SSC-276

FRACTURE BEHAVIOR CHARACTERIZATION OF SHIP STEELS AND WELDMENTS

SHIP STRUCTURE COMMITTEE

1978

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An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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SR-1224

Material requirements and design procedures to avoid catastrophic fractures of ship hull structures continues to be of great concern to designers. The Ship Structure Committee has undertaken a program to define and formulate fracture toughness criteria for steels up to 100,000 psi yield strength and their associated weldments.

The program entails (1) critical review and assessment of current knowledge (which has been completed and reported in SSC-244), (2) experimental data procurement, and (3) the development of design application procedure. An exploratory experimental project to test currently employed ship steels has been completed and reported in SSC-248.

The present report (SSC-276) provides additional experimental data for steels and associated weldments by a systematic series of large scaled tests typical of ship hull construction and service.

W. M. Benkert
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

FINAL REPORT

on

Project SR-1224

"Fracture Criteria"

FRACTURE BEHAVIOR CHARACTERIZATION OF SHIP STEELS AND WELDMENTS

by

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under

Department of the Navy
Naval Sea Systems Command
Contract No. N00024-75-C-4058

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U. S. Coast Guard Headquarters
Washington, D.C.
1978

ABSTRACT

In order to enlarge upon current understanding of the behavior of ship steels and weldments, a series of mechanical tests were performed on seven grades of ship steel. These steels were ABS-B, CS, AH-32, EH-32, ASTM A517-D, A678-C, and A537-B and covered the range of ordinary as-rolled, to high strength quenched and tempered alloys. In addition, all materials but the EH-32 were utilized to produce welded plates. These weldments, either manual shielded metal arc or submerged arc procedure, were then machined into test specimens.

The test program was designed to probe a large number of specimen and material parameters. The mechanical tests performed were the static tension test, the Charpy impact test, weld side bend test, dynamic tear test, and the drop weight-nil ductility temperature test. Two structural tests were designed to exercise the crack initiation and arrest capability of the steels. One of these tests was the standard explosion crack starter test while the other was a variation of the explosion tear test.

The results indicated the general superiority of the fracture performance of the high strength, quenched and tempered alloys over the ordinary ship steels. The structural tests demonstrated the superiority of the manual metal arc welding procedure. This result was generally confirmed by the results of the dynamic tear tests. The data were compared to the proposed fracture criterion proposed by Rolfe, et. al., as presented in SSC-244. Only one material, EH-32, passed all tests prescribed by the proposed criterion.

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I. INTRODUCTION

In its quest to improve the safety and reliability of welded ship hulls the Ship Structure Committee has initiated a series of projects in recent years aimed at evaluating the fracture behavior of ship steels. As part of this work, there has been a clear need for a suitable criterion for qualifying structural steels and weldments. In one of the earlier projects in this series, SSC-244, Rolfe, et. al.(1), proposed a tentative criterion for insuring adequate fracture resistance of a wide range of ship steels and weldments for primary and secondary structural applications. In a subsequent project, SSC-248, Hawthorne and Loss at the NRL(2) developed a limited data base on 1-inch thick ship steels and weldments for the purpose of evaluating, at least in a limited way, the SSC-244 proposed criterion.

The present work was, therefore, undertaken with two objectives in mind. The broad objective was the expansion of the understanding of the fracture behavior of ship steels and weldments. The second and more focused objective was to expand upon the NRL work cited above, in order that a more thorough evaluation of the proposed criterion, SSC-244, would be possible. This was done by conducting a comprehensive mechanical testing program on various heats of seven grades of ship steel, ranging from as-rolled, through normalized, and up to high strength, Q&T alloys. In particular, one or two heats each of ABS-B, AH, EH, CS, ASTM A517-D, A678-C, and A537-B were selected for fabrication of parent material and weldment specimens. Two weld procedures were evaluated during the course of this project: Manual Shielded Metal Arc Weld (SMAW) and the Automatic Submerged Arc Weld (SAW) processes. The testing program involved static tension tests, Charpy impact tests, weld side bends, drop weight-nil ductility temperature (DW-NDT) tests, dynamic tear tests, as well as two kinds of structural tests designed to exercise the crack initiation and arrest capability of the steels. One of these was the explosion crack starter test, and the other a variation of the explosion tear test, designed to test crack arrest capability.

The present project is a companion to the SR-231 project conducted concurrently at SwRI entitled "Fracture Criteria Based on Loading Rates." In that project, temperature and strain rate effects were examined on the same parent materials used here to determine their effects on strength and toughness of ship steels.

II. BASE MATERIALS AND WELDMENTS

A. Ship Plate

A total of twelve heats of ship steel plate were chosen for specimen fabrication. These heats were selected to represent typical samples of ordinary strength, quenched and tempered, and high strength-low alloy ship steels having yield strengths ranging from 40-100 ksi. Although it was desired that all plate be one inch thick, considerations of availability and timing imposed certain compromises. Most of the plate was obtained from Armco Steel Co. in Houston. Two small plates of ABS-B were obtained before this project was initiated through the Naval Research Laboratory, which declared these plates excess. Table 1 provides a summary of the heats used in this program. Throughout this report, "Heat No." is to be understood as the SwRI designation of heats 1-12.

A chemical analysis of samples from the twelve plate heats was conducted by Armco Steel. This analysis served not only to verify the Armco certification reports, but also to assure the composition of the two heats of ABS-B obtained through the NRL. Table 1 summarizes the results of that analysis.

Figures 1 and 12 indicate the shape and sizes of the plates received, and show how they were cut for specimen fabrication, according to the key provided in Table 2.

Although these heats were selected in an effort to encompass typical properties, the actual materials showed some deviations from the standards. Without discussing the test results in detail, these deviations will be noted so that they can be borne in mind while examining the results. It should also be remarked that there are requirements for only a few mechanical properties and that there does not exist a large data base for these properties. Thus, a single mechanical property that does not fit the "normal" range of values may not be too significant.

All heats were within the specified chemistry except for one. The ABS-CS had a manganese content of 1.42 vs 1.35 maximum allowable. All other elements for all materials fit either the ASTM or the ABS codes. Regarding the required tensile properties, there were two exceptions. The AH-32 exceeds the maximum allowable tensile strength of 85 ksi by 5 ksi; the yield and the elongation are acceptable. The other exception is one heat of A517; here the elongation is 13.6 percent, or slightly below the 16 percent value specified by ASTM.

Other properties, particularly the Charpy and NDT values, are more difficult to assess. For example, the NDT for ABS-B was found to be 50-60°F in this investigation. While this is higher than some other investigators have found, it should be noted that among four sources including this program, a spread of 60°F is reported between the highest and lowest NDT values. On the other hand, for ABS-CS material, three investigations including this one also report a spread of 60°F in the NDT. Sizable heat-to-heat variations can also be cited for Charpy and dynamic tear results. Thus, without a large

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Table 1. Summary of Chemistry and Hardness Tests Used in Report SSC-276

Material	SwRI Heat No.	Thickness (in.)	Brinell Hardness	Wet C	Mn	P	Wet S	Si	Cr	Ni	Mo	Cu	Ti	V	B	Cb	Al
ABS-DS	1	1.029	134	.10	1.07	.010	.015	.21	.13	.13	.02	.09	Nil	Nil	Nil	Nil	.02
ABS AH-32	2	1.010	183	.18	1.16	.012	.024	.26	.11	.07	.03	.11	Nil	.044	Nil	Nil	.03
ABS EH-32 (a)	3	1.026	149	.16	1.27	.010	.025	.22	.12	.09	.03	.09	Nil	.042	Nil	Nil	.02
ABS-CS (a)	4	1.013	143	.11	1.42	.016	.026	.34	.13	.04	.02	.03	Nil	Nil	Nil	Nil	.03
ASTM A517-D (b)	5	1.041	262	.18	0.61	.012	.022	.18	1.12	.19	.21	.30	.095	Nil	.002	Nil	.03
ASTM A517-D (b)	6	1.292	255	.18	0.55	.011	.012	.27	.98	.09	.20	.24	.101	Nil	.003	Nil	.04
ASTM A678-C (b)	7	1.421	217	.20	1.44	.010	.027	.45	.22	.22	.06	.13	Nil	Nil	Nil	Nil	.03
ASTM A678-C (b)	8	1.302	202	.19	1.55	.010	.013	.47	.18	.19	.07	.08	Nil	Nil	Nil	Nil	.03
ASTM A537-B (b)	9	1.058	159	.15	1.20	.010	.021	.40	.23	.13	.04	.09	Nil	Nil	Nil	Nil	.03
ASTM A537-B (b)	10	1.016	174	.17	1.32	.010	.019	.33	.21	.25	.06	.14	Nil	Nil	Nil	Nil	.02
ABS-B (c)	11	1.018	121	.18	1.04	.010	.020	.03	.01	Nil	Nil	.03	Nil	Nil	Nil	Nil	Nil
ABS-B (c)	12	1.018	126	.17	0.97	.020	.033	Nil	.01	Nil	Nil	.01	Nil	Nil	Nil	Nil	.00

(a) Normalized

(b) Q & T

(c) Semi-killed

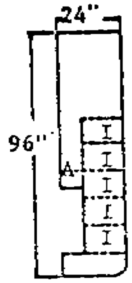


Fig. 1. Plate No. 1 - ABS Gr DS, 1" Thick

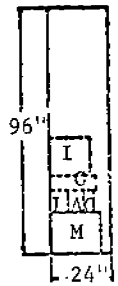


Fig. 2. Plate No. 2 - ABS Gr AH-32, 1" Thick

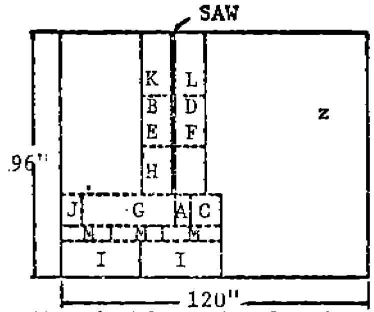


Fig. 3. Plate No. 3 - ABS Gr EH-32, 1" Thick

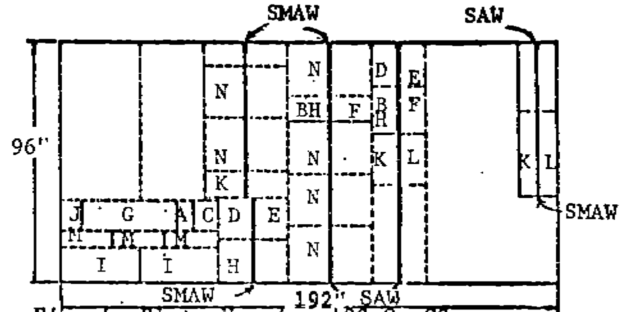


Fig. 4. Plate No. 4 - ABS Gr CS, 1" Thick

ROLLING DIRECTION FOR ALL PLATES

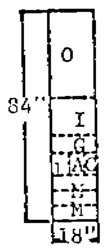


Fig. 5. Plate No. 5 - ASTM A517 Gr D, 1" Thick

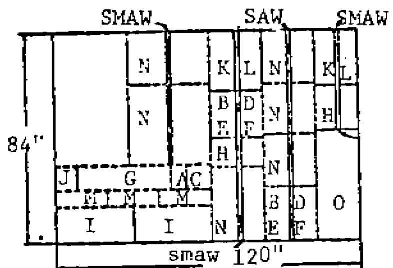


Fig. 6. Plate No. 6 - ASTM A517 Gr D, 1-1/4" Thick

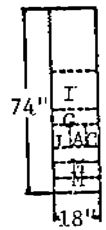


Fig 7. Plate No. 7 - ASTM A678 Gr C, 1-3/8"Thick

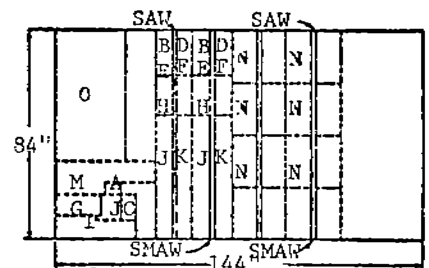


Fig. 8. Plate No. 8 - ASTM 678 Gr C, 1-1/4" Thick

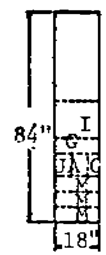


Fig. 9. Plate No. 9 - ASTM A537 C B, 1" Thick

Table 2. Key for Identifying Source of Specimens from Plates Shown in Figures 1-12

DESIGNATION	TEST TYPE	DESIGNATION	TEST TYPE
A	Static Tension, Parent	I	5/8" DT, Parent, L-T
B	Static Tension, Crossweld	J	5/8" DT, Parent, T-L
C	Charpy, Parent, L-T	K	5/8" DT, Weld
D	Charpy, HAZ	L	5/8" DT, HAZ
E	Charpy, Weld	M	1" DT, Parent, L-T
F	Weld Side Bend	N	1" ECST
G	5/8" DW-NDT, Parent, L-T	O	1" ET
H	5/8" DW-NDT, Weld		

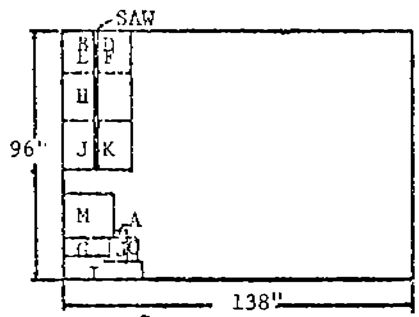


Fig. 10 - Plate No. 10 - ASTM A537 C12, 1" Thick

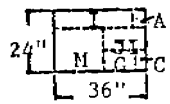


Fig. 11. Plate No. 11- ABS Gr B, 1" Thick

Fig. 12. Plate No. 12- ABS Gr B, 1"Thick

data base of material properties to draw from, it is very difficult to specify typical properties for a material, particularly when a test itself involves a degree of uncertainty as, e.g., in the Charpy test.

B. Welding Procedures

One of the objectives of this program was to study the fracture toughness of weldments used in the production of welded ships. This means that the procedures, filler metals, joint designs, etc., used in the project should all reflect shipyard practice.

A telephone survey of shipyards was made and consultations were held with SR-224 Committee members, steel company personnel, and SwRI welding engineers to define "typical" shipyard practice. These conversations revealed that two welding procedures are primarily used in ship fabrication; they are the Manual Shielded Metal Arc Weld (SMAW) and the Automatic Submerged Arc Weld (SAW). Based on these two procedures, the weld preparation was also chosen to suit "typical" shipyard practice. The other parameters such as filler metal, flux, etc., were chosen to match the particular materials, subject to being ABS approved consumables.

While it was the intention of the program to utilize typical ship weldments, the welds produced potentially differ from ship practice in two respects. The major point of variance would be the production of the weldments themselves. Because these welds were produced under "laboratory" conditions, it would be expected that the properties might differ somewhat from welds produced under production conditions. However, it must be emphasized that while there was no intention to exercise undue standards of quality control, the small scale of the job meant that the welds were probably more carefully made than would be the case under production conditions. It is expected that this factor would be reflected in less data scatter and in a more conservative evaluation of the proposed SSC-224 criterion.

The second potential difference lies in the relative size differential between the plates in this program and ship plates. Because some of the plate was in short supply relative to the number of specimens needed, it was not always possible to weld large plate segments and then remove specimens. While attempts were made to keep the pieces submitted for welding as large as possible, viz. 20 inches wide, it was not always possible to be so generous; a few pieces as narrow as 10 inches were split and welded. While it is certainly true that the residual stress distribution will differ with panel size, the fact that only small laboratory specimens were tested means that residual stresses were likely not a major problem. It is, however, a factor that should be borne in mind.

There were 12 heats of material involved in this program. Of these 12, six heats (six different materials) were selected to be welded and used for small specimens; four heats (three different materials) were selected for structural-type welded specimens. The materials and weld procedures used were:

Heat No.	Material	Weldments: Small Specimens	Weldments: Structural Specimens
3	ABS EH-32	SAW	
4	ABS-CS	SAW, SMAW	SAW, SMAW
5	ASTM A517-D	---- ----	SAW
6	ASTM A517-D	SAW, SMAW	SAW, SMAW
8	ASTM A678-C	SAW, SMAW	SAW, SMAW
10	ASTM A537-B	SAW	---- ----
12	ABS-B	SAW	---- ----

The details of the weld procedure for each of these materials are given in Appendix A. The one point where the procedures used deviate from the recommended procedures is that the bevel used in the joint preparation was 70° instead of 60°.* Since some of these bevels had already been made before the recommendation was received and since this was not perceived as a major technical point, all bevels were made to an included angle of 70°.

The filler metal was, in all cases, selected to match the Charpy impact energy and tensile strength of the base metal. Existing data were used to determine these match-ups.

The pieces used in preparing the weldments ranged from 96 inches by 22 inches (Grade CS) to 10 inches by 14 inches (Grade B). All welds were made transverse to the rolling direction. All pieces had tabs tack-welded to the ends of the weld path for run-out to allow full weldments for the entire length of the pass. Even with a full pass, the ends of all welds were removed prior to cutting for specimens. Generally, the ASTM Drop Weight Recommendation was followed, i.e., the specimens were taken at least one inch from the weldment end or any flame cut surface. In the case of plate 12, Grade B, which had already been cut into small pieces, the pieces were tacked together to form one longer piece which would allow a continuous groove for SAW passes.

In addition to the small specimens, i.e., dynamic tear, Charpy, etc., two kinds of structural specimens were prepared. One of these, the Explosion Crack Starter specimen, was removed from the same material and weldments as the small specimens. The other structural specimen, a variation of the Explosion Tear specimen, was a three-piece specimen prepared especially for this program. This latter specimen, described in Section 3H, required the joining of a brittle material, A36, with the more ductile test materials, CS, A517, or A678. Since the object of this test was to determine the arrest capabilities of the test material, the filler metal was deliberately made of a brittle material to prevent the weld from arresting the crack propagating out of the A36 steel. The joint design itself was the same as used in the other weldments i.e., 70° bevel, etc. The SAW process was used for the actual welding in all of the tear specimens.

Two examples of weld data sheets giving the actual welding information are included in Appendix B.

*Letter from George Kampschaefer to T.S. Cook, dated June 22, 1976.

C. Nondestructive Inspection

It was not considered necessary to conduct nondestructive inspection of all weldments, particularly those used for small laboratory test specimens. This decision was based on the fact that the small specimens sample a relatively small volume of weldment. What was done, however, was that during fabrication both the weld passes and the beveled edges of the base metal were monitored for defects. For example, when a delamination in the base metal intercepting the weld preparation surface was detected, it was ground out. Defects in the weld passes were noted and repaired during fabrication; magnetic particle inspection of the weldment surfaces was also carried out.

The Explosion Crack Starter specimens, on the other hand, sample a much larger volume of weldment. They are also used for crack propagation as well as crack initiation studies. This means that defects in the vicinity of the starter notch should be eliminated insofar as possible. Thus, the weldments used for the 18 Explosion Crack Starter specimens were subjected to a complete radiographic review. These tests showed that 13 of the specimens contained no defects. In the five remaining specimens, the acceptability of the defects was judged according to Ref. 3. The following defects were noted in Grade CS, SMAW, and the A517, SAW:

1. The most severe indications were linear and transverse indicators, which could be cracks or lack-of-fusion, or might be acceptable surface conditions.

2. The next most severe indications were the slag inclusions which were generally not connected and were for the most part acceptable.

3. The third type, and least severe indication listed, was clusters of porosity. Most of the porosity was believed to be found on the surface bead areas, and if it had been desirable, could have been eliminated by surface grinding. Most of this porosity would be judged borderline by ABS criteria.

In addition, one Grade CS, SAW, displayed a defect which was judged an acceptable surface condition.

The intent of the inspection was to insure that sound welds were being tested, not to allow unsound but acceptable ship weldments. Therefore, the more stringent ASME inspection was used but, as noted, only to provide a rigorous definition of weld defects. The results of this inspection required that interpretations be placed on these defects as to whether or not they would be repaired. Where a decision not to repair was made, this decision was usually justified in terms of the ABS inspection code.

Following a careful examination of the radiographic test results, it was judged that a transverse and a linear indication in the ABS-CS and a pair of transverse indications in the A517-D would not be acceptable by the ABS code. These indications could not be sufficiently resolved from the radiographic film to brand them as cracks or other unacceptable defects. All indications appeared to be near surfaces, so the weld area was ground and both ultrasonic and magnetic particle inspections were done without locating the suspected defects. Moreover, following several additional applications of grinding and inspection, no trace of the defects could be found. It was deemed that further effort was not justified and no weld repairs were attempted.

III. SPECIMEN FABRICATION

This section documents the specifications to which all specimens used in this project were fabricated. All welding and machining were done at Southwest Research Institute. In the case of the dynamic tear specimens, notches were produced in two different orientations; the key to the specimen orientation code is given as Figure 13.

A. Tension Specimens

Tensile specimens for parent and crossweld static testing were fabricated as 0.250 inch diameter round specimens having a gage length of 1.0 inch according to ASTM E 8. This specimen is proportional in scale, but smaller in size, to the standard ASTM 0.505 inch diameter Round Tension Test Specimen. The ends of the specimens were threaded to 1/2-13NC-2A for use with the grips in the Instron testing machine. All these specimens were taken with the long dimension in the rolling direction of the plate, from a cylinder whose axis was at the 1/4 T thickness position.

The particular tensile specimen was chosen for several reasons. While not sampling the entire weld, it certainly samples an adequate volume of material. In fact, by taking a quarter thickness location, it actually permits a more uniform sample of weld material than would a larger specimen which would have more weld metal but also more base metal as well. Moreover, this location samples the same material as does the Charpy specimen and so provides a more direct comparison. The base metal tensile specimen is not subject to these constraints but was chosen the same size for convenience. The 1.25 inch gage length was used because the 1.00 inch length causes extensometer gripping problems at the radius at the end of the gage length. Thus a longer gage was chosen to eliminate this problem. The basis for the stress-strain plots was a one inch gage length but the punch marks for the percent elongation were taken on the full 1.25 inch length.

B. Charpy V-Notch (C_V) Specimens

Standard Charpy V-Notch specimens of length 2.165 inches and cross section 0.394 x 0.394 inch were prepared per ASTM E 23. The long dimension of the specimen was taken in the rolling direction of the plate in all cases. The parent material, the weld material, and the heat affected zone C_V specimens were all machined in the L-T orientation. The notch was machined to a radius of 0.010" $\pm$ 0.001 inch in accordance with ASTM E 23 practice. All specimens were taken at quarter thickness; the weldment specimens had their notch cut perpendicular to the surface of the plate. The location of weld and HAZ specimens was selected by etching the material and then locating the center of the notch tip in the desired weldment area. No attempt was made to locate a minimum toughness zone through extensive material sampling as this would have been outside the scope of work. Since the joint design was double bevel (see Appendix A) this means that the Charpy values obtained are, to some extent, averages of weldment, HAZ, and base metal.

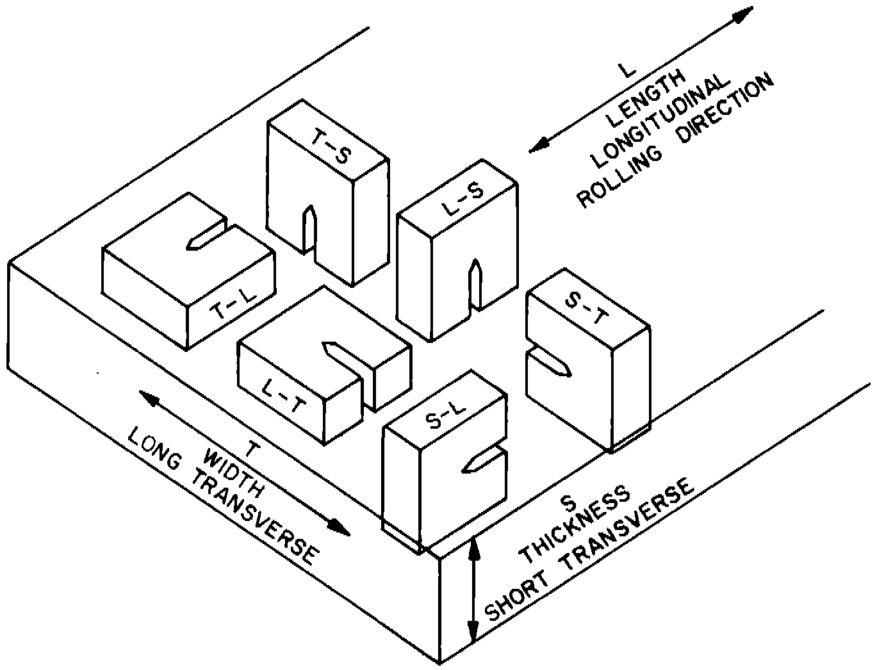


Figure 13. Specimen Orientation Code

C. Weld Side Bend Specimens

All weld side bend specimens were machined per ASTM E 190, "Side-Bend Specimen for Ferrous Materials." The long dimension of the specimen was taken in the rolling direction of the parent materials; the specimen itself was of full thickness.

D. Drop Weight - NDT Specimens

Drop weight nil ductility temperature (DW-NDT) specimens of 5/8 in. thickness (parent material and weld material) were prepared per ASTM E 208. Specimens were machined so that one side was at the surface of the parent plate, with a notched crack-starter weld bead placed on the as-fabricated tension surface in accordance with E208 specifications. The long dimension of the specimen coincided with the rolling direction of the plate. Brittle Murex Hardex N hard facing electrodes crack starter weld beads were applied to each specimen per ASTM E 208.

E. 5/8-Inch Dynamic Tear Specimens

The dynamic tear (DT) specimen test procedure is presently (1976) proposed as an ASTM standard. The specimen is a single edge notched beam 7.125 inches in length, 0.625 inch in thickness, and notched at mid-span to a depth of 0.475 inch, where the total specimen width is 1.60 inch. The specimen is dynamically loaded in three-point bending, on supports placed 6.5 inches apart, by a striker tup of radius 0.5 inch so as to place the notch in mode I tension loading. The specimen was tested in a double pendulum type machine, and total energy loss during separation was recorded. Details of the test specimen and test procedure may be found in Reference 4.

Parent material specimens were machined in the L-T and T-L orientations (Fig. 13), from the plate surface. Weld metal and HAZ specimens likewise were prepared from the plate surface with the long dimension of the specimen in the plate rolling direction. The notches of the weldment specimens were perpendicular to the surface. Following etching, the notch up was centered in the appropriate material. No attempt was made to locate a minimum toughness area. Most of the specimens were press-notched with a hardened tool steel blade sharpened to a razor edge at 45°. The blade was pressed into the machined notch to a depth of 10 mils in accordance with ASTM recommendations. Some of the specimens were fatigue precracked rather than press notched; this was done to determine the effect of notch acuity on the fracture energy measured by the dynamic tear machine. The fatigue crack provides a very sharp tip so that fracture consists of crack propagation only; the blunter pressed notch must devote part of its energy to starting the crack before the propagation phase. The precracking operation was accomplished in three point bending cyclic loading at 23 Hz with a maximum centerpoint load/cycle of 4500 lb. This cyclic loading was sufficient to create a crack of about .060 to .120 inch, visible from both ends, in approximately 5×10^4 cycles.*

* The specimens were subjected to from 22,000 to 145,000 cycles of load.

F. 1-Inch Dynamic Tear Specimens

In addition to the proposed ASTM standard for the 5/8-inch DT specimen mentioned above, there are at least two other similar but different test specimens used in evaluating the dynamic toughness of thick plate. The specimen used in this project differed from either of these two, but used features common to both. The specimen complied in length (10 in.) and width (3 in.) to ASTM E 436, but was a full 1-inch thick. The notch detail was similar to that prescribed by the NRL in their 1-inch D.T. specimen (Ref. 5), but was only 1-inch in depth. The specimen chosen for the present program was designed to be compatible with SwRI's large impact machine, which was developed for a 1-inch Drop Weight Tear specimen as defined by ASTM. As such the specimen used is shorter (10" vs 18") and narrower (3 " vs 4.75") than the NRL specimen, but is a full 1 inch thick. While this size difference means that the absolute energy measured by the two specimens will be different, the temperature dependence of the impact event should be the same.

The specimen was dynamically loaded in three-point bending, on supports placed 10 inches apart, by a striker tup of radius 1.0 inches so as to place the notch in mode I tension loading. The specimen was tested in a large (5000 ft-lb capacity) single pendulum type machine, and total energy loss during separation was recorded.

