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# UNCLASSIFIED

SERIAL NO. SSC-78

FINAL REPORT
(Project SR-124)

on

# PART II: INVESTIGATION OF THE PERFORMANCE OF WELDMENTS AND PRIME PLATE OF ABS-B STEEL

by

W. S. PELLINI and E. W. ESCHBACHER
Naval Research Laboratory

for

**SHIP STRUCTURE COMMITTEE**

Convened by
The Secretary of the Treasury

*Member Agencies—Ship Structure Committee*

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

*Address Correspondence To:*

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. SSC-78
BuShips Project NS-011-067

**JUNE 18, 1954**

# SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

June 18, 1954

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee sponsored investigations at the Naval Research Laboratory having to do with the properties of ship plate when subjected to drop weight and explosion bulge tests. Herewith is a copy of Part II of the Final Report of this investigation entitled "Investigation of the Performance of Weldments and Prime Plate of A.B.S.-B Steel" by W. S. Pellini and E. W. Eschbacher. The balance of the Final Report is contained in Part I and is being simultaneously distributed as SSC-77.

Any questions, comments, criticism or other matters pertaining to the Report should be addressed to the Secretary, Ship Structure Committee.

This Report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure
Committee.

Final Report
(Project SR-124)

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# PART II: INVESTIGATION OF THE PERFORMANCE OF WELDMENTS AND PRIME PLATE OF ABS-B STEEL

by

W. S. Pellini and E. W. Eschbacher

NAVAL RESEARCH LABORATORY

under

Department of the Navy
BuShips Project No. NS-011-067

for

SHIP STRUCTURE COMMITTEE

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## PART II: INVESTIGATION OF THE PERFORMANCE OF WELDMENTS AND PRIME PLATE OF ABS-B STEEL


### ABSTRACT

The relative performance of G180 and E6010 ABS-B ship plate weldments and prime plate was evaluated by the Explosion Bulge Test. The prime plate loses its ability to develop extensive deformation prior to fracture in the range of -60° to -80°F; the G180 weldment develops a similar loss in the range of +20° to 0°F, and the E6010 weldment in the range of +40° to 0°F. The effects of various types of defects, including arc strikes, porosity, and partial penetration, were investigated. It is shown that in the service temperature range of 20°F to 60°F only sharp, crack-like defects, such as developed by arc strikes, are sufficiently critical to eliminate extensive plastic deformation of weldments prior to failure.

The effects of shot peening of ABS-B steel is demonstrated to be detrimental with respect to the resistance of this steel to initiation and propagation of brittle fractures. Wrought iron considered as a possible material for crack arrestor straps is demonstrated to be less resistant to brittle fracture than ABS-B steels.


### INTRODUCTION

The RULES FOR BUILDING AND CLASSING STEEL VESSELS issued by the American Bureau of Shipping specify the use of Class

B* steel for plates over 1/2 in. and up to 1 in. thickness. In view of the importance of ABS-B steel to present and future construction of welded ships, the Ship Structure Committee has undertaken an extensive research program aimed at determining the performance characteristics of the prime plate and weldments. This report summarizes the results of various investigations conducted at the Naval Research Laboratory. The following aspects of the performance of prime plate and weldments were investigated.

1. Effect of sharp crack-like defects on the performance of prime plate and correlation to Charpy V transition data.
2. Effect of shot peening the prime plate surface. (Shot peening has been suggested as a possible method of increasing the resistance to fracture of ship plate).
3. Comparison of the relative fracture resistance of ABS-B ship plate with wrought iron plate. (Wrought iron had been suggested for crack arrestor strap inserts).
4. Effects of partial penetration weld defects on the performance of E6010 VV butt weldments of ABS-B ship plate with comparison to the effects of sharp crack defects, such as arc strikes.

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*The specification is based on chemical analysis as follows:

| %C | %Mn | %P | %S | %Si |
|---|---|---|---|---|
| .23 max. | .60--.90 | .04 max. | .05 max. | --- |

5. Comparison of the performance of E6010 and G180 VV* butt weldments.

The performance of weldments was investigated by the Explosion Bulge method. The relative fracture resistance of prime plate, shot peened plate, and wrought iron plate was investigated by the drop-weight method.

## MATERIAL

The material for Explosion Bulge tests of E6010 and G180 weldments and comparison prime plate was obtained from three 73-in. by 220-in. plates of 1-in. thickness rolled from one heat. Figure 1 illustrates the cutting procedures. The origin of the various weldments and prime plate specimens listed in Table I may be deduced from the figure. The remaining material was utilized for Direct Explosion tests to be reported separately[1].

