affected zone through understanding the relations between weld heat input, plate thickness and temperature, and corresponding cooling rates in the weld area and Jominy test data. Other investigations showed potential embrittlement in regions of the HAZ susceptible to strain-aging type phenomena. Still others showed embrittlement possible in the metallurgical areas heated just above the lower critical temperature.

However, the situation with the carbon steel plates remained the same, namely the potential for long disastrous failures in plate with the weld zone limited to the role of site or source of initiation. Commercial welding material and control of welding conditions could be relied on to eliminate the weld zones as paths for major fracture. Ultimately it became clear that the overall approach to fracture safe design with these steels required the use of sufficiently low transition temperature plate material to prevent extensive fracture.

Weldability and Fracture Toughness of High-Strength Steels

Weldability is a more complex practical matter for the high-strength steels than for the carbon steels. Not only the plate but also the heat-affected zone and the weld metal require consideration. Each can be viewed as a separate concern.

Conceptually and for practical testing purposes the weld metal is isolable for separate handling. However the fracture toughness problems there must be considered in relation to the steels being welded. For carbon steels the problem is minimal. Adequate toughness or toughness equivalent to that of the plate is readily obtained in the weld metal with relatively modest attention to the welding process using readily available filler materials. Welding of high-strength steels presents more stringent demands. As in the plate materials to which they are applied the problem is to maintain adequate toughness at elevated strength levels. Thus the weld metal toughness problem becomes more acute as higher strengths or more economic compositions or both are sought. Optimum properties are realized only by careful selection of filler material and appropriate control of the welding process.

Like the weld metal, plate material can be handled as a distinctly separate weldment component. It is clearly recognized that differences in amount and kind of alloying elements lead to differences in toughness characteristics at any strength level. Some of the steels in the Q+T group show neither a sharp transition temperature nor a high energy shelf while others do. It is evident that in Q+T steel weldments the plate remains a critical element for fracture control.

While the plate metal and HAZ can be viewed as separate entities, the plate must be regarded as the parent of the HAZ. Both are subject to the same metallurgical considerations. The fracture toughness realizable in each is dependent upon the nature and level of alloy content. The plate is heat treated for optimum toughness in prescribed thermal cycling processes under control in the mill. The more complex cycling experienced in the heat-affected zone is subject to less control in welding. It is unrealistic to expect the heat-affected zone to exhibit the same microstructures found in the plate. Control of the welding process must be the route to produce HAZ microstructures with optimum properties in a given steel. In general the hardenability of the steel dictates the latitude of welding conditions allowable for retention of the most favorable HAZ microstructure with resultant minimal damage.

Weldability Tests

Among the various procedures proposed for evaluating fracture performance of weldments three fundamentally different approaches can be recognized. One is to measure the tendency of plate to accept weld initiated fractures restricted to the transverse-to-weld path of travel. A second is to characterize the toughness of weld, plate and HAZ separately. A third is to use composite test procedures which allow simultaneous loading of all three components and a self-selected fracture path in the component of least resistance.

In specimens such as the Kinzel or Lehigh Longitudinal Bend tests[3] which force fracture transverse to the weld, the specimen is prepared by deposit of a weld bead on a plate surface along the length of the specimen. A notch cut across the width of the plate leaves a small amount of weld area at the root as a source of fracture in bend testing. Fracture so initiated is forced to take an extended path across the plate. Thus the fracture through the weld zone represents a minor fraction of the total fracture surface. Nevertheless, this test is sensitive to welding conditions and materials when used on plate capable of considerable ductility and represents an excellent simple approach to weldability testing. When transition curves are determined with this procedure, the effect of increasing weld zone brittleness is reflected in higher transition temperatures. When tested with extremely brittle weld zones the specimen becomes a slow-bend nil-ductility transition (NDT) temperature test of the plate, that is, a test of the parent material in response to a dynamic crack.

The Charpy test has long been used as a procedure to characterize fracture toughness of individual weldment components separately. From the early days of ship failure investigations when it was used with eminent success on carbon steel plates, this procedure has seen widespread acceptance and incorporation into codes for welding in application to weld metals, plate materials and heat-affected zones. The vast amount of data accumulated with this test procedure is an inducement to continued use. Often, like a hardness test it is used for quality control. However the test presents some difficulty when considered for quantitative toughness measurement. It has been amply demonstrated that correlations of Charpy data with data from other toughness tests are difficult and that, say 15 ft-lb Charpy V-notch energy in one steel may mean something entirely different in another. Thus complications occur in attempts at comparisons across broad families of steels.

The test presents other difficulties as in testing of thick sections or thick welds where tests at surface, center and intermediate positions may be mandatory, consequently expensive and in the case of nonuniform material, productive of perplexing data. Nevertheless the specimen has been applied to measurements of heat-affected zone toughness by positioning the base of the notch in various locations in the heat-affected zone. The method is tedious and fracture cannot be relied on to follow a fixed desired path through the complex, non-uniform, curved plane geometry of the heat affected zone. As a result data are susceptible to considerable scatter and difficulty of interpretation.

Before proceeding to a brief analysis of composite specimen tests it should be recognized that the heat-affected zone presents particular problems in toughness characterization. Unlike the weld metal or plate metal it is not physically isolable for direct testing. It must be tested *in situ* as a center element sandwiched between weld metal and parent plate. In usual commercial joints it is present as an undulated curved plane slanted to the plate surface and thus protected to a degree from fracture in both through-the-plate and across-the-plate directions. Additionally it is a relatively narrow zone. For these reasons containment of fracture within it for purposes of fracture toughness measurement poses considerable experimental difficulty as the lack of available data clearly indicates.

However, as following sections will show, both the Drop-Weight (DW) and Dynamic Tear (DT) test procedures are adaptable to quantitative toughness characterization of the HAZ. Prior to such adaptations the principal definitive approaches to determining the proclivity of the HAZ to fracture were the composite specimen tests such as the Explosion Bulge, Drop Weight Bulge and more recently the Delta test.