Parent material specimens only were fabricated, and all were in the L-T orientation (Figure 13). The specimens were press-notched after machining using the same procedure as prescribed by the proposed ASTM standard on 5/8-inch D.T. specimens as described earlier.

G. Explosion Crack Starter Specimens

The Explosion Crack Starter (ECST) test specimen is a structural-type specimen designed to exercise a complete welded section in biaxial bending. The test is described in detail in the NAVSHIPS report cited as Reference 6. The specimen is a full thickness welded plate 20" x 20" square, with the 2/3 T, 1/3 T double vee notch weld (as described in Appendix A) across the center of the specimen. A modified explosion bulge specimen, the ECST specimen has brittle Murex Hardex N crack starter beads placed over a length of 2.5 inches along the weld on one surface. The Hardex beads are notched in perpendicular directions to the specimen sides leaving a prescribed ligament, and do not extend into either the joint bead or the weld plate. The specimen then is placed atop a thick die having a 12-inch circular hole with a 2-inch radius beveled edge, as shown in Figure 14.

In the case of the 1-1/4-inch and the high strength 1-inch plate specimens a temper bead (per procedures, see Appendix A) was placed along either side of the test weld to temper the HAZ of the last filler pass. This resulted in a sizable crown on the weld. After placing the Hardex atop the crown, the starter crack was either too far from the plate surface or, if the weld was notched so that the crack tip was 0.090-in. from the surface, the crack tip was in the temper bead instead of the brittle Hardex. Based on the discussion in Reference 6, these temper beads were not considered to be part of the structural weld. This meant that the temper beads could be ground flat on the 1-1/4-in. specimens prior to applying the Hardex, when the temper beads exceeded 1/16 to 1/8 in. in height. The effectiveness of temper beads in such applications, it must be said, is open to question. In a recent report by the Mare Island

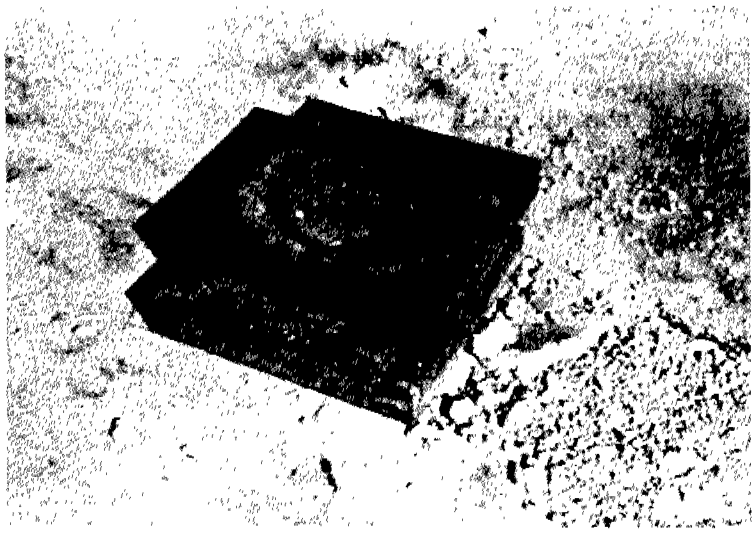


Fig. 14. Steel Dies for Explosion Crack Starter (ECST) Tests

Naval Shipyard [8] it was concluded, for example, that "there is no evidence to support the need for the temper bead technique on ASTM A537 Grade B steel."

H. Explosion Tear Specimens

The explosion tear (ET) test specimen was designed for this program to evaluate the crack arrest properties of the base plate material. Like the ECST specimen, it is a full thickness specimen which is composed of a 6.5-inch-wide strip of a brittle steel to which a strip of the base metal to be tested is welded on either side. The brittle center strip used in the present project was ASTM A36* of 1- and 1-1/4-inch thicknesses to match the thicknesses of the base materials being tested. The test is designed to test the crack arrest capabilities of several steels. To accomplish this, a fast running crack is needed which would enter a strip of the candidate steel. The A-36 was used as a brittle starter to produce such a fast running crack. Along with this, the weldment holding the specimen together was deliberately undermatched to prevent the arrest from taking place in the weldment. The total specimen size is nominally 22 inches in the direction of the welds by 25 inches in the transverse direction. In order to place the specimen in one-dimensional bending under an explosive charge, two 12-inch long flame cuts are placed parallel to the welds, 17 inches apart.

The standard ET specimen features a through-the-thickness, sharp crack of length equal to 2 T (twice the thickness), developed in the plate by a brittle weld "patch" technique. In the present investigation, a slightly different procedure was used. First, two holes were drilled at the ends of the starter crack and connected by flame cutting. The resulting crack was wide enough that a weld rod could be inserted; this allowed the Hardex to be deposited at the ends of the notch. The starter crack configuration was thus an open notch with only the tips filled with brittle Hardex.

During the test event the specimen is laid atop a thick steel die having a rectangular (12.5-inches x 18.5-inches) cutout with a 3-inch radius beveled edge on the two long sides, as shown in Figure 15, and the test specimen configuration is shown in Figure 15b. Details of the test procedure are to be found in Reference 7.

*Procured from Jorgensen Steel in Houston, TX.

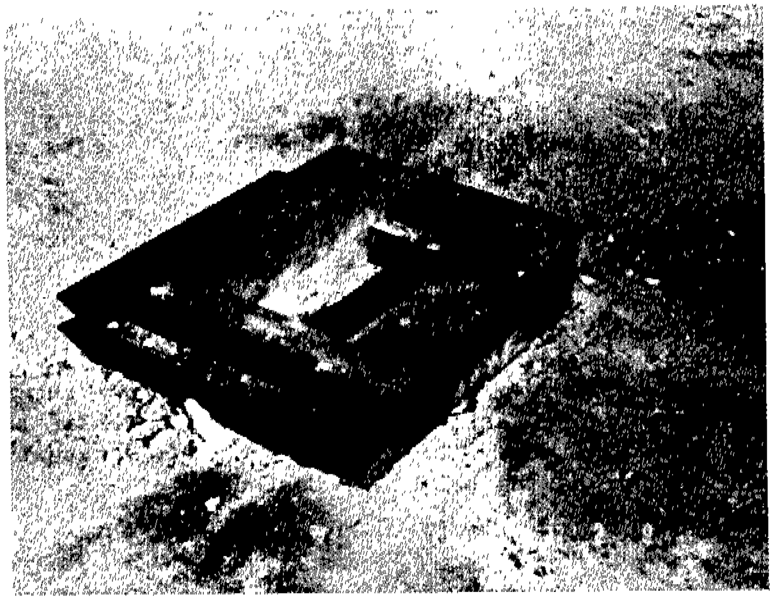


Fig. 15a. Steel Dies for Explosion Tear (ET) Tests

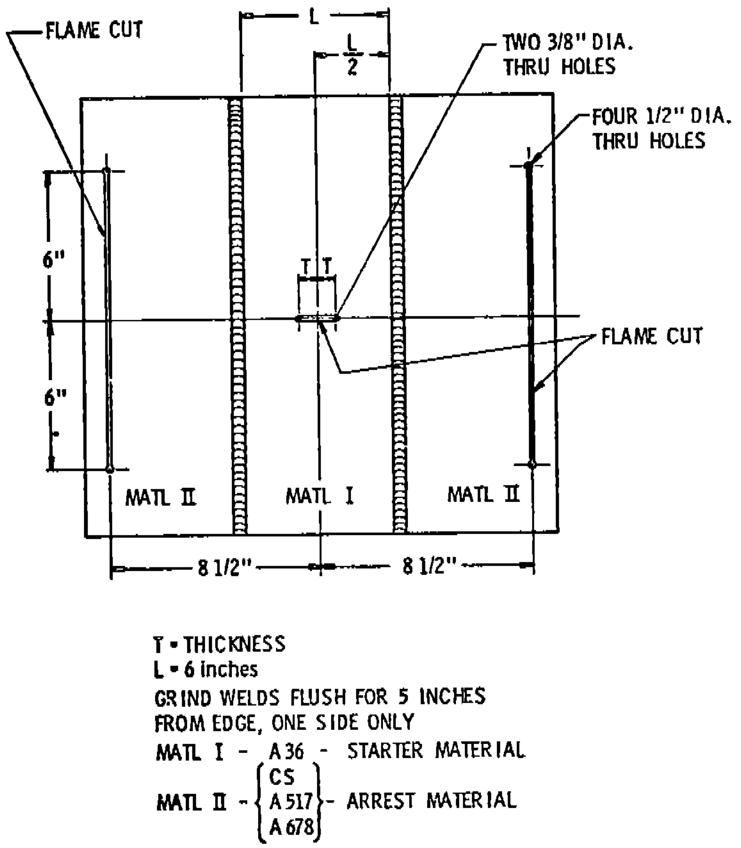


Fig. 15b. Special Explosion Tear Test Specimen

IV. MECHANICAL TESTING PROCEDURES AND RESULTS

A. Test Matrix

Table 3 presents a summary of the numbers and kinds of tests as related to each of the heats tested. Test specimen configurations are defined in Section III of this report. Only eleven of the twelve heats were tested in the present program; Heat Number 1, ABS-DS, is carried in the table for consistency with the heat designations of Program SR-231, in which Heat No. 1 was used in the test program. In the test data to be reported, minor deviations from this test matrix can be found. For example, in Heat No. 4, one of the Charpy HAZ specimens was lost in a mis-test. Further, all 18 ECST specimens indicated in Table 3 were made but not tested because the nature of that test procedure is to cease tests at higher temperatures if the weldment "passes" at a lower temperature. This screening process resulted in four of the ECST specimens not having had to be tested.

B. Tension Tests

Static tension tests were conducted on one specimen from each of Heats No. 2-11 to determine yield and ultimate strengths, elongation and reduction in area of the base materials. All tests were conducted at room temperature (75°F) and at a head rate of 0.01 inch/minute. A summary of the test data is provided in Table 4. Comparison of these data with those supplied by Armco Steel in their certification records of Heats 2-10 reveals the two sets to be mutually consistent. Some differences are present in comparing σ_y and σ_{ult} of Heats 6 and 8:

	σ_y SwRI/Armco	σ_{ult} SwRI/Armco
Heat 6: A517-D	128.2/113.7*	134.6/125.2*
Heat 8: A678-C	77.0/87.7	96.3/106.9

*Average of two values.

These differences are not considered important, however.

In addition to characterizing the parent material, cross-weld specimens were tested to evaluate the strength and elongation properties of the weld region. The test conditions for the cross weld specimens were the same as for the parent materials. Two weld procedures were evaluated in these tests: Shielded Manual Arc Weld (SMAW) and Submerged Arc Weld (SAW), as described in Section II.B. Table 5 presents a summary of the test data for the cross-weld specimens.

In comparing the results presented in Tables 4 and 5, there are eight heats comprising five different materials where a comparison is afforded between the base metal and one or more weldments. These comparative results are summarized in the following table:

Table 3. Overall Test Matrix

TEST TYPE	HEAT NUMBER (SEE KEY)												
	1	2	3	4	5	6	7	8	9	10	11	12	Σ
Static Tension, Parent	--	1	1	1	1	1	1	1	1	1	1	--	1[illegible]
Static Tension, Crossweld	--	--	1	2	--	2	--	2	--	1	--	1	[illegible]
Charpy, Parent (L-T)	--	15	15	15	15	15	15	15	15	15	15	--	15[illegible]
Charpy, HAZ	--	--	15	30	--	30	--	30	--	15	--	15	13[illegible]
Charpy, Weld	--	--	15	30	--	30	--	30	--	15	--	15	13[illegible]
Weld Side Bend	--	--	1	2	--	2	--	2	--	1	--	1	[illegible]
DW-NDT, 5/8", Parent	--	6	6	6	6	6	6	6	6	6	6	--	6[illegible]
DW-NDT, 5/8", Weld	--	--	6	12	--	12	--	12	--	6	--	6	5[illegible]
DT, 5/8", Parent (L-T)	--	6	6	6	6	6	6	6	6	6	6	--	6[illegible]
DT, 5/8", Parent (T-L)	--	3	3	3	3	3	3	3	3	3	3	--	3[illegible]
DT, 5/8", Weld	--	--	6	24	--	12	--	12	--	6	--	6	6[illegible]
DT, 5/8", HAZ	--	--	3	12	--	6	--	6	--	3	--	3	3[illegible]
DT, 1", Parent (L-T)	--	3	3	3	3	3	3	3	3	3	3	--	3[illegible]
Explosion Crack Starter (ECST)	--	--	--	6	--	6	--	6	--	--	--	--	1[illegible]
Explosion Tear (ET)	--	--	--	2	--	2	--	2	--	--	--	--	[illegible]

Key

Heat No.	Material	Heat No.	Material
1	ABS-DS	7	ASTM A678-C
2	ABS AH-32	8	ASTM A678-C
3	ABS EH-32	9	ASTM A537-B
4	ABS-CS	10	ASTM A537-B
5	ASTM A517-D	11	ABS-B
6	ASTM A517-D	12	ABS-B

Table 4 - Static Tension Test Results, Parent Material

Heat No.	Material	σ_y (ksi)	σ_{ult} (ksi)	% Elong.	% Red. Area	Gage Length (in.)
2	ABS AH-32	63.4	90.2	21.9	60.1	1.278
3	ABS EH-32	50.6	73.9	28.7	72.3	1.253
4	ABS-CS	45.0	69.6	29.4	68.4	1.281
5	ASTM A517-D	120.6	126.7	15.0	68.5	1.279
6	ASTM A517-D	128.2	134.6	13.6	65.0	1.284
7	ASTM A678-C	74.3	96.3	19.9	70.7	1.276
8	ASTM A678-C	77.0	96.3	23.0	71.8	1.268
9	ASTM A537-B.	61.8	82.0	29.7	73.9	1.275
10	ASTM A537-B	69.0	89.6	22.7	68.7	1.260
11	ABS-B	33.8	61.2	32.0	65.8	1.267

Note: Tests conducted at 75°F and a head rate = 0.01 inch/minute.

Table 5 - Static Tension Test Results, Cross Weld Specimens

Heat No.	Base Material	σ_y (ksi)	σ_{ult} (ksi)	% Elong.	% Red. Area	Gage Length (in.)
3	ABS EH-32(a)	70.7	86.7	14.1	61.6	1.301
4	ABS-CS(a)	53.6	74.5	21.6	74.8	1.215
4	ABS-CS(b)	58.5	75.6	17.4	69.0	1.273
6	ASTM A517-D(a)	99.8	112.5	16.4	65.2	1.241
6	ASTM A517-D(b)	95.4	106.9	6.2	24.1	1.201
8	ASTM A678-C(a)	77.5	93.6	16.9	66.8	1.266
8	ASTM A678-C(b)	79.3	97.5	18.6	70.5	1.274
10	ASTM A537-B(a)	71.1	86.6	16.2	61.2	1.336
12	ABS-B(a)	55.0	70.5	21.9	61.1	1.239

(a) SAW Weld Procedure

(b) SMAW Weld Procedure

Note: Tests conducted at 75°F and a head rate = 0.01 inch/minute.

Heat No.	Material	Heat Treat	σ_y Parent/SAW/SMAW	σ_{ult} Parent/SAW/SMAW
3	EH-32	Norm.	50.6/70.7/----	73.9/86.7/----
4	CS	Norm.	45.0/53.6/58.5	69.6/74.5/75.6
5	A517-D	Q&T	120.6/----/----	126.7/----/----
6	A517-D	Q&T	128.2/99.8/95.4	134.6/112.5/106.9
7	A678-C	Q&T	74.3/----/----	96.3/----/----
8	A678-C	Q&T	77.0/77.5/79.3	96.3/93.6/97.5
9	A537-B	Q&T	61.8/----/----	82.0/----/----
10	A537-B	Q&T	69.0/71.0/----	89.6/86.6/----

These comparisons indicate that for the base metals and weldments evaluated in this project, in the case of normalized steels, the weldments had higher yield and ultimate strengths than did the base metals. In examining the Q&T steels it appears that in the case of medium strength alloys (A537-B and A678-C) the SAW and SMAW weldments again had higher yield and ultimate strengths, but the differences were marginal, certainly much less important than for the normalized steels of lower strength. However, for the high strength Q&T alloy (A517-D) the parent material exhibited significantly higher yield and ultimate strengths than either the SAW or SMAW weldments.

C. Charpy V-Notch Tests

C_v testing was done in accordance with the provisions of ASTM E-23 on a 240 ft-lb Riehle impact pendulum testing machine. Machine calibration was accomplished by testing AMMRC supplied calibration specimens periodically. Cooling of the specimen from room temperature down to -110°F was accomplished by immersing the specimens in an agitated bath of methanol and dry ice for 10 minutes at temperature as required by ASTM. C_v testing above room temperature was accomplished by stabilizing the specimens in an agitated bath of water warmed by submersible heaters.

Results from the parent material C_v tests in the L-T orientation are to be found in Figures 16-25; detailed data are presented in Table 6. Fifteen specimens were tested for each heat; triplicate tests at each of five temperatures selected to cover the transition region and define the upper shelf energy level. Approximate upper shelf Charpy impact energies are summarized below.

Heat No.	Material	C_v (ft-lb)
2	AH-32	40
3	EH-32	70
4	CS	75
5,6	A517-D	65,55
7,8	A678-C	80,100
9,10	A537-B	75,55
11	B	50

Charpy impact tests also were conducted on welded specimens of selected heats. Tests conducted on specimens of SAW weldments from Heats 3, 10, and 12 were conducted to evaluate the relative energy absorption of the weld metal and HAZ for these three classes of materials. The results are presented in