The material for the partial penetration weld studies was obtained from a 3/4-in. thick plate rolled from a separate heat. The material for the evaluation of shot peening was taken from a 1-in. plate also of a separate heat. Except for the case of the three plates rolled from one heat, the material was taken directly from plate stock of the Philadelphia Naval Shipyard. The wrought iron plate was obtained from a commercial source.

The chemical analyses of the various plates are listed in Table II.

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*E7016 type conforming to MIL SPEC. E 986A (Ships).

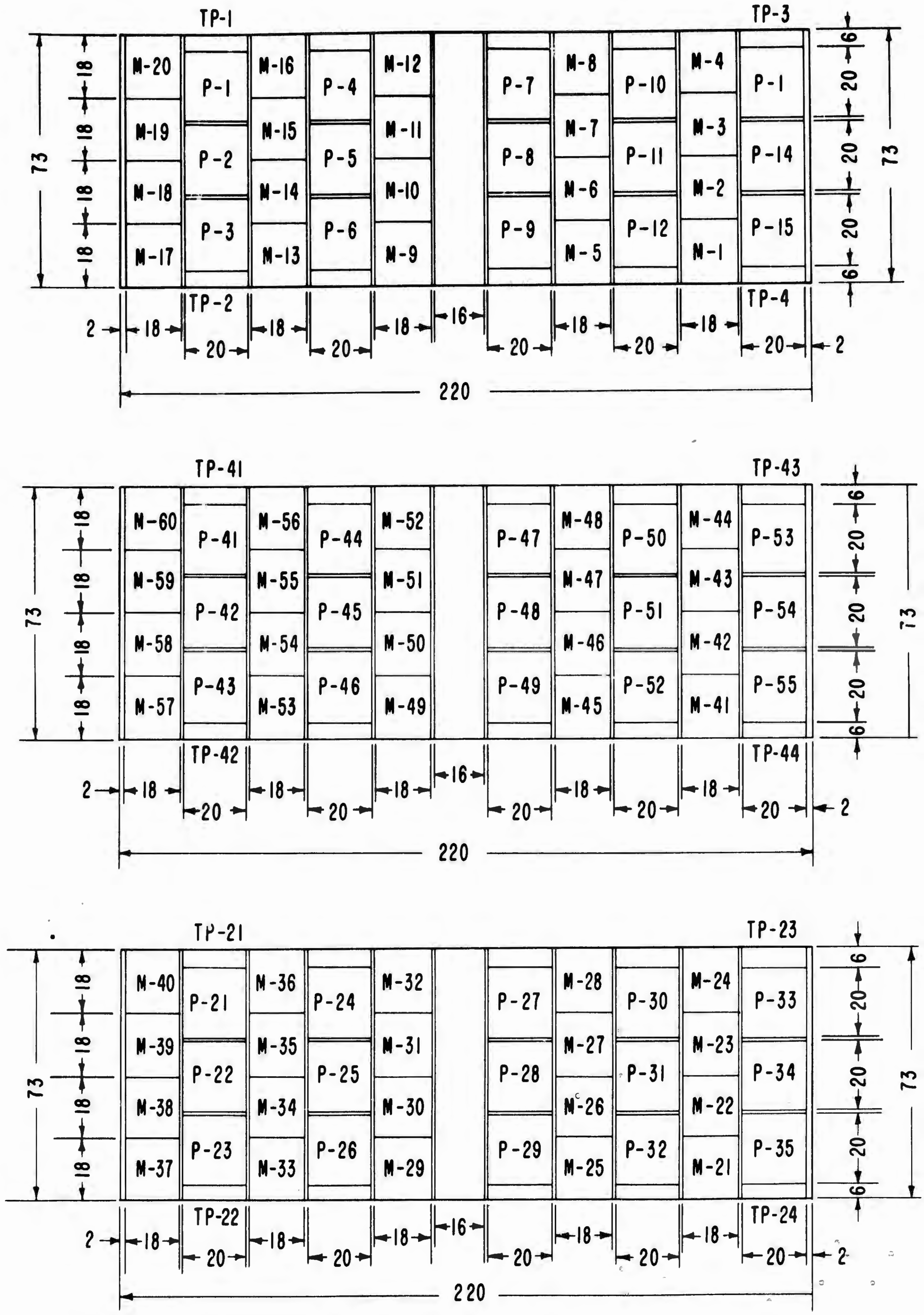


Fig. 1. Sectioning Diagrams for the ABS-B Steel Plates Used for Weldment Studies.