Table 1 — Chemical Compositions of Steels Studied

Steel Code	C	Mn	Si	P	S	Ni	Cr	Mo	V	Other
	Composition, wt-%									
J20	0.15	0.81	0.25	0.013	0.021	0.83	0.52	—	0.24	0.55 Cu
J25	0.12	0.32	0.17	0.006	0.014	2.33	1.26	0.34	—	—
J26	0.22	0.88	0.65	0.023	0.022	0.13	0.94	0.48	—	0.10 Cu
J31	0.18	0.87	0.26	0.011	0.019	0.25	0.66	0.24	0.04	0.10 Al
J32	0.18	1.15	0.28	0.009	0.024	0.07	0.05	0.25	0.01	0.06 Al
J34	0.18	0.58	0.28	0.015	0.019	0.20	1.05	0.25	0.03	0.10 Al
J38	0.18	0.84	0.64	0.006	0.019	0.05	0.69	0.19	0.03	0.10 Al
L6	0.21	0.57	0.28	0.008	0.024	0.03		0.69		0.004B, 0.06Al
L15	0.19	0.67	0.26	0.009	0.026	1.36		0.64		0.003B, 0.07Al
A543	0.14	0.30		0.010	0.018	2.94	1.62	0.46		
A537B	0.18	1.21	0.25	0.010	0.025	0.16	0.10	0.03		0.30Cu, 0.04Al

Some Composite Weldment Tests

A. The Explosion and Drop Weight Bulge Tests

The Explosion Bulge test (EB) was one of the earliest used to direct attention to heat-affected zone fracture problems. In conducting the test a specimen 14 x 14 in. is positioned over a circular opening in a die and loaded by offset explosion. Beginning in a small brittle weld bead a crack of natural sharpness propagates from the specimen center toward the specimen edges. Tests over a range of temperatures allow determination of NDT, fracture transition elastic (FTE) and fracture transition plastic (FTP) temperatures which are critical in the systematic presentation of the Fracture Analysis Diagram (FAD). In addition to the importance of the explosion bulge test to fracture analysis and engineering fracture mechanics, the specimen is interesting in that fracture is not biased in travel direction since a 1 to 1 loading situation prevails. Hence it is appropriate as a searching tool to determine the line of least fracture resistance in welded specimens.

A modified version of the Explosion Bulge test shown in Fig. 1 is the Drop Weight Bulge (DWB) test. Like the EB specimen, the DWB specimen is positioned over a circular opening in a die and loaded by the simple procedure of dropping sufficient weight on the specimen from a shop crane or other device.

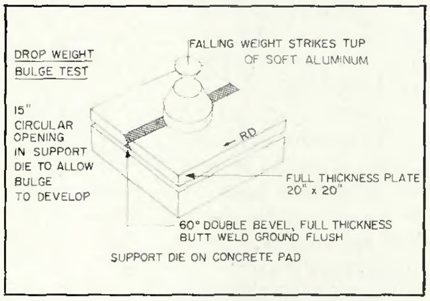

Fig. 1 — The Drop Weight Bulge test. A 2-in. diam surface patch of Hardex-N at the center of the "down" side serves as a crack initiator

In a program of tests,[4] seven steels, obtained through regular commercial channels, were tested as fully butt welded specimens in the drop-weight bulge procedure. All welds were made with E11018M electrode with 80 kJ/in. maximum heat input and maximum interpass temperature of 125 F. Specimens at 30 F were subjected to repeated impacts from a 6-ton weight falling from a height of 8 ft until eye-visible fracture occurred. Compositions of the steels are given in Table 1. Mechanical properties are given in Table 2. Some results are shown in Table 3. A significant point is the tendency for HAZ failures to be long. Figure 2 illustrates the range of DWB performance found, ranging

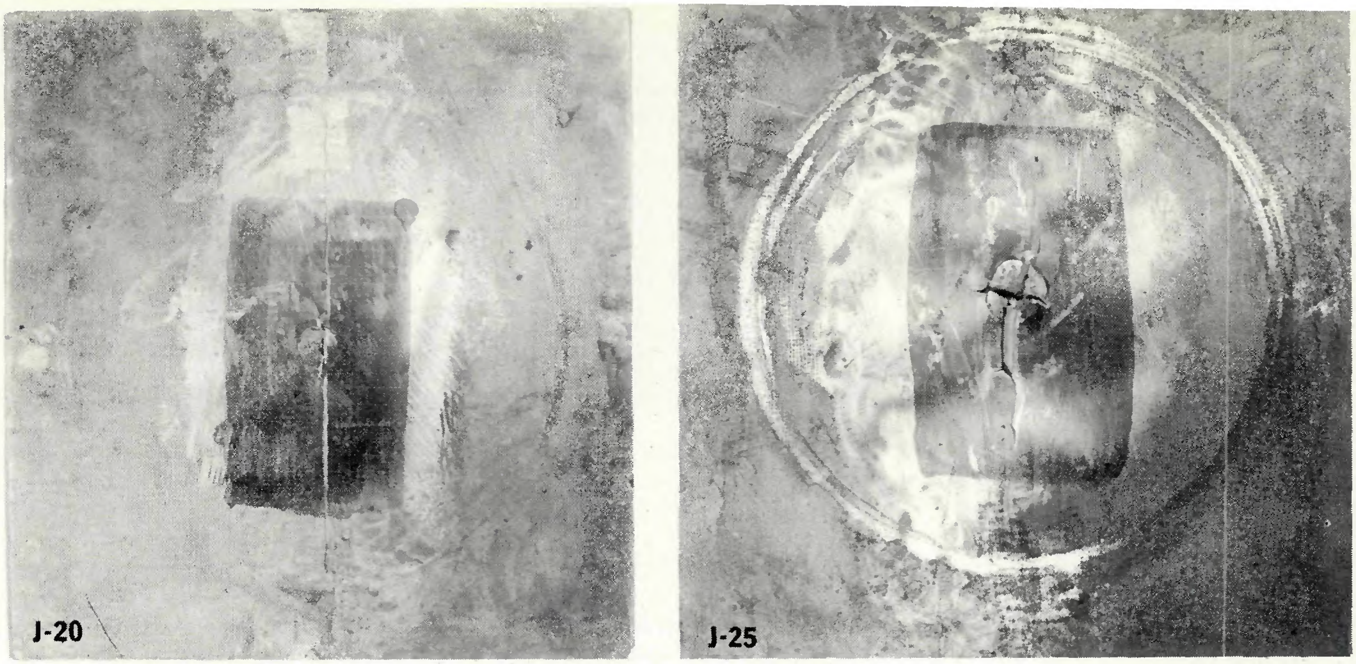

Fig. 2 — Fractured DWB specimens. Steel J20 fractured in a HAZ path 20 in. long in one 8-ft impact of the 6-ton weight. Four impacts produced a fracture confined to the weld metal in Steel J25. Both tests at 30 F, both 1-in. plates