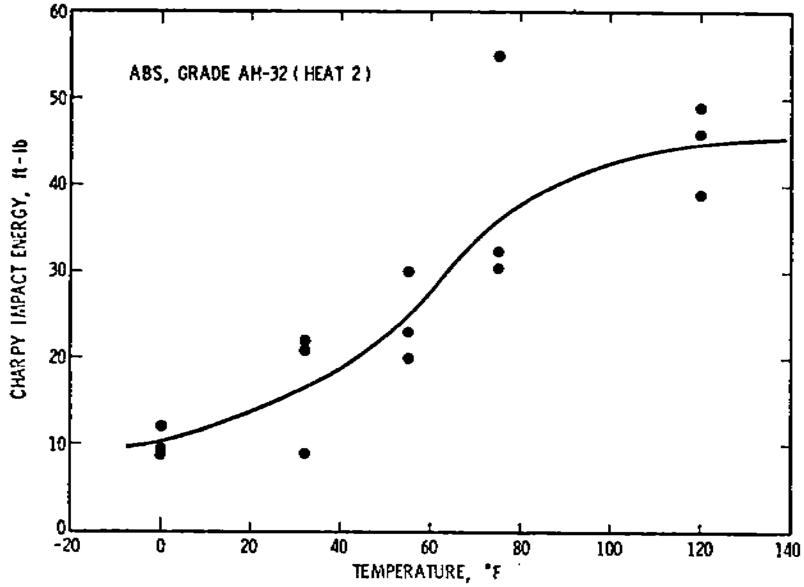


Figure 16. ABS, Grade AH-32 (Heat 2) Parent Material CVN

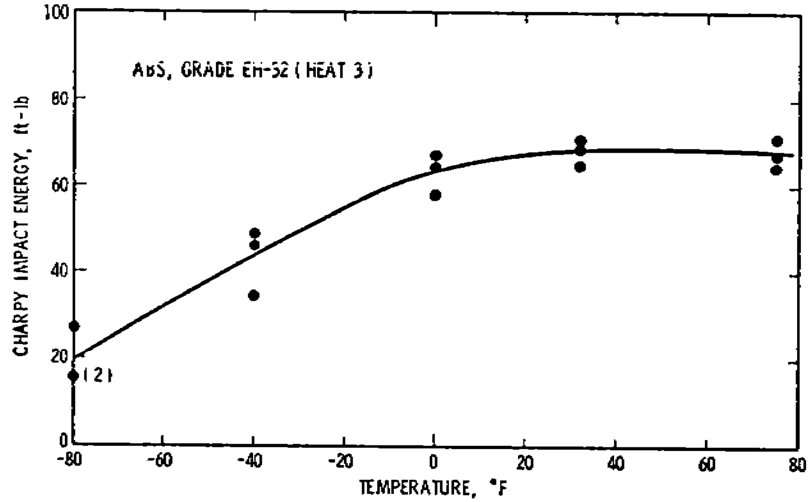


Figure 17. ABS, Grade EH-32 (Heat 3) Parent Material CVN

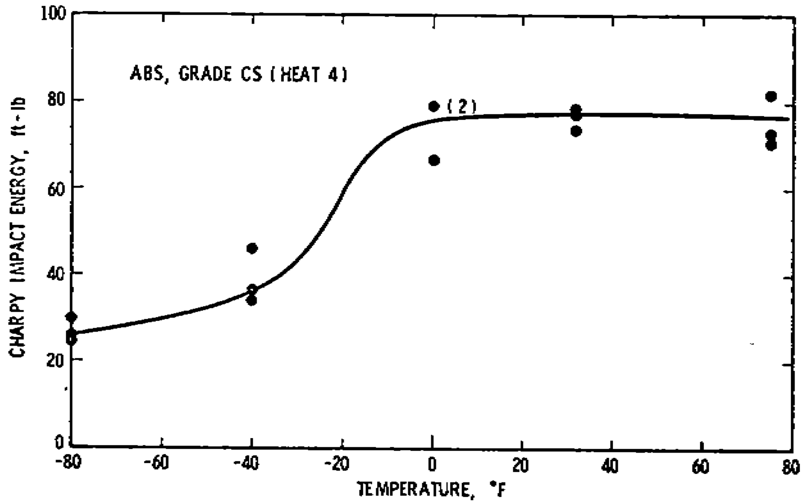


Figure 18. ABS, Grade CS (Heat 4) Parent Material CVN

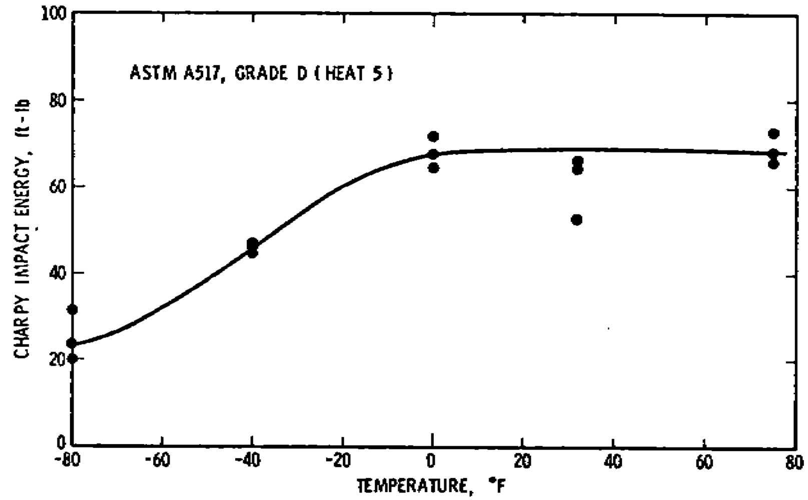


Figure 19. ASTM A517, Grade D (Heat 5) Parent Material CVN

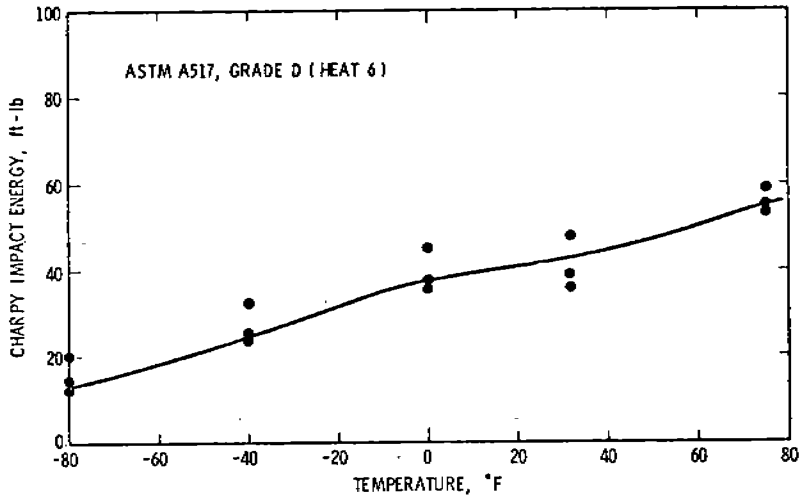


Figure 20. ASTM A517, Grade D (Heat 6) Parent Material CVN

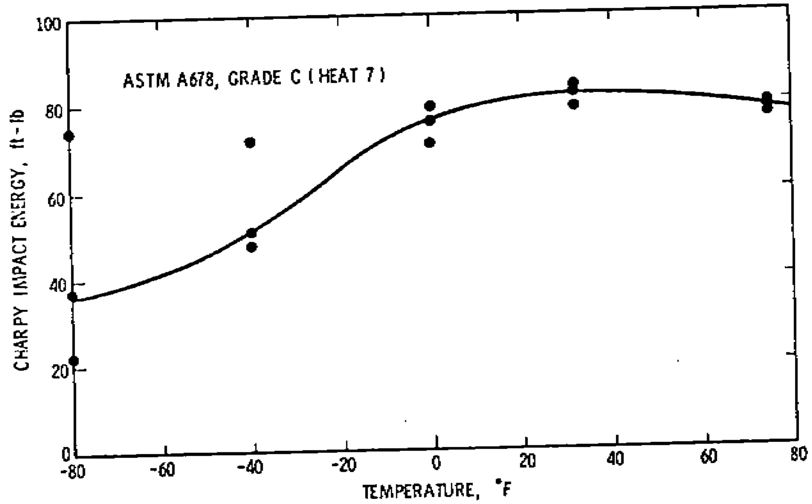


Figure 21. ASTM A678, Grade C (Heat 7) Parent Material CVN

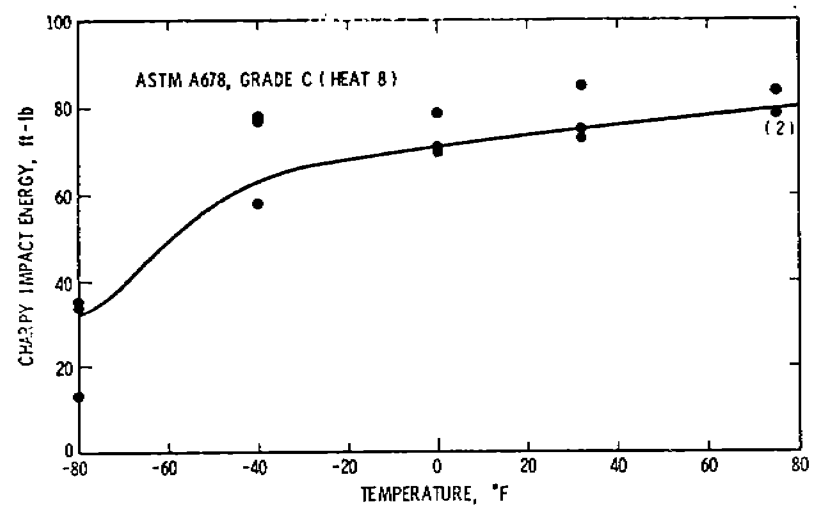


Figure 22. ASTM A678, Grade C (Heat 8) Parent Material CVN

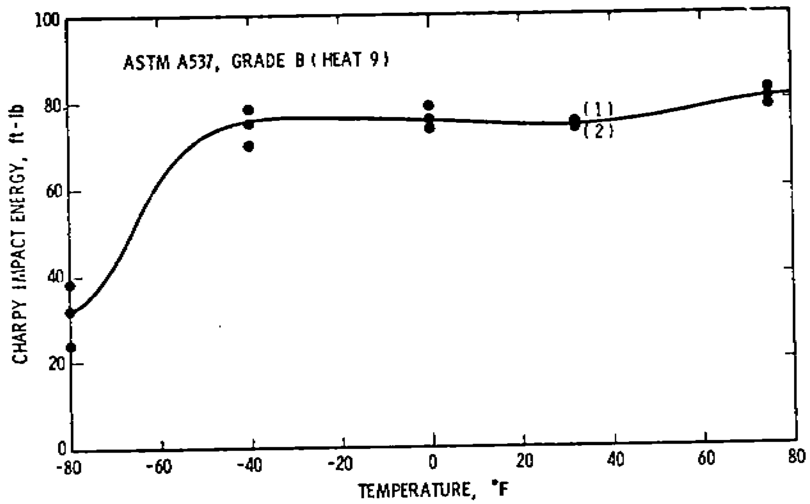


Figure 23. ASTM A537, Grade B (Heat 9) Parent Material CVN

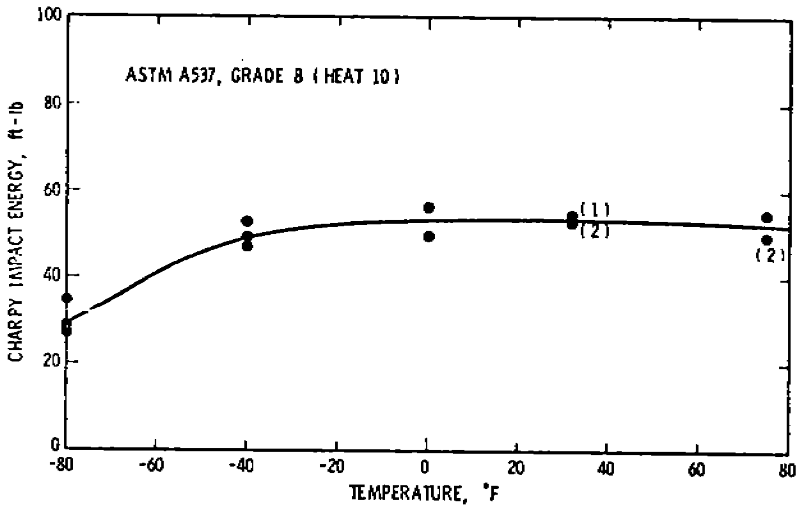


Figure 24. ASTM A537, Grade B (Heat 10) Parent Material CVN

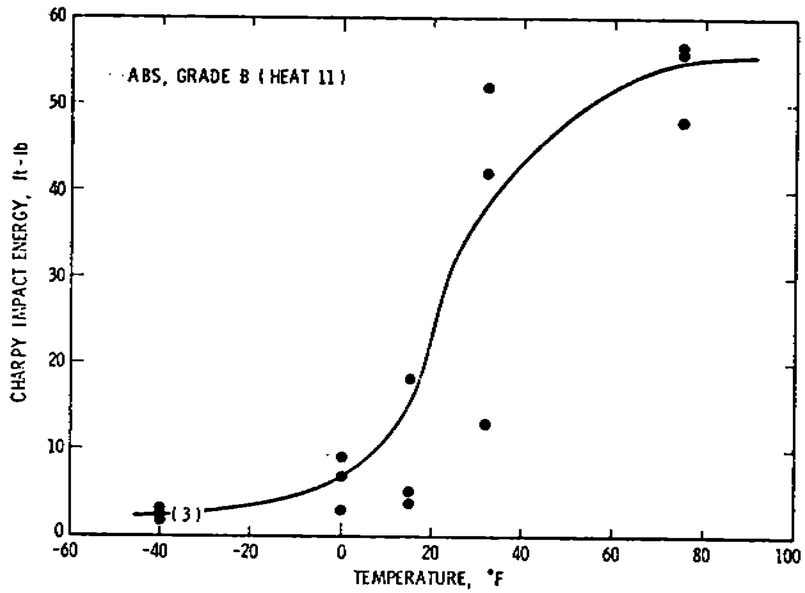


Figure 25. ABS, Grade B (Heat 11) Parent Material CVN

Table 6. C_V Test Results: Parent Material, L-T

Heat No.	Material	Test Temp, °F	Energy Ft-Lbs	Initial Width	Final Width	Lateral Expansion	Fracture App %
2	ABS AH-32	0	9	.394	.401	.007	0
		0	9.5	.394	.402	.008	0
		0	12	.394	.404	.010	0
		32	22	.395	.415	.020	11
		32	21	.395	.414	.019	21
		32	9	.395	.406	.011	30
		55	23	.394	.418	.024	37
		55	30	.394	.424	.030	35
		55	20	.394	.416	.022	24
		75	32.5	.394	.427	.033	44
		75	30.5	.395	.424	.029	50
		75	55	.394	.426	.032	45
		120	39	.394	.436	.042	79
		120	49	.395	.446	.051	95
		120	46	.395	.442	.047	90
3	ABS EH-32	-80	27	.394	.419	.025	20
		-80	15	.394	.407	.013	17
		-80	15	.394	.409	.015	15
		-40	34	.395	.429	.034	49
		-40	48	.394	.439	.045	39
		-40	46	.395	.439	.044	65
		0	64	.394	.450	.056	98
		0	58	.394	.440	.046	79
		0	67	.393	.451	.058	100
		32	65	.394	.456	.062	100
		32	70	.394	.460	.066	100
		32	69	.395	.456	.061	100
		75	65	.394	.457	.063	100
		75	71	.394	.463	.069	100
		75	67.5	.395	.457	.062	100
4	ABS-CS	-80	24	.394	.419	.025	18
		-80	25	.394	.419	.025	23
		-80	30	.394	.423	.029	21
		-40	36	.394	.431	.037	46
		-40	46	.394	.440	.046	64
		-40	34	.394	.431	.037	45
		0	79	.394	.461	.067	97
		0	67	.394	.454	.060	91
		0	79	394	.461	.067	100
		32	78.5	.394	.461	.067	100
		32	77.5	.394	.467	.073	100
		32	74	.394	.459	.065	100
		75	73	.394	.462	.068	100
		75	82	.395	.468	.073	100
		75	71	.395	.464	.069	100
5	ASTM A517-D	-80	31	.394	.414	.020	32
		-80	23	.394	.410	.016	26
		-80	20	.394	.407	.013	22
		-40	46	.395	.427	.032	50
		-40	47	.395	.425	.030	42
		-40	45	.394	.424	.030	45
		0	65.5	.394	.439	.045	100
		0	68	.394	.440	.046	100
		0	72	.394	.443	.049	100
		32	53.5	.394	.432	.038	68
		32	66	.394	.442	.048	100
		32	65	.394	.443	.049	100
		75	73	.394	.451	.057	100
		75	68	.395	.445	.050	100
		75	66.5	.394	.442	.048	100
6	ASTM A517-D	-80	20	.394	.406	.012	22
		-80	12	.394	.400	.006	17
		-80	14	.394	.403	.009	19
		-40	25	.394	.412	.018	44
		-40	32.5	.394	.416	.022	38
		-40	24	.394	.411	.017	57
		0	36	.394	.418	.024	40
		0	45	.394	.426	.032	47
		0	37	.394	.420	.026	37
		32	36	.394	.422		39
		32	39	.394	.423		40
		32	48	.394	.427		35
		75	59	.394	.435	.041	100
		75	54	.395	.435	.040	100
		75	55	.401	.440	.039	100
7	ASTM A678-C	-80	22	.395	.416	.021	40
		-80	74	.394	.434	.040	74
		-80	37	.395	.423	.028	38
		-40	51	.394	.436	.042	57
		-40	48	.394	.434	.040	48
		-40	72	.394	.449	.055	95
		0	71	.394	.451	.057	100

Table 6. C_v Test Results: Parent Material, L-T (Concl'd)

Heat No.	Material	Test Temp, °F	Energy Ft-Lbs	Initial Width	Final Width	Lateral Expansion	Fracture App %
		0	76	.394	.453	.059	100
		0	79	.394	.458	.064	100
		32	83	.394	.460	.066	100
		32	79	.394	.459	.065	100
		32	84	.394	.461	.067	100
		75	78	.394	.463	.069	100
		75	79	.394	.455	.061	100
		75	77.5	.394	.458	.064	100
8	ASTM A678-C	-80	54	.395	.436	.041	34
		-80	55	.395	.434	.039	45
		-80	33	.395	.421	.026	32
		-40	78	.394	.452	.058	62
		-40	97	.394	.463	.069	100
		-40	98	.394	.465	.071	100
		0	91	.394	.458	.064	100
		0	99	.394	.465	.071	100
		0	90	.394	.461	.067	100
		32	93.5	.394	.459	.065	100
		32	95	.395	.466	.071	100
		32	105	.394	.461	.067	100
		75	99	.394	.460	.066	100
		75	99	.394	.459	.065	100
		75	104	.394	.469	.075	100
9	ASTM A537-B	-80	32	.394	.425	.031	52
		-80	24	.394	.418	.024	40
		-80	38	.394	.428	.034	36
		-40	75	.394	.457	.063	100
		-40	70	.394	.453	.059	97
		-40	78	.394	.454	.060	100
		0	78	.395	.457	.062	100
		0	74	.395	.459	.064	100
		0	76	.394	.457	.063	100
		32	75	.394	.455	.061	100
		32	74	.394	.458	.064	100
		32	74	.394	.455	.061	100
		75	79	.395	.460	.065	100
		75	82	.394	.463	.069	100
		75	80	.394	.460	.066	100
10	ASTM A537-B	-80	34	.394	.427	.033	61
		-80	27	.395	.420	.025	46
		-80	28	.394	.422	.028	51

Heat No.	Material	Test Temp, °F	Energy Ft-Lbs	Initial Width	Final Width	Lat Expa
		-40	52.5	.394	.442	[illegible]
		-40	47	.394	.435	[illegible]
		-40	49	.395	.440	[illegible]
		0	80?	.394	.458	[illegible]
		0	49.5	.394	.442	[illegible]
		0	56	.395	.443	[illegible]
		32	54	.394	.445	[illegible]
		32	53	.394	.443	[illegible]
		32	53	.394	.441	[illegible]
		75	49.5	.394	.443	[illegible]
		75	50	.394	.444	[illegible]
		75	55	.395	.446	[illegible]
11	ABS-B	-40	2.5	.394	.396	[illegible]
		-40	2	.394	.400	[illegible]
		-40	3	.394	.396	[illegible]
		0	9	.394	.404	[illegible]
		0	7	.395	.405	[illegible]
		0	3	.394	.398	[illegible]
		15	5	.394	.401	[illegible]
		15	4	.393	.396	[illegible]
		15	18	.394	.418	[illegible]
		32	13	.394	.408	[illegible]
		32	52	.394	.445	[illegible]
		32	42	.394	.440	[illegible]
		75	56	.395	.449	[illegible]
		75	56.5	.394	.449	[illegible]
		75	48	.394	.445	[illegible]

Table 7 and are summarized in Figures 26-28. In Table 7 the difference between the final specimen width and the initial width (not shown, but averaged 0.395 in.) provided the values shown under the Lateral Expansion column.

There was no significant difference in Charpy energy levels between the weld metal and the HAZ specimens for the EH-32 steel. The upper shelf energy level was approximately the same as for the EH-32 parent material. The same conclusion holds for the A537-B specimens, although there the room temperature weld metal Charpy specimens outperformed the HAZ specimens somewhat. Upper shelf energy levels were about the same, averaging 55 ft-lb for parent, HAZ, and weld specimens. More important differences were found between weld and HAZ energy levels for the ABS-B plate. There, as can be seen in Figure 28, the HAZ energy levels at 32°F and 75°F were significantly higher than for the weld material.

One other series of Charpy tests was conducted, to evaluate the relative performance of SAW and SMAW weldments. This was done by preparing 15 Charpy specimens from weldments of each type for Heat 4 (ABS-CS), Heat 6 (A517-D), and Heat 8 (A678-C). Both weld and HAZ regions were evaluated in this series.

The tabular results are given in Table 7 and are shown graphically in Figures 29-31 for the HAZ materials, and in Figures 32-34 for the weld metals. No significant difference was found in the upper shelf impact energies in comparing the SAW and SMAW HAZ specimens of ABS-CS or A517-D heats or with their respective parent material upper shelf energy values. In the case of the A678-C HAZ specimens, the SMAW and the SAW specimens exhibited upper shelf energies, respectively, higher and lower than that of the parent material specimens.

An examination of the data from the weld metal specimens showed the SMAW weldments to have higher upper shelf energies than the SAW specimens for all three base plates. In the case of ABS-CS and A517-D, the energy levels for the SAW weld metal specimens was about the same as for the parent material, but in the case of A678-C, both SAW and SMAW specimens yielded upper shelf values decidedly lower than the parent material. These results are summarized below.

Approximate Upper Shelf C_v Energy Levels, Ft-Lbs

Heat No.	Material	Parent Material	HAZ Specimens		Weld Metal Specimens	
4	ABS-CS	75	SAW:	75	SAW:	80
			SMAW:	70	SMAW:	120
6	A517-C	55	SAW:	60	SAW:	55
			SMAW:	60	SMAW:	65
8	A678-C	100	SAW:	80	SAW:	60
			SMAW:	140	SMAW:	75

Table 7. C_v Test Results in Weld and HAZ Regions of Various Plates Welded with SMAW and SAW Processes

Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion	Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion
3/ ABS EH-32	SAW/ Weld	-100	15.0	0.414	0.019	4/ ABS-CS	SAW/ HAZ	-80	11.5	0.407	0.[illegible]
		-100	22.0	0.417	0.022			-80	8.0	0.401	0.[illegible]
		-100	15.0	0.410	0.015			-80	22.0	0.416	0.[illegible]
		-60	32.5	0.427	0.032			-40	22.0	0.419	0.[illegible]
		-60	21.5	0.420	0.025			-40	41.0	0.434	0.[illegible]
		-60	27.5	0.425	0.025			-40	37.0	0.431	0.[illegible]
		-20	56.5	0.450	0.055			0	58.0	0.449	0.[illegible]
		-20	50.0	0.445	0.050			0	56.0	0.448	0.[illegible]
		-20	51.0	0.447	0.052			0	58.5	0.451	0.[illegible]
		32	63.5	0.457	0.063			32	71.5	0.457	0.[illegible]
		32	63.5	0.456	0.061			32	66.0	0.456	0.[illegible]
		32	66.0	0.446	0.051			32	69.5	0.456	0.[illegible]
		75	67.0	0.461	0.066			75	78.5	0.463	0.[illegible]
		75	66.0	0.447	0.057			75	75.0	0.463	0.[illegible]
		75	66.5	0.459	0.054			75	75.0	0.464	0.[illegible]
3/ ABS EH-32	SAW/ HAZ	-100	7.5	0.404	0.009	4/ ABS-CS	SMAW/ Weld	-80	37.0	0.426	0.[illegible]
		-100	14.5	0.411	0.016			-80	31.5	0.422	0.[illegible]
		-100	18.0	0.412	0.017			-80	11.5	0.410	0.[illegible]
		-60	22.5	0.417	0.023			-40	53.5	0.438	0.[illegible]
		-60	24.0	0.419	0.025			-40	89.5?	0.459	0.[illegible]
		-60	28.5	0.421	0.027			-40	60.0	0.442	0.[illegible]
		-20	57.0	0.446	0.052			0	87.0	0.463	0.[illegible]
		-20	54.5	0.443	0.049			0	98.0	0.464	0.[illegible]
		-20	45.5	0.437	0.043			0	95.0	0.465	0.[illegible]
		32	64.5	0.455	0.061			32	131.0	0.478	0.[illegible]
		32	67.5	0.455	0.060			32	123.5	0.484	0.[illegible]
		32	67.5	0.453	0.058			32	108.5	0.473	0.[illegible]
		75	75.5	0.463	0.069			75	113.5	0.471	0.[illegible]
		75	70.5	0.460	0.065			75	118.0	0.466	0.[illegible]
		75	73.0	0.459	0.064			75	136.0	0.469	0.[illegible]
4/ ABS-CS	SAW/ Weld	-80	8.0	0.403	0.009	4/ ABS-CS	SMAW/ HAZ	-80	14.0	0.407	0.[illegible]
		-80	3.0	0.397	0.003			-80	13.0	0.406	0.[illegible]
		-80	8.5	0.404	0.010			-80	9.5	0.404	0.[illegible]
		-40	22.0	0.417	0.023			-40	37.5	0.430	0.[illegible]
		-40	29.0	0.424	0.030			-40	36.5	0.428	0.[illegible]
		-40	21.0	0.417	0.023			-40	27.0	0.422	0.[illegible]
		0	46.0	0.443	0.049			0	41.5	0.447	0.[illegible]
		0	46.5	0.443	0.049			0	55.0	0.446	0.[illegible]
		0	36.5	0.433	0.039			0			
		32	71.0	0.471	0.077			32	65.0	0.452	0.[illegible]
		32	73.5	0.465	0.070			32	60.0	0.450	0.[illegible]
		32	60.5	0.450	0.055			32	65.5	0.455	0.[illegible]
		75	84.5	0.461	0.067			75	70.0	0.458	0.[illegible]
		75	80.5	0.470	0.076			75	68.0	0.460	0.[illegible]
		75	85.5	0.465	0.071			75	67.5	0.461	0.[illegible]

Table 7. C_v Test Results in Weld and HAZ Regions of Various Plates Welded with SMAW and SAW Processes (Cont'd)

Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion	Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion
6/ ASTM A517-D	SAW/ Weld	-80	30.5	0.420	0.026	6/ ASTM A517-D	SMAW/ HAZ	-80	24.5	0.414	0.020
		-80	30.5	0.421	0.027			-80	25.0	0.412	0.018
		-80	33.0	0.422	0.028			-80	29.5	0.416	0.022
		-40	39.5	0.427	0.033			-40	27.0	0.414	0.020
		-40	39.0	0.429	0.035			-40	34.5	0.419	0.025
		-40	36.0	0.426	0.032			-40	39.5	0.422	0.028
		0	48.5	0.434	0.040			0	41.5	0.424	0.030
		0	45.5	0.433	0.039			0	42.0	0.425	0.031
		0	50.0	0.436	0.042			0	51.0	0.433	0.039
		32	52.5	0.438	0.044			32	69.0	0.441	0.047
		32	51.5	0.437	0.043			32	53.5	0.436	0.042
		32	50.5	0.438	0.044			32	43.5	0.431	0.037
		75	54.5	0.443	0.049			75	58.0	0.441	0.047
		75	56.0	0.444	0.049			75	63.5	0.445	0.051
								75	53.5	0.441	0.047
6/ ASTM A517-D	SAW/ HAZ	-80	20.0	0.406	0.012	8/ ASTM A678-C	SAW/ Weld	-80	13.0	0.407	0.013
		-80	21.5	0.408	0.014			-80	14.0	0.409	0.015
		-80	28.0	0.414	0.020			-80	13.5	0.408	0.014
		-40	24.5	0.411	0.017			-40	21.0	0.411	0.017
		-40	22.5	0.410	0.016			-40	19.5	0.414	0.020
		-40	36.0	0.422	0.028			-40	23.0	0.417	0.023
		0	48.5	0.429	0.035			0	34.5	0.429	0.035
		0	47.5	0.428	0.034			0	40.0	0.432	0.038
		0	51.5	0.435	0.041			0	39.5	0.432	0.038
		32	65.0	0.440	0.046			32	50.5	0.442	0.048
		32	65.6	0.445	0.051			32	49.5	0.438	0.044
		32	68.5	0.445	0.051			32	47.5	0.425	0.031
		75	64.5	0.445	0.051			75	63.0	0.454	0.060
		75	66.5	0.442	0.048			75	65.6	0.456	0.062
		75	64.0	0.443	0.049			75	66.5	0.454	0.060
6/ ASTM A517-D	SMAW/ Weld	-80	31.0	0.417	0.023	8/ ASTM A678-C	SAW/ HAZ	-80	19.0	0.411	0.017
		-80	26.0	0.412	0.018			-80	19.5	0.411	0.017
		-80	31.5	0.417	0.023			-80	14.5	0.411	0.017
		-40	36.0	0.423	0.029			-40	44.5	0.427	0.033
		-40	37.5	0.425	0.031			-40	43.5	0.429	0.035
		-40	34.5	0.419	0.025			-40	23.5	0.418	0.024
		0	52.5	0.437	0.043			0	39.0	0.432	0.038
		0	49.0	0.437	0.043			0	48.5	0.436	0.042
		0	39.5	0.428	0.034			0	44.0	0.432	0.038
		32	53.5	0.439	0.045			32	91.0	0.458	0.064
		32	63.5	0.445	0.051			32	74.5	0.450	0.056
		32	53.5	0.438	0.044			32	84.0	0.455	0.061
		75	71.5	0.453	0.059			75	70.0	0.451	0.057
		75	76.5	0.445	0.051			75	84.0	0.462	0.068
		75	70.5	0.446	0.052			75	78.5	0.455	0.061

Table 7. C_v Test Results in Weld and HAZ Regions of Various Plates Welded with SMAW and SAW Processes (Concl'd)

Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion	Heat No./ Material	Weld Type/ Location	Test Temp., °F	Energy, Ft-lb	Final Width	Lateral Expansion
8/ ASTM A678-C	SMAW/ Weld	-80	30.0	0.419	0.025	10/ ASTM A537-B	SAW/ HAZ	-100	24.0	0.418	0.023
		-80	28.5	0.424	0.030			-100	15.5	0.409	0.014
		-80	26.0	0.417	0.023			-100	16.0	0.411	0.016
		-40	46.0	0.431	0.017			-60	32.5	0.426	0.032
		-40	31.0	0.422	0.028			-60	31.0	0.423	0.029
		-40	40.0	0.428	0.034			-60	31.5	0.425	0.031
		0	69.0	0.452	0.058			-20	50.0	0.441	0.046
		0	62.0	0.443	0.049			-20	48.0	0.440	0.045
		0	63	0.449	0.055			-20	47.0	0.438	0.044
		32	76.5	0.454	0.060			32	50.0	0.444	0.049
		32	66.5	0.452	0.058			32	55.0	0.445	0.051
		32	71.0	0.450	0.056			32	56.5	0.446	0.052
		75	78.5	0.457	0.063			75	47.0	0.441	0.047
		75	71.5	0.440	0.046			75	52.0	0.447	0.052
		75	81.0	0.463	0.069			75	48.5	0.445	0.050
8/ ASTM A678-C	SMAW/ HAZ	-80	87.5	0.426	0.032	12/ ABS-CS	SAW/ Weld	-60	11.0	0.409	0.014
		-80	52.0	0.435	0.041			-60	11.0	0.409	0.014
		-80	88.0	0.431	0.037			-60	11.0	0.407	0.012
		-40	78.0	0.450	0.056			-20	38.0?		
		-40	50.0	0.431	0.037			-20	20.0	0.420	0.025
		-40	106.0	0.447	0.053			-20	21.5	0.422	0.027
		0	122.5	0.476	0.082			32	32.5	0.434	0.039
		0	123.5	0.476	0.082			32	26.5	0.432	0.037
		0	116.0	0.472	0.078			32	20.0	0.425	0.030
		32	136.0	0.483	0.089			75	42.5	0.445	0.050
		32	154.0	0.484	0.090			75	31.0	0.435	0.040
		32	147.5	0.477	0.083			75	31.5	0.435	0.040
		75	137.0	0.472	0.078			120	75.0	0.464	0.069
		75	129.5	0.478	0.084			120	54.5	0.462	0.067
		75	128.5	0.481	0.087			120	49.5	0.454	0.059
10/ ASTM A537-B	SAW/ Weld	-100	14.5	0.410	0.015	12/ ABS-CS	SAW/ HAZ	-60	16.0	0.410	0.016
		-100	11.0	0.408	0.013			-60	2.0	0.396	0.002
		-100	15.5	0.412	0.017			-60	2.5	0.396	0.002
		-60	29.5	0.426	0.031			-20	8.0	0.407	0.013
		-60	30.5	0.426	0.031			-20	16.5	0.413	0.019
		-60	31.5	0.428	0.033			-20	11.5	0.408	0.015
		-20	44.5	0.438	0.043			32	57.0	0.450	0.055
		-20	48.0	0.440	0.045			32	39.0	0.437	0.043
		-20	47.0	0.440	0.045			32	40.5	0.441	0.047
		32	57.0	0.452	0.057			75	54.5	0.453	0.059
		32	62.0	0.442	0.047			75	60.5	0.457	0.063
		32	54.5	0.447	0.052			75	60.5	0.457	0.063
		75	64.0	0.458	0.063			120	67.5	0.463	0.068
		75	66.0	0.461	0.066			120	50.0	0.449	0.055
		7	69.0	0.462	0.067			120	53.5	0.454	0.060

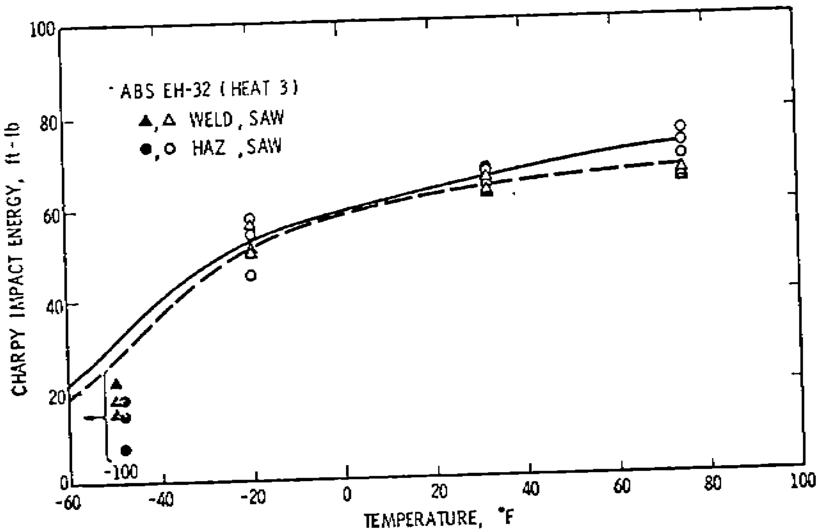


Figure 26. ABS-EH-32 (Heat 3)

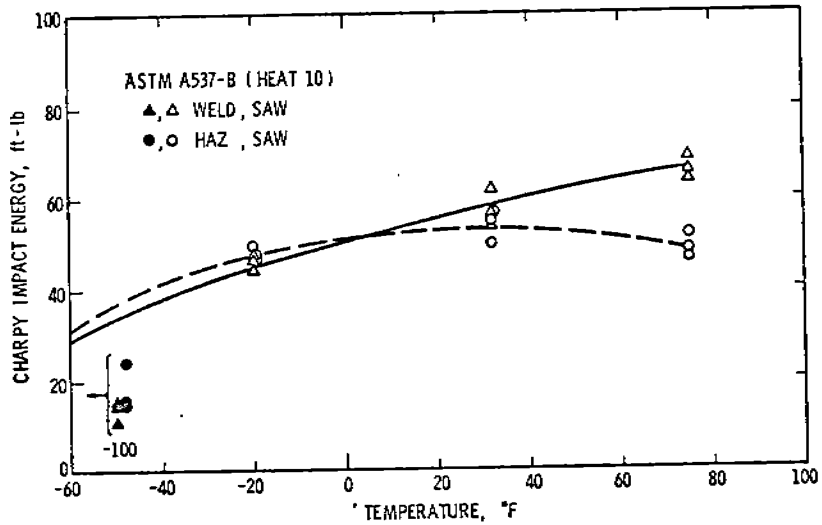


Figure 27. A537-B (Heat 10)

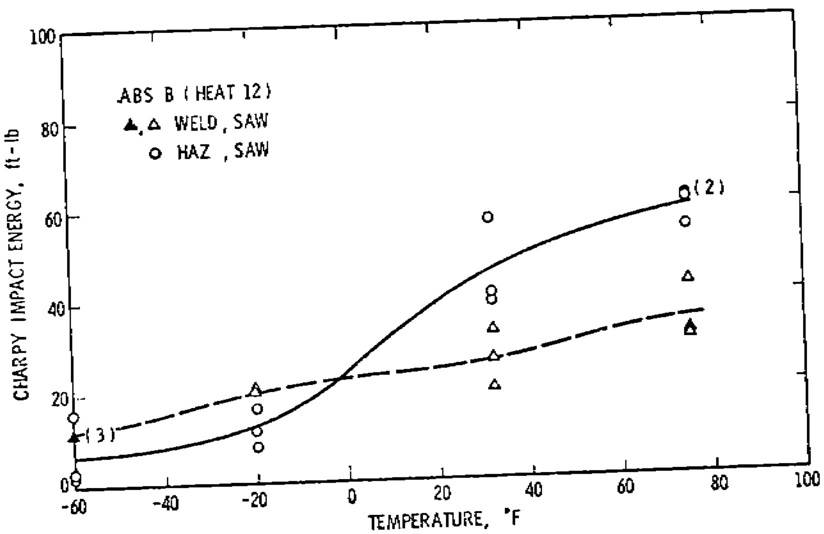


Figure 28. ABS-B (Heat 12)

