SSC-221

RESPONSE OF THE DELTA TEST TO SPECIMEN VARIABLES

SHIP STRUCTURE COMMITTEE

1971

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Present testing procedures for advanced materials for ship construction are often expensive with testing restricted to relatively few laboratories. In an attempt to reduce these costs, the Ship Structure Committee entered into a cooperative effort with the Pressure Vessel Research Committee of the Welding Research Council to investigate a suggested Delta specimen. The results of this research are reported herein.

These results indicate the Delta test is responsive to changes in the variables selected, but independent research by U.S. Steel Corporation on the stress distribution, to be reported later by the Welding Research Council, indicates that a highly biased stress field exists in the test specimen, and this should be thoroughly considered before the Delta test is used for validation purposes.

W. F. REA, III
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

SSC-221

Final Report

on

Project SR-186, "Delta Test Validation"

to the

Ship Structure Committee

RESPONSE OF THE DELTA TEST TO SPECIMEN VARIABLES

by

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under

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ABSTRACT

The Delta specimen has been applied to two different heats of A517 grade steel in one inch plate thickness and to the one heat in 1/2 and 2 inch plate thickness. Various modifications of the basic specimen have been investigated, a non-standard geometry and a composite form of the specimen into which different steel types were incorporated. The influences of various welding procedures have been examined as well as the performance of all steels in the non-welded condition. The specimen was found applicable and appropriate for all conditions tested, showing sensitivity to all variables. At the same time the specimen showed a consistency in behavior which could be rationalized with commercial experience and data from corollary tests. The steels examined showed several transitional behaviors when tested as weldments, these transitions occurring in place of fracture, length of fracture, load carrying changes and overall ductility measured by deflection at failure.

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INTRODUCTION

Increasing replacement of use of as-rolled carbon steel plate materials by quenched and tempered steel plate in engineering construction has been accompanied by increased concern relative to the weldability of these steels, particularly in respect to the related problem of fracture. In the process of mastering the weldability and fracture problem in the carbon steels, recognition developed that the real concern was the plate metal since this was the least fracture resistant component of weldments of these steels. Appropriate welding procedures using the readily available tough filler metals could essentially remove the fracture problem from the immediate weld area since both the weld deposit and heat affected zone can be much tougher than the carbon steel plate. The assessment of weldment toughness then was a relatively simple matter of measurement of toughness of the least tough component, the plate metal. The problem became more complicated in the weldments of quenched and tempered higher strength steels. In these, fracture may be a concern in either weld metal, base plate or heat affected zone. As a result the increased use of the Q+T plate steels has been accompanied by need of appropriate measurement of the fracture toughness not only of the steel which can be very tough but of all the metallurgical and mechanical components which result from welding. Two approaches have been used to attempt overall evaluation of the quenched and tempered steel weldments. The first has been use of the Charpy V-notch test to attempt to evaluate toughness in the individual areas, weld metal, heat affected zone regions and base plate. There are fundamental difficulties with this small specimen approach which become more pronounced with increased section thickness because of variation in properties in all areas from one plate surface to another for example. The second approach has been to attempt evaluation by measuring performance by testing a weldment composite. The two most prominently used specimens have been the wide plate tensile test and the explosion bulge test. Both have shown considerable merit but despite these, they present several difficulties, a major one being the requirement of appropriate facilities for testing and a second being cost. As a result there has been continuing interest in a more acceptable simplified approach.

Ideally a weldment specimen appropriate for Q+T steels should not only be easy to prepare and test but also should be of design such that both specimen geometry and mechanical testing method allow fracture to seek the least resistant path whether that be in weld metal, plate or heat affected zone without built in bias. The Delta specimen, evolved from research supported by the Welding Research Council through the Pressure Vessel Research Committee, was proposed to meet these requirements. The need for such a specimen is best recognized by considering the difficulty of appropriate tensile testing of wide plate weldments. In these if the weld line runs parallel to the tension direction, the effects of the weld and heat affected zone are minimized since while they may participate in starting a fracture they constitute only a minor fraction of the total specimen through which fracture can travel. If on the other hand the weld line is transverse to the applied tension in the plate specimen, other objections arise, for example, that the effect of significant weld stresses in the weld direction is minimized and that fracture is prejudiced in a direction parallel to the weld line. In either event, the loads for testing are so high that only a very few laboratories can conduct such tests. These difficulties are minimized in preparing and testing the Delta specimen which can be made using actual field welding conditions in a specimen of size convenient for testing and representative of a field weldment with a representative crack starting flaw from which failure may travel in the least resistant path, plate, weld metal or heat affected zone.

THE DELTA TEST SPECIMEN AND PROCEDURE

The geometry of a welded Delta test specimen shown in Figure 1 is a 24 inch equilateral triangle formed by welding together three segments formed by flame cutting a triangle from the geometric center to the mid-length of each of the three sides. The three segments so formed are then rejoined using the desired weld joint configuration and procedure. For the purposes of all work to be reported here, except as noted, the joint configuration and weld pass sequence used conformed to those shown in Figure 2a.

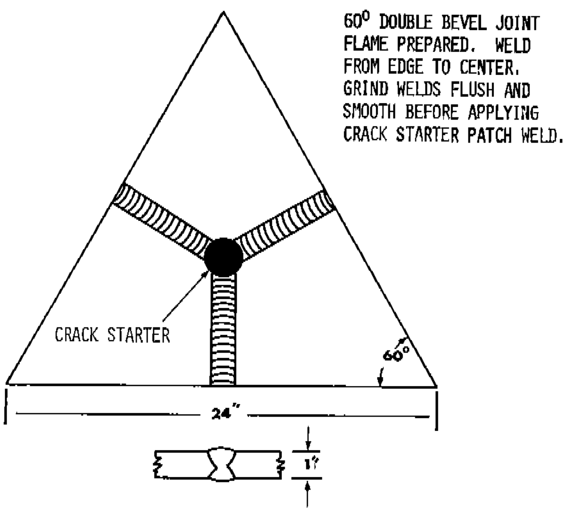
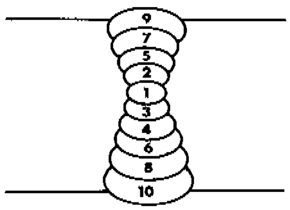
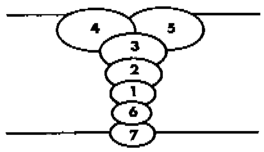


Fig. 1 - Delta Specimen, General Details



WELD PASS	DIA. ROD	TYPICAL HEAT INPUT JOULES/IN.
1,3	5/32"	35,000
2,4	3/16"	38,000
5,6	3/16"	48,000
7,8	1/4"	72,000
9,10	1/4"	85,000 MAX.

(A) STANDARD 5 PASS PER SIDE PROCEDURE, ONE-INCH PLATE



1,2	5/32	35,000 MAX.
3,4,5,7	3/16	57,500 MAX.
6	5/32	47,000 MAX.

(B) WELDING SEQUENCE, 1/2" PLATE

Fig. 2 - Standard Welding Procedure, 1" and 1/2" Plate

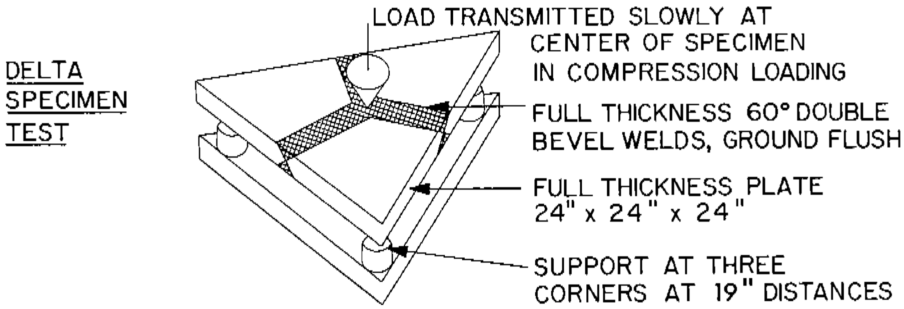


Fig. 3 - Testing the Delta Specimen, Schematic

These are designated "standard". Testing of the Delta specimen is accomplished as illustrated in Figure 3. The specimen is supported at the corners as a flat triangular plate on cylindrical column supports with hemispherically rounded contact points. The support points form a 19 inch equilateral triangle. Compressive load is applied to the specimen at the geometric center to cause a dishing deformation, using a cylindrical tup with end ground flat to present a one inch flat in contact with specimen surface. The crack starter weld applied as a patch on the surface only, prior to testing, is placed on the side of the plate welded last. That side is put on the down or tension side in testing. Specimens are tested to failure after being brought to desired test temperature, generally in an alcohol or other low temperature liquid bath cooled by dry ice. During the test a load vs. center point deflection curve is recorded. A head speed of 1½ inches per minute has been used in all tests reported here. Failure is judged to occur at the onset of a loss of the maximum load generally accompanied by visible tearing failure or sudden audible and visible failure. Other data available from the test are energy absorbed by the specimen, path of failure, length of fracture and mode of fracture. For all tests a mechanical machine of 180,000 lbs. capacity was used except for testing the two inch thick plate specimens.

SCOPE OF THE RESEARCH PROGRAM

Research for this report was performed under two successive contracts. The intent of the study in the first contract was (1) to investigate reproducibility of the specimen, (2) to determine influence of a modified crack starter weld bead, (3) to determine reproducibility of results when welding was performed by different operators at different laboratories, (4) to determine applicability of the procedure to other plate thicknesses, one-half inch and two-inch, and (5) to determine response of the test when specimens were of composite nature made of segments of different types of steel.

The second research contract covered (1) investigation of the effects of a second steel composition, (2) effect of change in welder, (3) effect of change in manual welding procedure, (4) effect of change in welding process and (5) effect of specimen geometry. In addition to the research on welded Delta specimens, all materials were tested in the prime plate condition. Table 1 following lists the separate variables investigated using the Delta specimen according to subject under study.

For purposes of correlation with the Delta test results, the researches included Charpy-V notch tests of all weld metals, all plate metals and Charpy V notch tests with notch in the weld heat affected zone of A517-F steel in 1/2, 1 and 2 inch plate welded Delta specimens. All Charpy tests were made over temperature ranges. Metallographic specimens from representative specimens were included in the study. Hardness determinations were also made on various specimens. All Delta specimens were photographed after testing.

SOME DETAILS ON DELTA SPECIMEN PREPARATION

A. ONE INCH THICK PLATE SPECIMENS

The Delta specimen can be prepared in many of various ways depending on the variables intended for study. The procedure used here and termed "standard" consisted of flame cutting the triangles into three sections later to

Table I - Delta Test Series - Part I

	Subject Under Study	Steel, Thickness	No. of Specimens	Variation from Standard Procedure	References Tables	References Figs.
1.	Reproducibility	A517-F, 1"	18	None	A-2	5,6,7,8
2.	Varied crack starter patch weld	A517-F, 1"	6	Crack starter weld in ring shape, 2"D	A-3	5,6,7,8
3.	Reproducibility	A517-F, 1"	6	Specimens welded by commercial research laboratory	A-5	10,11
4.	Reproducibility	A517-F, 1"	6	Specimens welded by shipyard	A-4	9,11
5.	Applicability to ½ inch plate	A517-F, ½"	12	½" plate and appropriate welding procedure	A-6,7	12,13,14
6.	Applicability to 2" plate	A517-F, 2"	6	2" plate and appropriate welding procedure	A-8,9	15,16,17
7.	Composite specimens, two steels	A517-F with A515-B, 1"	6	Welded with E7018 electrode	A-11	18,19,20
8.	Composite specimens, two steels	A517-F with A537-A 1"	6	Welded with E7018 electrode	A-12	18,19,20
9.	Composite specimens two steels	A537-A with A515-B, 1"	6	Welded with E7018 electrode	A-11	18,19,20
10.	Prime Plate	A517-F, 1"	6	None (not welded)	A-1	5,8
11.	Prime plate	A517-F, ½"	6	None (not welded)	A-6	12,14
12.	Prime plate	A517-F, 2"	6	None (not welded)	A-8	15,17
13.	Prime plate	A515-B, 1"	6	None (not welded)	A-10	18,20
14.	Prime plate	A537-A, 1"	6	None (not welded)	A-10	20,21
			DELTA TEST SERIES - PART II			
15.	Effect of steel composition	A517-E, 1"	6	None	A-14	25,26
16.	Effect of welder	A517-E, 1"	6 and 6	Regular welder & new welder	A-14	26,27
17.	Welding procedure	A517-E, 1"	6	Welded in steel mill lab, their manual procedure	A-14	26,27
18.	Welding process	A517-E, 1"	6	Submerged arc welded	A-14	26,27
19.	Specimen geometry	A517-F, 1"	6	Welds from plate center to apices of triangle	A-13	22,23,24
20.	Composite specimens	A517-F, A537-A	6	Three different steels-all welded in one specimen	A-15	28

be rejoined by welding. The sections were then provided with double 60°V-joints by flame cutting merely because this was convenient for manual welding procedure. Welding was performed in the flat position after the three sections were tacked together. It was found best to begin welding by deposit of a root pass in the starting side of each of the three weld joints using 5/32 inch electrode, this followed by a second pass with 3/16 inch electrode after which arc-air cleaning and disk grinding from the opposite side were practical. Following this, root passes could be placed in the cleaned root, followed by alternate side welding to complete the joints. Any pass sequence was completed in all three joints on one side of the plate before proceeding to the opposite side of the specimen. All welding proceeded from specimen edge to center. At any time, six specimens were in process, allowing plate temperature to be 125°F or below at onset of welding. During welding no weaving was used although some latitude on manipulation of electrode was necessary for satisfactory slag control and penetration. All joints were completed using 1/4 inch electrode and an intentional build up of reinforcement to a maximum of about 1/8 inch. This build up was removed by machining on a shaper followed by some hand grinding. Following removal of build up or reinforcement, the specimens were ready for application of the Hardex-N hard overlay patch weld at the central weld junction. A two-inch diameter circle was outlined by punch marks to guide the welder in controlling the size of this patch. The welding proceeded around the circumference of the circle lay-out and continued in circles of decreasing diameter, spiral style, until the patch was completed. All welding data, arc voltage, amperage and arc travel speed were measured and recorded. Details are shown in Fig. 2, Appendix.