Table 2 — Tensile Test Results

Steel code	Fracture code	Plate thickness in.	0.2% YS ksi	UTS ksi	Red. of area, %	Elong., %	Charpy-V, ft-lb at 30 F[a]
J20	P [b]	1	124.0	129.0	53.1	16.0	32-29
	T [c]	1	123.4	128.9	62.0	18.8	51-48
J25	P	1	83.3	97.7	68.0	24.0	105-99
	T	1	82.9	97.8	75.1	27.0	165-162
J26	P	1	106.8	120.1	53.5	19.0	32-29
	T	1	105.0	108.9	58.7	21.0	47-46
J31	P	1	113.6	121.4	48.9	15.0	26-25
	T	1	112.6	121.1	59.7	17.5	48-44
J32	P	7/8	116.3	121.3	53.3	16.3	38-30
	T	7/8	116.3	122.1	61.1	18.0	44-42
J34	P	1-1/8	111.3	117.3	53.2	16.5	28-27
	T	1-1/8	111.2	118.0	65.4	18.8	51-47
J38	P	1	108.8	117.7	59.2	19.0	31-30
	T	1	111.3	111.5	66.4	19.5	56-52
L6	P	1	100.0	Not tested		—	28
	T						40
L15	P	1	100.0	Not tested		—	20
	T						54
A543	P	1	88.0	110.0	—	25	76
	T						145
A537B	P	1	62.6	83.8	—	27	60
	T						82

(a) Values given are the high and low values measured at 30 F.
(b) Fracture parallel to rolling directions.
(c) Fracture transverse to rolling directions.

Table 3 — Drop-Weight Bulge Test Results at 30 F [a]

Code	No. of impacts to failure	Length of crack, in.	Location [b]
J20	1	20	HAZ
J25	3	4	Weld (minor plate tear)
J26	3	6	Plate
J31	3	18	Plate
J32	3	15	HAZ
J34	2	7	Plate (3 in.) and weld (4 in.)
J38	4	20	HAZ

(a) Long fractures occured in HAZ and plate only at this temperature.
(b) Only steel J25 resisted plate and HAZ fracture or both.

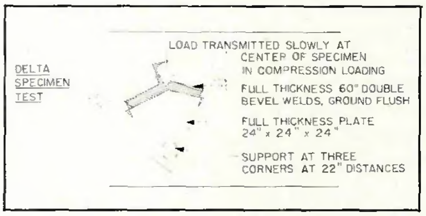

Fig. 3 — The Delta test procedure as conducted on welded plate. A 2-in. diam surface patch of Hardex-N at the center of the "down" side serves as a crack initiator. Both 1-in. plates

from the worst case, a flat break performance in J20 specimens after one impact which produced a full 20-in. fracture in the HAZ to the best case, a 4-in. weld metal fracture in J25 steel after 3 impacts resulting in a 4-in. bulge at specimen center.

In a later series of identical tests, steel L6 in welded condition was tested over temperature ranges using the 6-ton weight and a repeated 4-ft drop procedure until onset of failure. Table 4 gives the test results. NDT for this steel was −50 F, and of the weld and HAZ each −40 F.

These tests showed several items of note, namely the dependence of fracture location on test temperature, in keeping with NDT concepts, and tendency to fractures in the HAZ at test temperatures above NDT of plate, weld and HAZ.

In summary the DWB is a simply conducted discriminating test of weldability. Data from this dynamic type test correlate well with those from the slowly loaded Delta test specimen to be considered.

B. The Delta Test

This test illustrated in Fig. 3 like the DWB is a prototype test representing part of a weldment. The specimen is tested in a slow loading which causes fracture to begin in the brittle crack starter patch at the center of the "down" or tension face of the specimen. The specimen can be either of unwelded plate containing the crack starter patch weld or of plate welded in any desired manner.

Failure is defined as the appearance of a fracture, extended from the crack starter, which ordinarily occurs at a maximum load. Fracture in welded specimens is free to follow

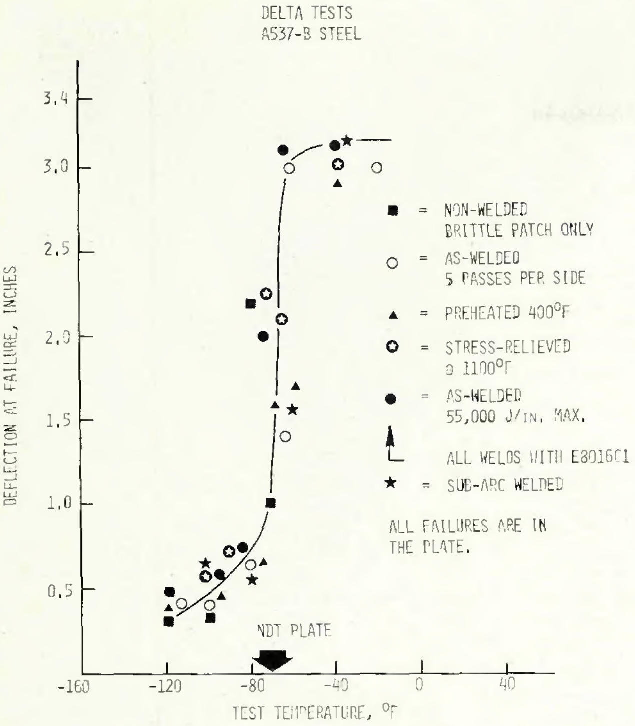

Fig. 4 — Results of Delta tests of 1-in. A537 steel in prime plate and welded conditions. All fractures in welded specimens occurred in plate

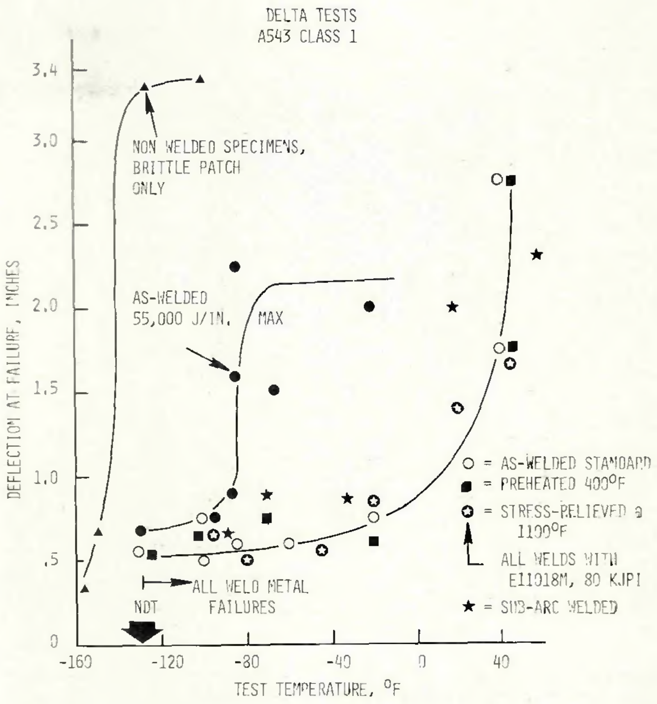

Fig. 5 — Results of Delta tests of 1-in. A543 steel in prime plate and welded condition. All fractures in welded specimens occurred in the weld metal

the path of least fracture resistance, weld metal, HAZ or plate. Tests conducted over temperature ranges develop transition curves. The most immediately useful index of failure is the center point deflection at failure but other measurements including yield, maximum and fracture loads, energy to cause failure, length of initial fracture, ease of extending failure, and path of failure are possible. The specimen is sensitive to base plate composition, weld filler metal, welding procedure and test temperature.