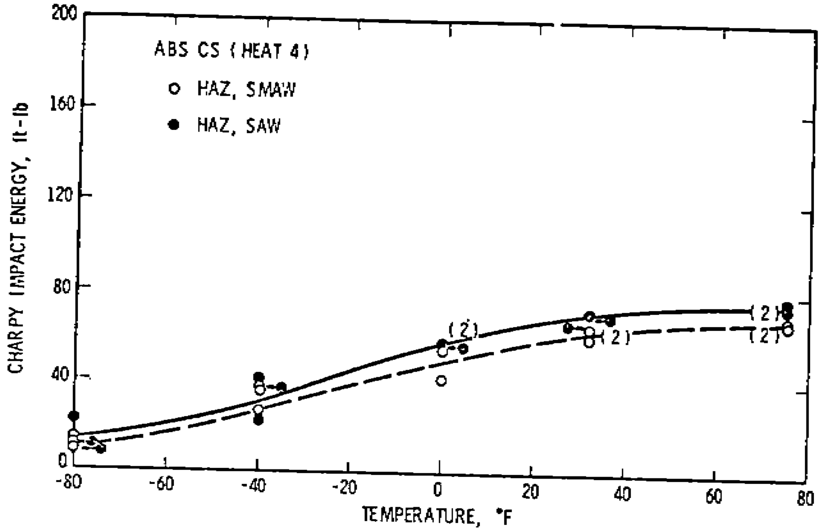


Figure 29. ABS-CS (Heat 4), C_v, HAZ

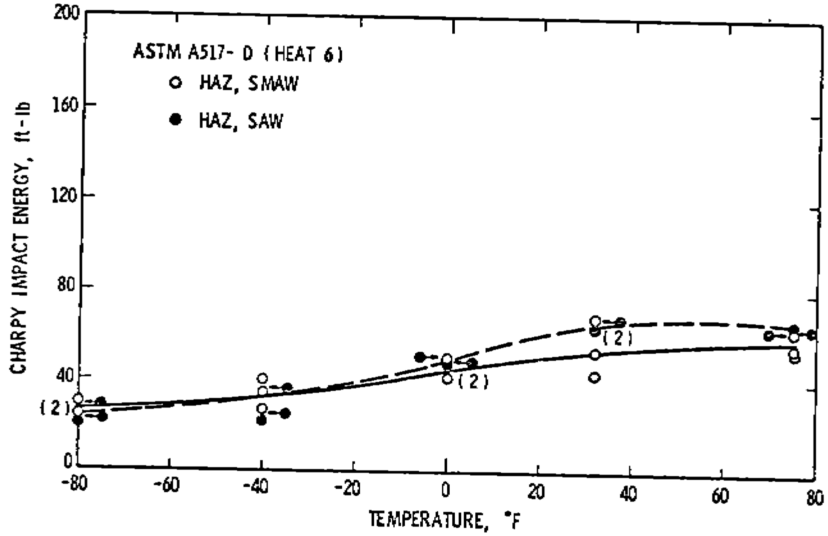


Figure 30. A517-D (Heat 6), C_v, HAZ

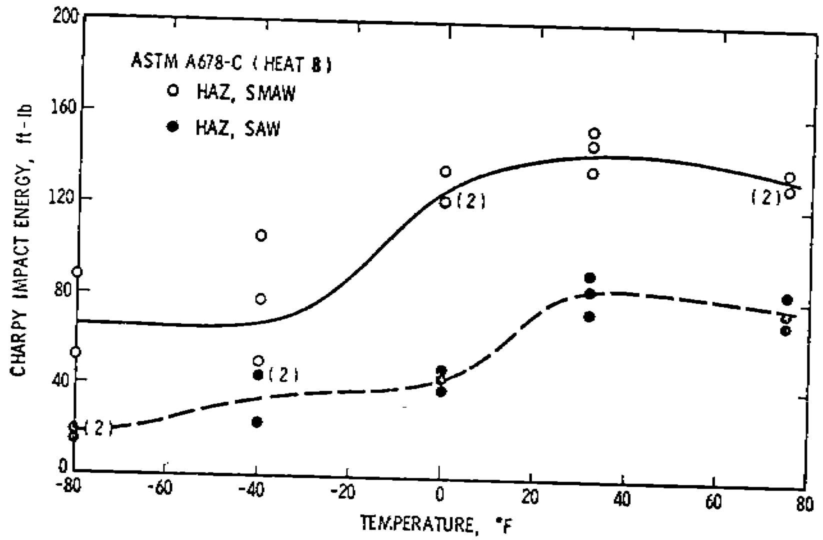


Figure 31. A678-C (Heat 8), C_v, HAZ

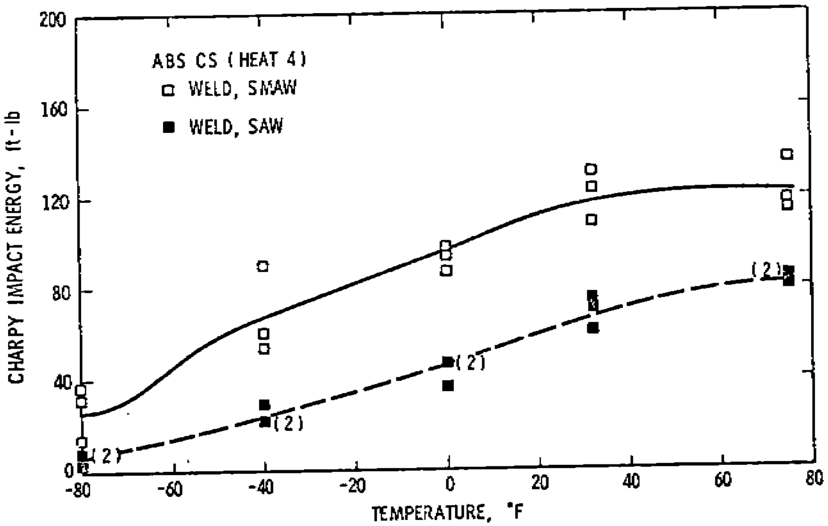


Figure 32. ABS-CS (Heat 4), C_v, Weld

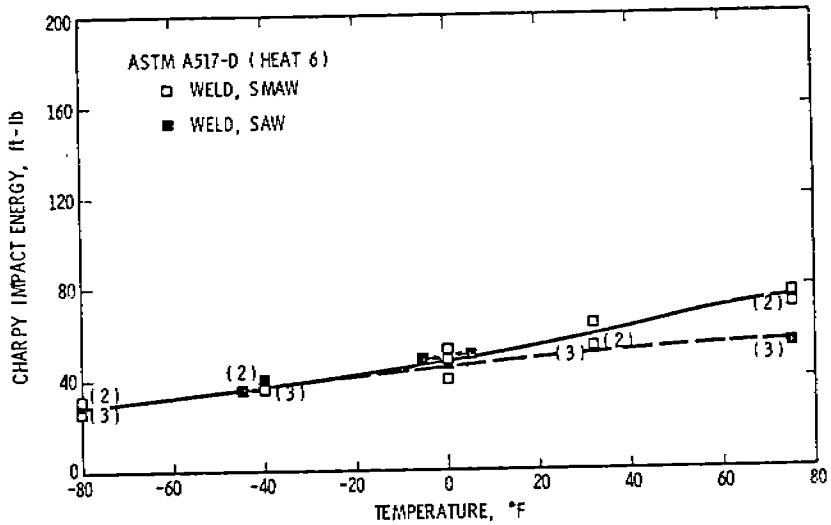


Figure 33. A517-D (Heat 6), C_v, Weld

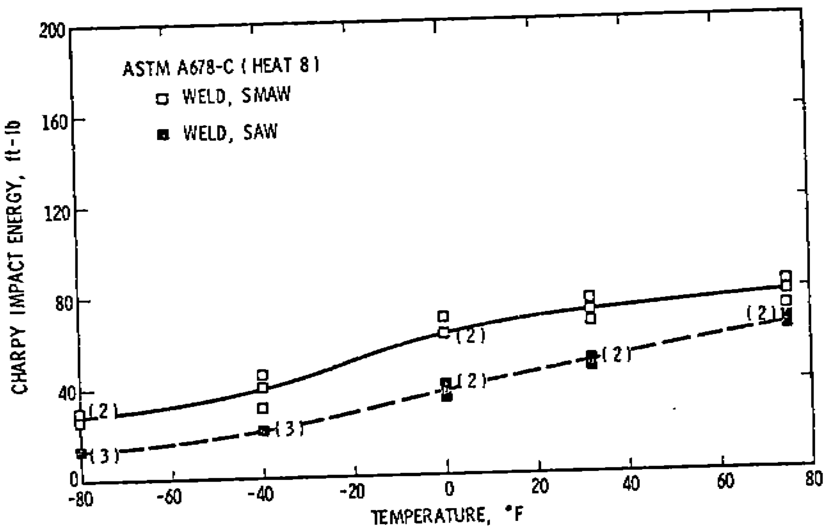


Figure 34. A678-C (Heat 8), C_v, Weld

D. Weld Side Bend Tests

Guided weld side bend tests were conducted on one SAW specimen from each of Heats 3 (EH-32), 10 (A537-B), and from one specimen each of SAW and SMAW weldments of Heats 4 (ABS-CS), 6 (A517-D), and 8 (A678-C). All tests were performed at room temperature (74°F) using an anvil with a diameter of 1.5 inches. The data are reported in Table 8.

Upon examination following testing the EH-32, the ABS-CS (both weld procedures), the A517-D SMAW, and the A537-B welds were found to be completely free of separations. In the remaining weldments, separations of two generic types were found: one type was a delamination originating in the parent material near the HAZ or in the HAZ penetrating into the parent material. The second type appeared on the specimen surface at the edge of the weld crown. The specific identification of these separations is discussed below.

In the A517-C SAW weldment both delamination and crown edge separations were found. No defect could be detected in the area of the small crown edge separation. There were two delamination separations; one in the base metal near the weld, and one in the HAZ extending into the base metal.

Three delamination separations were noted in the A678-C SMAW weld specimen; two small ones in the HAZ extending into the base metal, and one much larger about 1.5 inches from the edge of the HAZ out into the base metal. In the A678-C SAW specimen, a 3/8-inch-long crown edge separation extended parallel to the specimen surface out into the weld. No defect could be detected near this separation.

In the case of the ABS-B SAW weld specimen, a very tiny crown edge separation was noted at the surface; no associated defect was found.

Using the ASME code as a guide, all the results of the weld side bend tests were deemed acceptable. All of the subsurface separations were caused by delaminations in the base metal or opening up of the HAZ. None of these separations were associated with the weld metal. Some areas of delamination had been observed during the weld preparation, so their presence was no surprise. As they are associated with the base metal, there is nothing that can be done about them in a weld test.

The crown edge separations are associated with the weld, and are therefore potentially more serious. However, since they did not appear to be associated with any defects, these samples were also approved. Under ASME guidelines the weld crown could have been removed, thus removing the stress concentration at the weldment edge. In addition, for the high strength materials, an anvil of 2.5 inch diameter, rather than the smaller 1.5-inch anvil could have been used, obviously improving the results on these specimens.

E. Drop Weight - NDT Tests

Table 9 presents the complete test results for the DW-NDT tests conducted on parent material specimens. These tests were conducted on Heats 2-11, and provided nil ductility temperatures as summarized in the table. The ABS-B plate had the highest NDT (50°-60°F), followed by AH-32 (10°-20°F).

Table 8. Summary of Weld Side Bend Test Results

Heat No.	Material	Weldment	Comments
3	EH-32	SAW	No cracks
4	ABS-CS	SMAW	No cracks
4	ABS-CS	SAW	No cracks
6	A517-D	SMAW	No cracks
6	A517-D	SAW	2 delam. cracks; 1 in HAZ, 1 in base metal
8	A678-C	SMAW	2 delam. cracks in HAZ, 1 large delam. crack at edge of HAZ
8	A678-C	SAW	3/8" crown edge crack
10	A537-B	SAW	No cracks
12	ABS-B	SAW	Very small crown edge delam. crack

Table 9. 5/8" Drop Weight - NDT Test Results Parent Material

Heat No.	Material and NDT Range, °F	T°F	Drop Height	Break	No Break
2	ABS-AH-32 +10 to +20	-60	5'-0"	X	
		-30		X	
		+10		X	
		+50			X
		+40			X
		+20			X
		+20			X
		+30			X
		+20		X	
3	ABS EH-32 -50 to -40	-60	4'-2"	X	
		-40			X
		-30		X	
		-40			X
4	ABS-CS -60 to -50	-20	4'-2"		X
		-60		X	
		-40			X
		-50			X
		-50			X
5	ASTM A517-D -70 to -60	-40	6'-8"		X
		-90		X	
		-70		X	
		-60			X
		-60			X
6	ASTM A517-D -40 to -30	-40	6'-8"	X	
		-30			X
		-30			X
7	ASTM A678-C -100 to -90	-50	5'-0"		X
		-90			X
		-130		X	
		-110		X	
		-100		X	
		-90			X
8	ASTM A678-C -110 to -100	-50	5'-0"		X
		-90			X
		-130		X	
		-100			X
		-110		X	
		-100			X
9	ASTM A537-B -90 to -70	-60	5'-0"		X
		-90		X	
		-70			X
		-80			X
		-80		X	
		-70		X	
10	ASTM A537-B -80 to -60	-60	5'-0"		X
		-90		X	
		-80			X
		-80		X	
		-70		X	
11	ABS-B +50 to +60	0	4'-2"	X	
		+40		X	
		+80			X
		+60			X
		+50		X	
		+60			X

The two heats of A678-C had the lowest NDT, in the range -110°F to -90°F. DW-NDT data for the two heats of A537-B agreed reasonably well, and provided DW-NDT results in the range -90°F to -60°F. The two heats of A517-D gave quite different DW-NDT results, as can be seen from Table 9 : one value was in the range -70°F to -60°F, while the companion heat provided -40°F to -30°F. The DW-NDT test series on EH-32, a normalized steel, gave a result (-50°F to -40°F) close to that of ABS-CS, also a normalized alloy.

DW-NDT tests were also conducted on SAW weldments of Heats 3, 4, 6, 8, 10, and 12 as summarized in Table 10. SMAW weldments as well were tested for Heats 4, 6, and 8. These data showed the DW-NDT to be less than that of the respective base plate for ABS-CS and A517-D, and about the same for the A678-C. For each of these three heats, SAW weldments yielded a higher DW-NDT than did the SMAW weldment; in the case of ABS-CS, the DW-NDT of the SAW weldment was more than 100°F higher than that of the SMAW test result. This latter test result was surprising in that the two normalized heats (EH-32 and CS) with the SAW weldment gave such different DW-NDT results.

F. Dynamic Tear Tests

Dynamic Tear tests were conducted on specimens of 5/8-inch and 1-inch thickness. The 5/8-inch specimens were tested in a 2000 ft-lb capacity Mark II dynamic tear test machine, having a double pendulum arrangement. This machine is calibrated periodically using a static moment technique. Additionally, it is checked each day before a test series is conducted by letting the pendula swing freely through one complete cycle, then checking that the dial indicator reads zero ft-lbs energy. This machine also has an instrumented tup, so that a specimen fitted with a COD gage can provide information necessary for the calculation of a dynamic fracture toughness. This capability, however, was not used in the present project, although it was used in SR-231 testing.

The 1-inch thick specimens were tested in a large single pendulum 5000 ft-lb capacity machine. It is calibrated before a test series is undertaken in the same manner as described above.

Specimens were temperature conditioned in the same way as were the Charpy specimens, described in Section IV.C. Specimens were cooled by immersing them in an agitated bath of methanol and dry ice, and held at temperature for 20 minutes (rather than ten, as required by ASTM E-23 for C_v testing). Elevated temperature testing was accomplished by stabilizing the specimens in an agitated bath of water warmed by submersible heaters.

The data for the 5/8-inch parent material specimens having a press notch are presented in Tables 11 and 12, and shown graphically in Figures 35-44. The data in Table 11 are for specimens in the L-T orientation for Heats 2-11, and Table 12 shows the more limited number of data for T-L specimens from the same heats. Figures 35-44 include both L-T and T-L data for parent material specimens having press notches. A review of these data shows that there is no important difference in the DT energy for L-T and T-L orientations in the transition region or the upper shelf for Heats 3 (EH-32), 4 (ABS-CS), and 6(A517-D). The same conclusion can be tentatively drawn from the data for Heat 2 (ABS-DS), although the upper shelf is not adequately inferred for the T-L specimens from the data presented.

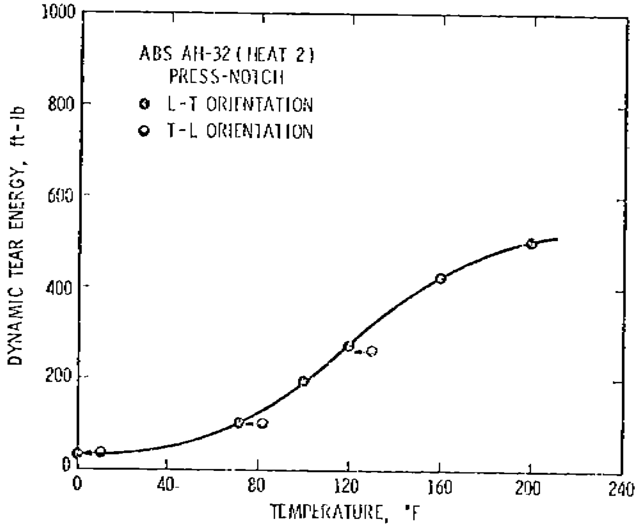


Figure 35. 5/8" Parent DT, Press-Notch, AH-32 (Heat 2)

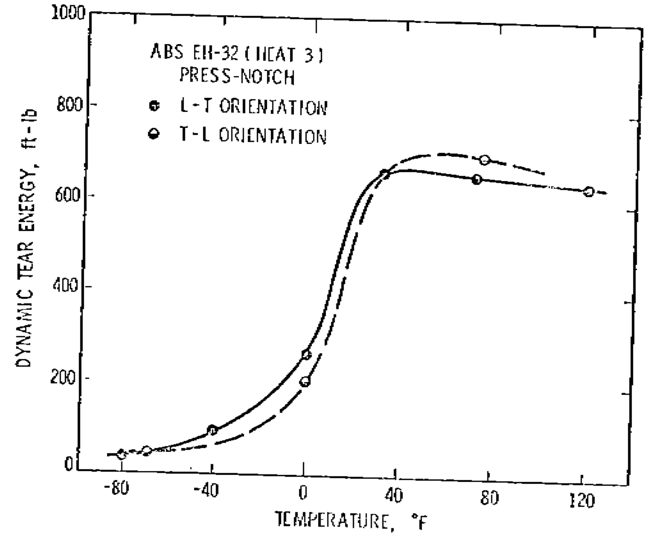


Figure 36. EH-32 (Heat 3), 5/8" Parent DT, Press-Notch

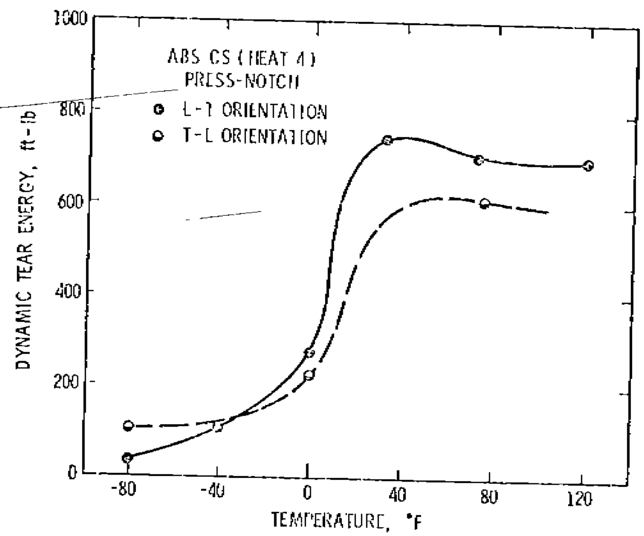


Figure 37. ABS-CS (Heat 4), 5/8" Parent DT, Press-Notch

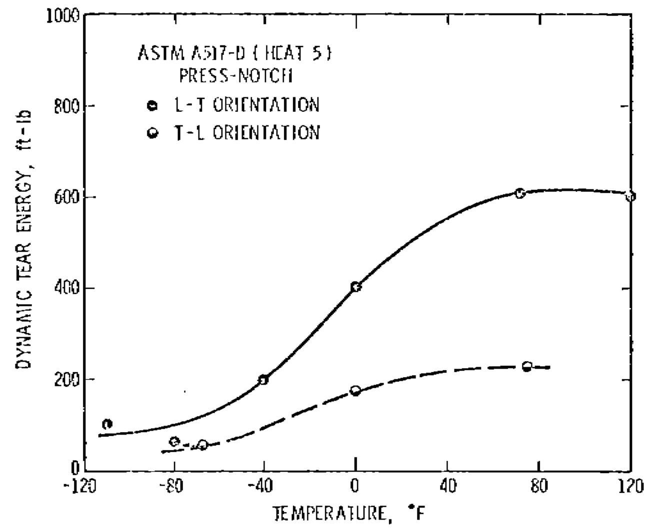


Figure 38. A517-D (Heat 5), 5/8" Parent DT, Press-Notch

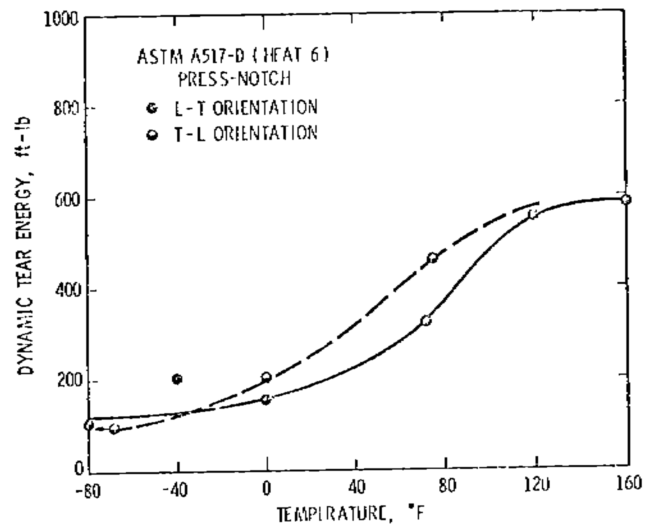


Figure 39. A517-D (Heat 6), 5/8" Parent DT, Press-Notch

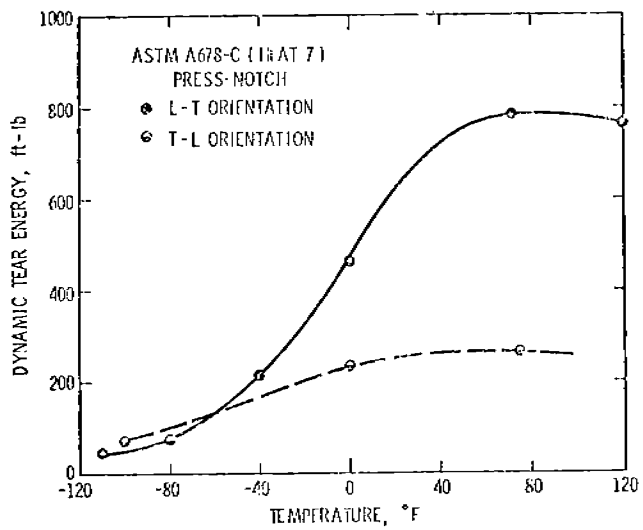


Figure 40. A678-C (Heat 7), 5/8" Parent DT, Press-Notch

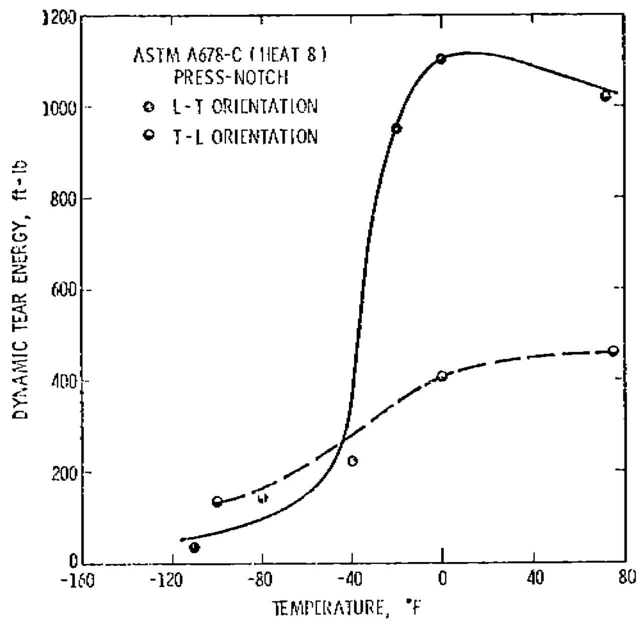


Figure 41. A678-C (Heat 8), 5/8" Parent DT, Press-Notch

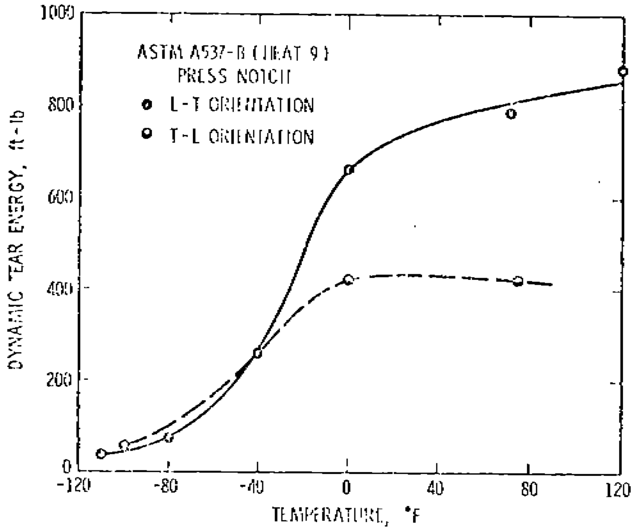


Figure 42. A537-B (Heat 9), 5/8" Parent DT, Press-Notch

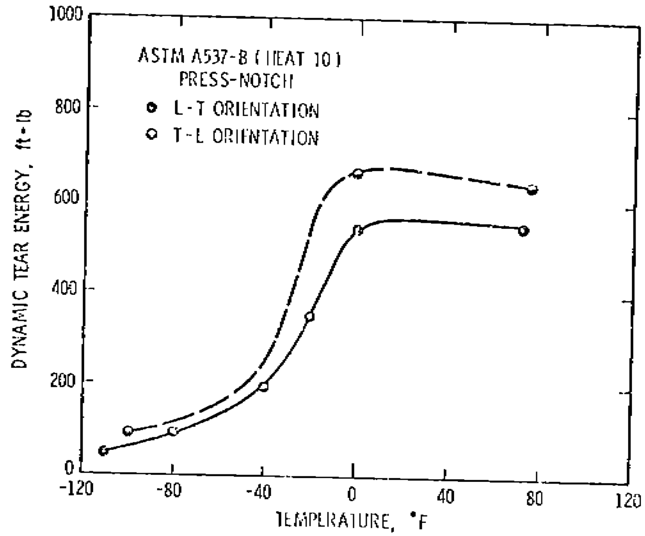


Figure 43. A537-B (Heat 10), 5/8" Parent DT, Press-Notch

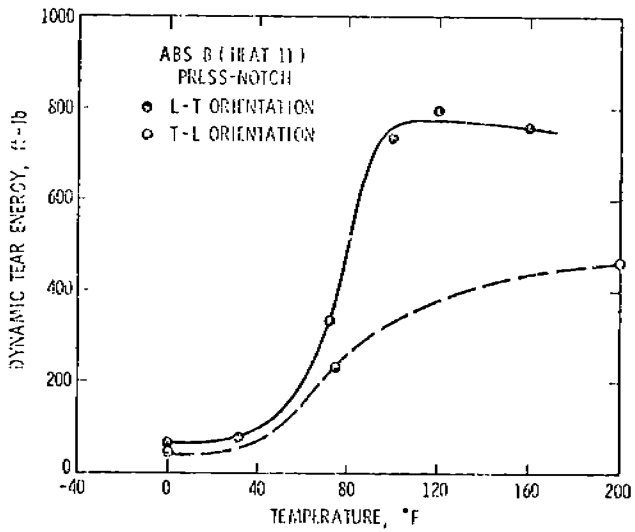


Figure 44. ABS-B (Heat 11), 5/8" Parent DT, Press-Notch

Table 10. 5/8" Drop Weight - NDT Test Results
SMAW and SAW Weldments

Heat No.	Base Material and NDT Range, °F	Weld Proc.	T°F	Drop Height	Break	No Break
3	ABS EH-32	SAW	-40	4'-2"		X
	-100 to -90		-100			X
			-100		X	
			-90			X
			-90			X
4	ABS-CS	SMAW	-60	4'-2"		X
	below -100		-100			X
			-100			X
	0 to +10	SAW	-60	4'-2"	X	
			-20		X	
			+20			X
			0		X	
			+10			X
			+10			X
6	ASTM A517-D	SMAW	-40	6'-6"		X
	-70 to -60		-50			X
			-70		X	
			-60			X
			-50			X
			-60			X
	-60 to -40	SAW	-40	6'-6"		X
			-50			X
			-70		X	
			-60		X	
			-50		X	
			-40		X	
8	ASTM A678-C	SMAW	-100	5'-0"	X	
	-100 to -90		-60			X
			-80			X
			-90			X
			-90		X	
			-80			X
	-80 to -70	SAW	-100	5'-0"	X	
			-60			X
			-80		X	
			-70			X
			-70			X
10	ASTM A537-B	SAW	-60	5'-0"		X
	below -100		-100			X
			-100			X
12	ABS-B	SAW	+40	4'-2"		X
	0 to +10		0		X	
			+20			X
			+10			X
			+10			X

Table 11. 5/8" Dynamic Tear Test Results, Parent Material, L-T Orientation, Press-Notch

Heat No.	Material	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs
2	ABS AH-32	0	30	72	100	100	195	120	275	160	425	200	505
3	ABS EH-32	-80	35	-40	90	0	265	32	665	72	660	120	640
4	ABS-CS	-80	35	-40	105	0	275	32	745	72	705	120	700
5	ASTM A517-D	-110	100	-80	60	-40	200	0	405	72	610	120	605
6	ASTM A517-D	-80	105	-40	200	0	155	72	325	120	555	160	585
7	ASTM A678-C	-110	45	-80	75	-40	215	0	465	72	785	120	765
8	ASTM A678-C	-110	35	-80	140	-40	220	-20	950	0	1105	72	1040
9	ASTM A537-B	-110	35	-80	70	-40	320	0	665	72	790	120	885
10	ASTM A537-B	-110	45	-80	90	-40	195	-20	350	0	540	72	550
11	ABS-B	0	65	32	75	72	335	100	735	120	795	160	760

Table 12. 5/8" Dynamic Tear Test Results, Parent Material, T-L Direction, Press-Notch

Heat No.	Material	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs
2	ABS AH-32	0	35	75	100	120	260
3	ABS EH-32	-80	40	0	205	75	700
4	ABS-CS	-80	110	0	225	75	610
5	ASTM A517-D	-80	55	0	175	75	230
6	ASTM A517-D	-80	95	0	200	75	460
7	ASTM A678-C	-100	70	0	235	75	265
8	ASTM A678-C	-100	135	0	410	75	460
9	ASTM A537-B	-100	55	0	420	75	420
10	ASTM A537-B	-100	95	0	665	75	640
11	ABS-B	0	45	75	230	200	460

For several of the heats, however, the upper shelf was lower for the T-L orientations than is the case for L-T orientations. This is true for Heats 5 (A517-D), 7(A678-C), 8 (A678-C), 9(A537-B), and 11 (ABS-B), where the upper shelf T-L energy is a small fraction of the corresponding L-T energy. In the case of Heat 10 (A537-B), this trend was reversed; the T-L upper shelf energy was indicated to be somewhat higher than the L-T shelf energy. The conclusion to be drawn is that the ratio of L-T to T-L upper shelf energy may vary from heat-to-heat of the same alloy, probably because of variations in the degree of cross-rolling in the manufacture of the plate.