TABLE I

Explosion Bulge Test Plates (See Figure 1)

| G180 | E6010 | Prime |
|---|---|---|
| P-21 | P-42 | P-1 |
| P-22 | P-43 | P-2 |
| P-23 | P-44 | P-3 |
| P-24 | P-45 | P-4 |
| P-25 | P-46 | P-5 |
| P-26 | P-47 | P-6 |
| P-27 | P-48 | P-7 |
| P-29 | P-49 | P-8 |
| P-30 | P-50 | P-9 |
| P-31 | P-51 | P-10 |
| P-32 | P-52 | P-11 |
| P-33 | P-53 | P-12 |
| P-34 | P-54 | P-13 |
| | P-55 | P-14 |

Charpy V and Drop-Weight Test Plates (See Figure 1)

P1 M30 M50

TABLE II

CHEMISTRY OF VARIOUS ABS-B PLATES

| Plate | Thickness | Source | C% | Mn% | Si% | P% | S% |
|---|---|---|---|---|---|---|---|
| P1 | 1" | PNSY (Special) | .20 | .72 | .04 | .018 | .053 |
| M30 | 1" | PNSY (Special) | .19 | .76 | .04 | .015 | .043 |
| M50 | 1" | PNSY (Special) | .19 | .77 | .04 | .012 | .043 |
| Miscellaneous | 1" | PNSY (Stock) | .22 | .81 | .04 | .018 | .047 |
| Peening Test | 1" | PNSY (Stock) | .18 | .77 | .05 | .015 | .040 |
| Partial Penetration | 3/4" | PNSY (Stock) | .19 | .60 | .04 | .010 | .015 |

## CHARPY V AND DROP-WEIGHT TESTS OF PRIME PLATE

The Charpy V energy transition data for the three 1-in. plates rolled from one heat are presented in Figure 2. The M50 and M30 material was obtained from the center regions of two separate plates, and the P1 material from the edge of the remaining plate. Material from a miscellaneous plate of 1-in. thickness obtained from yard stock is included for comparison. It is noted that the test points obtained for the various samples permit drawing of only one curve at the lower portion of the transition range. Figure 3 presents the Charpy V transition data for the 1-in. thick material used for the shot peening investigation. The transition curve for this plate is closely similar to the curves presented in Figure 2 for the other 1-in. plates.

Drop-weight tests were performed in accordance with procedures described in previous reports[2,3]. Briefly, a hard-surfacing weld bead is placed at the center of a 3 1/2-in. by 14-in. test piece (see Figure 3 photograph inserts), and a notch is cut across the bead to facilitate cracking. The specimen is cooled to test temperature, placed across a 12-in. span, and then loaded by the fall of a weight which impacts at midspan. The brittle weld cracks on loading, thus developing a sharp cleavage crack notch (synthetic sharp crack defect). The test is aimed at determining the highest temperature at which the minute amount of deformation, corresponding