Temperature dependency of fracture path in welded specimens is an essential possible result because as in the DWB or EB test, fracture is free to occur in the least resistant path. Thus, essentially three basic patterns of performance are possible depending on the temperature vs. fracture toughness characteristics of the three individual weld zones. That is, either weld metal, plate or HAZ can control the fracture process.

Given the deflection at failure vs temperature characteristics of base plate (unwelded except for the crack starting brittle patch), it follows that welded specimens of that material cannot show better performance. They can show equal performance only if the weld metal and HAZ show equivalent or superior fracture resistance. This is illustrated in Fig. 4.[5,6] Similarly, if the weld deposit has less fracture resistance than the plate, the weld metal will control the fracture characteristics when the HAZ retains sufficient fracture resistance. This is illustrated by the tests described by Fig. 5. Finally, sufficient deterioration in the HAZ will make it an available path for fracture and result in Delta specimen performance of the type shown in Fig. 6. Properties of the steels are given in Tables 1 and 2.

Many instances of performance patterns intermediate between those shown in Figs. 4, 5, and 6 are possible and have been found but the principles illustrated appear inviolable. The transition temperature for unwelded parent plate in the Delta test determined from the deflection at failure vs test temp. curve has shown ex-

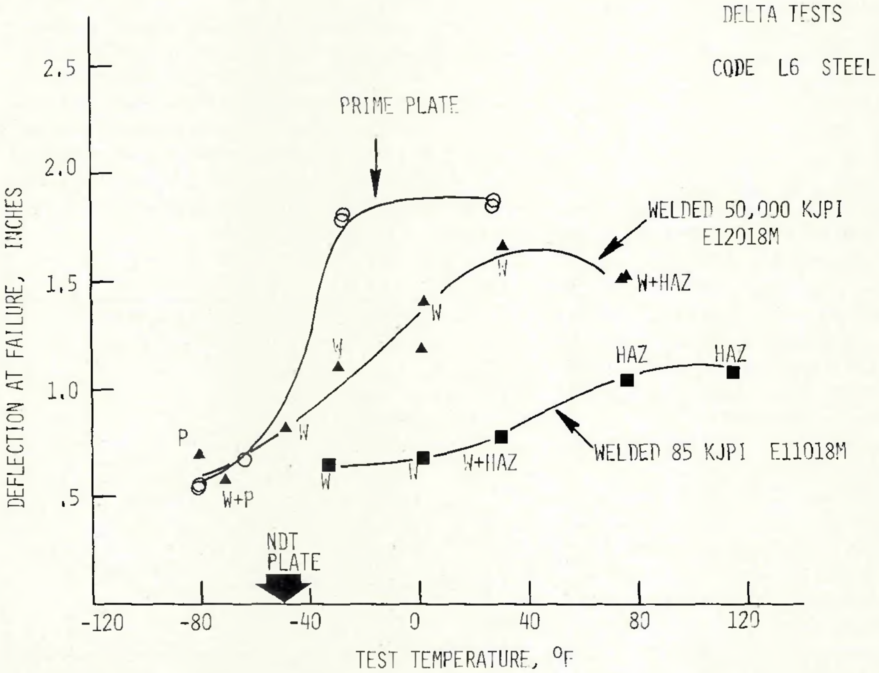

Fig. 6 — Results of Delta tests of 1-in. L6 steel, prime plate and welded. Lower heat input welding considerably reduced tendency to HAZ fractures

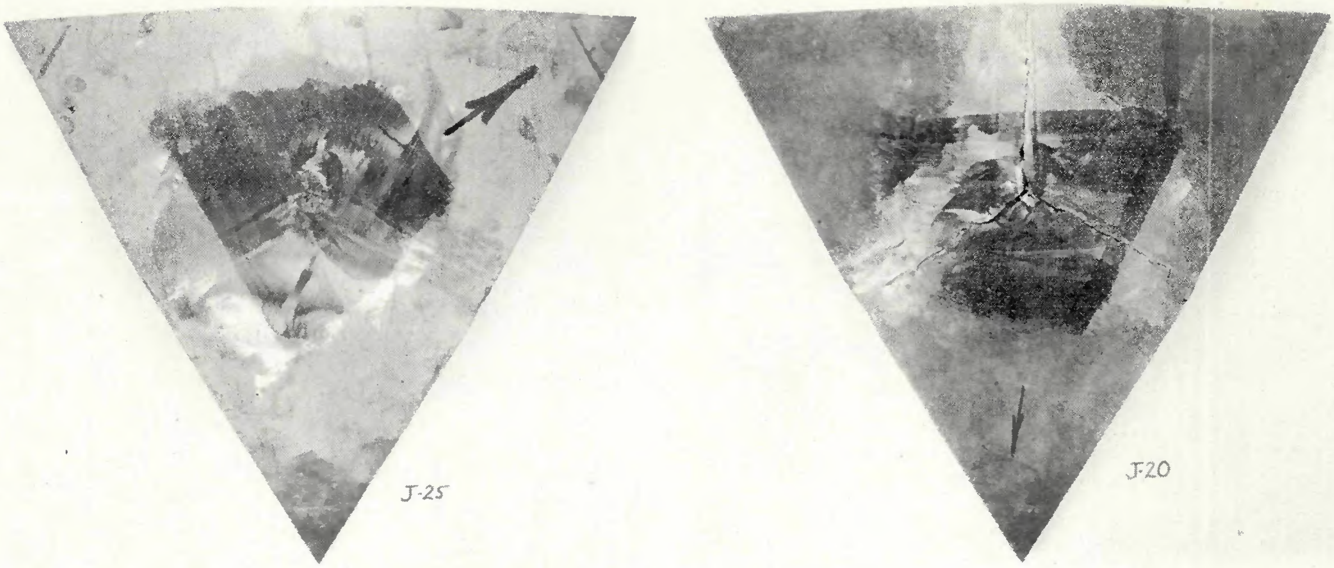

Fig. 7 — One-in. Delta specimens which after initial failure were forced to 3-in. deflection to extend fractures. Failure in J25 steel is limited to the weld metal while in the J20 steel fracture extends to the edges primarily through the HAZ