B. ONE-HALF INCH THICKNESS SPECIMENS, A517-F STEEL

Because this was the first effort at testing Delta specimens from 1/2 inch thick plate it was found desirable to use a relatively large number of specimens for determination of overall characteristics. These were welded manually according to the plate manufacturer's recommendations using a single 60°-V joint as shown in Figure 2. In other respects the procedure conformed to that used for the one inch plate except that maximum head input level was limited to 57,000 JPI.

C. TWO INCH THICK PLATE SPECIMENS, A517-F STEEL

These were welded manually using a double 60°V made it necessary to use a three inch diameter hard surface crack starter patch to be certain the patch would lie on plate metal as well as weld metal.

D. COMPOSITE SPECIMENS OF DIFFERENT STEELS, ONE INCH THICK

These specimens were formed by the usual procedure except that in each specimen two segments were of one steel while the third was of another, for example two segments of A537-A steel, one of A515-70 steel. E7018 filler metal was used for welding all composites primarily because it is a matching strength electrode for both A537 and A515 steels and produces a quite tough deposit appropriate for the purposes here.

THE DELTA TEST AND TYPES OF DATA

In attempting to measure brittleness or fracture characteristics it is important to recognize that brittleness or lack of it can be manifested in various ways and in various measurements. Consequently various types of data were taken from each Delta test to afford as much data as possible for comparison and analysis of the variables being studied. They include:

1. load values at yielding, failure or maximum load
2. strain values at yielding, failure or maximum load, expressed as deflection
3. path of fracture (plate, weld, HAZ or mixed)
4. length of fracture
5. drop in load at fracture

Although the first three types of data have been the types usually used as indices of performance, the latter two dealing with performance after the event of failure has initiated can be helpful in fuller description of behavior. For example, if in two specimens to be compared failures occur at the same loads and deflections, one specimen shattering at failure and the other experiencing a short tear, it is obvious that the two behaviors are different and the short tearing failure is to be preferred. Similarly the gradual falling in load, characteristic of slow tearing failures, is to be preferred over the sudden drop accompanying the formation of sudden fractures. As the data will demonstrate long fractures were accompanied by large drops in carried load and were necessarily sudden. Short failures on the other hand were generally manifested by the appearance of slow visible tearing at the onset of slow loss of maximum load.

It has been found from Delta testing of ten different heats of steels of the types considered in this report that there is some similar behavior among them in the welded condition. Brief consideration will be helpful here.

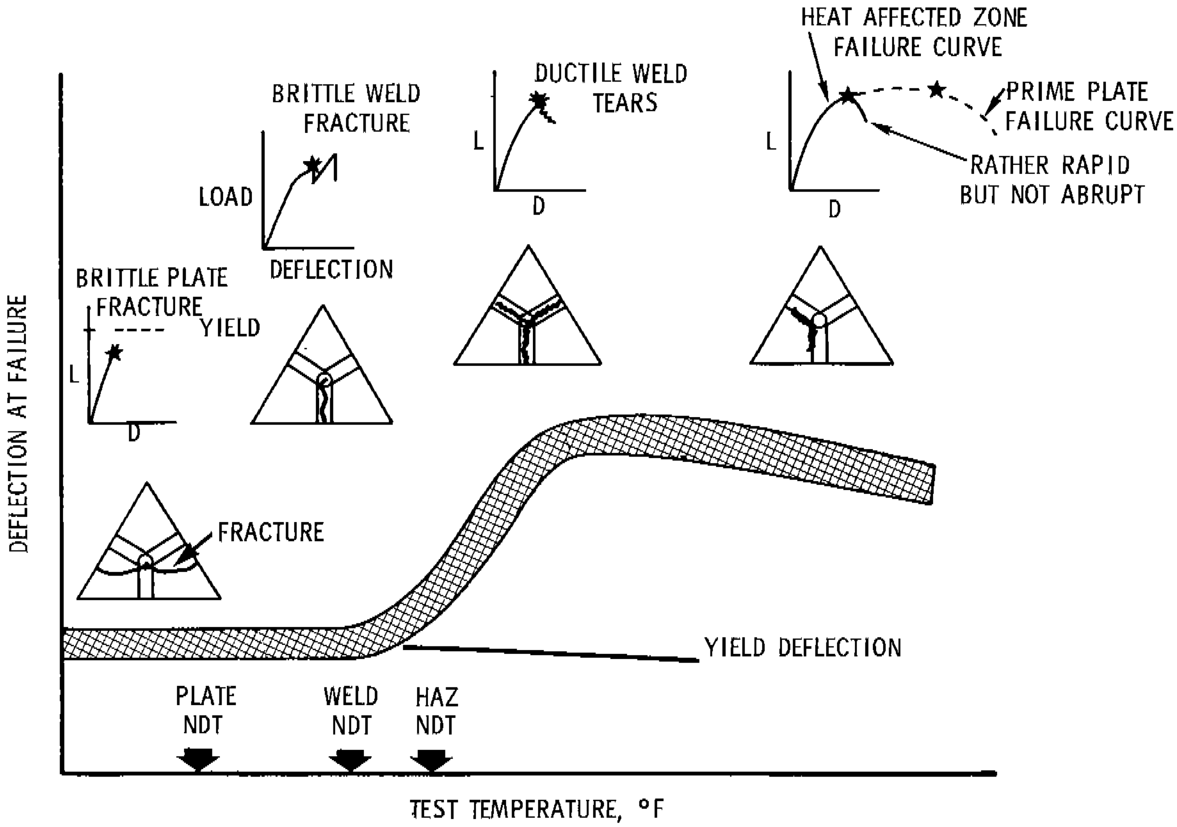


Fig. 4 - Generalized Load-Deflection Diagram

Figure 4 shows that several types of transitional behavior occurred as test temperature was raised from below plate metal NDT to temperatures at and above the room temperature range. The transitions were associated. First, there were transitions in location of fracture. Brittle plate fractures occurred only in tests near or below NDT of the plate. These began in the crack starter but ran only in the plate, ultimately as much as three inches away from the weld. Fractures at temperatures just above NDT generally were brittle but restricted to the weld metal. Increasing test temperatures resulted in tougher weld metal, shorter weld metal fractures and increased deflection at failure. With higher test temperatures a pronounced rise in deflection at failure occurred due to toughened weld metal. In this region a transition from weld path tearing failure to failure alongside the weld took place. These transitions were accompanied by changes in the load-deflection patterns and extent of fracture. Figure 4 then illustrates transitions in (1) deflection at failure, (2) path of failure, (3) length of fracture and (4) load to cause fracture. Further as the load-deflection diagrams at the top of Figure 4 show, fracture occurred without any general yielding at sufficiently low temperatures. Further, at temperatures on the upper shelf, forcing fractures to extend after they began produced significant load-deflection patterns, especially when fractures ran in the heat affected zone region. These ran at rapidly falling loads but not with the speed associated with cleavage fracturing in carbon steels. That is, the energy required to extend fractures by tearing in the heat affected zone was significantly low.

DISCUSSION OF RESEARCH DATA - PART I

(a) General, Delta Tests

Data taken in the Delta testing are presented in tabular form in the Appendix. For each specimen tested, the test temperature, load at specimen yield, fracture load, specimen deflection at failure, length of failure outside the crack starter patch, location of fracture and load loss at fracture are recorded. Where meaningful or necessary for comparison purposes these data are plotted in the report.

The data on "load loss at fracture" are helpful in indicating the type of fracture noted. In general, sudden fractures tended to be long and accompanied by appreciable drop in the load sustained by the specimen. Tearing failures, which are necessarily gradual, on the other hand occurred at or near upper shelf temperatures and were accompanied by only slight or negligible loss in load. Thus little if any distinction should be drawn between load losses recorded as zero versus losses of two or three thousand pounds, these orders of drop being very difficult to measure. The data will show that both load loss at fracture and fracture lengths showed temperature transitional character.

In respect to determining the occurrence of failure, in almost all cases, the deflection at failure was judged or detected without difficulty. However, there were instances when a crack, particularly a weld metal crack began with audibility but without visibility or indication on the load recorder. These were not interpreted as constituting failure since they were obviously limited to the area beneath the crack starter patch weld. Furthermore the occurrence of these was almost always followed by major failure upon continued but very little additional deformation. Hence some discretion was required in evaluating those particular performances. Of one-hundred fifty specimens tested for this report, only nine specimens were in this category.

The tables in the appendix record place and length of failures. There may be some question as to the recording of some long failures as occurring in both weld and plate. This type failure, particularly at low temperature, was common, with both failures occurring to all appearances simultaneously, no indication of separate fractures detectable either by sound, appearance or load change. If indeed these were separate occurrences, they took

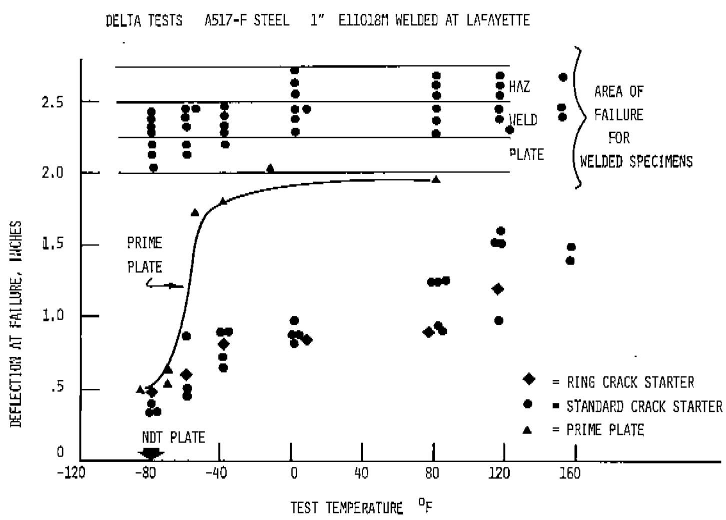


Fig 5 - Load-Deflection vs. Temp., Failure Path for 1" A517-F Specimens, Standard Procedure

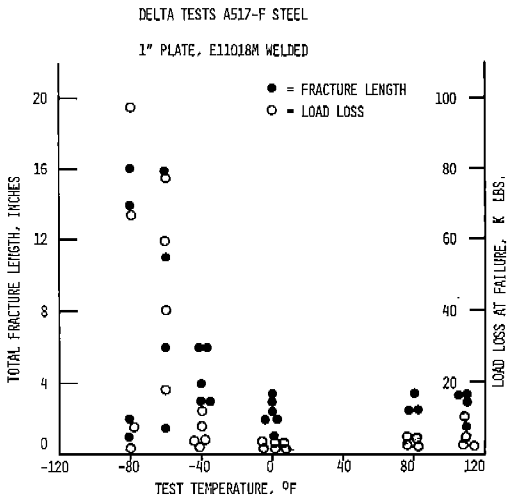


Fig. 6 - Fracture Length, Load Loss A517-F Steel, 1" Plate, E11018-M Welded, Standard Procedure

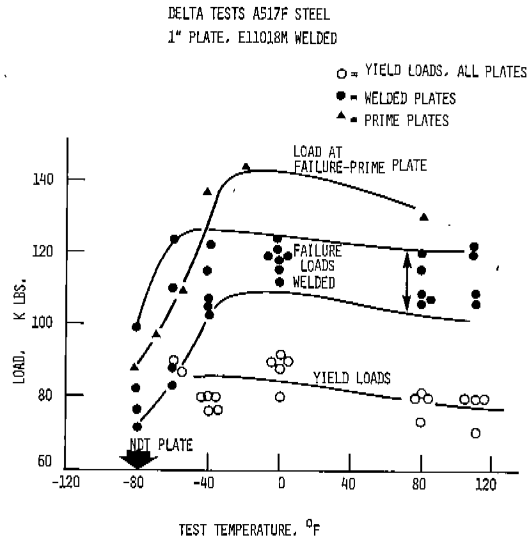


Fig. 7 - Load at Failure vs. Temp., 1" A517-F Delta Specimens, Standard Procedure Welds

place almost simultaneously without any opportunity to judge the order. Respecting the place or path of failure, comment needs to be made concerning only the designation of a fracture as located in the heat affected zone (HAZ). All fractures were classified by location according to surface appearance on the tested specimen. Fractures identified as plate or weld metal in character always lie clearly in those areas throughout the entirety of the fracture and through the entire plate thickness. Cracks designated as occurring in the heat affected zone do not always necessarily follow the heat affected zone through the plate thickness. They may, because of the geometry of the heat affected zone, veer from it at some distance below the starting surface and enter the plate in a straight through direction.