The DT data from the 5/8-inch weld metal and HAZ specimens having press notches are presented in Tables 13 and 14, and are represented graphically in Figures 45-50. These data represent tests on Heats 3 (EH-32), 4 (ABS-CS), 6 (A517-D), 8 (A678-C), 10 (A537-B), and 12 (ABS-B) all with SAW weldments. In addition, tests on heats 4, 6, and 8 were conducted also with SMAW weldments, to afford a comparison between upper shelf energies for SAW and SMAW welds, in both weld metal and HAZ regions.

In comparing results from weld metal tests, the SMAW process produced higher upper shelf DT energies in all cases (Heats 4, 6, and 8) than did the SAW process. The difference was significant in the case of Heat 4, where the SMAW upper shelf was about 1200 ft-lb compared to the SAW upper shelf, which was about half that value.

It is more difficult to draw conclusions regarding upper shelf values for weld metal and HAZ specimens for SAW weldments, since only three data points were available for HAZ specimens. Therefore, one can only point out probable trends. In general, upper shelf DT energies tended to be equal to or higher for weld metal than for HAZ materials of SAW weldments. This observation is supported by the data from Heats 3, 4, 6, and 10. The results from Heat 12 suggest the reverse, although again, the conclusion is tentative due to the paucity of data. The Heat 8 results also are ambiguous in this respect.

An effort was made to compare the toughness performance of weld metal and HAZ specimens having press-notches with those having precracked notches. This was done by testing twelve weld metal specimens (six SMAW and six SAW) and six HAZ specimens (three SMAW and three SAW) fabricated from Heat 4, ABS-CS 1-inch plate. These specimens were not press-notched, but precracked as described in Section III.E. prior to test.

The results of these 5/8-inch precracked DT tests are compiled in Table 15, and are shown graphically in Figures 51 and 52. Figure 51 presents all the precracked data. Only in the case of the weld metal/SAW specimens was the upper shelf DT energy defined. The weld metal/SMAW specimens exhibited the highest fracture energy in the transition region of any specimen group, but the upper shelf was not defined by testing up to 160°F. The two groups of HAZ specimens contained only three points each* and no definitive conclusions could be reached about the location of the transition region and upper shelf. It is reasonably clear, however, that both the HAZ/SMAW and the HAZ/SAW weldments to exhibit higher DT energies in the transition region, and presumably on the upper shelf, than the weld region/SAW group.

*One HAZ/SAW specimen was lost in a mis-test, leaving only two useful specimens in this group.

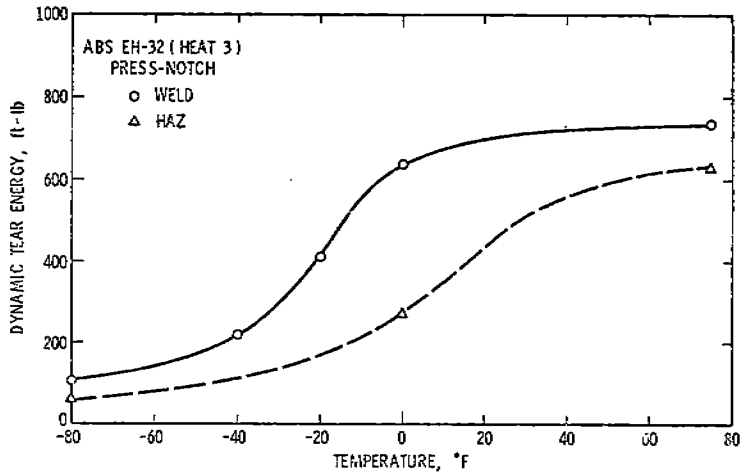


Figure 45. EH-32 (Heat 3), 5/8" Weldment DT, Press-Notch

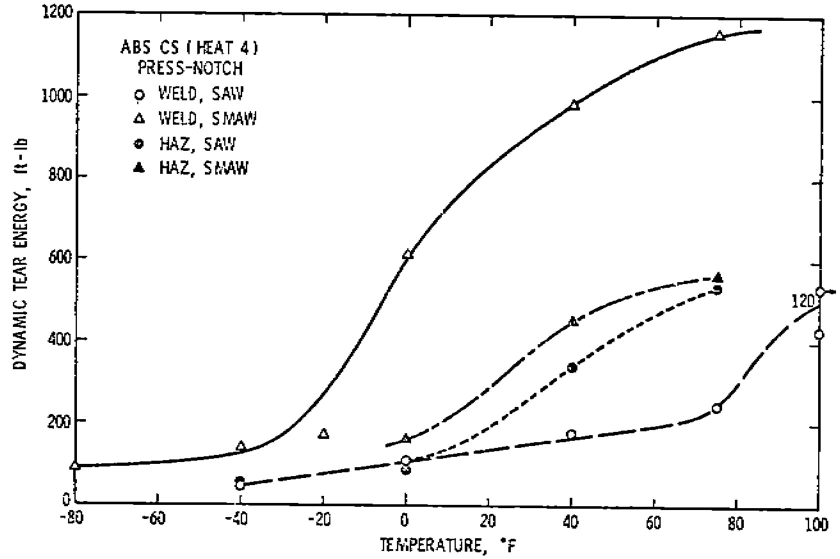


Figure 46. ABS-CS (Heat 4), 5/8" Weldment DT, Press-Notch

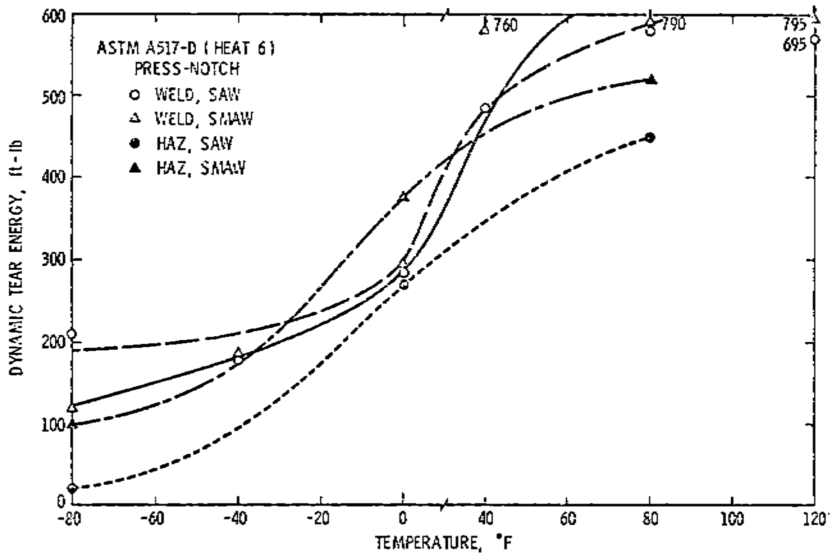


Figure 47. A517-D (Heat 6), 5/8" Weldment DT, Press-Notch

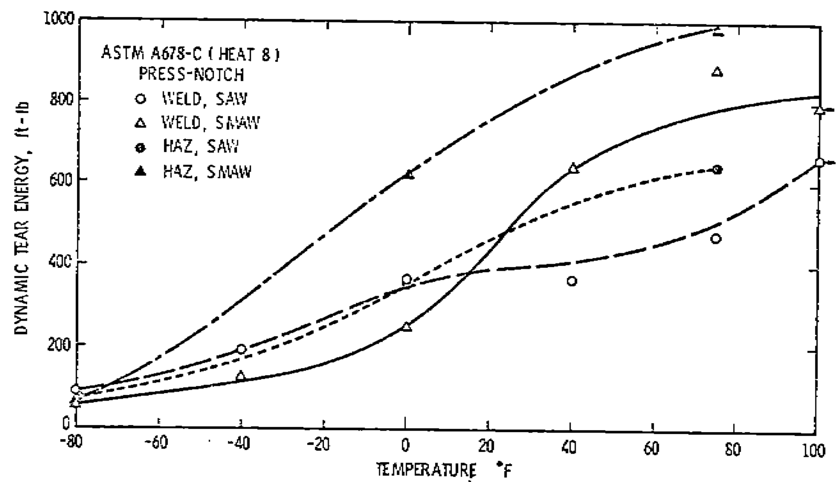


Figure 48. A678-C (Heat 8), 5/8" Weldment DT, Press-Notch

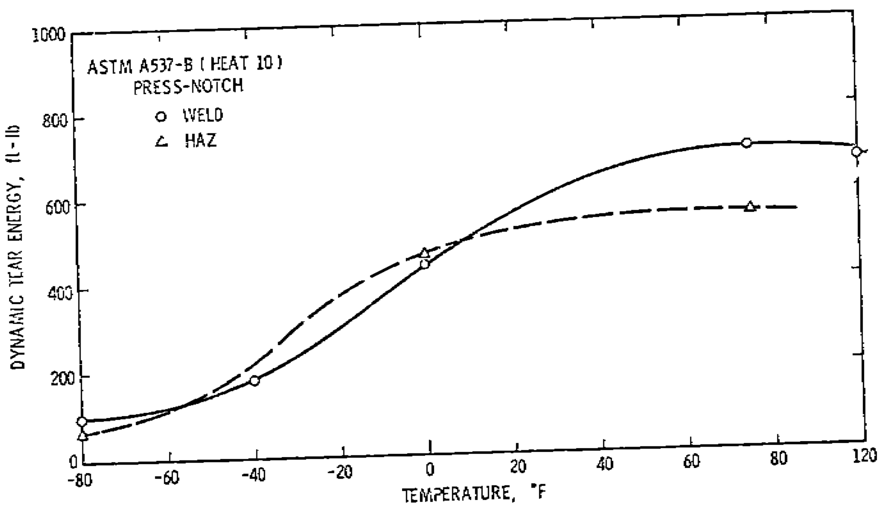


Fig. 49. A537-B (Heat 10), 5/8" Weldment DT, Press-Notch

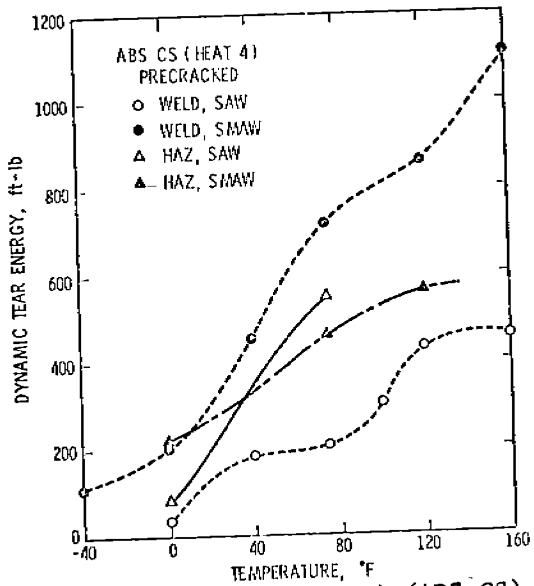


Fig. 51. 5/8" DT, Heat 4 (ABS-CS), Weld and HAZ; Precracked

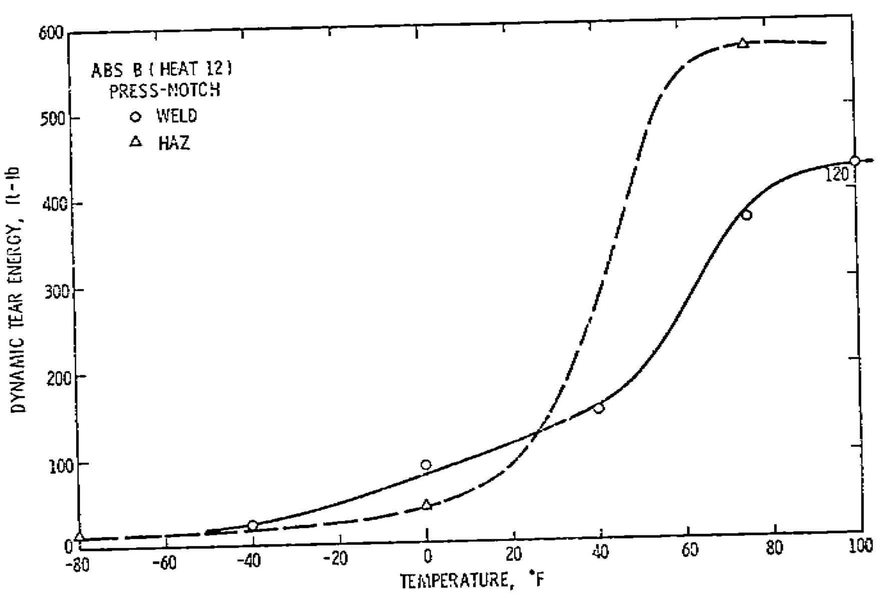


Fig. 50. ABS-B (Heat 12), 5/8" Weldment DT, Press-Notch

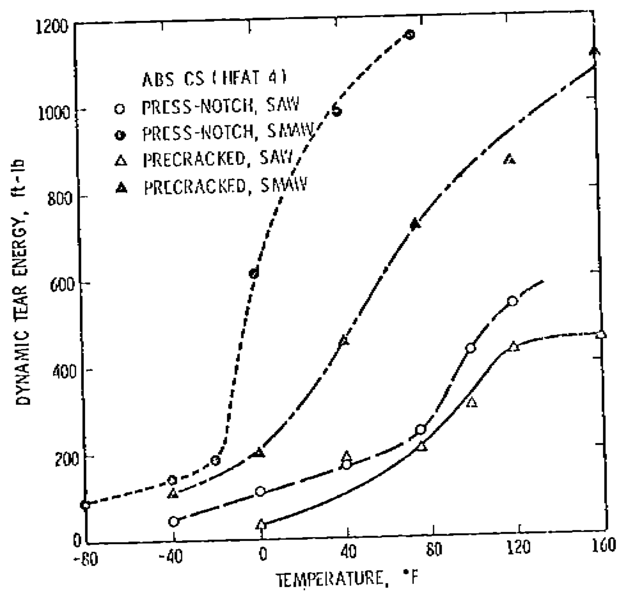


Fig. 52. Comparison of Press-Notch vs Precracked 5/8" DT Results - Heat 4 (ABS-CS)

Table 13. 5/8" Dynamic Tear Test Results, Weld Region, Press-Notch, SAW (* or SMAW) Weld Procedure

Heat No.	Material	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs
3	ABS EH-32	-80	105	-40	220	-20	410	0	620	75	740		
4	ABS-CS	-40	45	0	110	40	180	75	245	100	430	120	535
4*	ABS-CS	-80	90	-40	140	-20	185	0	615	40	985	75	1160
6	ASTM A517-D	-80	220	-40	180	0	285	40	485	75	580	140	695
6*	ASTM A517-D	-80	120	-40	185	0	295	40	760	75	790	120	795
8	ASTM A678-C	-80	90	-40	190	0	355	40	365	75	475	120	665
8*	ASTM A678-C	-80	55	-40	125	0	250	40	640	75	885	120	795
10	ASTM A537-B	-80	100	-40	180	0	440	75	700	120	670		
12	ABS-B	-40	25	0	90	40	150	75	370	120	460		

Table 14. 5/8" Dynamic Tear Test Results HAZ, Press-Notch SAW (* or SMAW) Weld Procedure

Heat No.	Material	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs	T°F	Ft-Lbs
3	ABS EH-32	-80	60	0	275	75	630		
4	ABS-CS	-40	50	0	90	40	340	75	535
4*	ABS-CS	0	165	40	455	75	565		
6	ASTM A517-D	-80	20	0	270	75	450		
6*	ASTM A517-D	-80	100	0	375	75	520		
8	ASTM A678-C	-80	75	0	365	75	645		
8*	ASTM A678-C	-80	60	0	620	75	985		
10	ASTM A537-B	-80	65	0	465	75	550		
12	ABS-B	-80	15	0	45	75	570		

Table 15. 5/8" Dynamic Tear Test Results, Precracked Notches

Temperature °F	D.T. ENERGY, FT-LB			
	Weld Region, SAW	Weld Region, SMAW	HAZ Region, SAW	HAZ Region, SMAW
-40	--	110	--	--
0	35	200	85	210
40	185	455	--	--
75	205	720	550	465
100	305	--	--	--
120	430	860	--	560
160	455	1110	--	--

Figure 52 draws a comparison between the DT fracture performance of Heat 4 weld metal specimens having press-notches and having precracks. This comparison is made both for SMAW and SAW weldments. As the figure indicates, the upper shelf was defined only for the precracked/SAW specimen group, as the three other groups evidently had an upper transition region temperature above 160°F. Nevertheless, some useful conclusions can be made from the data. The press-notch/SMAW group displayed by far the highest fracture energy in the transition region, followed by the precracked/SMAW group. The precracked/SAW group has the lowest upper shelf behavior of all the four groups; the press-notch/SAW specimens then have a higher toughness than the precracked/SAW specimens.

There are perhaps two general conclusions that can be drawn from the limited testing done with precracked specimens. The first is that the SMAW weldment is tougher than the SAW weldment in the case of precracked DT specimens. The second is that, in comparing precracked energy levels with press-notch levels, apparently the weld process influences absorbed energy more than does the notching operation. That is, the two SMAW groups exhibited higher toughness than did the two SAW groups, but within each group the press-notch specimens yielded higher DT energy in the transition region than did the precracked specimens. The higher energy absorption levels associated with press-notches occur because the press-notch is blunter than the fatigue crack, and because the press-notch has a residual field of compressive stresses at the notch tip which must be overcome by the external forces before the crack can be extended.

The final series of DT tests was conducted on 1-inch thick plates of base metal of Heats 2-11, with specimens taken in the L-T orientation. The results are presented in Table 16 and in Figure 53. The data are sparse (only three tests per heat) and therefore can only provide tentative indications of the upper shelf energy for 1-inch specimens with press notches. These data were intended to be useful in evaluating the scaling between 5/8-inch and 1-inch specimens.

The fact that the 1-inch DT data were too limited both in number and in temperature range to define upper shelf energy values makes it impossible to evaluate thickness scaling with any confidence. In their analysis of DT scaling effects, Judy and Goode[9] proposed the empirical expression $E = R_p(\Delta a)^2 B^{1/2}$ for the upper shelf fracture energy, where Δa is the unbroken specimen ligament ahead of the notch, and B is the specimen thickness. R_p is a material constant, which is interpreted as the fracture energy of the 5/8-inch ASTM proposed standard DT specimen. Using this approach one concludes that for the 1-inch DT specimen used in this project, $E_{1''} = 4 \times E_{5/8''}$, i.e., the upper shelf energy level for the 1-inch specimen should be about four times that of the 5/8-inch specimen.

A review of the 1-inch DT data and fracture appearance shows that no upper shelf levels were defined. Beyond the fact that only three tests per heat were conducted, the fracture surfaces failed to indicate any full shear failures as should be produced by specimens tested at the upper shelf temperature. Because of increased plane strain constraint, thicker specimens generally have a higher transition temperature, and hence must be tested at a higher temperature to define the upper shelf DT energy.

Table 16. 1" Dynamic Tear Test Results, Parent Material

Heat No.	Material	TEST TEMPERATURE -80°F	-60°F	0°F	75°F	160°F
2	ABS AH-32	--	--	6	33	765
3	ABS EH-32	--	38	261	1392	--
4	ABS-CS	--	29	445	1465	--
5	ASTM A517-D	19	--	1049	1114	--
6	ASTM A517-D	26	--	141	571	--
7	ASTM A678-C	38	--	747	1849	--
8	ASTM A678-C	42	--	1204	2691	--
9	ASTM A537-B	33	--	1717	1983	--
10	ASTM A537-B	33	--	638	804	--
11	ABS-B	--	--	11	33	2345

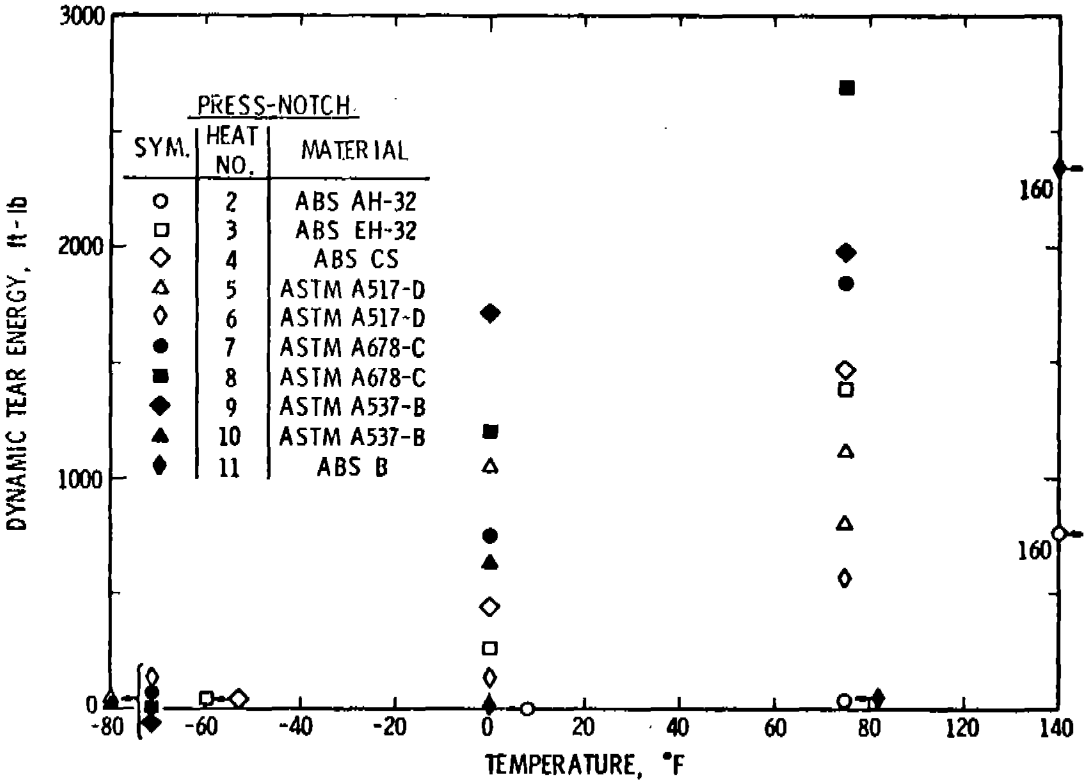


Figure 53. 1" Parent DT, Press-Notch.

The tabulation below compares the 1-inch DT data with the 5/8-inch data and with the expected 1-inch upper shelf energy (four times the 5/8-inch upper shelf energy). Also shown are the approximate percentages of a full shear fracture surface exhibited by the highest temperature test for that heat.

Heat No.	Material	E_1=measured 5/8" DT shelf	E_2=predicted 1" DT shelf	E_2^*=highest recorded 1" DT value	% Shear, E_2^* fracture surface
2	AH-32	(550)	(2200)	765 at 160°F	30
3	EH-32	650	2600	1392 at 75°F	50
4	CS	700	2800	1465 at 75°F	50
5	A517-D	600	2400	1114 at 75°F	70
6	A517-D	600	2400	571 at 75°F	60
7	A678-C	750	3000	1849 at 75°F	70
8	A678-C	1000	4000	2691 at 75°F	50
9	A537-B	850	3400	1983 at 75°F	40
10	A537-B	550	2200	804 at 75°F	20
11	B	750	3000	2345 at 160°F	50

()=estimated

None of the fracture surfaces associated with E_2^* values exhibited full shear, and none of the ratios E_2^*/E_1 approached E_2. These two facts are mutually supportive and simply indicate that upper shelf impact energy values were not achieved with the present 1-inch specimens, and thus any scaling comparisons with 5/8-inch DT specimens are at best speculative.

V. EXPLOSION STRUCTURAL TESTS AND RESULTS

A. Test Matrix

Table 3 presents a summary of the numbers of Explosion Crack Starter (ECST) and Explosion Tear (ET) specimens tested of each heat. Details regarding design and preparation of the ECST and ET specimens are given in Section III of this report. While all 18 ECST specimens were fabricated, only 14 were tested due to the screening nature of the test sequence, whereby tests at higher temperatures are deleted if the weldment "passes" at lower temperature.