Table 4 — Results of Drop-Weight Bulge Tests on Steel L6 in Welded Condition[a]

Test temp., F	Bulge at fracture, in.	No. of impacts	Fracture length, in.	Fracture location
-70	0.75	1	14 (flat)	Plate
-40	2.00	1	14 (tear)	Plate
-10	1.50	2	15 (tear)	HAZ (2 in. in plate)
+70	2.00	4	15 (tear)	HAZ

(a) Using a 6-ton weight with repeated 4-ft drops until onset of failure.

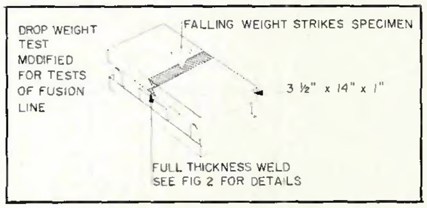

Fig. 8 — The modified Drop Weight test to measure NDT of the HAZ. The notch in the crack starter is positioned along the HAZ

cellent correlation with the DW-NDT in tests of 21 heats of steel. Likewise Delta tests of welded specimens have never shown flat-break failures in the base plate at test temperatures above the NDT temperature although they may show equivalent brittleness due to extensive weld zone failure.

Available data have allowed comparison of Delta behavior and DWB behavior of several steels considered in the previous section. In the DWB tests as conducted (successive impacts of a 6-ton weight) detection of the point of first failure was not possible because in the process of being subjected to the final impact, fractures both began and extended.

To approach parallel performance, Delta specimens previously tested only to the point of failure were additionally deformed to a total of 3 in. of center point deflection to extend the initiated failures. The results portrayed in Fig. 7 and Tables 3 and 5 clearly show parallel performance of the steels in the two tests, the dynamic DWB and the slowly loaded Delta. Steels subject to ready fracture extension in the HAZ in the DWB showed similar character in the Delta test. The nature of the extended HAZ fractures indicates a low-energy tearing mechanism. J25 steel showed no HAZ fracture in either the Delta or DWB tests. Instead localized weld metal tearing was the only mode of failure.

In summary, the Delta test is a conveniently conducted weldment test which allows fracture to find the least resistant path. This specimen like the DWB and EB exposes all elements of the weld to the applied load simultaneously. Interaction among the various components is complex. Thus the specimen is advantageous in examining the response of any one steel to weld metals of different toughness or strength levels or both, to deterioration of toughness of the HAZ under different welding conditions and to other variables. The clearly demonstrated dependency of fracture path on test temperature is in keeping with DW-NDT principles and correlative with results of other tests.

Table 5 — Results of Test With Delta Specimen at 30 F[a]

Steel code	Length of crack, in.	Location
J20	24	HAZ
J25	1	Weld
J26	4	Weld
J31	8	Weld (terminated at HAZ)
J32	2	Weld
J34	17	HAZ
J38	20	Weld and HAZ

(a) Delta test specimens tested beyond onset of failure to 3 in. deflection at 30 F. Data are comparable to those in Table 3. It is expected that all steels except J25 would show HAZ fractures at higher test temperatures.

Testing Toughness of HAZ in Some Q + T Plate Materials

A. The Drop Weight Test

This test, shown modified in Fig. 8, originally developed for plate material, has also been used successfully in testing weld metal. In the test a dynamic unstable crack generated in the brittle crack starter weld is presented to the base plate. Under the conditions of limited plastic strain in the test a crack will either extend significantly or not depending on the material and test temperature. By the procedure now well known the nil-ductility transition (NDT) temperature or the temperature for significant *crack extension* for given materials can be established.

This temperature is the important

reference for the Fracture Analysis Diagram (FAD) and has been shown to have a high correlation index with other significant fracture tests and service failures. The test has been applied to weld metal as well as to plate materials ranging from 30 to 100 ksi yield strength. A simple step can be taken to measure the NDT temperature for weld metal by preparing a specimen so that fracture traverses through the weld metal of a fully welded joint.

In a recent NRL investigation[4] it was found possible to measure the NDT temperature of heat affected zones in various steels. This was accomplished by preparing DW specimens of standard dimensions having transverse butt welds at the specimen center. A relatively flat plane of HAZ, as in a square butt weld, presented a path for fracture in the through-the-plate thickness direction. Some details are shown in Fig. 9. The steels examined had chemical compositions and mechanical properties shown in Tables 1 and 2. Table 6 indicates differences in toughness between the steels and HAZ's in them as indicated by NDT temperature difference.

Reference to Table 6 will show that the average ΔT (NDT HAZ minus NDT plate) for the six steels is 60 F or essentially the temperature difference between NDT and FTE. All the low alloy Q + T steels showed measurable NDT in the HAZ. In testing steel J25 fractures would not occur in the HAZ. They occurred only in the weld metal. The data show clearly the potential for HAZ deterioration in welding. Reference to the Charpy-V shelf data for the parent steels in Table 2 shows 25 to 38 foot pounds (P-direction) as typical shelf values in the low alloy steels. The J25 steel which did not permit HAZ fracture showed 100 ft-lb shelf and −150 F NDT. Data to be presented later will deal with absolute measurement of fracture toughness in the plate vs the HAZ for these steels.

The point to be re-emphasized here is that weldments must be viewed as composites. The toughness of parent material is not necessarily carried over into the HAZ or matched by the joint filler metal.

B. The DT Text

The DT test procedure,[7] which has been widely used to characterize fracture toughness of both weld metal and base metal, presents geometric features which suggested the possibility of successful application to the HAZ. The availability of quantitative toughness data on the HAZ together with parallel data on weld metal and plate has obvious advantage.