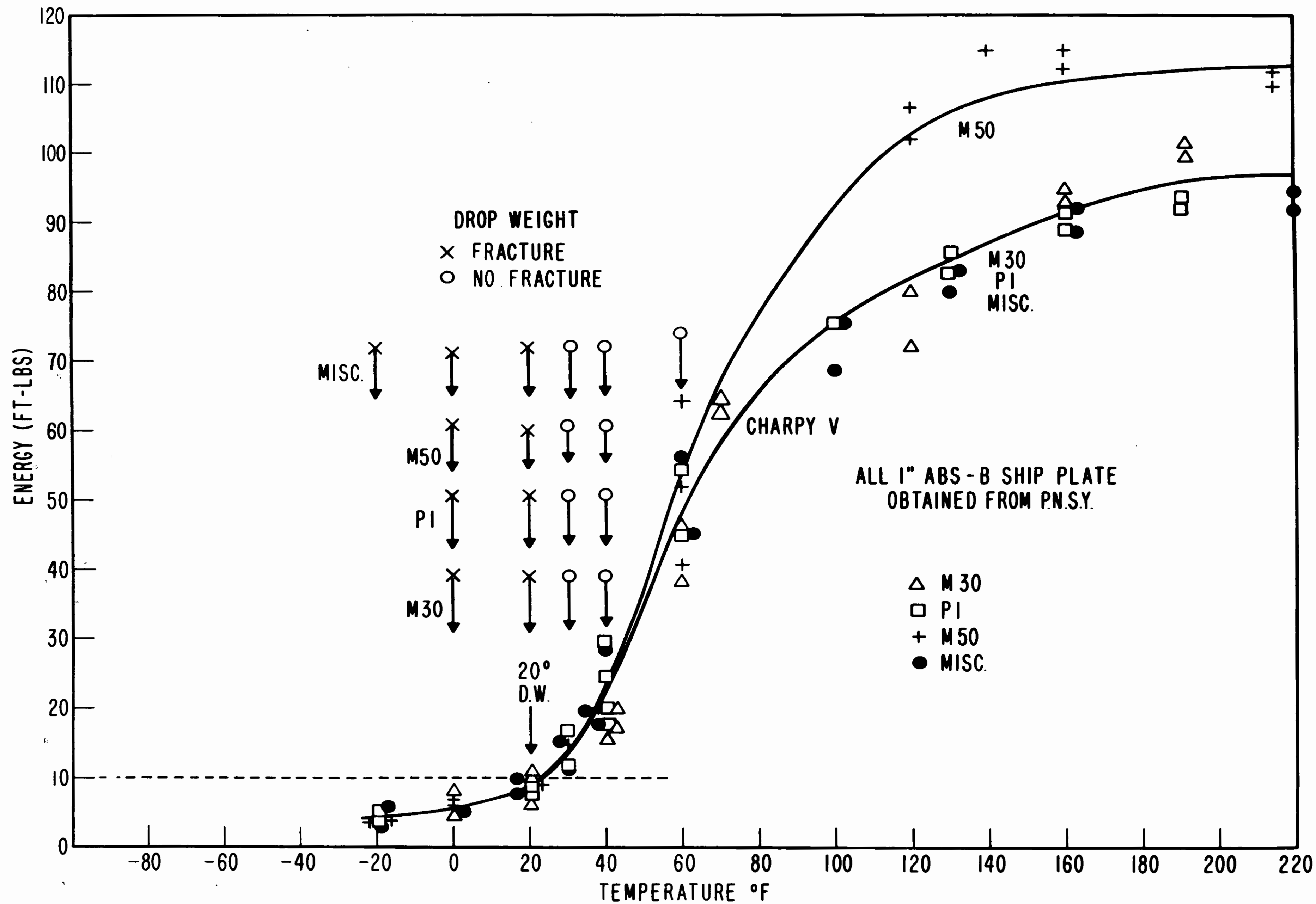


Fig. 2. Charpy V Transition Curves and Drop Weight Test Data.