B. Explosion Crack Starter Tests

Three specimens each of the SMAW and SAW weld procedures were fabricated for Heat 4 (ABS-CS), Heat 6 (A517-D), and Heat 8 (A678-C) as described in Section III.G. of this report. The six specimens from Heat 4 were 1-inch thick each, whereas the Heat 6 and Heat 8 specimens were each 1-1/4 inches thick. The test procedure was to test first a given weldment type/heat specimen at 0°F. If the specimen did not fail, i.e., if no cracking was noted which extended into the elastic hold-down region, the specimen was retested under the same conditions. If the specimen survived the second shot, that weldment type/heat was considered to have passed. If the specimen failed on either the first or second shots at 0°F, a second specimen was tested in the same manner at 32°F. The pass/no pass result of that test indicated whether or not a third specimen was to be tested at 75°F. Thus, each weldment type/heat combination involved at least one, and at most three specimens, with a maximum of six explosive shots.

Specimens tested at either 0°F or 32°F were cooled in an agitated bath of methanol and dry ice and held for at least 30 minutes for the specimen temperature to stabilize. In the case of specimens tested at 75°F, the specimens were warmed to equilibrium in an agitated bath with submersible heaters.

All testing was performed at a remote test facility near the SwRI campus. Both 7-and 12-pound charges of cast Pentolite were used, and the charge standoff distance was adjusted to account for charge weight and for plate thickness. Seven-pound charges were used for the 1-inch plate, and 12-pound charges for 1-1/4-inch plate. A complete summary of the ECST test series is given in Table 17. The dies used to support the ECST specimen during the test event are shown in Figure 14, while Figure 54 shows the ECST test configuration, with the cast Penolite disk supported above the specimen by a cardboard stand prior to the test event. Figure 55 a-n shows a picture of each specimen tested after one or both shots.

Each ECST specimen was measured for thickness at intervals 1.5 inches apart transverse to and in the direction of the weld (see e.g., Figure 55m) before testing, and after each shot. All thickness measurements were made with a through transmission ultrasonic instrument* having thickness scale ranges of 0-1.25 and 0-2.5 inches. Before measurements, the instrument was calibrated with standard steel blocks of thickness 0.5, 1.0, and 2.0 inches.

*Sonray Caliper, manufactured by Branson Instrument Co.

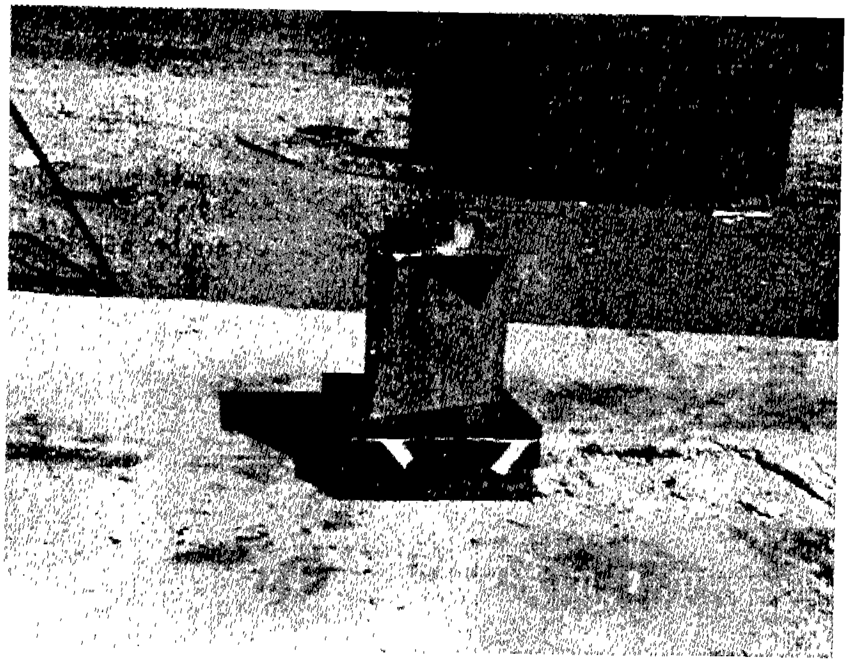


Figure 54. Explosion Crack Starter Test Configuration Showing Penolite Disk Supported by Cardboard at Proper Standoff Height from Specimen

Heat No.	Weld/ Material	FIRST SHOT					SECOND SHOT				
		T°F	Charge Wt (Lb)	Standoff (in.)	Time (sec)	Fail/ No Fail	T°F	Charge Wt (Lb)	Standoff (in.)	Time (sec)	Fail/ No Fail
4	SMAW/ABS-CS	0	7	15	61	Fail	--	--	--	--	--
	SMAW/ABS-CS	32	7	15	48	Fail	--	--	--	--	--
	SMAW/ABS-CS	75	7	15		No Fail	75	7	15		No Fail
	SAW/ABS-CS	0	7	15	54	Fail	--	--	--	--	--
	SAW/ABS-CS	32	7	15	48	Fail	--	--	--	--	--
	SAW/ABS-CS	75	7	15		No Fail	75	7	15		Fail
6	SMAW/A517-D	0	12	19	59	No Fail	0	12	17	48	No Fail
		--	--	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--	--	--
	SAW/A517-D	0	12	15	72	Fail	--	--	--	--	--
	SAW/A517-D	32	12	17	54	Fail	--	--	--	--	--
	SAW/A517-D	75	12	17		No Fail	75	12	17		Fail
8	SAW/A678-C	0	12	19	61	No Fail	0	12	17	50	No Fail
		--	--	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--	--	--
	SMAW/A678-C	0	12	15	61	Fail	--	--	--	--	--
	SMAW/A678-C	32	12	17	49	Fail	--	--	--	--	--
	SMAW/A678-C	75	12	17		No Fail	75	12	17		No Fail

Table 17. Explosion Crack Starter Test Summary

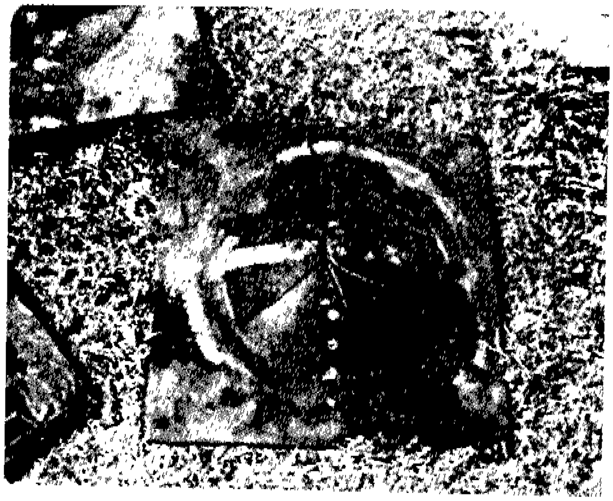


Fig. 55a

Heat 4 (ABS-CS), 1" thick.
SMAW weld, 0°F.
Condition after one shot.

Fig. 55b

Heat 4 (ABS-CS), 1" thick.
SMAW weld, 32°F.
Condition after one shot.

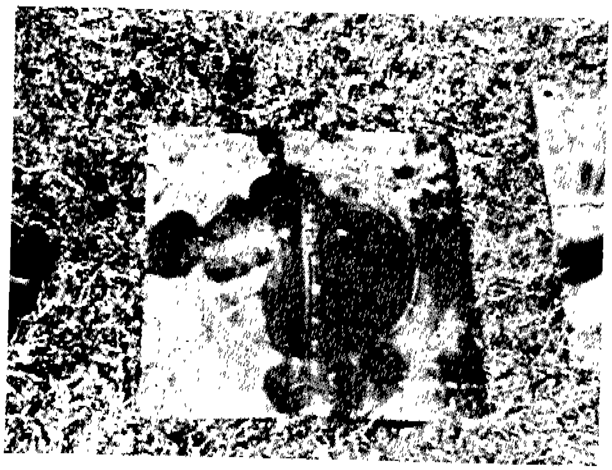


Fig. 55c

Heat 4 (ABS-CS), 1" thick.
SMAW weld, 75°F.
Condition after two shots.

Figures 55 a-n. Explosion Crack Starter Test Specimens, Post-Test

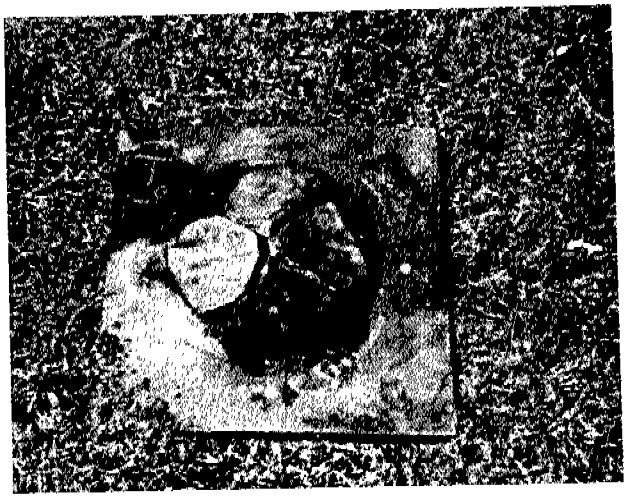


Fig. 55d

Heat 4 (ABS-CS), 1" thick.
SAW weld, 0°F.
Condition after one shot.

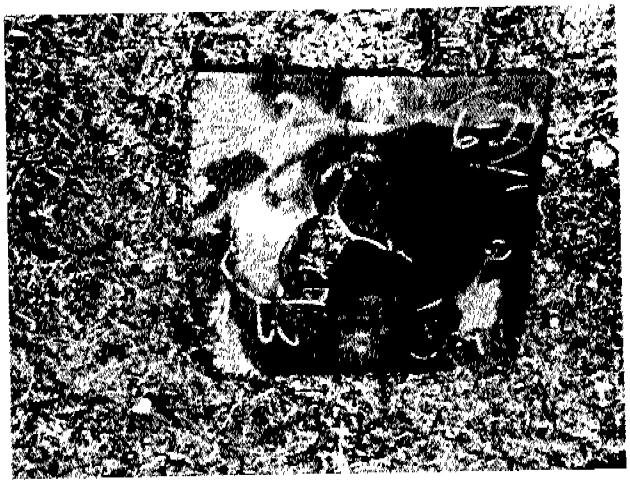


Fig. 55e

Heat 4 (ABS-CS), 1" thick.
SAW weld, 32°F.
Condition after one shot.

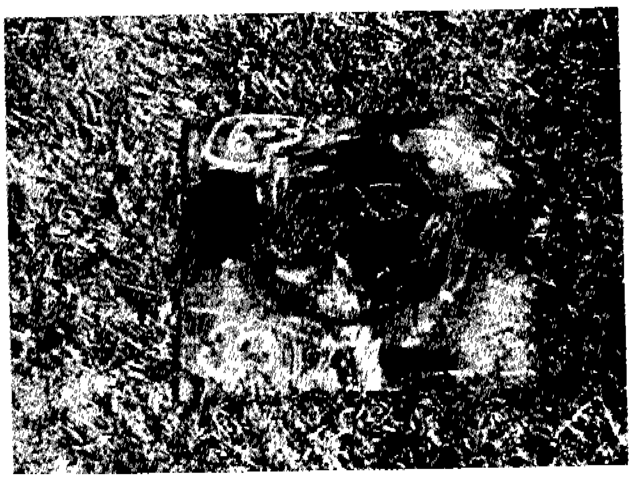


Fig. 55f

Heat 4 (ABS-CS), 1" thick.
SAW weld, 75°F.
Condition after tw shots.

Figures 55 a-n. Explosion Crack Starter Test Specimens, Post-Test

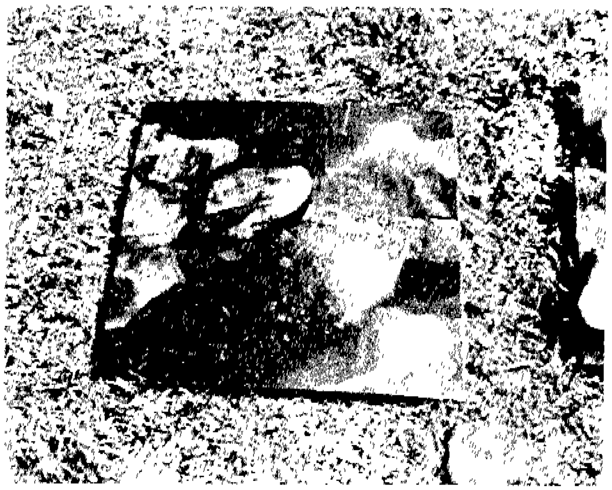


Fig. 55g

Heat 6 (A517-D), 1-1/4" thick.
SMAW weld, 0°F.
Condition after two shots.

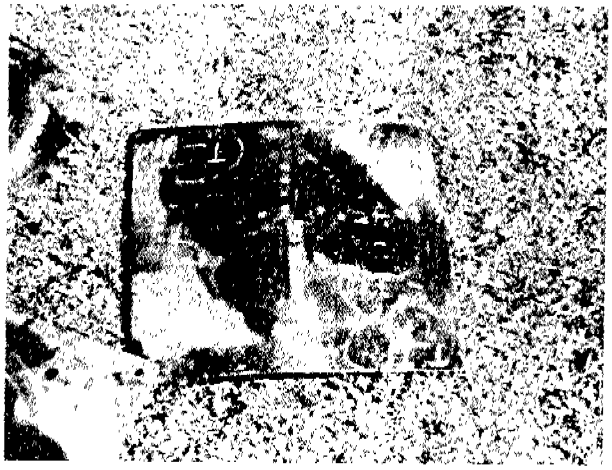


Fig. 55h

Heat 6 (A517-D), 1-1/4" thick.
SAW weld, 0°F.
Condition after one shot.

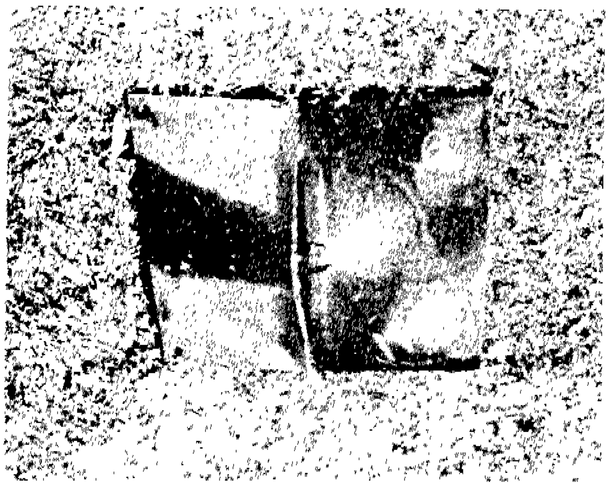


Fig. 55i

Heat 6 (A517-D), 1-1/4" thick.
SAW weld, 32°F.
Condition after one shot.

Figures 55 a-n. Explosion Crack Starter Test Specimens, Post-Test

Fig. 55j

Heat 6 (A517-D), 1-1/4" thick.
SAW weld, 75°F.
Condition after two shots.

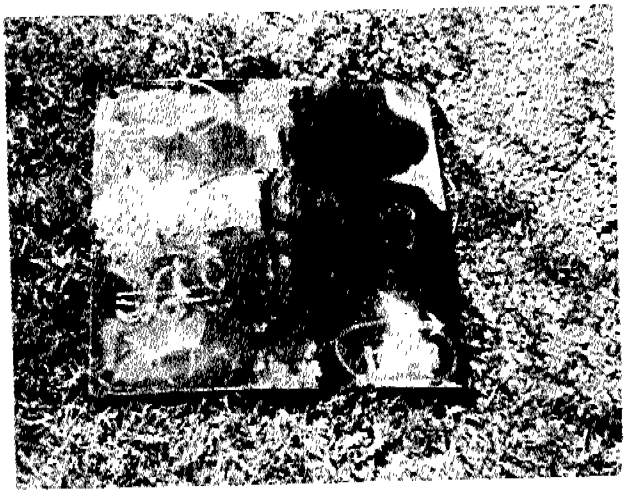


Fig. 55k

Heat 8 (A678-C), 1-1/4" thick.
SAW weld, 0°F.
Condition after two shots.

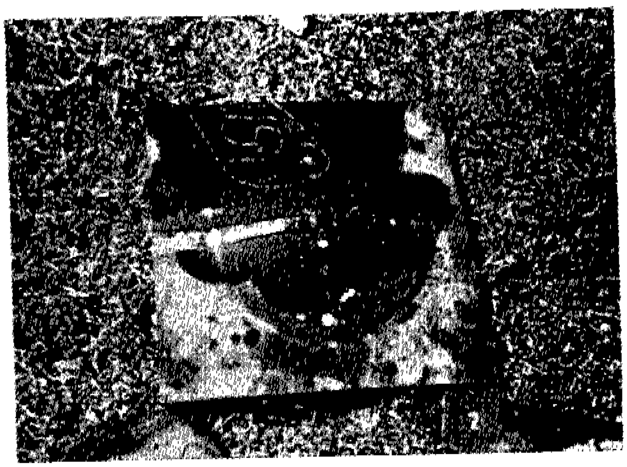


Fig. 55l

Heat 8 (A678-C), 1-1/4" thick.
SMAW weld, 0°F.
Condition after one shot.

Figures 55 a-n. Explosion Crack Starter Test Specimens, Post-Test

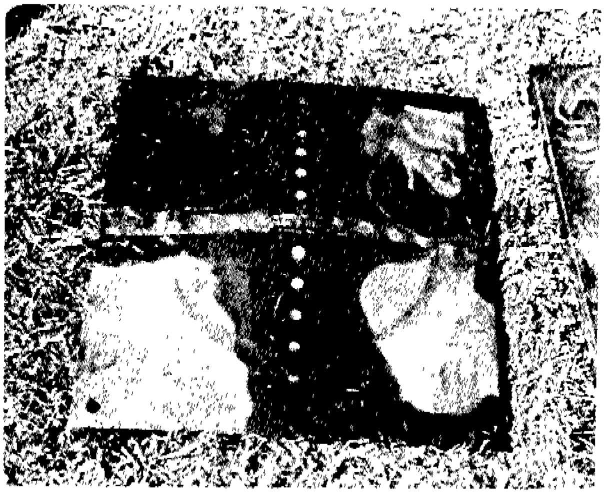


Fig. 55m

Heat 8 (A678-C), 1-1/4" thick.
SMAW weld, 32°F.
Condition after one shot.

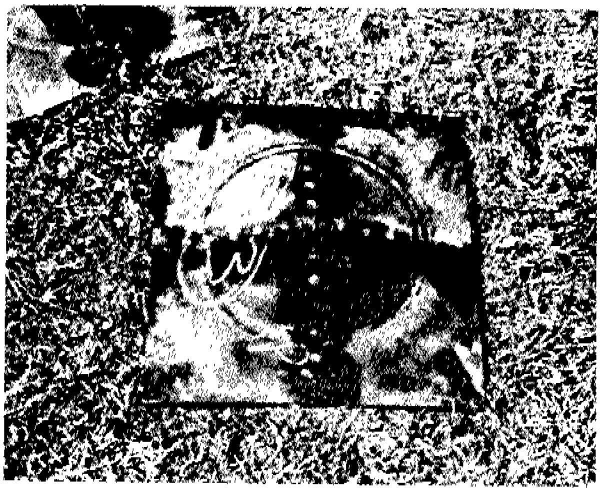


Fig. 55n

Heat 8 (A678-C), 1-1/4" thick.
SMAW weld, 75°F.
Condition after two shots.

Figures 55 a-n. Explosion Crack Starter Test Specimens, Post-Test

In taking field measurements, a spot of oil is placed on the region where the thickness is to be measured to couple the transducer to the steel surface.

Table 18 presents the initial thicknesses (prior to the first shot) of the specimens as measured ultrasonically. For each specimen, all initial thickness measurements were identical to two significant figures after the decimal. The final thickness data presented in Table 18 were taken from the ECST specimens following each shot. These figures are to be subtracted from the initial thickness data given in Table 18 to evaluate thinning distributions. In Table 18 the column labeled "Point No." references point 0 to the specimen midpoint, and points ±1, ±2, etc., to locations spaced at intervals of 1.5 inches either side of the center. In two cases shown in the table, thickness data were not obtained. In the two cases where UT data were not obtainable, the plate had been bulged only slightly, and the thickness distribution is presumed to be very nearly the same as in the undeformed configuration.

According to Navy procedures for interpretation of ECST test results,[6] a specimen is considered to have passed if any cracks that develop are confined to the bulge region of the plate, i.e., no cracks propagate into the elastic hold-down region. Thus, cracks are permitted, but must be retained in the plastically-deformed material. In addition to this requirement, a specimen should exhibit at least 6% thinning after the second explosive shot (i.e., 3% per shot). It is against these requirements that specimens in this project were judged to have "passed" or "failed."

The results of the ECST test series, Table 17, led to the following results:

Material/Weldment	Test Result
ABS-CS/SMAW	passed at 75°F
ABS-CS/SAW	failed
A517-D/SMAW	passed at 0°F
A517-D/SAW	failed
A678-C/SAW	passed at 0°F
A678-C/SMAW	passed at 75°F

The ABS-CS series with SMAW welds passed the test nicely (see Figure 55c) insofar as the cracking criterion is concerned, and the thinning, at 4.9% after the second shot, was considered acceptable to judge the specimen as having passed. The same holds true in the case of A678-C with SMAW weld procedure. As revealed in Figure 55n, no cracking was present after the second shot at 75°F, and the thinning (6.25%) was sufficient to pass the weldment unequivocally.

The A517-D/SMAW weldment which was passed after two shots at 0°F is shown in Figure 55g. Despite the blowout of a single large fragment, there was no cracking into the elastic hold-down region. The maximum thinning was 5.5%, about sufficient to qualify the weldment marginally. The A678-C/SAW weldment, which also was passed, is shown in Figure 55k. Although there was rupture along the HAZ as well as across the weld, these cracks all were contained within the bulge region. The thinning was only 3.1%, and in retrospect this specimen should have been reshot to qualify it unconditionally.

Table 18. ECST Specimen Thicknesses Following Test

Material/Weld	Shot No.	Temperature and Initial Thickness (in.)	Point No.	Thickness Across Weld (in.)	Thickness With Weld (in.)
ABS-CS/SMAW	1	0°F	-3	1.01	1.01
			-2	1.00	0.97
			-1	0.95	0.96
		1.02	0	--	0.98
			1	0.98	0.99
			2	0.99	1.00
			3	1.01	
ABS-CS/SMAW	1	32°F	-3	1.02	0.99
			-2	0.99	0.98
			-1	0.97	0.98
		1.02	0	--	0.98
			1	0.95	0.99
			2	0.95	1.02
			3	0.99	
			4	1.02	
ABS-CS/SMAW	1	75°F	-3	0.99	0.99
			-2	0.97	0.95
			-1	0.95	0.95
		1.02	0	--	
			1	0.95	0.95
			2	0.98	0.96
			3	1.00	0.99
ABS-CS/SMAW	2	75°F	-4	1.01	0.96
			-3	0.96	0.88
			-2	0.90	0.86
			-1	0.87	0.86
		1.02	0	--	0.86
			1	0.88	0.89
			2	0.93	0.92
			3	0.99	0.96
ABS-CS/SAW	1	0°F	-3	1.02	1.02
			-2	1.02	1.01
			-1	1.01	1.01
		1.02	0	--	1.01
			1	1.01	1.01
			2	1.01	1.01
			3	1.01	1.01

Material/Weld	Shot No.	Temperature and Initial Thickness (in.)	Point No.	Thickness Across Weld (in.)
ABS-CS/SAW	1	32°F	-4	1.01
			-3	1.01
			-2	1.00
			-1	0.99
		1.02	0	--
			1	0.99
			2	1.00
ABS-CS/SAW	1	75°F	-3	
			-2	1.00
			-1	0.98
		1.01	0	--
			1	0.97
			2	0.99
			3	1.01
ABS-CS/SAW	2	75°F	-3	0.99
			-2	0.98
			-1	0.96
		1.01	0	--
			1	0.95
			2	0.95
			3	
A517-D/SMAW	1	0°F 1.28	Unable to Measure	
A517-D/SMAW	2	0°F	-5	1.28
			-4	1.27
			-3	1.27
			-2	1.27
			-1	1.26
		1.28	0	--
			1	1.26
			2	1.27
			3	1.28
A517-D/SAW	1	0°F	-3	1.28
			-2	1.28
			-1	
		1.28	0	--
			1	1.28

Table 18. ECST Thicknesses Following Test (Concl.)

Material/Weld	Shot No.	Temperature and Initial Thickness (in.)	Point No.	Thickness Across Weld (in.)	Thickness With Weld (in.)
A517-D/SAW	1	32°F	-4		1.28
			-3		1.27
			-2		1.27
			-1		1.27
		1.29	0		1.27
			1		1.28
			2		1.28
A517-D/SAW	1	75°F 1.28	Unable to Measure		
A517-D/SAW	2	75°F	-5	1.28	
			-4	1.27	
			-3	1.27	1.26
			-2	1.27	1.26
			-1	1.26	1.24
		1.28	0	--	1.21
			1	1.26	1.25
			2	1.27	1.26
			3	1.28	1.28
A678-C/SAW	1	0°F	0	--	
		1.28	1	1.27	1.26
A678-C/SAW	2	0°F	-4		1.26
			-3	1.26	1.26
			-2	1.26	1.26
			-1	1.25	1.25
		1.28	0	--	1.25
			1	1.26	1.26
			2	1.25	1.27
			3	1.25	
A678-C/SMAW	1	0°F	-2	1.27	
			-1	1.24	1.26
		1.28	0	--	1.25
			1	1.23	1.24
			2	1.23	1.26
			3	1.25	1.28

Material/Weld	Shot No.	Temperature and Initial Thickness (in.)	Point No.	Thickness Across Weld (in.)
A678-C/SMAW	1	32°F	-2	1.28
			-1	1.25
		1.28	0	--
			1	1.25
			2	1.26
A678-C/SMAW	1	75°F	-3	1.28
			-2	
			-1	1.25
		1.28	0	--
			1	1.26
A678-C/SMAW	2	75°F	-3	1.28
			-2	1.26
			-1	1.23
		1.28	0	--
			1	1.20
			2	1.22
			3	1.25
			4	1.28

In summary, it is noted that the SMAW weldments outperformed the SAW weldments in two (ABS-CS and A517-D) of the three heats considered, and the SMAW weldment still passed in the case of the third weldment, only at a somewhat higher temperature than the SAW weldment. Another way of evaluating these results is to note that two weldments failed to pass the ECST test criteria at any temperature; these were both SAW weldments.

C. Explosion Tear Tests

Two ET specimens each of Heats 4 (ABS-CS) and 8 (A678-C), and one each from Heats 5 and 6 (both A517-D) were fabricated as described in Section III.H. of this report. The center strip was ASTM A-36 steel, and the weldments were deliberately undermatched with the adjoining parent materials in an effort to insure that the crack, once initiated from the Hardex crack starter, would not be arrested by a tough weldment. It was planned that two shots would be applied to each specimen, if necessary, to initiate a running crack, although all six specimens each developed a crack into the adjoining parent material on the first shot. The two specimens of ABS-CS were 1 inch thick (as was the A-36 center strip), and the two heats of A678-C were each 1-1/4 inch thick (as was the A-36 center strip). The A517-D specimens were mixed; one was 1 inch thick and the other 1-1/4 inch thick, with the A-36 center strip matched to thickness.

The experimental test setup was similar to that of the ECST tests, described in the preceding subsection. All tests were conducted at a specimen temperature of 32°F. Cast Penolite charges of 7 pounds (for 1-inch specimens) and 12 pounds (for 1-1/4-inch specimens) were used to explosively-load the specimens. The test results are summarized in Table 19, and Figures 56 a-f show the condition of each specimen after the test. A specimen was considered to have passed if all cracks that penetrated into the base material strips on either side of the A-36 were arrested in the base material. As can be seen from the table and from the figures, the CS specimens both failed and the A517-D and A678-C test results were mixed in that both groups had one specimen that passed, and one that failed. In the case of the A517-D the thinner of the two specimens passed. In the two A678-C tests the specimen loaded at a standoff of 15 inches failed, while the companion specimen loaded at a standoff of 17 inches (a less severe test) passed.