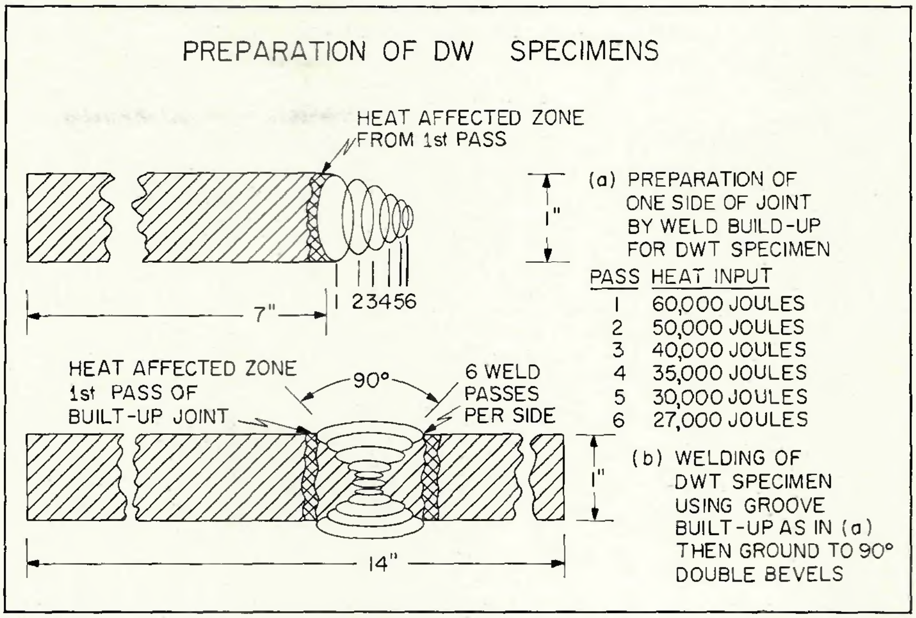

Fig. 9 — Welding and preparation of DW specimens. Similar procedure was used for DT specimens

Table 6 — NDT Temperature Comparison[a]

Welded vs Unwelded Plate Specimens
(3-1/2 by 14 in. Specimens)

Code	NDT temp., plate, F	NDT temp., welds, F[b]	NDT temp., change (Δ t,) F
J20	-80	-40	+40
J25	-150	below -50[c]	
J26	-90	-30	+60
J31	-80	+10	+90
J32	-90	-20	+70
J34	-80	-10	+70
J38	-50	-30	+20

(a) NDT temperature of plate material vs NDT temperature when fracture travels in the HAZ of specimens prepared as in Fig. 8. Average upward change in NDT temperature (Δ t) for the six steels which allowed HAZ fracture is about 60 F or the NDT to FTE shift.
(b) Welds were notched at the fusion line.
(c) No HAZ cracks occurred.

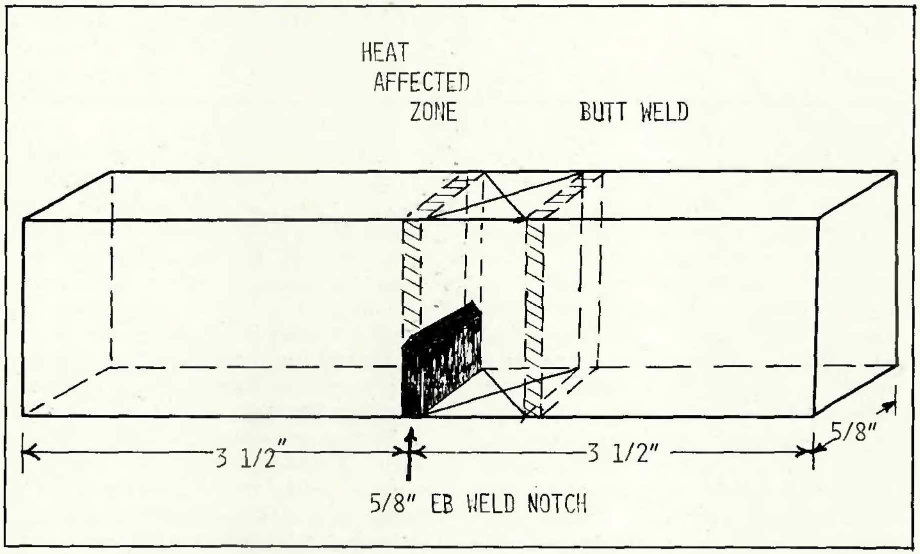

Fig. 10 — Schematic of DT specimen and notch placement. Welds to produce the HAZ for fracture travel were made at 85kJ/in.

Table 7 — DT energy, Ft-Lb, Test Data from Tests of Plate and Specimens with HAZ Notch[a]

(a) Steel L6

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
120	301	80	237 [b]
70	271	80	236 [b]
70	290	10	192
40	292	-20	149
0	241	-50	55
-40	193		
-80	147		
-120	44		

(b) Steel L15

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
120	160	80	144
70	168	80	126
40	188	55	125
0	149	10	143
-40	111	-50	83
-80	97		
-120	96		

(c) Steel J20

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
No tests	No tests	80	205
		80	188
		10	129
		10	145
		-20	137
		-40	86

(d) Steel J25

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
80	947	120	526
0	995	120	537
-40	956	80	377
-80	672	50	273
-120	339	50	341
-160	135	0	258
-180	93	0	212
		-50	97
		-50	103
		-100	62
		-100	63

(e) Steel J31

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
120	255	80	175
70	211	80	174
40	217	40	221
0	175	40	190
-40	136	-20	93
-80	86		

(f) Steel J32

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
120	283		
70	261	40	109
40	236	0	115
0	252	0	116
-40	224	-20	117
-80	111	-40	99
-120	50	-40	95

(g) Steel J34

Plate Test temp. F	Plate Energy, ft-lb	HAZ Test temp. F	HAZ Energy, ft-lb
120	287	140	171
70	294	100	188
70	255	80	190
40	255	80	150
0	203	80	194
-40	177	40	163
-80	75	0	102
		-20	133
		-40	123

(h) Weld fractures or mixed weld-HAZ fractures

Steel	Temp, deg F	Energy, ft-lb
L6	120	288
L6	40	269
L15	80	297
L15	40	254
L15	-20	202
J20	120	483
J20	80	374
J20	40	387
J20	0	241
J31	80	368
J31	80	323
J31	10	232
J32	120	292
J32	-40	95
J34	120	475

(a) All-HAZ notched specimens failed through the weld metal.
(b) Some mix of weld and HAZ fracture.