(b) Triplicate Specimen Tests of One Inch A517-F Steel Plate

The outcome of these tests is presented graphically in Figures 5, 6 and 7. Several features from Figure 5 should be noted. First, respecting deflection at failure, the data indicate substantial difference between the prime plate and welded plates typical of this type steel. The data for welded specimens in the upper portion of Figure 5 represent the locations of failures and show a shift in fracture path in moving from the lowest to highest test temperatures, the pattern generally following that of Figure 4. These shifts are illustrated photographically in the Appendix as Illustration 1. Plate metal fractures occurred at -60° and -80°F whereas weld metal fracture predominated at -40°F. At 0°F and above heat affected zone fractures occurred sometimes mixed with weld metal failure. The data in Figure 5 show a behavior not noted in previous Delta tests of steels of this type and that is a possible second pronounced ductility transition at about 80°F in addition to that at about -60°F. Respecting reproducibility, it appears that all test temperatures except that of 0°F fortuitiously fell in the transition zones where scatter is normally expected. In that light especially it can be concluded that the reproducibility was quite satisfactory. Clearly the data at 0°F, not in a transition region, show essentially no scatter.

Although the data at the top of Figure 5 are helpful in explaining some of the performance of the Delta specimens, further illumination is possible from Figure 6 relating lengths of fractures and load loss to test temperatures. That data plot confirms the sharp transition at -60°F in Figure 5 and again relates that transition to the length of fracture and load loss. Since all the fractures at 80° and 120°F were of the ductile tearing type, there is no transition indicated on the basis of fracture length at failure. Figure 8 showing the Charpy-V characteristics of weld metal, plate metal and heat affected zone indicates a rather close match in Charpy-V toughness of all three areas at lower test temperatures even though the usual scatter in data from weld metal and heat affected zones is present. The plate metal toughness in the Charpy test appears to be significantly higher than that in weld or HAZ at test temperatures -40°F and higher. Further analysis of the Delta specimen data is given in Figure 7 which shows change in load carrying characteristics with change in test temperature. A notable point made in Figure 7 is that yielding failed to occur in specimens tested below -60°F again confirming the transitions noted at that temperature region in Figures 5 and 6.

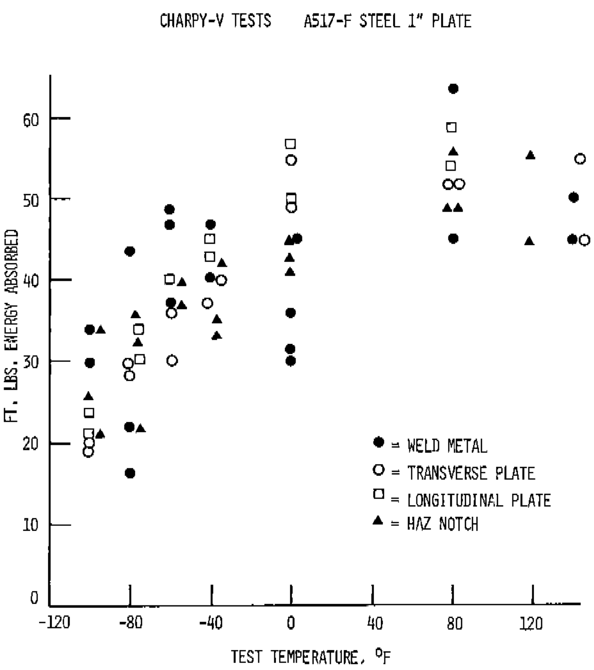


Fig. 8 - Charpy-V Data, Weld Metal, Plate Metal, and HAZ Locations, A517-F 1" Plate

The close match of weld metal toughness and plate toughness at the temperatures near the plate NDT present an interesting situation. As a result of this close match the transfer of failure from plate to weld with rising test temperature has not been as distinct as in previously reported tests of some ten other heats where the match was not as close. The difference here is in the prominence of weld metal fracturing along with the plate near NDT and below. However, considering the Charpy data of Fig. 8 the Delta data are reassuring and indicate mixed fracture paths should not be unexpected at the lowest test temperatures where both weld metal and plate metal show low Charpy toughness.

This series of tests showed several temperature dependent transitions occurred in performance of welded Delta specimens, in path of failure, in deflection at failure and in load-carrying capacity. The data confirm previous findings that although brittle plate failure is not normally to be expected above plate NDT, low deflection at failure is possible at test temperatures above plate NDT if the weld metal can sustain brittle fracture. The tests demonstrated that the length of fracture can be used to assess specimen behavior and that length of fracture correlates very well with load loss sustained at failure.

(c) Effect of Modified Crack Starter Weld Patch

This investigation related to modification of the standard crack starter patch weld described as being deposited in the form of a circular surface stringer bead of Hardex-N around the circumference of a two inch circle at the center plate position of the Delta specimen instead of the standard filled circle technique. The Delta test data are represented in Figures 5, 6 and 7 and show no deviation in behavior from that of standard specimens. Observations of fractured specimens indicated the technique to be as effective in crack starting as the standard patch. In general the results of these tests were indistinguishable from those of conventionally prepared specimens.

(d) Specimens Welded by Other Organizations

Six specimens welded in a shipyard but tested at Lafayette College performed as illustrated in Figure 9. The data points reproduce reasonably well those obtained from tests of the specimens prepared at Lafayette. The specimens prepared in the shipyard were welded in accordance with the procedure used at Lafayette. However, in preparation of the specimen that was later tested at -80°F some difficulty was encountered with weld metal cracking. This specimen was repair welded with preheat of 200°F after initial welding with the 125°F maximum interpass temperature resulted in weld metal cracks. That particular specimen was the only one of this steel which did not fail in the plate metal when tested at a temperature below the NDT. It is possible that the factor which accounted for the weld cracking in fabrication was also responsible for the weld metal failure encountered in the Delta testing. Some confirmation of this may be seen in Figure 11 showing somewhat lowered weld metal toughness at -100°F though a detailed explanation would be difficult.

Six Delta specimens welded in a commercial research laboratory were tested at the temperatures used for specimens tested at Lafayette. The deflection to failure data are presented in Figure 10 and show two points lying appreciably above the data curve which represents the 30 specimens tested previously (24 welded at Lafayette, 6 in a shipyard). The deviation was probably due to weld metal characteristics in these specimens. Considerable difficulty due to weld metal cracking was experienced by the commercial research laboratory welders in adhering to the standard welding procedure calling for 125°F maximum interpass temperatures. Accordingly a 125°F preheat and 250°F interpass temperature procedure was developed which along with standard heat inputs allowed crack free welding. The Charpy tests of both the commercial laboratory and the shipyard weld metals concentrated in the lower temperature ranges showed little difference (the shipyard data at -100°F excepted) from the Lafayette weld metals. However, the yield loads for the Delta specimens prepared in the commercial research laboratory (Appendix Table 5) do show some difference from those plotted in Figure 7 and may be associated with effects on the weldments occasioned by use of increased interpass temperatures in welding or other unknown factors.

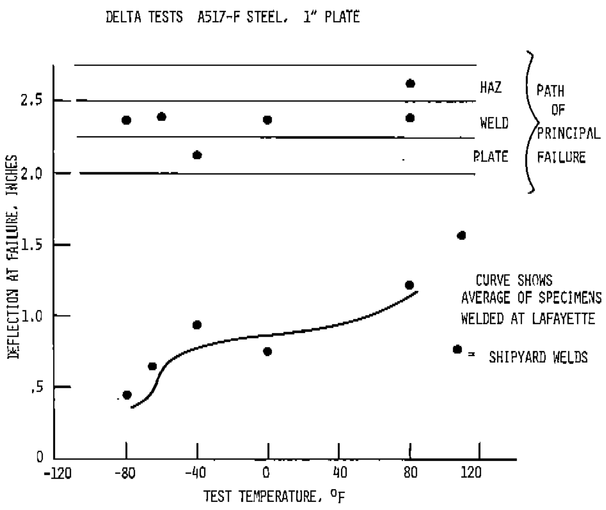


Fig. 9 - Deflection at Failure vs. Temperature, 1" A517-F Plate, Shipyard Welds

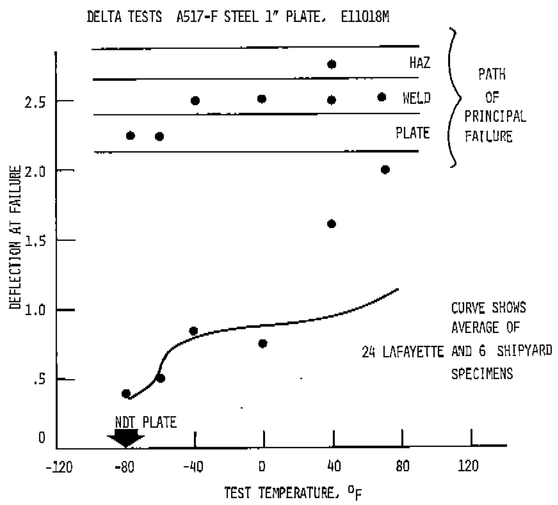


Fig. 10 - Deflection at Failure vs. Temperature, 1" A517-F Plate, Commercial Laboratory Welds

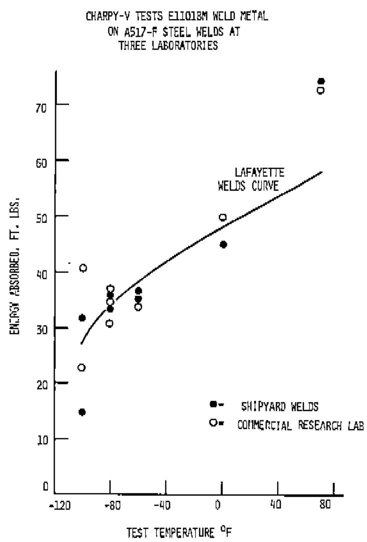


Fig. 11 - Charpy Data, Weld Metals, Three Laboratories

The principle observation to be made from these tests is that specimens prepared by different welders in different laboratories behaved essentially identically when welding procedures used were identical. The instances where dissimilar behaviors occurred were those in which modified welding procedures and/or repair were necessary for successful weld fabrication. It is not known whether the modified weld procedures were needed because of in-lot variation in welding electrode or steel or other possible unknown variables. Emphasis can be placed however, on the fact that identically prepared specimens performed essentially identically.

(e) One-half Inch Plate Tests, A517-F Steel

The pattern of performance in the one-half inch plates, welded and prime plate, departed somewhat from that of one inch plates and two inch plate and that of the generalized pattern of Figure 4. The reason for this as will be shown is the relatively low toughness of plate metal compared to that of weld metal. In Figure 12 prime plates show a transition temperature at about -80°F. This temperature is an estimated NDT, FTE minus 40°F, and close to a -90°F NDT determined in a modified NDT dropweight procedure using one half inch plate (a 90 mil stop distance), there being no accepted standard NDT procedure for one-half inch plate. The welded specimens in Figure 12 show a transition at about -60°F based on deflection at failure accompanied by a transition in path from plate essentially to HAZ. The transitions at -60°F in welded plate shown in Figure 12 were accompanied by transition in load at failure shown in Figure 13. The interesting feature of these tests is that the transitions were associated essentially with a plate metal to HAZ fracture transfer with rising test temperature, the weld metal being little involved. That this should be is demonstrated in Figure 14 which shows that weld metal in these specimens was considerably tougher than the plate metal. The heat affected zone in the Charpy tests as conducted showed intermediate toughness. Illustration 2 (Appendix) and Appendix Table 7 both illustrate that at all temperatures only relatively short fractures occurred and that weld metal involvement was minor whenever it was involved in fracture. Table A-7 shows further that fractures in welded specimens were always relatively short but that those at -60°F occurred without prior yielding and with detectable drop in load. These were sudden, therefore fast running cracks of NDT character. It can be reasoned that the failures at -60°F and below though brittle were of relatively short length because the thin one-half inch specimen can store relatively little energy for release upon fracture initiation.