Table 19. Explosion Tear Test Summary

Heat No.	Arrest Material	Thickness (in.)	T°F	Charge Wt (Lb)	Standoff (in.)	Time (sec)	Pass/ No Pass
4	ABS-CS	1.	32	7	15	55	No Pass
4	ABS-CS	1.	32	7	15	57	No Pass
5	A517-D	1.	32	7	15	60	Pass
6	A517-D	1-1/4	32	12	17	56	No Pass
8	A678-C	1-1/4	32	12	15	66	No Pass
8	A678-C	1-1/4	32	12	17	53	Pass

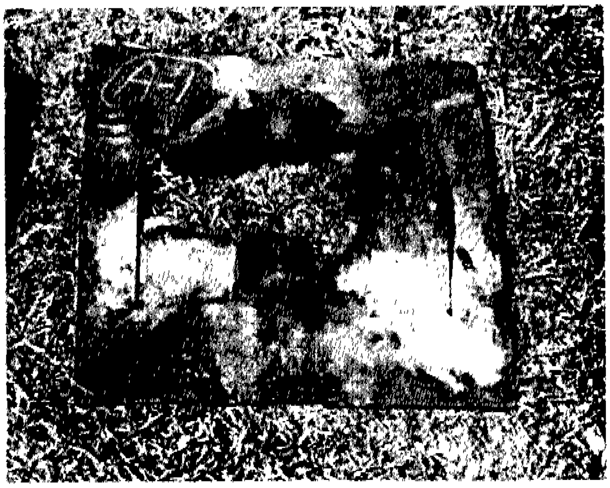


Fig. 56a

Heat 4 (ABS - CS), 1" thick.
32°F.
Condition after one shot.
(No crack arrest).

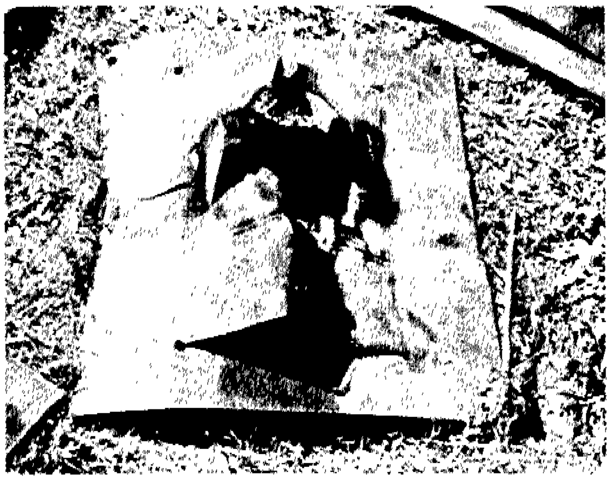


Fig. 56b

Heat 4 (ABS-CS), 1" thick.
32°F.
Condition after one shot.
(No crack arrest).

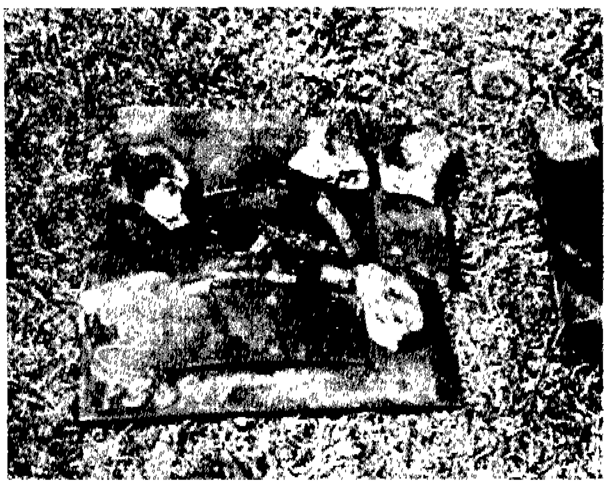


Fig. 56c

Heat 6 (A517-D), 1" thick.
32°F.
Condition after one shot.
(Cracks arrested).

Figures 56 a-f. Explosion Tear Test Specimens, Post-Test

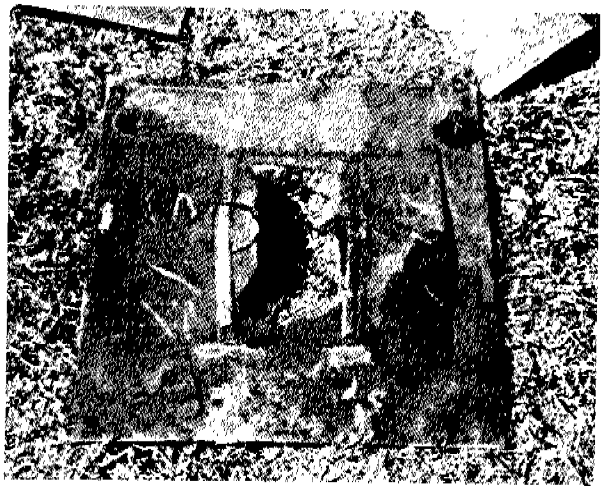


Fig. 56d

Heat 6 (A517-D), 1-1/4" thick.
32°F.
Condition after one shot.
(No crack arrest).

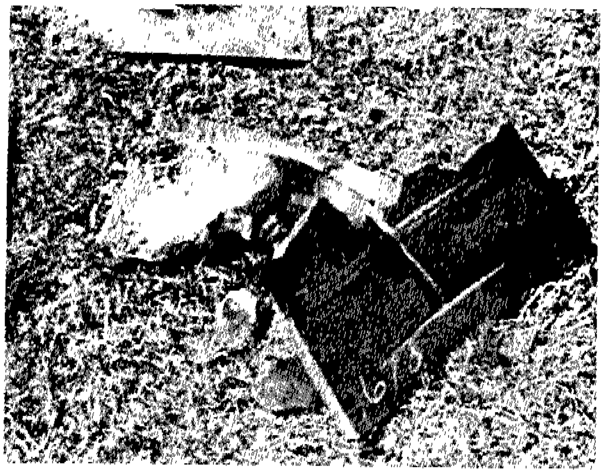


Fig. 56e

Heat 8 (A678-C), 1-1/4" thick.
32°F.
Condition after one shot.
(No crack arrest).

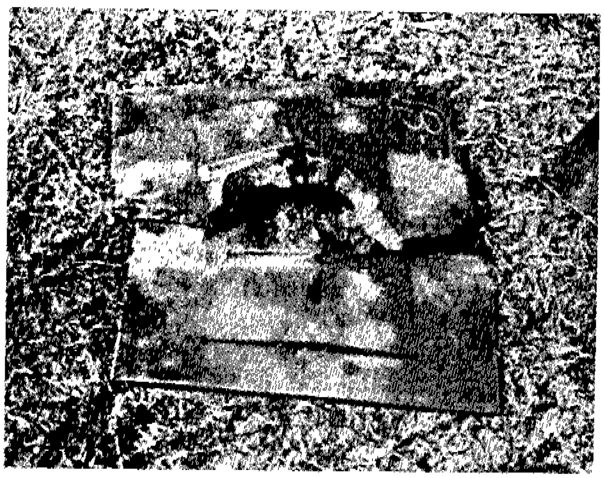


Fig. 56f

Heat 8 (A678-C), 1-1/4" thick.
32°F.
Condition after one shot.
(Cracks arrested).

Figures 56 a-f. Explosion Tear Test Specimens, Post-Test

VI. DISCUSSION OF RESULTS

A. Relation to SSC-244 Criterion

In their report on fracture control guidelines for welded steel ship hulls,[1] Rolfe, et al, set out a tentative criterion for qualifying toughness and crack arrest properties of ship plate. One of the principal objectives of the present SR-224 program has been to evaluate the proposed Rolfe criterion in light of data generated on parent materials and weldments. Therefore, it is necessary to summarize the SSC-244 criterion before beginning a discussion of the significance of the present data.

The principal factors considered to be of importance in developing the SSC-244 criterion for controlling the susceptibility of welded structure to brittle fracture were:

1. Material toughness at the particular service temperature, loading rate, and plate thickness.

2. Size of flaw at the point of fracture initiation, regardless of whether the flaw is an arc strike or a large fatigue crack.

3. Stress level, including residual stress.

The purpose of the SSC-244 project was to develop a criterion for the assurance of adequate fracture resistance of ship steels and weldments in service environments.

The criterion proposed in Ref. 1 can be summarized in the following three propositions:

1. Parent material, weld regions and HAZ regions in primary structure must have an NDT (as measured by the DW-NDT test) no higher than 0°F. Parent materials, weld and HAZ regions used in secondary structure must have an NDT no higher than +20°F.

2. To insure that toughness is satisfactory, 5/8-inch DT tests at 75°F on parent, weld, and HAZ specimens must result in absorbed energy levels no less than E_{75}:

$$E_{75} = \frac{25}{6} (\sigma_y + 60) \tag{1}$$

where

σ_y is the yield strength in ksi and E_{75} is in ft-lbs.

3. Fail safe design can be achieved through the use of crack arrestor strips. Parent materials used for crack arrestors must meet or exceed the following absorbed energy level E_{32} as measured on 5/8-inch DT specimens tested at 32°F:

$$E_{32} = \frac{10}{3} (\sigma_y + 140) \tag{2}$$

where

σ_y is the yield strength in ksi and E_{32} is in ft-lb.

In order to evaluate the applicability of the SSC-224 proposed criterion, it is of obvious importance to test the data base generated in the present SR-224 project against the criterion. Such a comparison leads to the following observations.

With respect to the NDT as measured by the drop weight test, AH-32 fails to qualify for primary structure applications, and marginally qualifies for secondary structure. ABS-B does not qualify even for secondary structure applications because of its high nil ductility temperature. EH-32, A517-D, A678-C, and A537-B all qualify unconditionally on this count for primary structural applications in both SMAW and SAW weldments. ABS-CS qualifies for secondary structure, and possibly could meet the 0°F criterion for primary structure, but the SAW weld region data gave somewhat high DW-NDT readings. Some of these findings are supported by other recent data. In Reference 2 the DW-NDT for ABS-B and CS base metal varied, respectively, from 20-30°F, and -40 to -10°F, disqualifying the former and qualifying the latter by the SSC-244 rules. Reference 9 reports an NDT for ABS-B of 20°F and for CS of -70°F.

Turning now to the SSC-244 requirements for absorbed energy levels, Eq. (1), the present data for press-notched 5/8-inch DT specimens (L-T orientation) were selected for comparison. EH-32, A678-C, A537-B, and ABS-B all passed this control unconditionally, whereas AH-32 does not even come close to passing. A517-D also fails to meet the standard given by Eq. (1), but not by the wide disparity as in the case of AH-32. The ABS-CS passed the required minimum energy level in the case of the SMAW weld process, and would also have passed for the SAW process except for a somewhat low energy value for the weld metal (the parent and HAZ specimen groups passed by wide margins).

Finally SSC-244 requires the crack arrest capacity of the parent materials to be tested and qualified via Eq. (2). The AH-32, A517-D, and ABS-B clearly failed this test, whereas the EH-32 and CS materials appear to have passed. A678-C and A537-B gave conflicting results among heats; some heats of these steels may be expected to meet the SSC-244 crack arrest requirements, and some may not. These results are generally consistent with the findings from the Explosion Tear tests reported in Section V.C. There it was found that the CS specimens failed the test, while the A517-D and the A678-C gave mixed results, one specimen of each group passed while its companion failed. However, it should be noted that the DT curve for the CS material shows a very sharp transition region, with 32°F being just on the upper shelf. Hence a small variation in heat properties, etc., could account for the lack of arrest in the ET test.

In order for a steel to be placed in service in either primary or secondary structural applications, according to SSC-244 it must meet both the NDT and the energy absorption tests. In consideration of this, EH-32, A678-C, and A537-B pass these tests for both the SAW and the SMAW weld processes. The ABS-CS was found to be acceptable with the SMAW process for primary structure, and some heats could possibly qualify with the SAW process in primary applications. The AH-32, A517-D, and ABS-B failed to meet the joint NDT/toughness requirements.

Consideration of the NDT, toughness, and arrest capabilities in combination reveals that one material, EH-32, exceeds all tests. However, CS, A678-C, and A537-B can pass with certain heats and weld processes. The AH-32, A517-D, and the ABS-B are inadequate to meet all three tests recommended by SSC-244. These conclusions are summarized below:

Material	NDT OK for P or S Structure?*	Toughness OK ?	Crack Arrest OK?
AH-32	Marginally OK for S	No	No
EH-32	Yes	Yes	Yes
CS	OK P with SMAW; OK S with SAW	OK SMAW; Maybe SAW	Yes
A517-D	Yes	No	No
A678-C	Yes	Yes	Yes, some heats
A537-B	Yes	Yes	Yes, some heats
B	Not even for S	Yes	No

*P = Primary Structure
S = Secondary Structure

It is important to point out that the present data show there to be a considerable amount of heat-to-heat scatter in some cases. This is particularly true of energy level values at 32°F and the NDT. These heat-to-heat variations within materials result in some heats meeting the SSC-244 crack arrest requirements and others of the same material do not.

In recognition that Charpy V-Notch testing technology is more widespread and common than DT testing, SSC-244 tentatively proposed an alternative to 5/8-inch DT testing by substituting the Charpy test. This approach obviously requires developing C_v values that are "equivalent" to the proposed toughness requirements. Two such equivalences were proposed for the 75°F toughness requirements, and one for the 32°F crack arrest requirement. In Appendix E of Ref. 1 these proposed linear relationships between DT and C_v values are set forth. For purposes of evaluating the SSC-244 criterion with Charpy data from the present project, these empirical relationships are used in the form given below.

Notch toughness requirement:

$$C_v = \frac{1}{60}(59\sigma_y - 1220) \qquad (3)$$

Alternative notch toughness requirement:

$$C_v = 4(1 + 0.1\,\sigma_y) \qquad (4)$$

Crack arrest requirement:

$$C_v = \frac{1}{60}(2480 + 19\,\sigma_y) \qquad (5)$$

In all of these expressions σ_y is expressed in ksi and C_v in ft-lb.

If the SSC-244 criterion is examined with the present Charpy data* rather than the DT data as discussed previously, several observations can be made. To begin with, Eq. (4) above is a much weaker requirement than is Eq. (3), especially for normalized and Q&T steels having high yield strengths. In fact, all parent specimen tests at 75°F and all combinations of SMAW and SAW weldments in the weld and the HAZ regions at 75°F equalled or exceeded the requirement given as Eq. (4). This requirement was proposed by Rolfe, et al., based on an empirical correlation between dynamic tear and Charpy absorbed energies. If used to test the present data base, no materials or weldments would have been screened out. This is not the case, however, in applying Eq. (3) to the present Charpy data. This requirement in fact accepts/rejects the same parent materials (at 75°F) as does the 5/8-inch DT requirements: AH-32 and A517-D parent materials are both rejected. In applying Eq. (3) to the weld and HAZ test results with SMAW and SAW weldments, the same holds true; Eq. (3) screens out A517-D and passes the rest, just as the 5/8-inch DT requirement does. Thus, apparently the DT and the Charpy tests are equally and consistently successful in qualifying weldments and parent materials for toughness at 75°F. This conclusion must be regarded as tentative, however, until further confidence is achieved by evaluating more data.

Eq. (5) is advanced in Ref. 1 as a tentative requirement for evaluating the crack arrest capabilities of the base metal. Applying this standard against the present Charpy data results in the acceptance of EH-32, CS, and A678-C, and the rejection of AH-32, A517-D, and ABS-B as crack arrest materials. The two heats of A537-B gave mixed results: Heat 9 passed and Heat 10 failed to meet the energy absorption requirement given as Eq. (5). These conclusions also are consistent with those derived from the crack arrest requirements from 5/8-inch DT specimens discussed earlier.

The inference should not be drawn from this report that simply because a material is operating below its NDT, it is doomed to inevitable failure. The criterion simply indicates that catastrophic cracking is a distinct possibility if the material is unable to dissipate energy by plastic flow at the tip of a crack. When operating below its NDT, a steel is likely to permit crack propagation (if a crack exists or is initiated) at high speed and with no dissipation of energy.

B. Assessment

In recent years there have been heightened demands placed on ship designers to reduce weight and costs, increase working stresses, and take advantage of some of the higher strength Q&T alloys available. These demands, in turn, appeal for criteria of some kind by which base metals and weldments can be effectively qualified before being placed into service. In developing a criterion, or set of rules such as those proposed in SSC-244[1], there appear to be three broad questions which must be addressed if the criterion is to be an effective one.

*In making these comparisons, groups of three repeat data reported here were averaged. The effect of C_v data scatter is therefore not directly considered.

1. Does the criterion provide an adequate measure of toughness and crack arrest capacity over the service temperatures of interest?

2. Are the tests involved widely used and inexpensive enough to facilitate its adoption and use by the shipbuilding industry?

3. Are the requisite tests capable of discriminating good from bad materials and weldments without producing so much scatter as to disqualify many sound materials and weldments?

In the present evaluation of the criterion proposed in SSC-244 it is appropriate to address these three questions.

With regard to crack toughness and arrest capabilities, a basic goal of any fracture control program must be the prevention of brittle, plane strain fracture and the assurance that the crack extension process includes at least some energy-consuming plasticity. To insure this, one must be certain that the temperature, loading rate, and section thickness do not combine to produce plane strain conditions. In dealing with thicknesses in the range $0.75'' \leq T \leq 1.5''$, if one somehow can approximate rate effects, then it merely becomes necessary to insure that the bulk of the ship's operating temperature range does not incorporate any regime of plane strain material behavior. Since little operation in less than 0°F environments is seen, the requirement that the NDT of the metal be less than this appears to be a necessary first step.

Suppose a crack begins growing subcritically in a structure. What determines whether this crack will run or not? Simply put, a high toughness can accommodate a large crack, so it is desirable that the material exhibit non-plane strain behavior.

In order to measure and qualify such properties a test is needed that will subject a realistically sized specimen containing a crack to a rapidly applied load. (The load should be fairly rapid since increased load rate shifts the temperature curves to the right and hence reduces the factor of safety.) If the material exhibits reasonable deformation over the appropriate operating range of the vessel, then the material in question may prove satisfactory.

Qualification of weldments is a similar problem; in about 95% of the cases, the HAZ is the weak link in an otherwise good weldment. Hence if the HAZ can demonstrate the same degree of deformation as the parent material, then not only will the crack be difficult to cause to go unstable, but it will also be difficult for it to maintain a fast fracture due to the energy balance.

The principal problem then appears to be placing values on the plasticity needed during crack extension to insure adequate toughness. Since an elasto-plastic, dynamic solution of an impact specimen is not available, the alternative is then to define the plasticity requirement rather arbitrarily. As long as experience continues to support this choice, there is no one way to choose one approach for a fracture control criterion over another. For example, the SSC-244 criterion requires a specified measure of plastic deformation and strength through the NDT. Another approach (also discussed in Ref. 1) has been through the use of the Charpy, rather than the DT specimen, by measuring the percentage of shear area and specifying a level of absorbed energy. The two approaches are, of course, equivalent provided a correlation is available by which DT energy levels can be converted into C_v energy levels.

There are, of course, several common objections to the Charpy specimen: its small size precludes exercising a reasonably large volume of material, and eliminates plane strain constraint characteristic of thick plate. In addition, the machined notch does not behave like a true notch. These factors, which are somewhat mitigated by cost and simplicity of use advantages, tend to scatter the C_v data more widely than is usually found in DT data. On the other hand, the Charpy specimen may, by virtue of its small size, have certain advantages in measuring weld and HAZ toughness. The resolution of the question as to which specimen--C_v or DT-- is best suited to a fracture control criterion must ultimately be resolved on the basis of the three questions set forth at the beginning of this subsection. There are, however, at least three reasons which are persuasive in the choice of the DT specimen over the Charpy specimen. First, C_v data are traditionally required in triplicate, which makes these tests more expensive in the long run than standard 5/8-inch DT tests. Secondly, most available data indicate that the transition in DT curves agrees with the NDT, while the C_v transitions do not. Finally, the data developed during the present investigation indicate that on the basis of scatter, the DT test is preferable.

In further support of the preceding statement, it is of interest to examine the following comparison.

Material	Source	NDT, °F	DT Energy, Ft-Lb 0°F	DT Energy, Ft-Lb 32°F	DT Energy, Ft-Lb 75°F	C_v, Ft-Lb 0°F	C_v, Ft-Lb 32°F
CS	SwRI*	-60, -50	275	--	700	80	--
CS	Bethlehem (10)	-70	1000	--	930	110	--
CS	NRL [2]	-40, -10	--	--	--	>200	--
B	SwRI*	+50, +60	--	80	300	--	35
B	Bethlehem [10]	+20	--	87	150	--	42
B	NRL [2]	+20, +30	--	--	--	--	20
B	SR-202 [1]	0, +15	--	100	220	--	10

*Present investigation

Although the C_v data suggest considerable scatter, neither are the DT data immune from this criticism. It is also interesting, and indeed alarming, to note that the spread of the DW-NDT temperatures for the two materials presented is 60°F. All this seems to suggest that the scatter tolerances permitted by any effective criterion may have to be set rather wide in order to accept the majority of material. Hand-in-hand with this approach, however, comes a decrease in structural reliability.

In the final analysis, the present investigation showed the criterion proposed by Rolfe, et al,[1] to be a reasonable one for the weldments investigated. In view of the fact that only one material (EH-32) passed all tests of the criterion for both weld procedures investigated, it may be suspected that the criterion could be overly conservative, disqualifying some steels and thin weldments that may in fact perform perfectly satisfactorily in service. This caveat is merely speculation at this point, however, and only through more extensive laboratory test experience can needed confidence be gained.

VII. RECOMMENDATIONS

1. To the extent the present project has been able to evaluate the SSC-244 criterion proposed by Rolfe, et al, the criterion appears to be effective in qualifying base metals and weldments, although perhaps more restrictive than need be. The criterion should be tested further against other candidate ship steels and weld procedures to gain confidence. The use of the Charpy test as a substitute for the 5/8-inch press-notch DT test needs more justification before it is accepted as part of the criterion.

2. Additional work needs to be done to determine whether the 5/8-inch DT specimen is adequate to evaluate the toughness of the weld and HAZ, or whether small mismatches between notch tip and weld or HAZ location give rise to unacceptably large apparent property gradients. The ECST test should be considered as a substitute for the DT qualification of weld and HAZ regions if the problem raised above appears serious.

3. An understanding of the reasons for heat-to-heat and weld-to-weld property variations (NDT, DT) should be developed, and the latter should include shipyard inspection and QC considerations. Whether or not there is a synergistic effect between base metal quality and weld quality should be determined. A statistical representation of heat-to-heat and weld-to-weld variations should be developed and incorporated into the criterion for qualifying materials and weldments. It may well be that a "go-no go" criterion will be too severe in which case a statistical distribution of acceptable values must be developed.

4. Further analytical and experimental investigation of the dynamic, elasto-plastic response of the 5/8-inch press-notch DT specimen needs to be undertaken, so that sensible limits can be imposed on its use as a qualification test in the criterion. This effort is also needed to tie the DT test to dynamic fracture toughness.

5. These recommendations need to be merged with those from Report SSC-275 (on load rate effects) for further evaluation of the proposed SSC-244 criterion.

REFERENCES

1. "Fracture-Control Guidelines For Welded Steel Ship Hulls," by S. T. Rolfe, D. M. Rhea, and B. O. Kuzmanovic, Ship Structure Committee Report SSC-244, Project SR-202, 1974.

2. "Fracture Toughness Characterization of Shipbuilding Steels," by J. R. Hawthorne and F. J. Loss, Ship Structure Committee Report SSC-248, Project SR-220, 1975.

3. American Bureau of Shipping, Guide for the Classification of Manned Submersibles, 1968 Edition, Section 2.2.5.

4. "Proposed Method for 5/8-in. (16-mm) Dynamic Tear Test of Metallic Materials," 1976 Annual Book of ASTM Standards, Part 10, 777-784.

5. "Standard Method for the 1-Inch Dynamic Tear Test," by P. P. Puzake and E. A. Lange, NRL Report 6851, U.S. Naval Research Laboratory, February, 1969.

6. "Standard Procedures for Preproduction Testing Materials by the Explosion Bulge Test," Revision 1, NAVSHIPS 0900-005-500, Department of the Navy, November, 1965.

7. "Review of Concepts and Status of Procedures for Fracture-Safe Design of Complex Welded Structures Involving Metals of Low and Ultra-High Strength Levels," by W. S. Pellini, R. J. Goode, P. P. Puzak, E. A. Lange, and R. W. Huber, NRL Report 6300, U.S. Naval Research Laboratory, June, 1965.

8. "Report on Evaluation of Weldability of ASTM A537, Grade B Steel," Engineering Technical Report, Mare Island Naval Shipyard, December 1975.

9. "Ductile Fracture Equation for High-Strength Structural Metals," by R. W. Judy, Jr. and R. J. Goode, NRL Report 7557, U.S. Naval Research Laboratory, April 3, 1973.

10. "Toughness Evaluation of Electrogas and Electroslag Weldments," Bethlehem Steel Corp., March 1975.

APPENDIX A

WELDING PROCEDURES

WELDING PROCEDURE FOR ABS GRADE EH 32

Scope: This specification is for the joining of ABS-type EH 32 material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction and conforms to ABS welding requirement for hull structure.

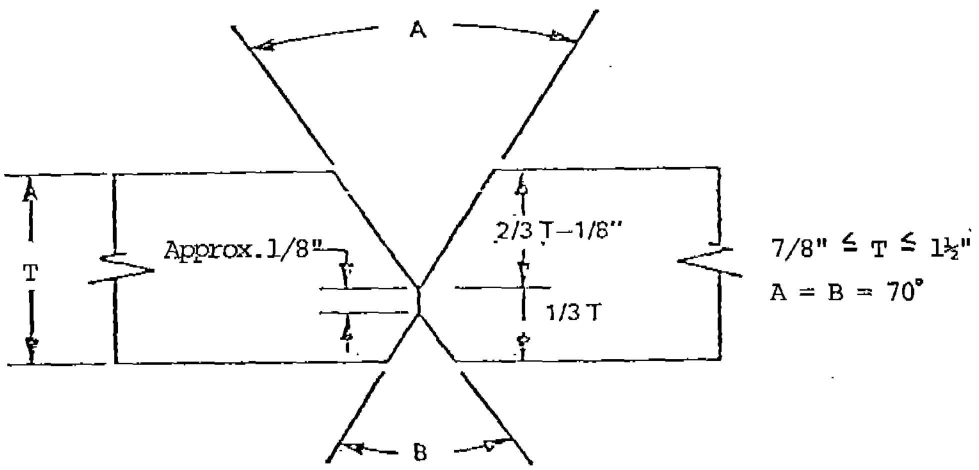
Base Material: ABS Grade EH 32.

Filler Metal and Flux: Armco W-18 wire 1/8 and 5/32 inches, Lincoln 860 flux. Seal welding prior to automatic sub-arc: E-9018-M E-9018-M electrode for manual; E-8018 usually used for base metal repairs.

Preheat and Interpass Temperature: Although ABS does not require a preheat in normal practice, butt welds up to 1-1/2 inches may have a preheat of 150°F minimum and maximum interpass temperature of 300°F. The maximum heat input shall be 60,000 J/in.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



Preparation of Base Material: The edges of surfaces to be prepared by any of the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E-9018-M and ground flush with the adjacent material.

Joint Welding Procedure and Cleaning: The welding technique shall be such that weld heads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

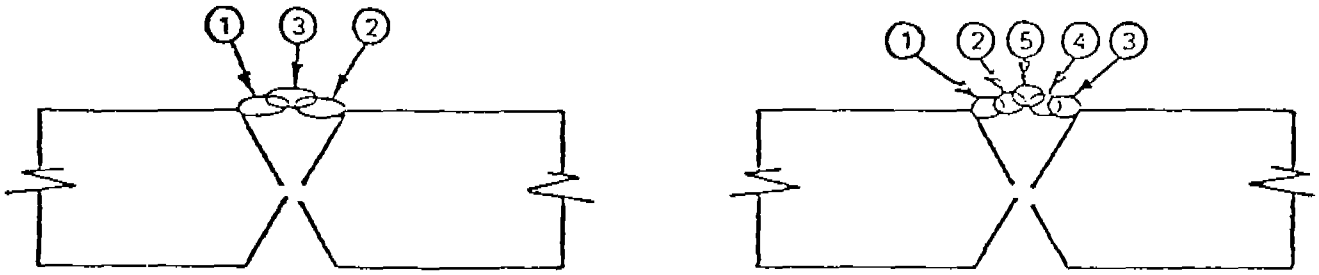
Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat ± 15°.

Welding Repair: Welding may be repaired with Manual Shielded Metal Arc Process.