The test procedure is illustrated in Fig. 10. As described earlier, the requisites for meaningful and successful use of the test to measure HAZ toughness are (a) that a relatively flat plane of HAZ be produced in it to serve as a possible fracture path and (b) that fracture be contained in the inherently narrow HAZ plane so presented. Appropriate geometric configuration of the specimen was accomplished much as shown in Fig. 9. The edge of the plate was beveled slightly. A buttering type weld bead on that surface produced a weld bead with a relatively flat plane of HAZ at the bottom. This HAZ served as the path for potential fracture in the completed specimen. Buildup on that weld to allow a double-Vee groove butt joint for joining the first plate to an identically prepared plate resulted in a flat welded plate from which standard ⅝ in. DT specimens were machined.

The problem of containment of a fracture within the HAZ has been met commonly in experimental attempts to measure toughness. However in the specimen as designed in Fig. 9 and 10, it can be justifiably hypothesized that fracture can be contained in the HAZ (a) if the bounding materials of weld metal and parent material are tougher and (b) if the plastic zone size of the HAZ material is sufficiently small, that is, if the HAZ is of sufficiently low notch toughness. Conversely absence of either condition should allow the fracture to veer from the HAZ plane into the bounding material.

Six steels were tested. All were examined in previously described Delta, DWB and DW-NDT test procedures. Properties of the steels were given in Table 2. DT tests over temperature ranges were conducted (a) on the parent steels and (b) on the specimens of these steels welded and prepared for HAZ toughness measurement. The electron beam brittle weld technique was used in notching in all cases. The data from the tests are shown in Fig. 11. Although limited availability of the materials did not allow more data, the trends are clear and the investigation can be regarded as quite successful. Table 7 gives data on tests of all steels.

The data showed differences among steels in proclivity to HAZ fracture and deterioration. Code J25 steel which in all previous tests, Delta, DWB and DW-NDT, did not develop HAZ fractures, likewise developed none in the DT tests of the HAZ. All DT specimens of this steel fractured in the weld metal. All other steels showed susceptibility to HAZ fracture. Code L6 steel showed a tendency to mixed weld and HAZ fractures.

In some specimens prepared for HAZ evaluation, the electron beam brittle weld notch veered from the HAZ into the weld metal. These specimens when identified and tested showed greater toughness than the HAZ or plate of some steels. Data for these tests are included in Table 7. Further the DT data from tests of J25 steel (welded) really describe weld metal toughness since none followed a HAZ path. They permit the conclusion that the DT energy curve for the HAZ of that steel would lie somewhere between that for the unwelded plate and that shown for weld metal in Fig. 11. This places the HAZ toughness for J25 steel higher than that of any of the other parent plate materials.

Ratio Analysis Diagram Interpretation of DT Test Data

Figure 12 presents Pellini's Ratio Analysis Diagram for 1-in. plate from a report to be published.[10] This version of the diagram classifies fracture properties in three modes — plastic, elastic-plastic and plane strain. The elastic-plastic range of conditions is defined as that between plastic and plane strain or between K_{Ic}/σ_{ys} ratios of 1.0 and 0.63. On the diagram are entered the DT data for HAZ and plate of the low alloy steels tested for this report. The entry is in the form of the heavy blocks representing the range of shelf energy or maximum energy determined. The implication to be drawn is that while the plate materials meet a yield or over-yield condition of failure, the HAZ notch tests show a fall to not meeting it and approach or fall below lower bound conditions.

In arriving at yield strength figures for the HAZ for this plot, conservative estimates were used based on hardness values. If higher values are estimated, it appears that the HAZ tests exhibit an approach to plane strain conditions. The DT energies noted for the low alloy steel HAZ regions and referenced to the K_{Ic} values are in agreement with values previously reported.[11] The tabular portion of Fig. 12 indicates the critical depth of long thin surface cracks to be expected at the nominal stress values shown for plane strain conditions. Pellini's report further amplifies on this diagram to show that nominal stress for plane strain fracture is 0.3 yield stress at a K_{Ic}/σ_{ys} = 0.63 and 1.0 yield stress at a ratio of 1 for a 3-in.-through-the-plate flaw.

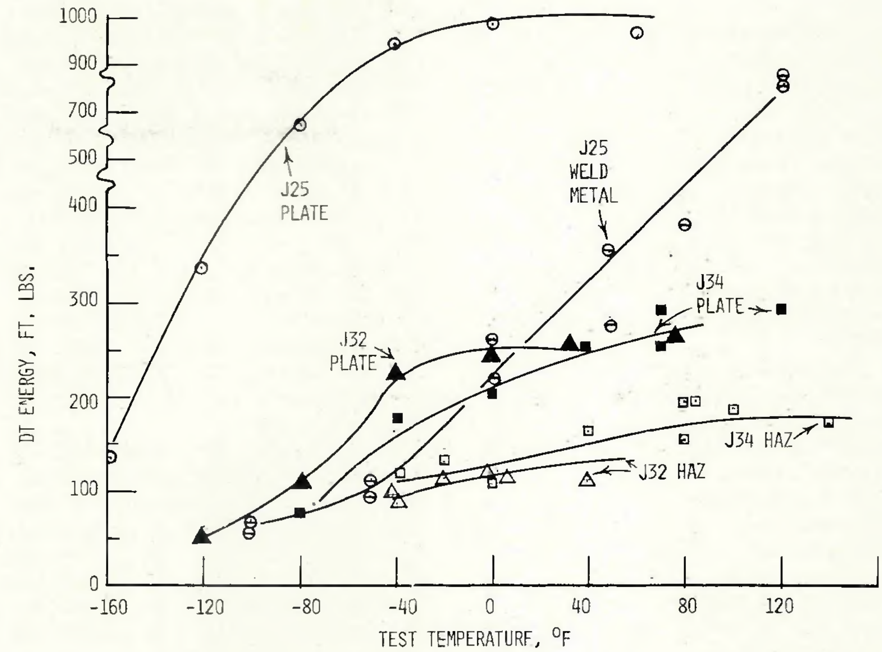

Fig. 11 — 5/8 in. DT energy relations, plate to HAZ in steels J25, J32 and J34 steels. No fractures occurred in J25 steel HAZ paths

Summary

Satisfactory fracture toughness of a weldment depends upon adequate fracture resistance in all three weldment components — base metal, weld metal and heat affected zone. Each is a potential fracture path.