In attempting to correlate the Delta test performance of the welded one-half inch plate with the Charpy-V data, some interesting points arose. First the Charpy data in Figure 14 clearly show that the plate metal was markedly

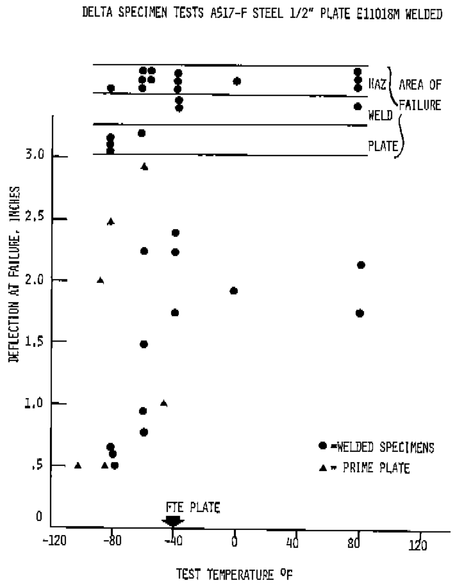


Fig. 12 - Delta Specimens, Deflection at Failure vs. Temperature, 1/2" A517-F

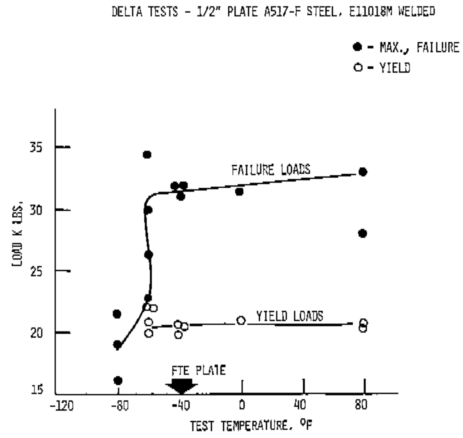


Fig. 13 - Loads at Failure vs. Temperature, 1/2" A517-F Delta Specimens

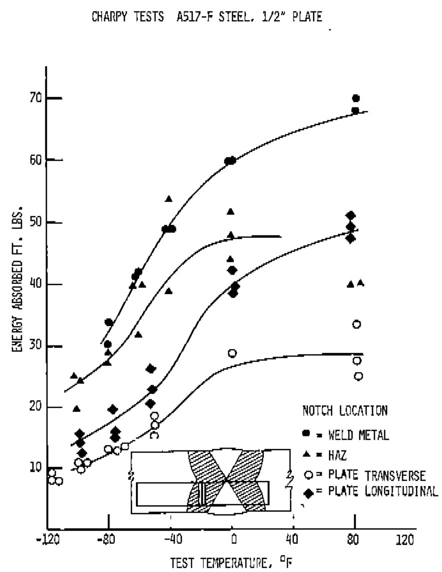


Fig. 14 - Charpy Tests, A517-F, 1/2" Plate, Three Notch Locations

less tough than the weld metal and second that the toughness of the one-half inch plate was markedly lower than that of the one inch A517-F plate in Figure 8 though both came from the same heat. Consultation with two manufacturers of this type steel indicated that this situation is not uncommon in this type steel. No reason is known for this lower toughness in one-half inch plate. The toughness of the weld metal in the one-half inch weldments was essentially the same as that in the one-inch weldments shown in Figure 8. Thus the finding that the weld metal was involved in only a minor way with fracture in the one-half inch specimens as shown in Table A-7 and Figure 12 is quite consistent with the experience that the fracture path in Delta tests follows the path of least resistance. However, the question arises then as to why a predominance of heat affected zone failures should have occurred since Figure 14 indicates it to be tougher than the plate metal. There are several reasons. First as indicated earlier, path of fractures is reported from surface appearance at the time of the test. Second, metallographic cross-sections of one-half inch welded plate fractures indicated that fractures designated HAZ in general initiated at the HAZ fusion line region of the last pass weld, a region not subjected to later pass tempering and thus quite brittle. As Illustration 3 (Appendix) shows these fractures were found sometimes to move to plate metal at subsurface locations or to stay in the fusion line area, sometimes on the weld metal side. What becomes clearly pertinent then is that the attempts to measure Charpy-V toughness of the HAZ and the resulting data on that toughness are useful for the purposes here in that the procedure showed the composite heat affected zone toughness higher than that of the plate. The Delta test fractures clearly avoided the tough composite path where Charpy toughness was measured sometimes to stay in the brittle fusion line area. Toughness of that area is prevented from measurement in the Charpy test due to the geometric limitation involved in trying to place a notch in that line in the joint geometry used and in half inch plate. The brittleness of the fusion line when untempered has been demonstrated many times in many laboratories.

To summarize briefly here, fracture in Delta tests on one-half inch plate were consistent with experience and Charpy toughness data. Brittle plate fractures predominated at and below NDT temperatures. Above NDT the weld metal was involved in fracture in only a minor way, due to superior toughness. Fracture preference above NDT was found to be initiation at plate surface in the fusion line-HAZ region with transfer to the low toughness plate occasionally. No fractures were found to be predominantly in that region of the HAZ shown tougher in Charpy tests than the plate material. The superiority of toughness in the HAZ as measured here to the toughness of the one-half inch plate was consistent with general knowledge and experience. The tests showed the Delta procedure discriminated between welded and unwelded plate, produced transitional type behavior in welded specimens and resulted in fracture patterns and paths consistent with measured and known toughness data of individual components of the weldments.

(f) Two-Inch Plate, A517-F Steel

The two inch plate specimens were welded at Lafayette College. No difficulty was experienced in welding these specimens. Due to the width of the completed weld throat it was necessary to use a three inch diameter crack starter on plate, weld metal and heat affected zone. The specimens were tested at Naval Research Laboratory by the author because of the availability there of the necessary capacity testing machine. Load deflection curves were recorded. The loads were obtained from strain gages placed on the loading tup. The same general behaviors shown by the one inch plate were observed in the two inch plate. Data are presented in Figures 15 and 16.

Figure 15 illustrates the behavior of welded plates measured by deflection at failure was not radically different from that of the unwelded plate, both showing a sharp transition temperature at about -40^{O}F. Figure 16 shows the ductility transition was accompanied by a sharp change in fracture lengths and load at fracture. These were accompanied by a transition in path of failure changing from plate to weld to heat affected zone with rising temperature as exhibited by welded one inch plate. This is shown in Appendix Illustration 4. Figure 16 demonstrates that below yield, low-load failure occurred in the two-inch specimen at the test temperature -100^{O}F, clearly below NDT. Figure 17 portrays the Charpy data for notch positions in the weld metal, heat affected zone and base plate. The similarity in toughness in all three zones accounts in large measure for the rather small difference in deflection at failure between the welded and unwelded plates in Fig. 15.

This series of tests demonstrated the Delta specimen response of two inch plate followed the generalized patterns found for one inch plate shown in Figure 4. Brittle plate fractures were found to occur only near and below plate NDT. Fracture at shelf temperatures involved the HAZ.

(g) Composite Specimens, One Inch Plate Steels

The purpose of this part of the investigation was to determine the response of the Delta specimen when it was formed by joining segments of significantly different types of steels. Three steels were used, A515-70 (as-rolled carbon plate), A537-A (C-Mn plate normalized and tempered) and the A517-F used for the bulk of the project. They represent three different strength levels, 45K psi, 75K psi and 100K psi yield strengths respectively with accordingly different compositions and properties as given in Table 2. The steels were paired off against each other in three different groups of six Delta specimens each. Thus in one set of six specimens, each specimen was made by welding one segment of A537-A steel to two segments of A515-70 steel. The second set was composed of A537-A and A517-F steels and the third set of A537-A and A515-70 segments. The welding was performed with E7018 electrode since this was appropriate for the lowest strength plate metal present in all cases. The standard welding procedure was followed. In order to establish a baseline for comparative purposes, all three steels were tested separately in the prime plate condition as Delta specimens.

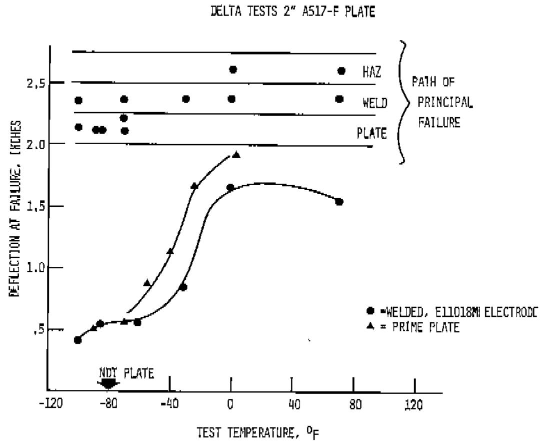


Fig. 15 - Delta Test Data, 2" Plate, A517-F, Deflection at Failure, Fracture Location

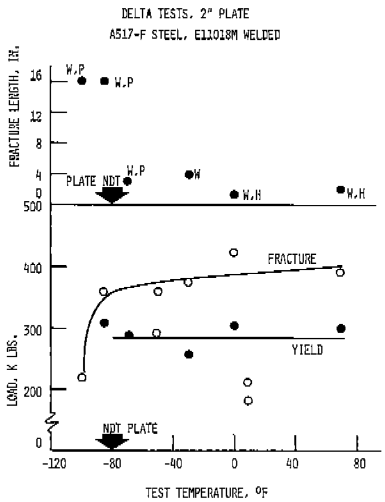


Fig. 16 - Delta Test Data, 2" Plate, A517-F, Fracture Length and Location, Loads at Fracture vs. Temperature

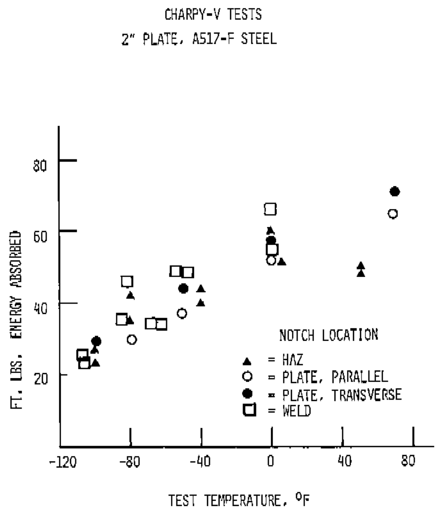


Fig. 17 - Charpy Data, 2" Plate, A517-F, Various Notch Locations

The results are portrayed in Figures 18 and 19. Figure 18 demonstrates that the performance of the composite specimens treated there was dictated by the least fracture resistant material in the composite, in this case the A515-70 plate which is less tough than either of the steels A537-A or A517-F or the weld metal deposit of E7018 electrode. All fractures in these composite specimens took place in the A515-70 plate, none in the heat affected zone or weld metal. This behavior confirms previous experience with welded A212-B (now A515) Delta specimens which showed no weld metal or heat affected zone failures. Figure 20 shows the toughness of the E7018 weld deposits and of the A515 plate as compared to that of A537-A steel (Figure 21) and A517-F steel, the A515 plate being far inferior to all other elements in the composite Delta specimens.

Table II - Chemical Composition and Mechanical Properties

A. A517-F Steel, Three Thicknesses

Chemical Analysis, % for 1/2, 1 and 2 Inch Plate

C -	.17
Mn	.89
P	.015
S	.015
Si	.19
Ni	.84
Cr	.52
Mo	.42
V	.04
B	.003

Tensile and Mechanical Tests

	1/2"	1"	2"
Yield, .2%		115,000	109,500L 109,300T
Tensile psi		126,000	122,300L 120,400T
Elongation %		18.5	18.8L 19.0T
RA %		60.0	62.0L 61.0T
NDT	FTE (-40)	$-80^{\circ}F$	$-80^{\circ}F$

B. A515-Gr.70 Flange, 1"

Chemical Analysis

C -	.28%
Mn	.73
P	.011
S	.017
Si	.24

Tensile Tests

Yield	46,500
Tensile	80,200
Elongation	23.0%
Bends	OK

C. A537-A, 1"

Chemical Analysis

C -	.20
Mn	1.33
P	.012
S	.020
CU	.29
Si	.25
Ni	.18
Cu	.11
Mo	.05
Al	.024

Tensile and Mechanical Tests

Yield	59,200
Tensile	84,200
% El, 8"	26%
Bends	OK
NDT	$-60^{\circ}F$

CVN, ft.lbs.	$-75^{\circ}F$	$-60^{\circ}F$	0°	RT°
Trans.	39	50	82	85
Long.	28	29	54	61

Figure 19 illustrates the point of Figure 18 further showing a sharp transition near the $-60^{\circ}F$ NDT of the A537-A plate which is higher than that for the A517-F plate and approximately the same estimated as that for E7018 weld metal ($-50^{\circ}F$). The very similar toughness of the A537-A plate, A517-F plate and E7018 weld metal in the temperature region around $-60^{\circ}F$ is largely accountable for the scatter shown in Figure 19. In addition this is in the transition temperature range for all the three materials. The experience here confirms previous findings from Delta tests of welded A537-B steel (similar to A537-A except that it is Q+T). That steel showed no heat affected zone fractures or weld metal failures with the result that welded performance was essentially identical to non-welded when tough E8016C1 weld metal was used.