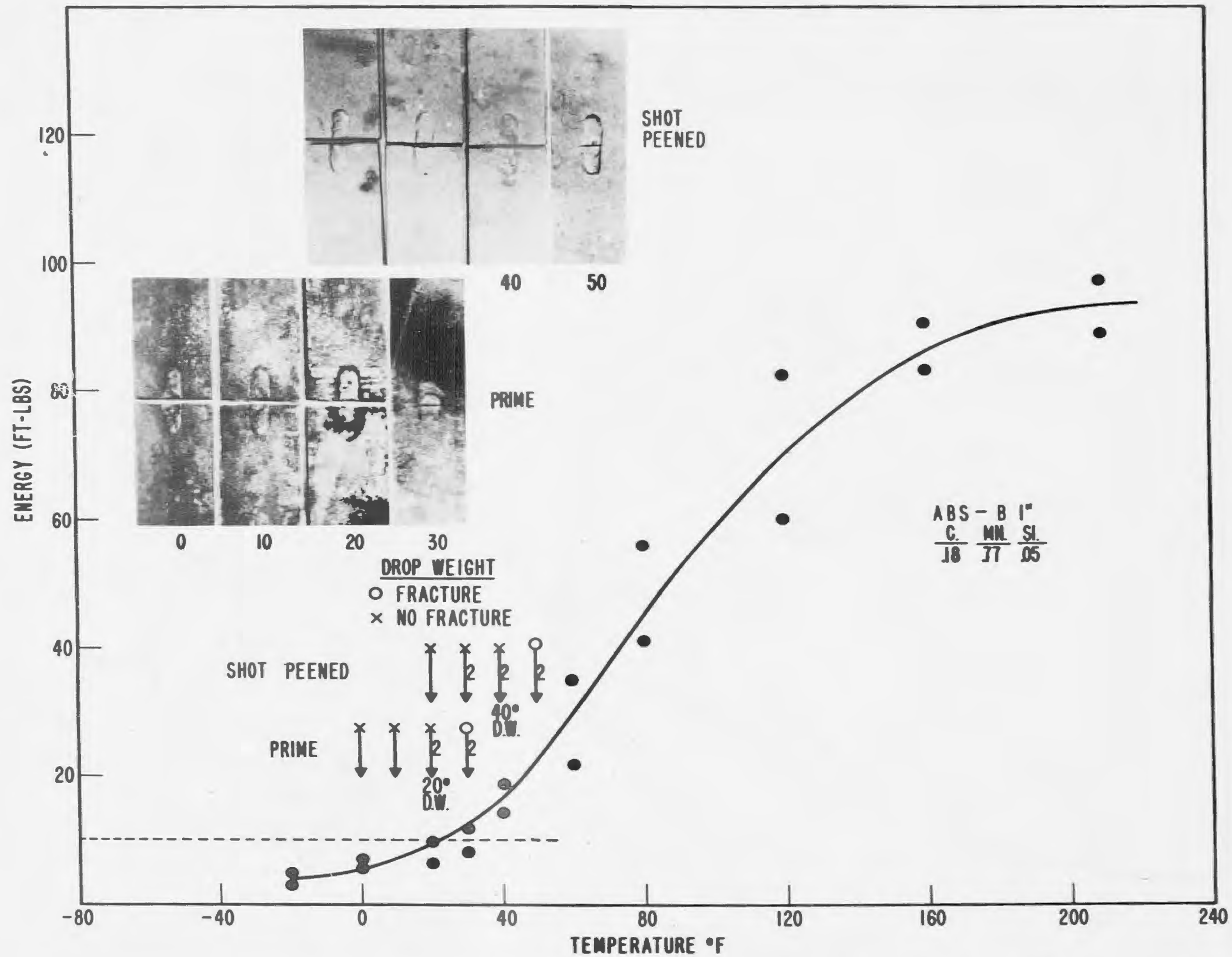


Fig. 3. Charpy V Transition Curve for ABS-B Steel Used in Shot Peening Investigation. Drop Weight Test Transition Temperature is Raised 20°F as the Result of Shot Peening the Surface.

to 2° of bend in the presence of the sharp crack-like defect, results in brittle fracture of the steel. The subject temperature is termed the drop-weight nil-ductility transition and denotes that at and below this temperature the steel has no appreciable ductility in the presence of sharp crack defects.

The drop-weight test data presented in Figures 2 and 3 show that the highest fracture temperature of each of the four 1-in. thick ABS-B steels was 20°F. The Charpy V energy at 20°F is 8 to 10 ft-lb for all of the steels which is in agreement with the general relationship of the drop-weight nil-ductility transition temperature and Charpy V energy established previously for semikilled and rimmed mild steels of ABS-A type[2,3]. Briefly, the drop-weight nil-ductility transition always occurs at temperatures within the range of Charpy V 3--10 ft-lb and most frequently at temperatures corresponding to Charpy V 5--8 ft-lb. Tests to date of approximately forty ABS-A ship plate steels, including steels of wartime manufacture and steels taken from fractured ships, have indicated drop-weight nil-ductility transition temperatures ranging from 0°F to 60°F and with greatest frequency at 20° to 30°F. Thus, the four ABS-B steels cannot be considered superior to the majority of the steels tested previously which conform to the present ABS-A classification. This statement does not imply that the quality range of the ABS-B type is the same as that of ABS-A type, since it is not known if with extensive sampling the ABS-B steels will cover a similar range of 0° to 60°F. Information of this type would be highly desirable.

## EFFECTS OF SHOT PEENING

Shot peening of ship plate and welds has been suggested as a possible means of increasing the resistance to fracture of ship structures. While shot peening affects only the surface material, it was considered that the effects of the treatment could be appreciable inasmuch as the initiation and propagation of brittle fracture is strongly controlled by minute amounts of shearing (shear lip) at free surfaces. Previous work at this Laboratory[4] disclosed that shear lips of .010 in. to .020 in. thickness were sufficient to prevent propagation of fractures.

The drop-weight test was used to evaluate the effects of shot peening. Drop-weight test specimens were prepared from ABS-B ship plate of 1-in. thickness and divided into two groups. One group was forwarded to a commercial shot peening concern. Shot peening was accomplished with 1/16-in. diameter steel shot using a 1/4-in. by 3-in. nozzle operating at 100 lb. per sq. in. The nozzle was held 4 in. from the plate, and the surfaces were peened uniformly for five minutes. Both sides of the specimens were treated in this manner. It should be noted that the brittle crack-starting weld was placed on the specimen prior to peening. Approximately three weeks elapsed between the time of peening and testing of the drop-weight specimens. This fact is of interest from a standpoint of strain aging which may be expected to have occurred in the cold worked surface material.