Tempering Beads: Tempering welds, although not required, shall be made so a new heat-affected zone will not be created. The temper bead toe should land approximately 1/8 inch from the base material (see sketch, Tempering Bead Technique, below).



TEMPERING BEAD TECHNIQUE

Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Interpretation of Heat Cycle: Preheat temperature shall be maintained until the weld is complete or welds have been deposited equal to 1/3 of the wall thickness. Lower temperatures gradually until they are the ambient temperature.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 ipm, 1/8 inch +5/32 inch. Armco W-18 filler metal, Lincoln 860 Flux. 150°F preheat, 300°F maximum interpass temperature. Heat input, 40,000 to 60,000 J/in.

AUTOMATIC SUBMERGED ARC WELDING PROCEDURE

1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-9018-M electrode. 150 °F preheat, 300°F maximum interpass temperature. Heat input, 30,000 J/in. (max).

MANUAL SHIELDED METAL ARC WELDING PROCEDURE

Scope: This specification is for the joining of ABS-CS material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction, and conforms to ABS welding requirements for hull structures.

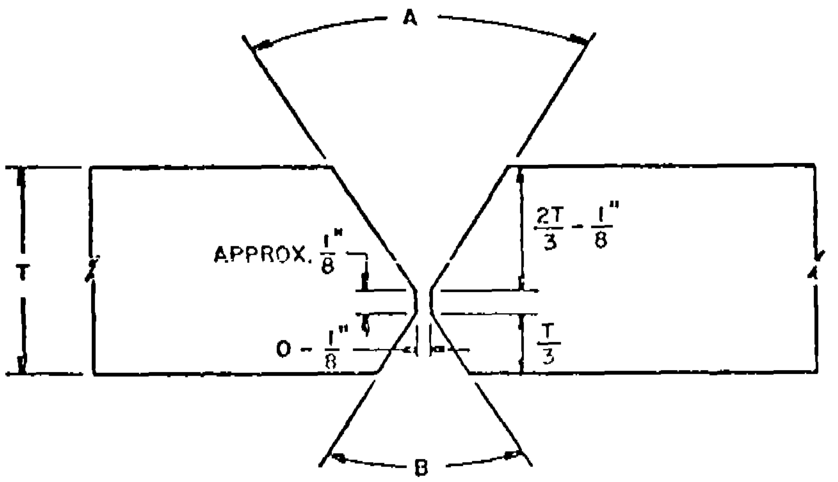
Base Material: ABS Grade CS.

Filler Metal and Flux: Lincoln L-60 wire and 1/8 and 5/32 inches, Lincoln 860 flux. Seal welding prior to automatic sub-arc: E-8018-C3 1/8 inch electrode for manual.

Preheat and Interpass Temperature: 50°F minimum.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal Weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



$\frac{7}{8}'' \leq T \leq 1\frac{1}{2}''$

$A = B = 70°$

Preparation of Base Material: The edges of surfaces to be prepared by any of the the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches. Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E-8018-C3 and ground flush with the adjacent material.

Joint Welding Procedure and Cleaning: The welding technique shall be such that weld beads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat $\pm$ 15°.

Welding Repair: Welding may be repaired with Manual Shielded Metal Arc Process.

Tempering Beads: Tempering weld beads shall not be required.

Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 ipm, 1/8 inch +5/32 inch. Lincoln L-60 filler metal, Lincoln 860 Flux.	AUTOMATIC SUBMERGED ARC WELDING PROCEDURE
1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-8018-C3 electrode. 30,000 J/in. (nominal).	MANUAL SHIELDED METAL ARC WELDING PROCEDURE

WELDING PROCEDURE FOR A517 GRADE D

Scope: This specification is for the joining of A517 material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction, and conforms to ABS welding requirements for hull structures.

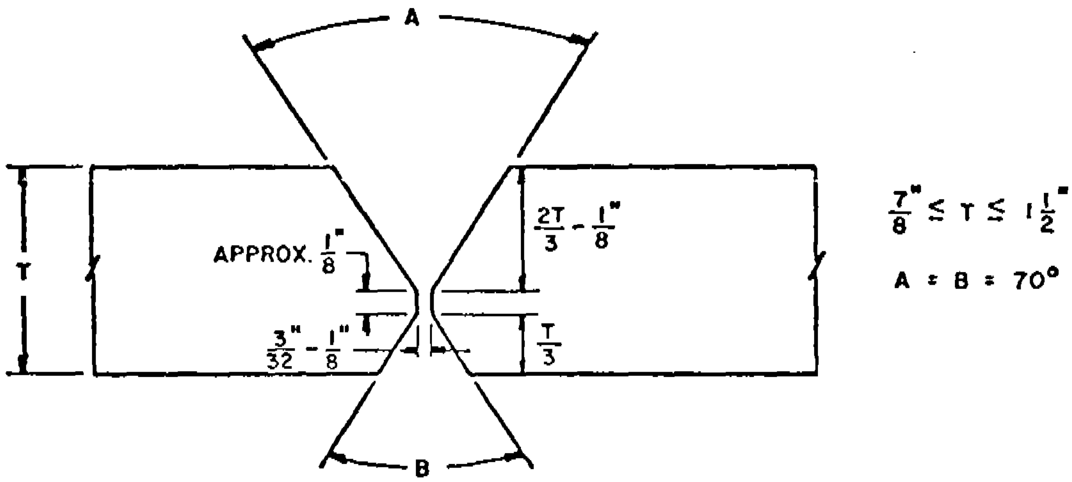
Base Material: ASTM 517-D

Filler Metal and Flux: Armco W-25 wire 1/8 and 5/32 inches, Linde 709-5 flux. Seal welding prior to automatic sub-arc: E-11018-M electrode for manual.

Preheat and Interpass Temperature: Butt welds up to 1½ inches shall have a preheat of 200°F minimum and maximum interpass temperature of 300°F. The maximum heat input shall be 60,000 J/in.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



Preparation of Base Material: The edges of surfaces to be prepared by any of the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches. Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E 11018-M and ground flush with the adjacent material.

Joint Welding Procedure and Cleaning: The welding technique shall be such that weld beads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

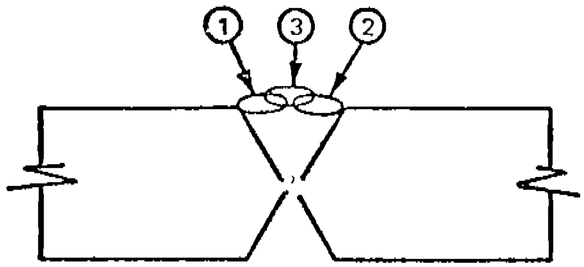
Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

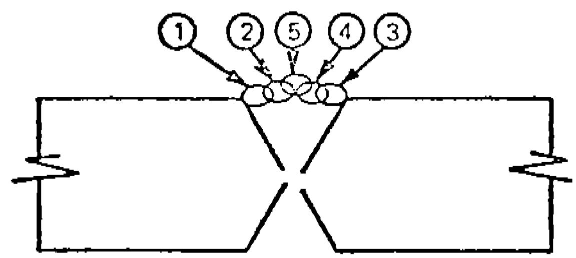
Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat ± 15°.

Welding Repair: Welding may be repaired with Manual Shielded Metal Arc Process.

Tempering Beads: Tempering welds shall be made so a new heat-affected zone will not be created. The temper bead toe should land approximately 1/8 inch from the base material (see sketch, Tempering Bead Technique, below.)





TEMPERING BEAD TECHNIQUE

Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Interpretation of Heat Cycle: Preheat temperature shall be maintained until the weld is complete or welds have been deposited equal to 1/3 of the wall thickness. Lower temperatures gradually until they are the ambient temperature.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 ipm, 1/8 inch +5/32 inch. Armco W-25 filler metal, Linde 709-S flux. 200°F preheat, 300°F maximum interpass temperature. Heat input, 40,000 to 60,000 J/in.

AUTOMATIC SUBMERGED ARC WELDING PROCEDURE

1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-11018-M electrode. 200°F preheat, 300°F maximum interpass tempreature. Heat input, 30,000 J/in. (max).

MANUAL SHIELDED METAL ARC WELDING PROCEDURE

WELDING PROCEDURE FOR A678 GRADE C

Scope: This specification is for the joining of A678 material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction, and conforms to ABS welding requirements for hull structures.

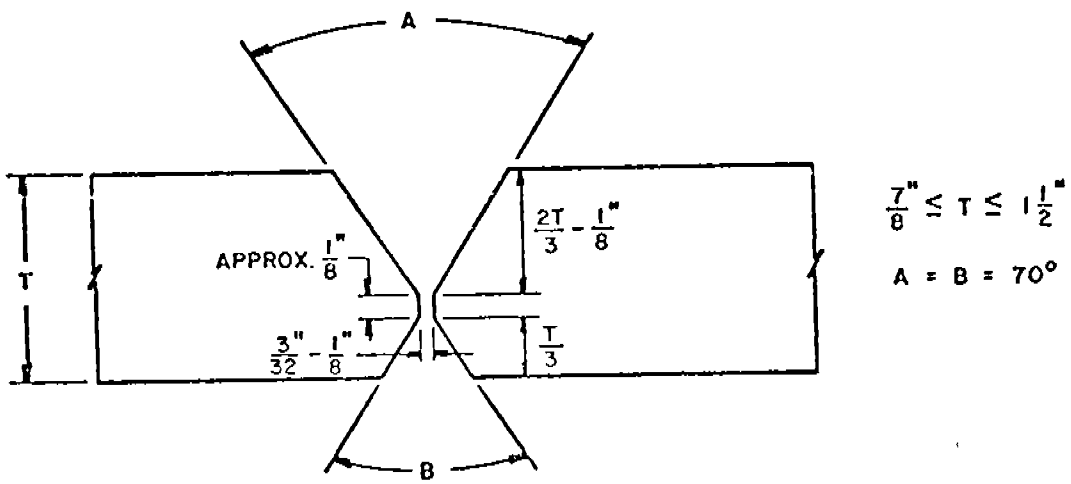
Base Material: ASTM A678 Grade C.

Filler Metal and Flux: Armco W-18 wire 1/8 and 5/32 inches, Lincoln 860 flux. Seal welding prior to automatic sub-arc: E-9018-M electrode for manual.

Preheat and Interpass Temperature: Butt welds up to 1½ inch shall have a preheat of 150°F minimum and maximum interpass temperature of 300°F. The maximum heat input shall be 60,000 J/in.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



Preparation of Base Material: The edges of surface to be prepared by any of the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches. Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E-9018-M and ground flush with the adjacent material.

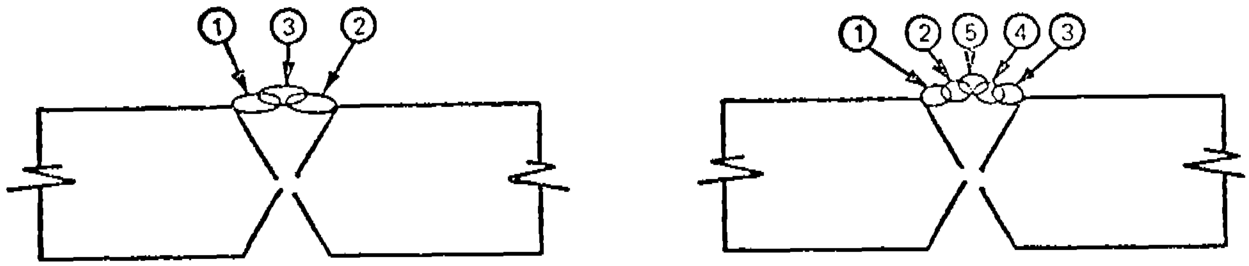
Joint Welding Procedure and Cleaning: The welding technique shall be such that weld beads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat $\pm$ 15°.

Tempering Beads: Tempering welds shall be made so a new heat-affected zone will not be created. The temper bead toe should land approximately 1/8 inch from the base material (see sketch, Tempering Bead Technique, below.)



TEMPERING BEAD TECHNIQUE

Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Interpretation of Heat Cycle: Preheat temperature shall be maintained until the weld is complete or welds have been deposited equal to 1/3 of the wall thickness. Lower temperatures gradually until they are the ambient temperature.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 imp, 1/8 inch +5/32 inch. Armco W-18 filler metal, Lincoln 860 flux. 150°F preheat, 300°F maximum interpass temperature. Heat input, 40,000 to 60,000 J/in.	AUTOMATIC SUBMERGED ARC WELDING PROCEDURE

1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-9018-M electrode. 150 °F preheat, 300°F maximum interpass temperature. Heat input, 30,000 J/in. (max).

MANUAL SHIELDED METAL ARC WELDING PROCEDURE

WELDING PROCEDURE FOR A537 CLASS B

Scope: This specification is for the joining of A537 material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction, and conforms to ABS welding requirements for hull structures.

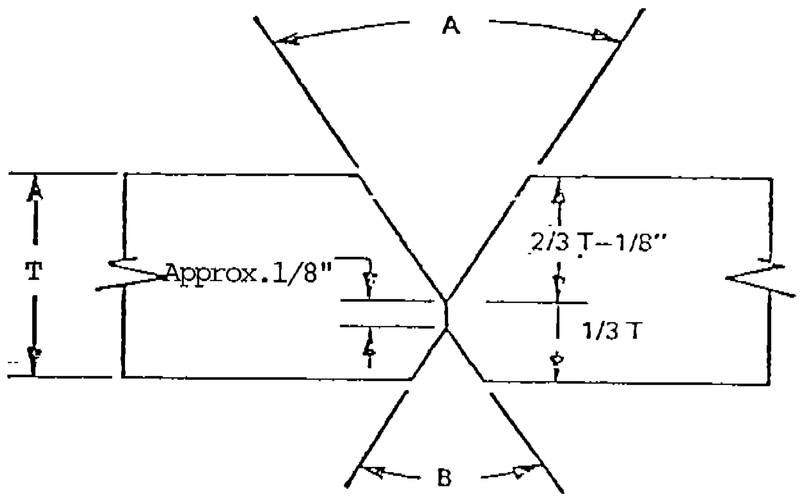
Base Material: ASTM A537 Class B.

Filler Metal and Flux: Armco W-18 wire 1/8 and 5/32 inches, Lincoln 860 flux. Seal welding prior to automatic sub-arc: E-9018-M electrode for manual.

Preheat and Interpass Temperature: Butt welds up to 1½ inch shall have a preheat of 150°F minimum and maximum interpass temperature of 300°F. The maximum heat input shall be 65,000 J/in.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



$7/8" \leq T \leq 1\frac{1}{2}$
$A = B = 70^\circ$

Preparation of Base Material: The edges of surfaces to be prepared by any of the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches. Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E-9018-M and ground flush with the adjacent material.

Joint Welding Procedure and Cleaning: The welding technique shall be such that weld beads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

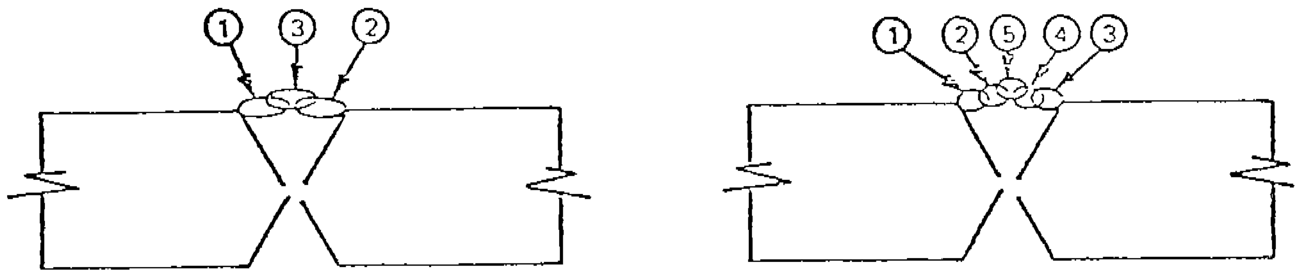
Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat $\pm$ 15°.

Welding Repair: Welding may be repaired with Manual Shielded Metal Arc Process.

Tempering Beads: Tempering welds shall be made so a new heat-affected zone will not be created. The temper bead toe should land approximately 1/8 inch from the base material (see sketch, Tempering Bead Technique, below.)



TEMPERING BEAD TECHNIQUE

Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 ipm. 1/8 inch +5/32 inch. Armco W-18 filler metal, Lincoln 860 flux. 150°F preheat, 300°F maximum interpass temperature. Heat input, 40,000 to 60,000 J/in.

AUTOMATIC SUBMERGED ARC WELDING PROCEDURE

1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-9018-M electrode. 150 °F preheat, 300°F maximum interpass temperature. Heat input, 30,000 J/in. (max).

MANUAL SHIELDED METAL ARC WELDING PROCEDURE

WELDING PROCEDURE FOR ABS-B GRADE

Scope: This specification is for the joining of ABS-B material to itself. This procedure is one which simulates a procedure which might be used in actual merchant ship construction, and conforms to ABS welding requirements for hull structures.

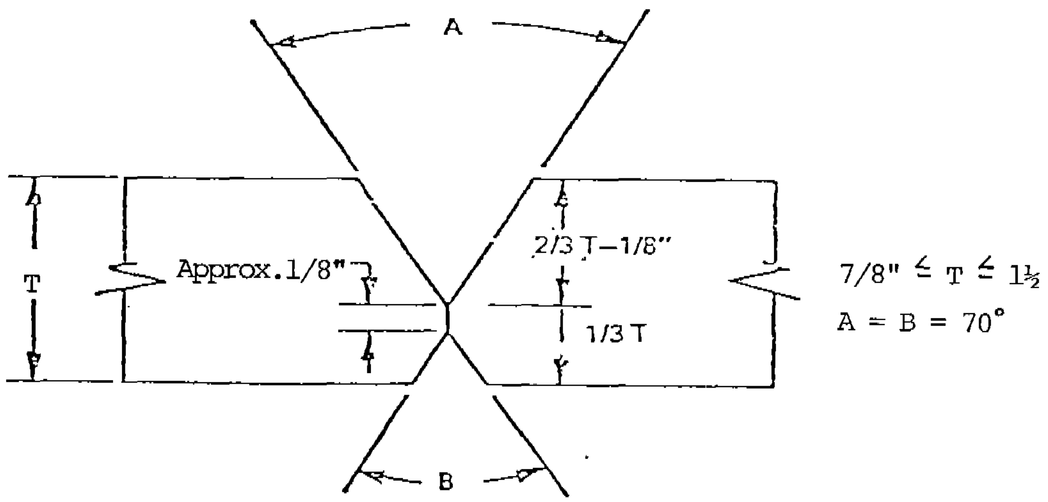
Base Material: ABS Grade B

Filler Metal and Flux: Lincoln L-60 wire 1/8 and 5/32 inches, Lincoln 860 flux. Seal welding prior to automatic sub-arc: E-8018-C3 1/8 inch electrode for manual.

Preheat and Interpass Temperature: 50°F minimum.

Process and Electrical Characteristic: Automatic sub-arc-DC reverse polarity: Manual shield arc-(Seal weld) DC reverse polarity.

Joint Design: The design shall be as shown below.



Preparation of Base Material: The edges of surfaces to be prepared by any of the following: flame cutting, air carbon arc gouging, chipping, machining, grinding, or plasma cutting. The surfaces to be welded shall be cleaned of any matter that may be detrimental to sound welds. The second side of the joint shall be chipped, ground, or air carbon arc gouged to sound metal prior to welding. Flame gouging shall not be used. The surfaces to be welded shall be reasonably smooth and free of notches. Notches shall be ground. Deep notches shall be filled with Manual Shield Arc E-8018-C3 and ground flush with the adjacent material.

Joint Welding Procedure and Cleaning: The welding technique shall be such that weld beads are uniform in contour and taper smoothly into the base material at the toe. Grinding may be used to accomplish a smooth contour if necessary. All slag or flux remaining or any bead of weld shall be removed prior to depositing the next successive weld bead.

Arc strikes shall be avoided insofar as possible; care must be taken to strike arcs in the weld groove or in the way of the weld so they will be incorporated in the welds.

Defects: Any cracks or blow holes that appear on the surface of any weld shall be removed by chipping, grinding, or air carbon arc gouging before depositing the next successive weld bead. Broken or cracked tacks shall be removed prior to seal welding.

Welding Position: Flat $\pm$ 15°.

Tempering Beads: Tempering weld beads shall not be required.

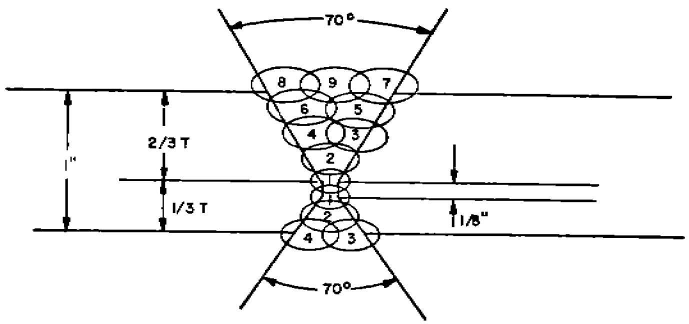
Tacking: For sub-arc welding, tacks shall be made using E-8018-C3 electrodes. These tacks shall be made so they can be incorporated in the seal weld.

Welding Procedure

1.0 inch plating shall be welded using the following procedure: 450 to 500A, 30V, 15 to 20 ipm, 1/8 inch +5/32 inch. Lincoln L-60 filler metal, Lincoln 860 flux.	AUTOMATIC SUBMERGED ARC WELDING PROCEDURE
1.0 inch plating shall be welded using the following procedure: 115-150A, 25V, 7 ipm, 1/8 inch +5/32 inch. E-9018-M electrode.	MANUAL SHIELDED METAL ARC WELDING PROCEDURE

APPENDIX B - SAMPLE WELDED JOINT DETAILS

Weld Joint Detail
SMAW



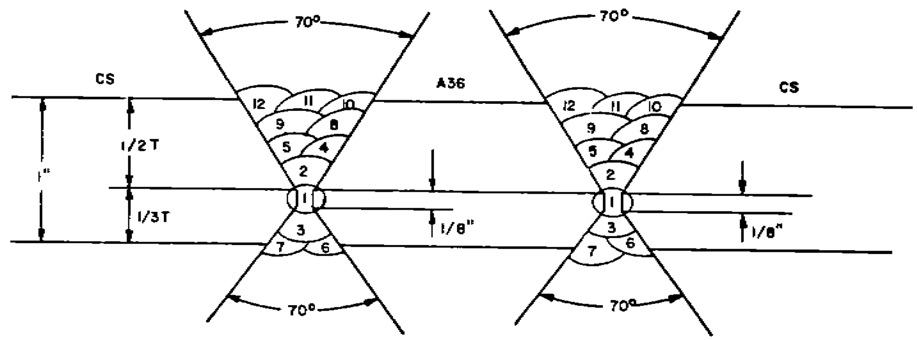
SMAW 8018-C3

Root Bead	Multi Beads
Electrode 1/8"	Electrode 5/32"
Amps 125	Amps 150
Volts 20.5	Volts 25
IPM 4-5	IPM 5-17

Weld Length 31-1/2"

Note: 1. Plate was tacked and clamped to I-Beam.
2. #1 is root bead on both sides.
3. Magnetic particle inspected; found o.k.

Weld Joint Detail
SAW



SMAW Pass #1 Root Bead

Amps 120-130
Volts 20-21
IPM 6-7

Magnafluxed Back Side of Root Bead
SAW passed #2 thru 12
Amps 450-500
Volts 28-31
IPM 15-20

Used 860 Flux; with L-60 wire.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SSC-276	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FRACTURE BEHAVIOR CHARACTERIZATION OF SHIP STEELS AND WELDMENTS. (FRACTURE CRITERIA FOR WELDED SHIP STRUCTURE)		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) P. H. Francis T. S. Cook A. Nagy		8. CONTRACT OR GRANT NUMBER(s) N00024-75-C-4058
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southwest Research Institute San Antonio, TX 78284		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Dept. of the Navy Naval Sea Systems Command Washington, D.C. 20362		12. REPORT DATE May 1978 13. NUMBER OF PAGES 82
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Ship Structure Committee U.S. Coast Guard Headquarters Washington, D.C. 20590		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

UNLIMITED

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In order to enlarge upon current understanding of the behavior of ship steels and weldments, a series of mechanical tests were performed on seven grades of ship steel. These steels were ABS-B, CS, AH-32, EH-32, ASTM A517-D, A678-C, and A537-B and covered the range of ordinary as-rolled, to high strength quenched and tempered alloys. In addition, all materials but the EH-32 were utilized to produce welded plates. These weldments, either manual shielded metal arc or submerged arc procedure, were then machined into test specimens.

The test program was designed to probe a large number of specimen and material parameters. The mechanical tests performed were the static tension test, the Charpy impact test, weld side bend test, dynamic tear test, and the drop weight-nil ductility temperature test. Two structural tests were designed to exercise the crack initiation and arrest capability of the steels. One of these tests was the standard explosion crack starter test while the other was a variation of the explosion tear test.

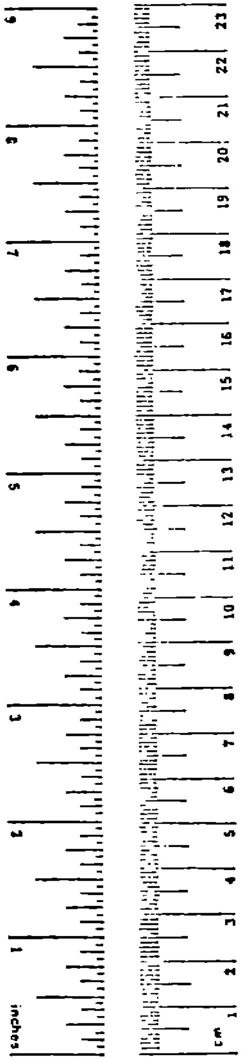
The results indicated the general superiority of the fracture performance of the high strength, quenched and tempered alloys over the ordinary ship steels. The structural tests demonstrated the superiority of the manual metal arc welding procedure. This result was generally confirmed by the results of the dynamic tear tests. The data were compared to the proposed fracture criterion proposed by Rolfe, et. al., as presented in SSC-244. Only one material, EH-32, passed all tests prescribed by the proposed criterion.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

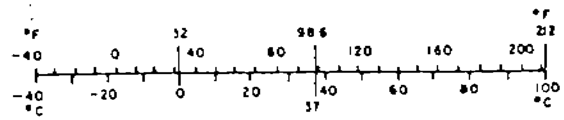
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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These documents are distributed by the National Technical Information Service, Springfield, Va. 22151. These documents have been announced in the Clearinghouse journal U.S. Government Research & Development Reports (USGRDR) under the indicated AD numbers.

SSC-261, *Preventing Delayed Cracks in Ship Welds - Part I* by H. W. Mishler. 1976. AD-A031515.

SSC-262, *Preventing Delayed Cracks in Ship Welds - Part II* by H. W. Mishler. 1976. AD-A031526.

SSC-263, (SL-7-7) - *Static Structural Calibration of Ship Response Instrumentation System Aboard the Sea-Land McLean* by R. R. Boentgen and J. W. Wheaton. 1976. AD-A031527.

SSC-264, (SL-7-8) - *First Season Results from Ship Response Instrumentation Aboard the SL-7 Class Containership S.S. Sea-Land McLean in North Atlantic Service* by R. R. Boentgen, R. A. Fain and J. W. Wheaton. 1976. AD-A039752.

SSC-265, *A Study of Ship Hull Crack Arrester Systems* by M. Kanninen, E. Mills, G. Hahn, C. Marschall, D. Broek, A. Coyle, K. Masubushi and K. Itoga. 1976. AD-A040942

SSC-266, *Review of Ship Structural Details* by R. Glasfeld, D. Jordan, M. Kerr, Jr., and D. Zoller. 1977. AD-A040941.

SSC-267, *Compressive Strength of Ship Hull Girders - Part III - Theory and Additional Experiments* by H. Becker and A. Colao. 1977. AD-A047115.

SSC-268, *Environmental Wave Data for Determining Hull Structural Loadings* by D. Hoffman and D. A. Walden. 1977. AD-A047116.

SSC-269, *Structural Tests of SL-7 Ship Model* by W. C. Webster and H. G. Payer. 1977. AD-A047117.

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SSC-271, *A Correlation Study of SL-7 Containership Loads and Motions - Model Tests and Computer Simulation* by P. Kaplan, T. P. Sargent, and M. Silbert. 1977. AD-A049349.

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