The salient observation to be made from these series of tests is that when the Delta specimen was of composite nature more complicated than the case in which only one steel is used, the path of fracture was that of the least resistant material. Further the performance of such specimens was essentially identical to that of specimens containing only the least fracture resistant steel.

DISCUSSION OF RESEARCH DATA - PART II

Upon completion of the research described under Discussion - Part I of this report it appeared desirable to investigate several more variables. During the period Part I

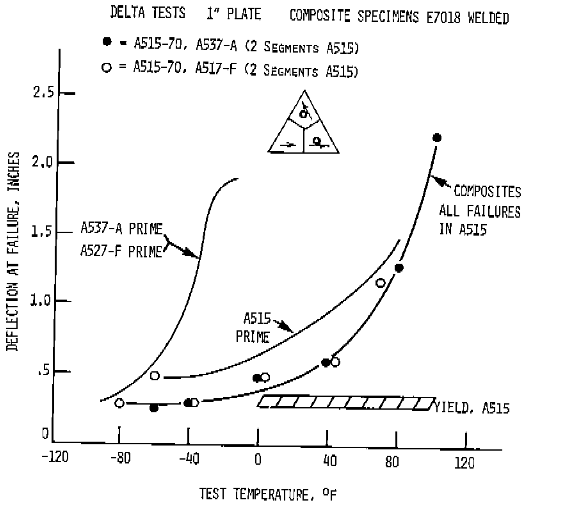


Fig. 18 - Composite Delta Specimens, Deflection at Failure vs. Temperature, A515-70, A537-A, A517-F

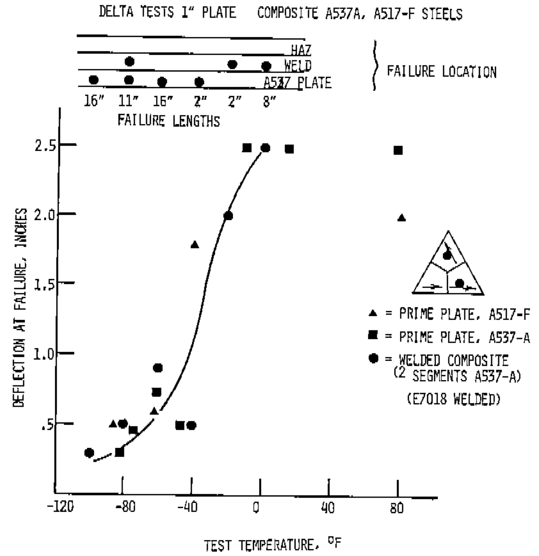


Fig. 19 - Composite Delta Specimens, Deflection at Failure vs. Temperature, A537-A, A517-F Specimens

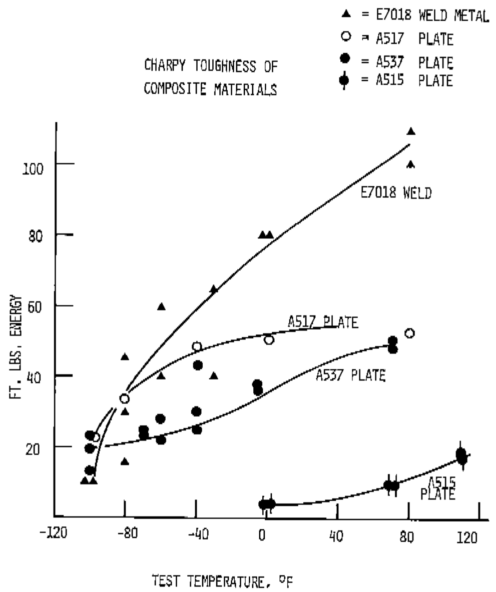


Fig. 20 - Charpy Data, E7018 Weld Metal, A537-A Plate, A515-70 Plate, A517-F Plate

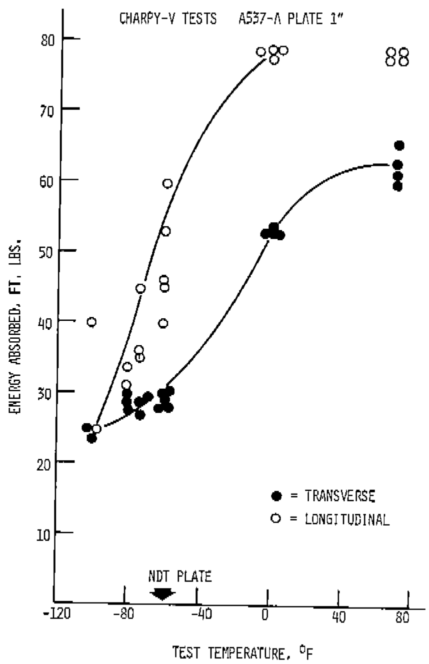


Fig. 21 - Charpy Data, A537-A Plate

research was being conducted, the U.S. Steel laboratory was performing independent research on strain and stress distribution in the Delta specimen under load. The U.S. Steel research was performed using electrical resistance strain gages on non-welded Delta specimens with no central crack starter weld. This condition was quite different from that of a welded specimen which incorporates a crack starter patch, residual welding stresses and a non-homogeneous character in respect to mechanical properties to be found in weld metal, heat affected zone and plate. However, the U.S. Steel research findings are useful in understanding the Delta specimen behavior in that they showed fractures from specimen center to plate edge should be favored over fractures from specimen center to the apex of the specimen. The U.S. Steel work is to be reported in a Welding Resarch Council Bulletin in 1971. In general the findings can be interpreted as supporting the research conducted for this program. As a result of the U.S. Steel research it was felt that the research reported here under Part II should include a modified specimen with the weld lines running from center specimen to apices of the Delta triangle. Further it was felt that the research should be expanded to include a steel of mechanical properties similar to those of the A517-F steel of Part I but with chemistry slightly different. Hence, one-inch thick A517-E steel was selected to determine the sensitivity of the specimen to this change. Additionally it was felt that any effects of different welding procedures should be determined by using "standard" Delta welding conditions as a basis for comparison against field and shop welding conditions of the types recommended by the steel manufacturer. Further check on effect of changes in welding condition was felt desirable as occasioned by performance of "standard" welded specimens fabricated by a welder not previously experienced in welding Delta specimens. Finally for Part II of the investigation it was decided it would be valuable to determine the response of the Delta specimen when three substantially different steels are tested together in a composite Delta specimen, one segment of each of the three steels.

(a) Effect of Modified Specimen Geometry, Center to Apex Welds

The original design of the Delta specimen was based on the concept that it should represent a weldment with a potential flaw so placed that in testing to failure equal opportunity for fracture is given weld metal, plate metal and heat affected zone. The U.S. Steel research indicated that the specimen favors failure from the central crack starter to the mid-length of the sides of the specimen in the path of the weld metal in the standard specimen. The purpose of this portion of the investigation was then to investigate a suggested change in geometry by preparing and testing specimens in which the weld lines extended from

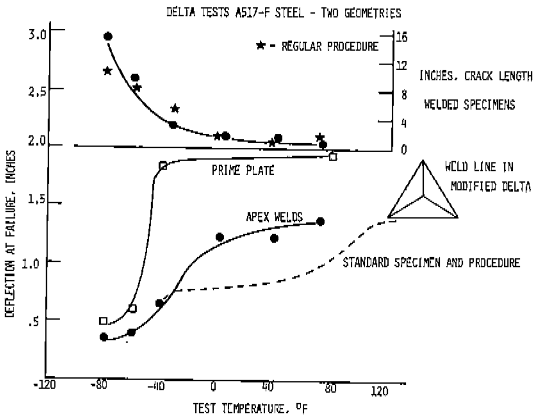


Fig. 22 - Delta Specimen Data, A517-F, Modified Specimen, Apex to Center Welds

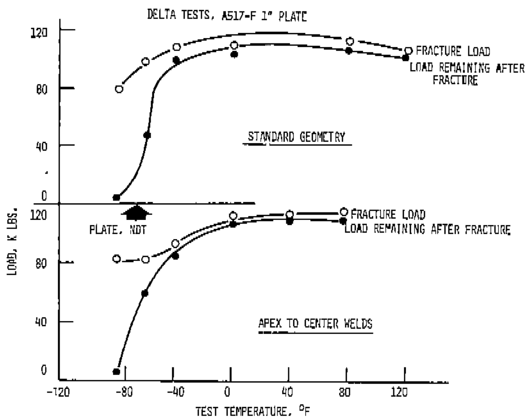


Fig. 23 - Loads at Fracture, 1" A517-F Delta Specimens Apex, vs. Standard Geometry

the center of the plate to the apices of the triangle rather than to the sides. The weld line in this arrangement is therefore not in the path of a maximum transverse bending moment.

Six specimens of A517-F one inch steel plate, from Part I of the project welded as indicated in Figure 22 were tested at the temperatures used for the same steel in standard configuration specimens. The deflection at failure characteristics are given in Figure 22 along with the plotted data on crack length at failure for both the standard and modified geometry specimens. Three features of Figure 22 are noteworthy. First, specimens welded apex to center showed higher deflections at failure at test temperatures 0°, 40° and 80°F than conventionally welded specimens. All fractures in the apex welded specimens failed in the plate. Second, the deflections at failure for these specimens although greater than for conventional specimens was lower than that for prime plate, despite the fact that no fractures in these specimens followed paths in weld metal or heat affected zones. Third, the fracture lengths at failure were essentially independent of the specimen geometry. In addition the low temperature transition in the "apex welded" specimens matched that for conventionally welded specimens identically.

To compare further the behavior of the standard and apex welded specimens, the data for Figure 23 were taken from load-deflection curves. The value of load remaining on a specimen after fracture has occurred is useful as an additional measurement to compare performances. The plots in Figure 23 indicate that for the welded Delta specimens of A517-F steel -40°F is the temperature below which ability of the specimen to carry load is very adversely affected by the occurrence of a fracture irrespective of specimen geometry. Thus the general outcome of this part of the investigation indicates that the "apex weld" geometry resulted in a somewhat more favorable behavior than the "standard" geometry. The"apex" specimen biases failure from the weld path and does not represent the "worst case" situation which may be more meaningful in examination of actual weldments particularly when the fracture problem may lie in weld metal. However despite the fact that fractures followed plate paths this specimen modification still reflected a change in performance due to welding. This is probably due to the role the weld metal under the crack starting patch plays. The weld metal at some test temperatures above NDT of the plate is less tough than the plate and fails in the apex weld specimens as it would in a standard geometry specimen and thus presents an enlarged flaw to the plate, resulting in performance poorer than that shown by prime plate but better than that shown by standard welded specimens in which the fracture once initiated is free to continue travelling in weld metal.

(b) One Inch Plate to A517-E Specification

The study to validate the Delta specimen was extended to include a second composition in the general A517 classification. Accordingly one inch thick plate to A517-E specification was included in the program. Properties and composition are given in Table 3.

Tests of the steel welded at Lafayette using standard Delta procedure produced data shown in Figures 24 and 25. Shortage of material allowed testing of only four prime plate specimens rather than the six originally planned. Figure 24 illustrates the general behavior found in the A517-E material to be quite similar to that of A517-F steel. Specimens prepared by the Lafayette welder exhibited a ductility transition in Figure 24 at about the same temperature, $-60^{\circ}F$, as prime plate specimens but showed poorer performance than prime plate when tested above that temperature where fractures transferred from the plate to the less fracture resistant weld metal. The $-60^{\circ}F$ temperature here as in the A517-F specimens defined that below which yielding failed to occur. Figure 25 illustrates the change in load carrying characteristics for welded and prime plate specimens. The performance is very similar to that for the A517-F steel. The similarities between the two steels overshadow any differences as measured in the Delta test.

Figure 26 portrays the Charpy characteristics of the A517-E plate metal and various weld metal deposits. The A517-E plate metal appears to be more anisotropic than the A517-F plate but the toughnesses of weld metals from standard procedure welds were comparable. With these

Table III - A517-E, 1"

Chemical Analysis %	Tensile and Mechanical Tests			
C - .15	Yield	115,200 psi		
Mn - .52	Tensile	122,800 psi		
P - .014	Elongation %	18.5		
S - .020	RA %	64.8		
Si - .30	Bends	OK		
Cr - 1.65				
	CVN, Ft.lbs.	$+75^{o}F$	0^{o}	-50^{o}
Mo - .48	Long.	75	64	49
Cu - .25	Trans.	41	33	28
Ti - .076				
B - .002				

similarities and the fact that plate metal fractures did not occur in either steel above $-60^{o}F$ it is not surprising that the behavior of the two steels was very similar.

The outcome of these tests indicated that the difference between A517-F steel and A517-E steel in welded Delta tests was modest and within the range to be expected considering the main dissimilarity between the two was one of slightly different chemistry.