Figure 3 presents the results of the drop-weight tests of shot peened material in comparison to the prime material which was described in the previous section as equivalent to the three other 1-in. thick ABS-B plates. It is observed that shot peening raised the fracture temperature to 40°F indicating a distinct impairment of this steel due to cold working of the surface metal.

It is concluded that shot peening adversely affects the properties of the surface material of ship plates with consequent decrease in the resistance to the initiation and propagation of brittle fracture. In this respect it should be noted that peening of the last pass of E6010 VV butt weldments of 1-in. thick ABS-B steel was demonstrated[5] to be highly detrimental to the performance of the weldments due to cold work embrittlement of the weld metal.

## COMPARISON WITH WROUGHT IRON

Wrought iron has been suggested as a possible material for use in crack arrestor straps. Obviously, for such use it should be demonstrated to exceed the fracture resistance of

ABS-B ship plate by an appreciable margin.

The wrought iron used for this investigation represents material from present commercial production. It was obtained in the form of a 1-in. thick rolled plate. The analysis and tensile properties were determined to be as follows:

| %C | %Mn | %Si |
|---|---|---|
| .03 | .02 | .07 |

| | Tensile Strength lb. per sq. in. | Yield Strength lb. per sq. in. | %Elongation in 2 in. | %Reduction of Area |
|---|---|---|---|---|
| D1 | 51,000 | 26,500 | 16.5 | 22.0 |
| D2 | 47,000 | 26,700 | 12.0 | 22.7 |

(D1 and D2 represent two mutually perpendicular directions--direction of rolling not known).

Microstructures in two mutually perpendicular directions are shown in Figure 4. The slag stringer lengths were found to be approximately 1/8 in. actual length in both directions, and considerable difficulty was encountered in attempting to deduce the direction of rolling. It is probable that the material was heavily cross-rolled.

Charpy V and drop-weight test data for the D1 and D2 directions are presented in Figure 5. The data indicate no significant difference due to direction of rolling and a resistance to fracture initiation (+50°F D.W.T.) which corresponds to the poorest of the ABS-A type ship plates tested to date. This material is obviously not suited for use as crack arrestor straps. Figure 6 illustrates the appearance of the drop-