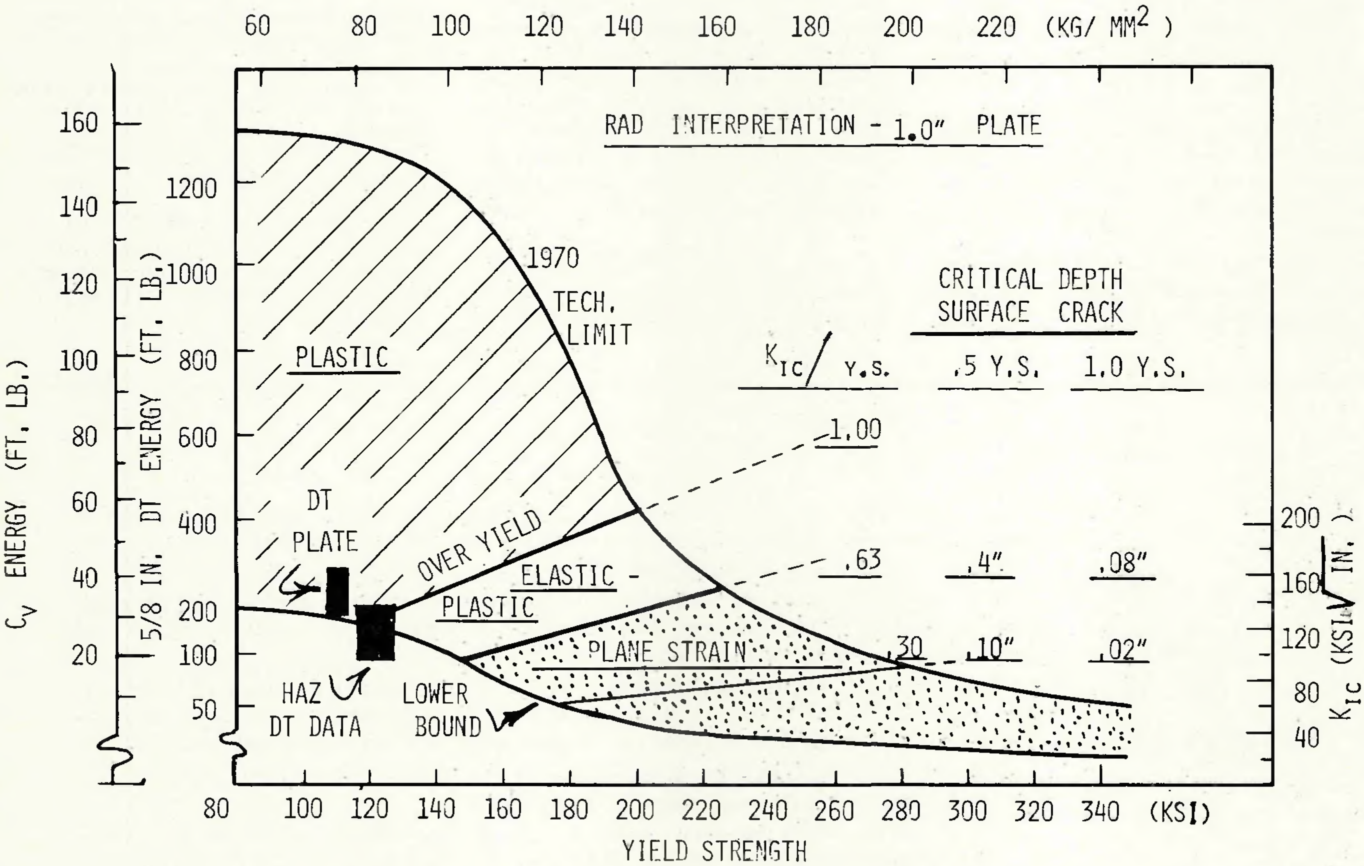

Fig. 12 — Ratio Analysis Diagram referencing of 5/8 in. DT data for steels and HAZ's. Critical depth of surface cracks of long thin nature are shown for failure at 0.5 and 1.0 yield-strength stress levels at plane strain conditions.

Quantitative procedures have been available to evaluate the toughness of the plate and weld metal separately, but the heat-affected zone has posed particular experimental problems. To meet the recognized need for a procedure to evaluate relative HAZ toughness, composite specimen test procedures such as the Explosion Bulge, the Drop Weight Bulge, and more recently, the Delta were designed. These allow fracture to find a preferential path whether in plate, weld or HAZ.

The evolution of the Fracture Analysis Diagram and Ratio Analysis Diagram pointed out the need for quantitative characterization of toughness not only in weld metal and plate but also in the HAZ. The Drop-Weight test which provides NDT temperature values for key reference in the FAD has been shown adaptable for application to the HAZ in this report. Similarly the Dynamic Tear test which provides data for reference in the Ratio Analysis Diagram has been shown adaptable for characterizing HAZ toughness in quantitative terms.

Steels obtained through commercial sources were examined in four weldability testing procedures: the DWB and Delta composite approaches, and the DW and DT techniques. Data from all tests document the possibility of preferred fracture paths in the HAZ in low-alloy steels and the absence of such paths in high-alloy steel when welded under identical conditions typical of commercial practice. However from metallurgical considerations it should be possible to optimize the properties of the HAZ of the low-alloy steels and to degrade the properties of the high-alloy steel by adjustment of the welding parameters.

From an interpretive standpoint, the occurrence of HAZ fractures in all test procedures has considerable practical significance. The extended HAZ failures in Delta and DWB tests indicate low level fracture resistance. The data from the Drop-Weight and Dynamic-Tear test showed HAZ fractures to be low energy failures. Since the zone is narrow it can entertain through-fracture only if the plastic zone size is small, that is, if the material has low toughness. Consequently, fractures confined to the HAZ can be only of the flat type due to conditions of or near plane strain type. Reference of the DT data on HAZ fractures to the RAD confirms the predictions of low fracture toughness.

Consequently, any HAZ fracture whether in a test specimen or a structure must be viewed as due to low toughness in that path. Ductile tough fractures with shear lips cannot be confined in the narrow width of the HAZ. Thus the DT test data show for the low-alloy steels that statistically they meet a yield criterion of failure, ($K_{Ic}/ys = 1$), in the plate but the possibility of not meeting it in the HAZ.

The importance of using practical test methods to characterize the toughness of the HAZ evolves from the fact that the information from them is necessary to define appropriate welding parameters for specific steels. The need for such definition in terms of heat input, preheat temperature, welding technique, etc. which can be used for optimized performance and to preclude the possibility of brittle fracture in the HAZ is self-evident. The data in this report constitute additional evidence that optimized weldment performance requires tighter control of welding parameters as steel hardenability is decreased or strength level is increased.

Acknowledgment

The author wishes to acknowledge the support of the U.S. Naval Research Laboratory in conduct of most of the laboratory work necessary for this report. He wishes also to acknowledge the considerable editorial assistance of William S. Pellini in preparation of the manuscript. Credit is due Mrs. Erna Tilton of Lafayette College for secretarial assistance.

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