(c) Variations in Welding Procedure, A517-E, One Inch Plate, Standard Procedure, Second Operator

A competent welder without previous experience in welding Delta specimens prepared six specimens of A517-E steel with standard procedure and the same electrode material used by the welder who had prepared all other specimens discussed to this point. The new welder encountered no difficulties and produced workmanlike welds.

A steel mill laboratory prepared six welded specimens using their recommended manual shielded metal arc (E11018M) procedure. This consisted of preparing a single-vee, 60^{o} included angle, gapped 0 to 1/8 inch with no land face. The joints were filled using 15 passes, preheat of 100^{o} to $150^{o}F$ and interpass temperature of $300^{o}F$ to $350^{o}F$. A seal bead was deposited on the root side. Weaving to 2½ times electrode diameter was permitted. Maximum heat input was 50,000 joules per inch compared to the 80 KJI imposed in the Lafayette standard procedure.

The steel mill laboratory also prepared six Delta specimens using their recommended submerged arc technique consisting of a double-bevel 60^{o} included angle joint with

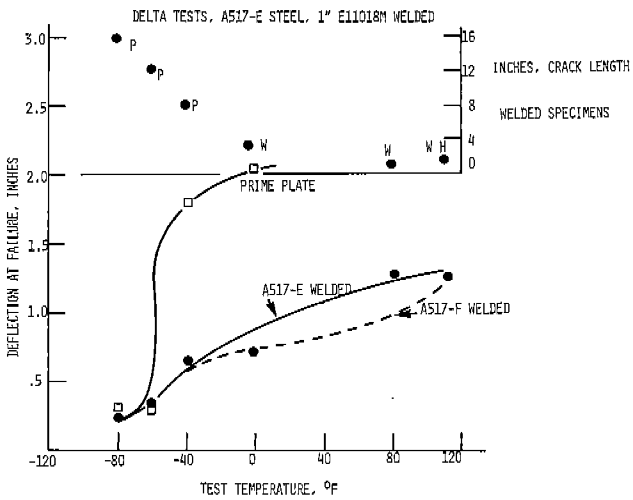


Fig. 24 - Delta Specimen Data, A517-E 1" Plate, Deflection at Failure and Crack Length vs. Temperature

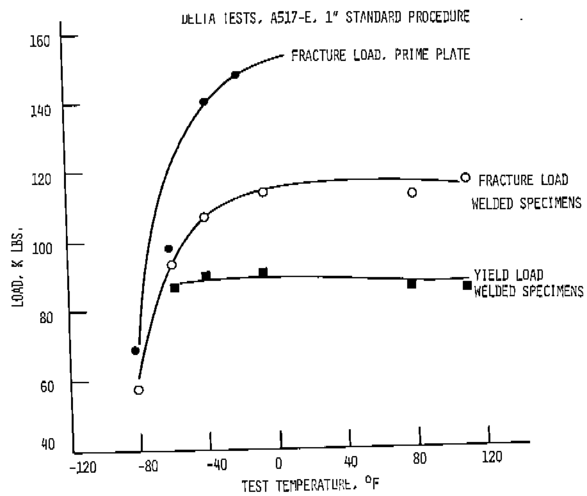


Fig. 25 - Delta Specimens, Load at Fracture, 1" A517-E Plate

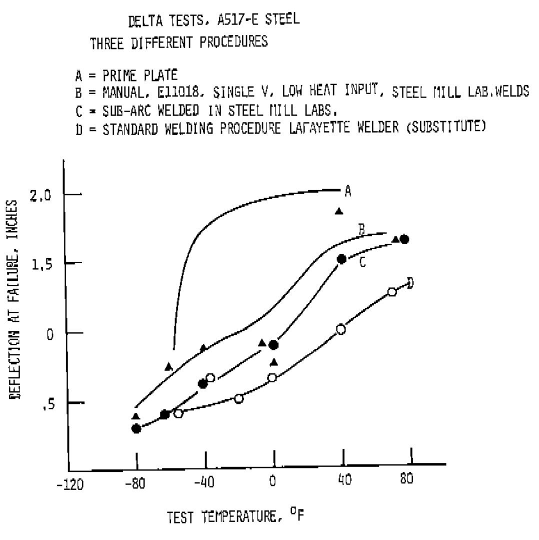


Fig. 26 - Charpy Data from Three Welding Procedures, A517-E Plate

.080" gap, no land face, 15 passes, preheat 100/150°F, interpass temperature 250/300°F and maximum heat input of 55,000 joules per inch, filling passes with 1/8 inch wire, cover passes with 5/32 inch wire.

All specimens were tested at Lafayette after removal of seal beads and reinforcement and application of Hardex-N crack starter. Because the throat width was wider than "standard" in the specimens welded in the steel mill laboratory it was necessary to use a larger than standard Hardex-N patch diameter to place crack starting metal on weld and plate (maximum diameter of three inches). All specimens were tested with the last side welded put on the tension or down side. Deflection at failure data are presented in Figure 26. These indicate that the change in procedure from "standard" to either submerged arc or controlled low heat input welds was effective in producing improved performance. Specimens welded at Lafayette by the substitute welder essentially duplicated the performance of those by the regular welder.

The Charpy-V data of Figure 27 are helpful in explanation of the relative performances of A517-E Delta specimens. The Charpy data correlate well with the data from the Delta specimens prepared in various procedures. This confirms findings in prior investigations, namely that improved weld metal quality is helpful in improved overall weldment performance, particularly in the temperature ranges or conditions where sudden plate metal failure does not occur.

These tests indicated that change in welding procedure is effective in changing response of welded Delta specimens. The changes found were in the direction of commercial experience and of the generally expected order. At the same time the tests indicated that competent welders using the same welding procedure can produce specimens with duplicable performance.

(d) Composite Specimens, Three Steels in One Specimen

The purpose of this investigation was to determine the sensitivity of the Delta specimen to presence of three different steel types in composite specimens. The three steels were A517-F, A515-70 and A537-A all considered and tested earlier under Program-Part I individually as prime plate and then as composites of two steels. Here the three steels were joined, one segment each, in each of six specimens as previously with E7018 manual welds following the standard procedure. The results are shown graphically in Figure 28. All failures at 0°F and above occurred as short fractures into the A515-70 plate while the fractures at lower temperatures were in the A515-70 plate and weld concurrently at -60°F or in the weld at -40°F. This performance duplicated that in

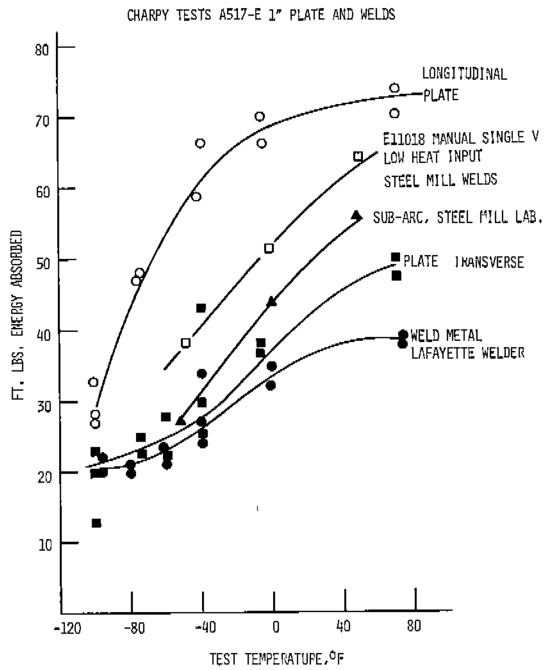


Fig. 27 - Delta Tests, Effect of Welding Procedure, 1" A517-E Plate

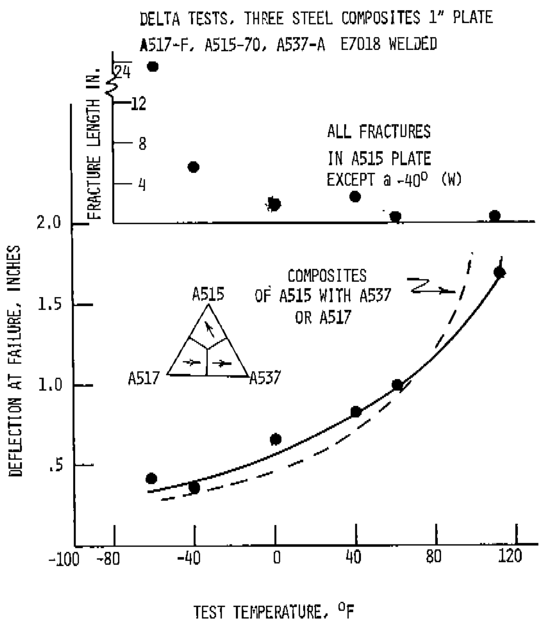


Fig. 28 - Delta Specimen Behavior of Three Steel Composites, A517-F, A537-A, A515-70

the composite tests when A515-B was welded into specimens with either of the two other steels. Comparison of deflections at failure in Fig. 28 with performance shown in two-steel composites in Figure 18 indicates very similar performance. The similar behavior is to be expected in consideration of the relative toughnesses of the materials shown in Figure 20. There again the least tough material, A515-70, is shown to have governed composite performance.

This series of tests indicated strongly a tendency of fracture to follow paths in the lowest toughness material when paths were available in four materials, weld metal or any of three steels, all in the same specimen. The data were in agreement with those from Part I of this investigation where composite specimens of two steels joined by E7018 weld metals were tested and which showed fracture to occur in the least tough material as judged by Charpy tests.

SUMMARY

Data obtained in this investigation indicated response of the Delta specimen when used to measure the weldability and performance of the several steels examined. Primary observations and findings were as follows:

1. The Delta specimen was applied to 1/2, 1 and 2 inch thickness steels of the A517 classification.

2. The specimen was consistently responsive to changes in material, welding procedure and process.

3. Transitional behaviors developed in such relevant factors as path of fracture, length of fracture, deflection and load carrying characteristics.

4. The standard specimen design in which the welds were positioned to run in a line from specimen center to specimen edge developed a more searching test of the relative properties of the base metal, weld metal and heat affected zone than the specimen in which the welds extended to the apex of the triangle.

5. The crack starter weld technique was effective and relatively insensitive to slight modification or variation.

6. A correlation between Charpy data obtained from fractured Delta specimens and data from Delta tests indicated a general consistency in measured relative toughness and least fracture resistant path obtained in the Delta specimen.

7. Composite weldments of the tougher A537 and A517 steels with A515 steel were incapable of performance better than that of the welded A515 steel alone in Delta specimens.

8. The two steels A517-E and A517-F behaved similarly in Delta tests prepared by the same shielded metal arc manual process.

9. Low heat input manual arc welding applied to the A517-E steel resulted in better performance than high heat input arc welding, a finding consistent with commercial experience.

10. The fracture properties of the weld metal, plate and heat affected zone were the controlling factors at testing temperatures above the NDT of the plate.

ACKNOWLEDGMENTS

Grateful acknowledgment is due Woodrow Hartzell and Sherwood Yeisley for their expert and invaluable technical assistance and support and for their many suggestions in conduct of this research. Acknowledgment is also due Joseph C. Friedman for his expert welding and assistance. Mrs. Erna Tilton aided generously in preparation of this report. The U.S. Naval Research Laboratory at Washington, D.C. made available a 1,000,000 lb. capacity testing machine to test the 2 inch thick Delta specimens.

REFERENCES

1. "Delta Test Determination of Fracture Characteristics of Carbon Steels", L. J. McGeady, Welding Journal, Research Supplement, Jan. 1968.

2. "The Delta Test Applied to Quenched and Tempered Steels", L. J. McGeady, Ibid, March 1968.