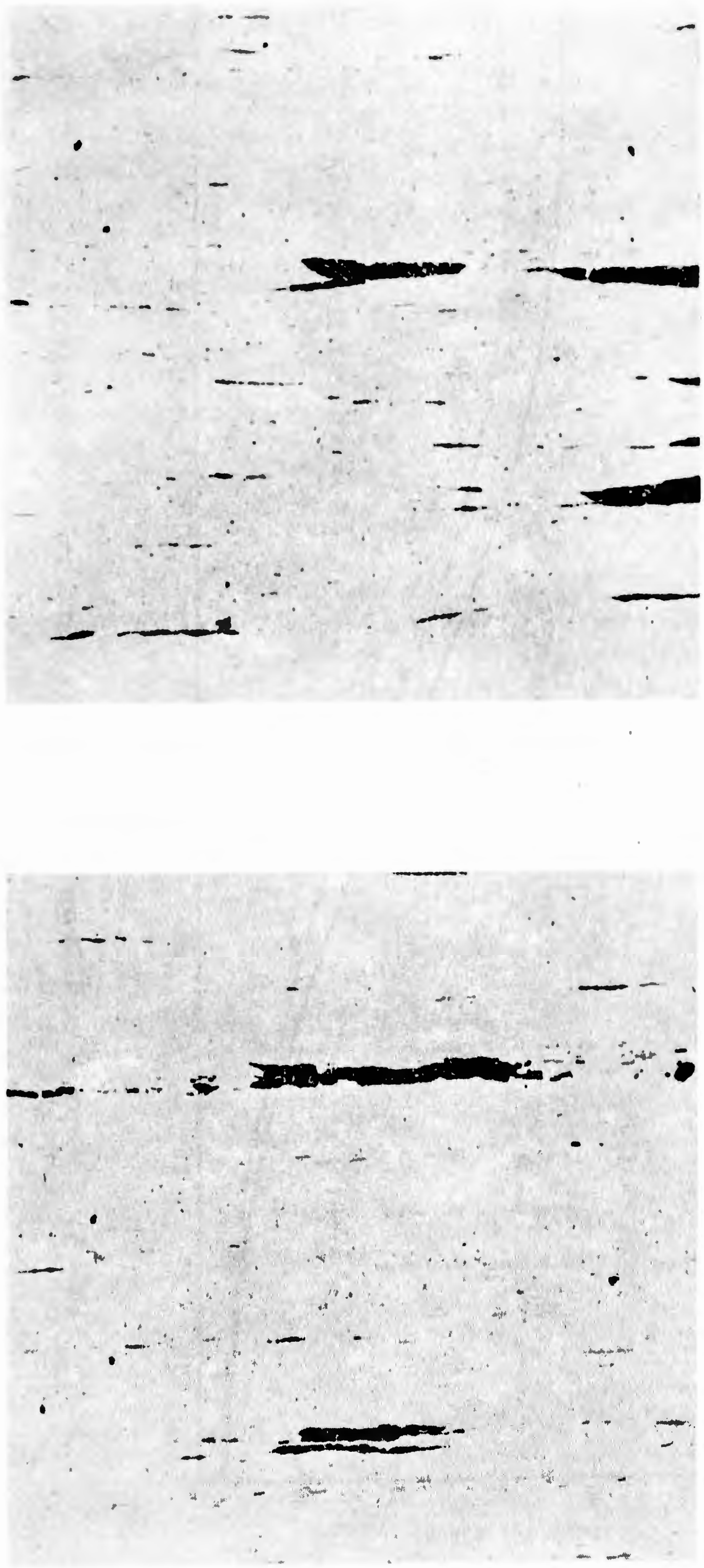

Fig. 4. Microstructure of Commercial Wrought Iron. 50X

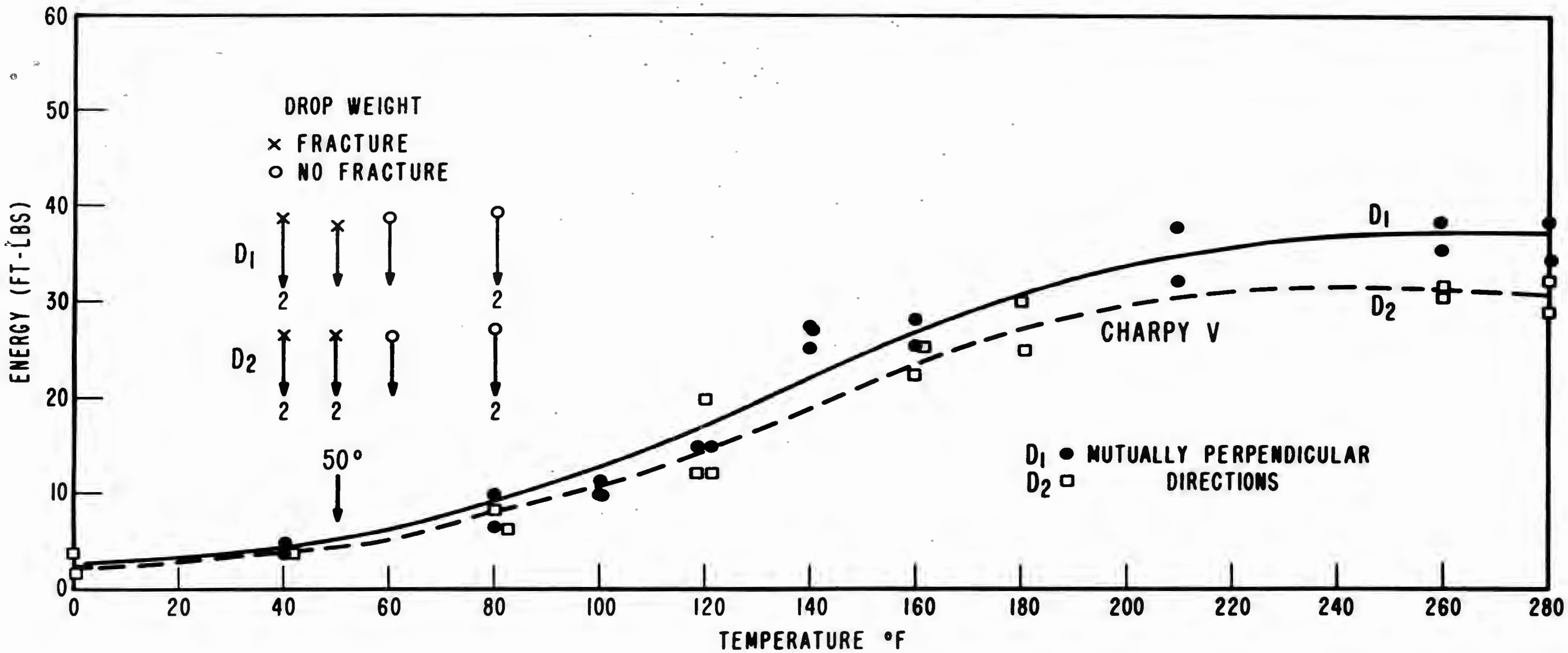


Fig. 5. Charpy V and Drop Weight Test Data for Commercial Wrought Iron.