APPENDIX TABLES

Table A-1 - Delta Test Data, Prime Plate

One Inch Thick A517-F Steel, Crack Starter Surface Patch Weld Only

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size",-Area	Lbs. Load Loss at Fracture
+80°F	D44	80,000	124,000	2.0	1"	2,000
-20°F	D43	87,000	145,000	2.25	1"	2,000
-40°F	D45	88,500	138,500	1.8	10"	72,000
-65°F	D46	94,000	112,000	.65	16"	94,000
-75°F	D48	None	98,500	.50	16"	62,500
-80°F	D47	None	87,000	.45	16"	87,000

Table A-2 - Delta Test Data

One Inch Thick A517-F Steel, E11018M Welded, Standard Procedure

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area		Lbs. Load Loss at Fracture
160°F	D-33	80,000	116,000	1.40	3	H,W	0
	D-15	80,000	104,000	1.35	2	W	0
115°F	D-12	80,000	122,000	1.50	3	W	0
	D-32	80,000	108,000	.90	3½	H	0
	D-19	70,000	106,000	1.50	3½	H,W	2,000
80°F	D-9	80,000	115,000	.95	3½	W,H	2,000
	D-26	80,000	120,000	1.25	2½	H,W	3,000
	D-29	80,000	108,000	.90to1.25	2½	H,W	0@.9;2,000@1.25
	D-14	73,000	106,500	1.25	3	H,W	0
0°F	D-25	80,000	124,000	1.0(	2	W,H	0
	D-28	87,000	120,000	.91	2	H	0
	D-5	92,000	111,600	.81	3½	W	0
	D-30	90,000	115,500	.87	1	W to H	0
	D-4	90,000	118,300	.87	3	W	2,000
-40°F	D-6	76,000	105,000	.90	4	W	2,000
	D-31	80,000	115,000	.90	6	W,P	2,000
	D-34	80,000	106,000	.75	3	W	0
	D-16	76,000	102,000	.625	6	W	15,000
-60°F	D27	90,000	124,200	.88	16	W,P	19,000
	D36	None	88,700	.45	6	W	60,000
	D18	None	83,000	.50	1½	W	80,000
-80°F	D35	None	77,000	.35	2	W,P	7,000
	D2	None	72,000	.35	14	W,P	70,000
	D11	None	82,000	.40	1	W	1,000

Table A-3 - Delta Test Data

A517-F Steel, One Inch Effect of Notch Variation

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area		Lbs.Load Loss at Fracture
115°F	D7	80,000	123,000	1.20	1½	H	0
80°F	D3	80,000	106,000	.90	2	W,H	0
0	D1	90,000	119,000	.87	2½	W	2,000
-40°F	D10	80,000	121,000	.80	3	W	8,000
-60°F	D8	88,500	110,000	.60	11	P,W	40,000
-80°F	D13	None	99,500	.50	16	W,P	99,500

Table A-4 - Delta Test Data

One Inch, A517-F, Welded by a Shipyard Laboratory

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area		Lbs.Load Loss at Fracture
80°F	D38	84,000	112,000	1.20	3	H,W	0
0°F	D42	86,000	124,000	1.38	1	W	0
-40°F	D41	87,000	115,000	.95	1	W	5,000
-65°F	D39	87,000	97,500	.65	3	W	17,500
-80°F	D37	None	90,800	.45	6	W	10,000

Table A-5 - Delta Test Data

One Inch, A517-F, Welded in a Commercial Research Laboratory

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area		Lbs.Load Loss at Fracture
70°F	D17	71,000	113,000	2.0	2	W	2,000
40°F	D22	73,000	108,000	1.6	2	W,H	2,000
0	D20	71,000	98,500	.75	2	W	8,000
-40°F	D24	80,000	111,000	.85	16	W	54,000
-60°F	D23	76,000	88,000	.50	15	P	88,000
-80°F	D21	None	77,500	.40	19	W+P	77,500

Table A-6 - Delta Test Data

One-Half Inch A517-F, Prime Plate

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area	Lbs. Load Loss at Fracture
-45°F	F7	21,200	36,000	2.80	1"	0
-60°F	F20	21,000	35,000	no failure	no failure	-
-80°F	F19	23,400	33,000	2.25	1"	4,000
-80°F	F9	26,400	36,000	2.50	1"	0
-85°F	F8	25,800	38,000	2.00	3"	0
-100°F	F10	25,200	29,200	.85	1/2"	2,000

Table A-7 - Delta Test Data

One-Half Inch, A517-F, Welded With Single 60°V
7 Passes E11018-M Electrode, 57,500 JPI max. Heat Input

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size"	-Area	Lbs. Load Loss at Fracture
80°F	F16	19,500	33,000	2.	1	H	0
80°F	F 7	20,200	28,000	1.75	3	H,W	0
0	F 8	20,500	31,300	1.93	3	H	0
-40°F	F13	20,500	32,500	2.40	2	H,W	0
-40°F	F14	20,500	32,000	1.75	2	W	0
-40°F	F18	20,500	31,000	2.25	3	H	0
-60°F	F10	22,000	23,000	.78	1	H	1,000
-60°F	F11	20,000	30,000	1.50	1	H,P	1,000
-60°F	F17	22,000	26,250	.95	2	H	1,000
-60°F	F 5	20,000	34,100	2.25	1	H,W	1,000
-80°F	F12	None	21,750	.65	2	P	1,500
-80°F	F 6	None	19,000	.50	2	P	1,500
-80°F	F 9	None	16,000	.60	2	P,H	1,000

Table A-8 - Delta Test Data

Two Inch Prime Plate

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area	Lbs.Load Loss at Fracture
0	14	330,000	420,000	1.72	1	0
-25°F	11	337,000	414,000	1.67	1	0
-40°F	10	312,000	390,000	1.14	4	35,000
-55°F	9	287,000	360,000	.75	16	320,000
-70°F	8	None	320,000	.52	16	320,000
-90°F	7	None	325,000	.50	16	325,000

Table A-9 - Delta Test Data

Two Inch Plate E11018-M Welded

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area		Lbs.Load Loss at Fracture
70°F	5	300,000	395,000	1.55	2	W,H	0
0	3	305,000	425,000	1.67	1	W,H	5,000
-30°F	4	265,000	380,000	.84	4	W	65,000
-70°F	6	288,000	287-360,000	.52-.94	3	W,P	15,000
-85°F	2	310,000	360,000	.55	16	P	360,000
-100°F	1	None	220,000	.40	16	P	220,000

Table A-10 - Delta Test Data

A515-B Prime Plate and A537-A Prime Plate

(a) A537-A Prime Plate

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area	Lbs.Load Loss at Fracture
80°F	L-8	52,000	87,000	2.5+	None	0
15°F	L-10	53,000	90,000	2.5+	None	0
-10°F	L-5	53,000	82,000	2.5+	½	0
-40°F	L-9	54,000	62,000	.5	4	2,000
-60°F	L-7	None	66,500	.75	2"-8"	0 - 66,500
-80°F	L-6	None	57,000	.33(.50)	3"-8"	0 - 57,000

(b) A515-B Prime Plate

Test Temp.	Speci-men No.	Yield Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area	Lbs.Load Loss at Fracture
70°F	H-5	34,000	50,200	1.0	2	5,000
80°F	J-4	37,000	50,000	1.4	2	3,300
40°F	H-2	37,000	47,000	.85	7"	2,000
0	J-1	42,000	51,000	.72	14	51,000
-40°F	H-6	42,000	46,300	.45	16	46,300
-60°F	J-2	None	49,500	.78	18	49,500

Table A-11 - Delta Test Data

Composite Specimens

(a) One Inch A515-B and A517-F Steels, E7018 Welded

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area	Lbs. Load Loss at Fracture
70°F	CP1	42,000	68,500	1.20	A515 10"	34,000
40°F	CP2	40,000	52,000	.60	A515 6"	8,000
0	CP3	44,000	54,800	.50	A515 12"	36,000
-40°F	CP4	None	42,000	.30	A515 4"	6,000
-60°F	CP5	52,000	62,000	.48	A515+W,16"	60,000
-80°F	CP6	None	53,000	.30	A515+W,16"	53,000

(b) One Inch A515-B and A537-A Steels

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area	Lbs. Load Loss at Fracture
100°F	CP7	30,500	58,800	2.00+	2" A515	1,000
80°F	CP8	30,000	63,000	1.30	2" A515	1,000
40°F	CP9	30,200	58,500	.6	11" A515	1,000, 24,000
0	CP10	32,000	58,000	.50	16" A515	58,000
-40°F	CP11	None	54,000	.30	16" A515	54,000
-60°F	CP12	None	46,300	.25	16" A515	46,300

Table A-12 - Delta Test Data

Composite Specimens One Inch A517-F and A537-A Steels

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area	Lbs. Load Loss at Fracture
0	CP13	58,000	92,000	2.50	8" W	28,800
-20°F	CP14	56,000	87,500	2.00	2" W	2,000
-40°F	CP15	60,000	67,500	.50	2" A537	5,000-3,000
-60°F	CP16	56,000	77,200	.90	16" A537	77,200
-80°F	CP17	58,000	74,000	.50	3"W,8"A537	30,000
-100°F	CP18	None	56,000	.15-.30	16" A537	56,000

Table A-13 - Delta Test Data

Apex to Center Welds A517-F Steel, One Inch, E11018-M Welded

Test Temp.	Speci-men No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size", -Area	Lbs. Load Loss at Fracture
75°F	DA91	84,000	117,000	1.40	1½ P	1,000
40°F	DA92	84,000	113,000	1.25	1 P	1,000
0	DA94	87,000	114,000	1.0-1.5	1½ P	---
-40°F	DA95	90,000	94,000	.65	2 P	7,000
-60°F	DA96	None	83,000	.25-.50	10 P	23,000
-80°F	DA93	None	83,000	.4	16 P	82,000

Table A-14 - Delta Test Data

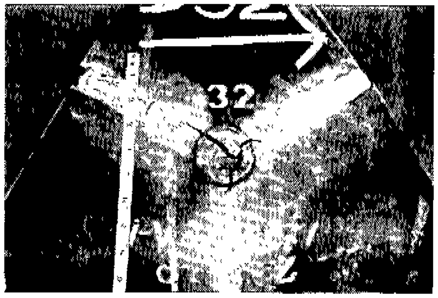
A517-E Steel, One Inch

Test Temp.	Speci- men No.	Yield . Load,Lbs.	Maximum Load,Lbs.	Deflection at Failure,In.	Fracture Size",-Area	Lbs.Load Loss at Fracture
	(a) Prime Plate					
-20°F	N13	97,000	147,000	2.05	3/4"	11,000
-40°F	N16	97,000	140,000	1.80	11"	93,000
-60°F	N14	97,000	97,000	.43	11"	67,000
-80°F	N15	None	68,000	.30	16"	68,000
	(b) Welded at Lafayette, Standard Procedure					
110°F	N1	88,000	116,500	1.25	1½" W,H	1,000
80°F	N11	87,000	112,000	1.25	1" W	2,000
-5°F	N2	94,000	114,000	.50-.70-.90	8" W	52,000
-40°F	N8	90,000	108,000	.65	16" W,P	84,000
-60°F	N3	86,000	94,000	.60	8" P	44,000
-80°F	N10	None	58,000	.25	16" P	58,000
	(c) Welded at Lafayette, Substitute Welder					
70°F	N5	88,500	124,000	1.25	1" W,H	2,000
40°F	N4	92,000	116,500	1.00	1" W	2,000
0	N6	88,500	110,000	.63	3" W	10,000
-20°F	N12	94,000	100,000	.50	1" W	---
-40°F	N7	82,000	112,000	.65	8" W	45,000
-60°F	N9	None	86,000	.40	6" P	6,000
	(d) Manual Shielded Metal Arc,					
70°F	561	87,000	127,000	1.65	1" W,H	1,000
40°F	564	90,000	135,500	1.85	2" W,H	1,000
0	565	86,000	116,000	.90	2" H,P	0
-40°F	562	87,000	123,000	.90	2" P	8,000
-60°F	566	87,000	110,000	.75	1" W	10,000
-80°F	563	None	78,000	.40	2" P	not determined
	(e) Submerged Arc Welded					
70°F	572	94,000	127,000	1.62	1" W	1,000
40°F	576	85,000	123,000	1.50	2" H	2,000
0	575	85,000	118,000	.87	2" W	3,000
-40°F	571	85,000	114,000	.60	8" P	4,000
-60°F	573	---	80,000	.40	8" P	80,000
-80°F	574	None	65,000	.325	8" P	65,000

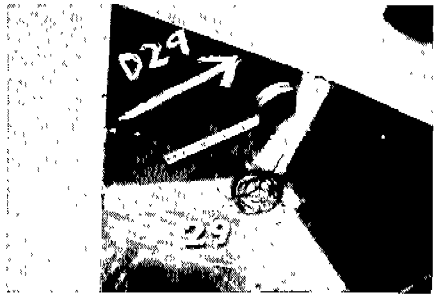
Table A-15 - Delta Test Data

Three Steel Composites,
1" Plate Welded Standard Procedure, E7018 Weld Metal
D = A517-F, J = A515-70, L = A537-A

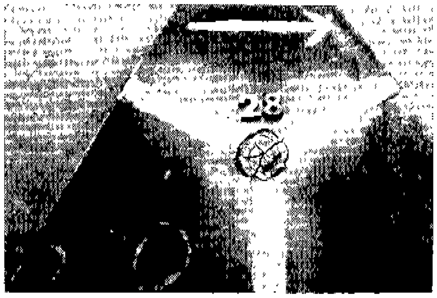
Test Temp.	Specimen No.	Yield Load, Lbs.	Maximum Load, Lbs.	Deflection at Failure, In.	Fracture Size",-Area	Lbs. Load Loss at Fracture
110°F	DJL6	47,000	77,000	1.70	1", A515	1,000
60°F	DJL5	52,000	69,500	1.00	1", A515	1,000
40°F	DJL1	52,000	76,000	.85	3", A515	2,000
0	DJL2	48,500	68,000	.70	2", A515	2,000
-40°F	DJL3	52,000	57,000	.35	6", W	8,000
-60°F	DJL4	52,000	67,500	.45	24", A515,W	67,500



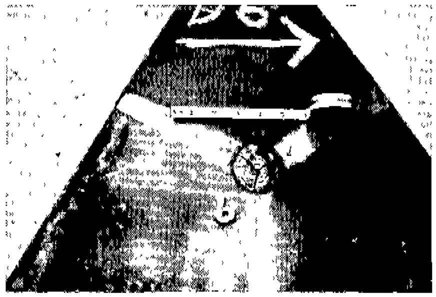
(a) Specimen D-32 tested at 115^{o}F showing predominant failure in HAZ with some minor weld metal fracture.



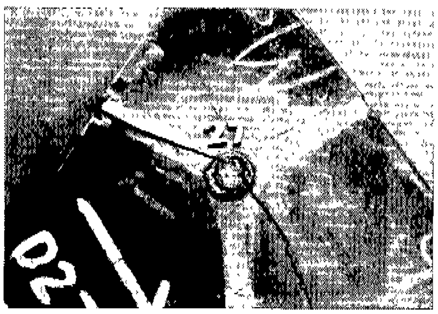
(b) Specimen D-29 tested at 80^{o}F showing failure in HAZ and weld metal.



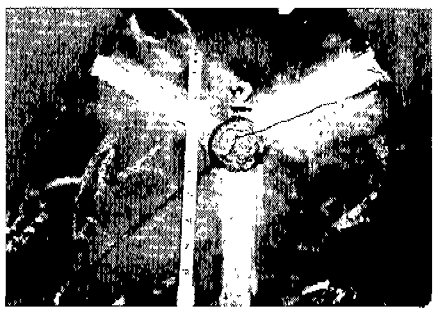
(c) Specimen D-28 tested at 0^{o}F showing predominantly HAZ fractures.



(d) Specimen D-6 showing predominately weld metal fractures of sudden type.

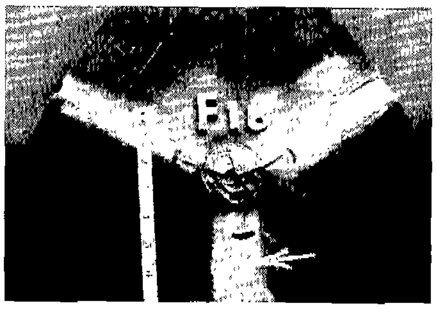


(e) Specimen D-27 tested at -60^{o}F showing sudden fractures through both plate and weld.



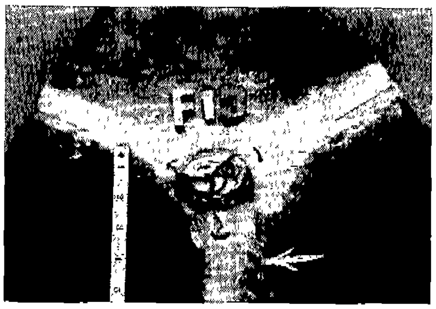
(f) Specimen D-2 tested at -80^{o}F showing sudden fracture through both plate and weld.

Illustration 1 - Fracture paths in one-inch A517-F Delta Specimens, E11018 welded, standard procedure.

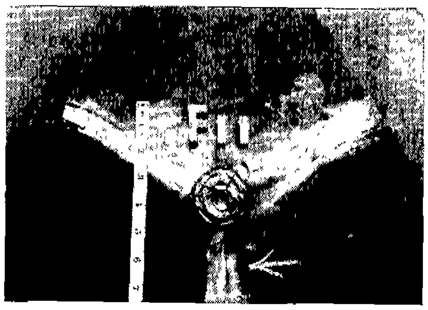


(a) Specimen F-16 tested at 80°F showing predominately HAZ fractures at surface.

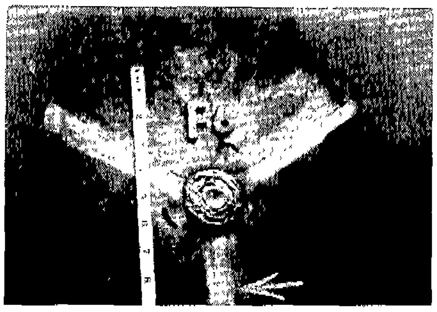
(b) Specimen F-8 tested at 0°F showing mainly HAZ with some minor weld tearing.



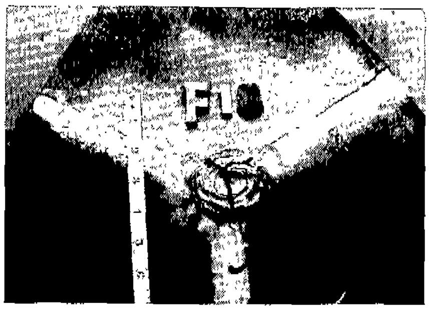
(c) Specimen F-13 tested at -40°F showing both HAZ fracture and some weld metal tears.



(d) Specimen F-11 tested at -60°F showing a short plate fracture turning to HAZ.



(e) Specimen F-6 tested at -80°F showing plate metal fractures exclusively.



(f) Specimen F-18 tested at -40°F showing two legs cracked in HAZ, one leg in weld. See macros in Illustration 3.

Illustration 2 - Fractures in Delta specimens of one-half inch A517-F plate, E11018 welded.

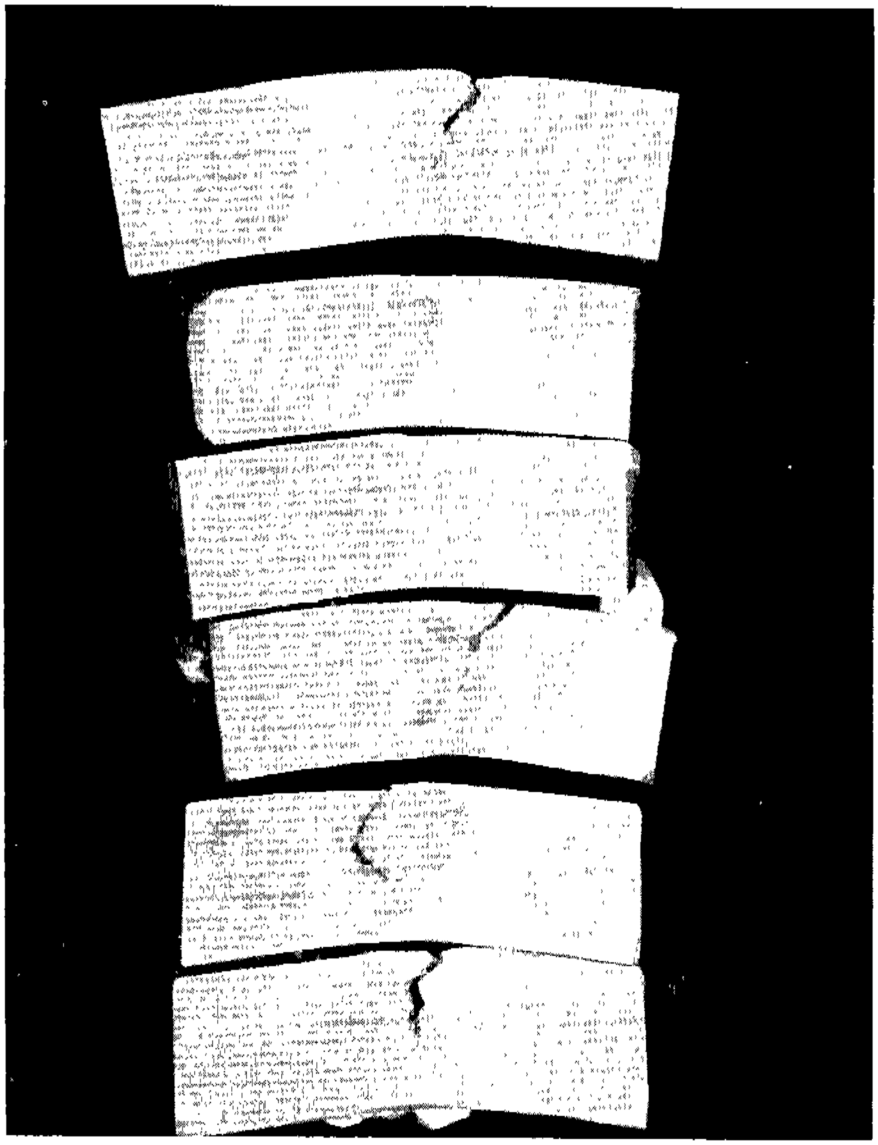
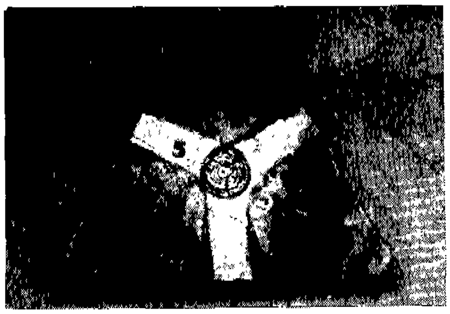
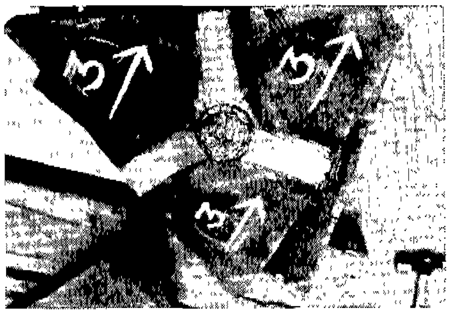


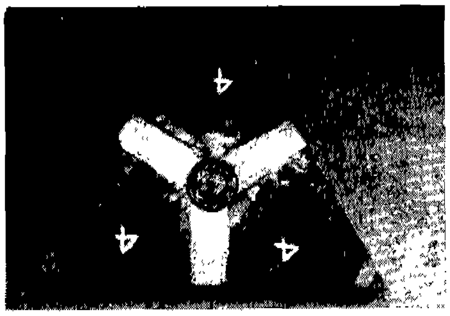
Illustration 3 - Cross-sections of fractured one-half inch Delta specimen fractures. All sections were taken about one-half inch from the crack starter patch weld. From top to bottom: specimens F-16 tested at 80°F and F-8 at 0°F both showing fractures originating in fusion line area, specimens F-13 and F-14 and a second section from F-13 showing variation in fracture location at surface and sub-surface path, and specimen F-18 tested at -40°F sectioned at a position showing a weld metal surface crack turning to fusion line.



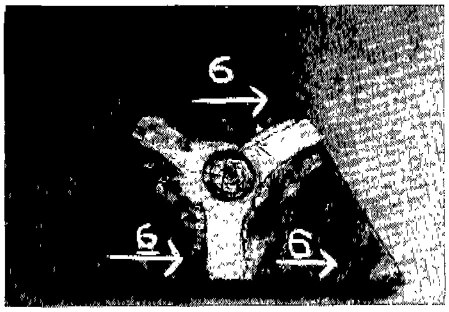
(a) Specimen 5 showing tearing fracture turning from weld to HAZ



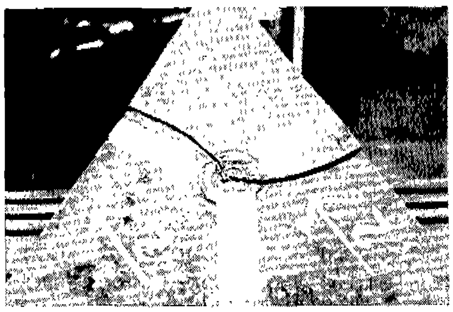
(b) Specimen 3 showing tearing fracture turning from weld to HAZ



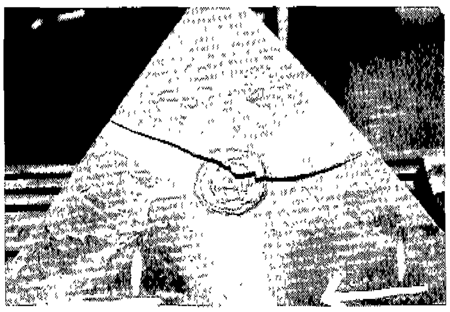
(c) Specimen 4 tested at -30°F showing long sudden weld metal fracture.



(d) Specimen 6 tested at -70°F showing short sudden fracture originating in weld and turning into plate.



(e) Specimen 2 tested at -85°F showing sudden shattering fractures in plate, one in a path across rolling direction, the other more nearly in a path parallel to rolling.



(f) Specimen 1 tested at -100°F showing sudden simultaneous fractures in both plate and weld metal.

Illustration 4 - Fractures in two-inch thick A517-F, E11018 welded Delta specimens.

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13. ABSTRACT

The Delta specimen has been applied to two different heats of A517 grade steel in one inch plate thickness and to the one heat in 1/2 and 2 inch plate thickness. Various modifications of the basic specimen have been investigated, a non-standard geometry and a composite form of the specimen into which different steel types were incorporated. The influences of various welding procedures have been examined as well as the performance of all steels in the non-welded condition. The specimen was found applicable and appropriate for all conditions tested, showing sensitivity to all variables. At the same time the specimen showed a consistency in behavior which could be rationalized with commercial experience and data from corollary tests. The steels examined showed several transitional behaviors when tested as weldments, these transitions occurring in place of fracture, length of fracture, load carrying changes and overall ductility measured by deflection at failure.

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