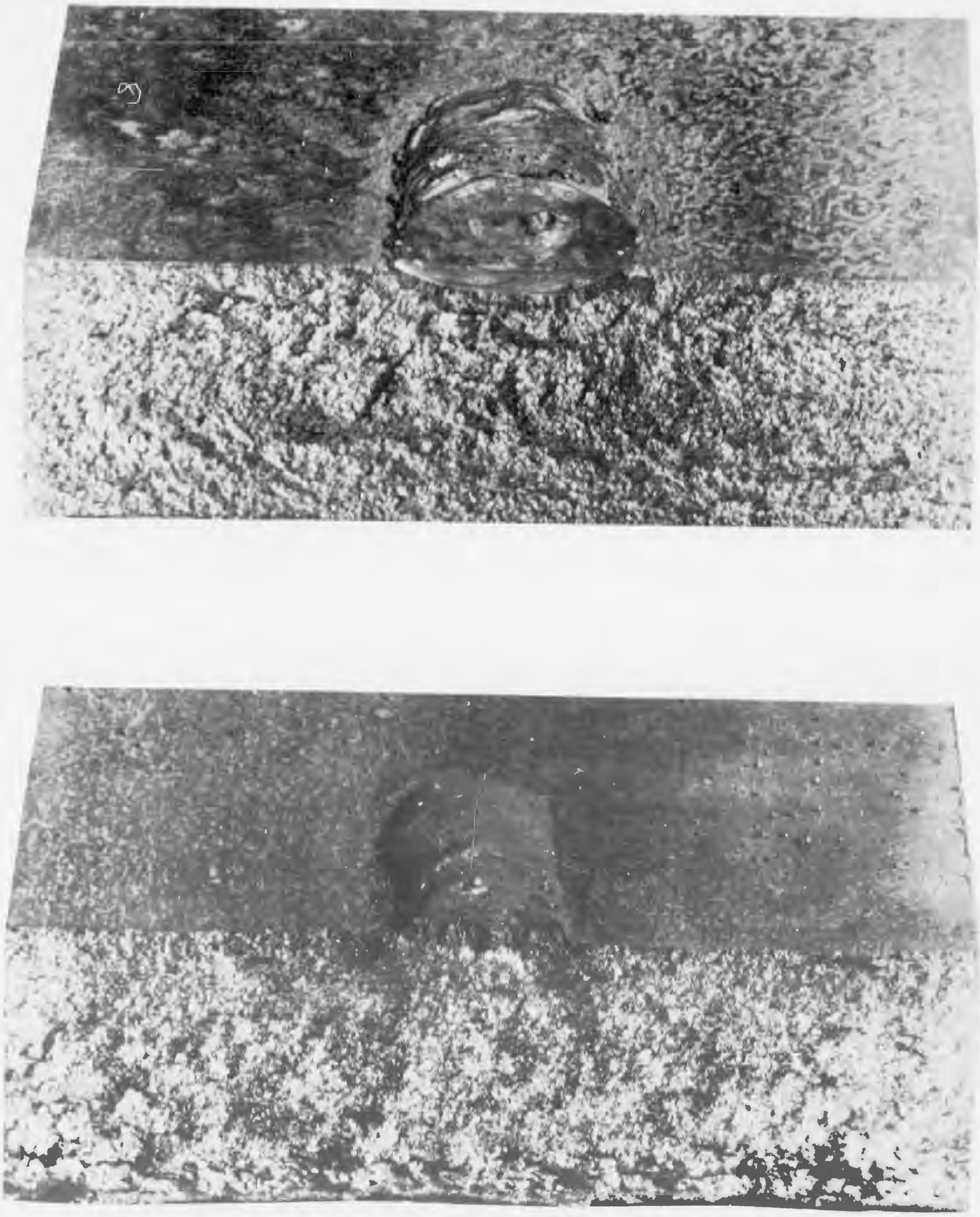

Fig. 6. Fracture Surfaces of Ship Plate Steel (Top) and of Wrought Iron (Bottom); Broken Halves of Drop Weight Test Specimens.

weight fracture specimens of wrought iron in comparison to ship plate steel. In each case the fractures are of perfectly "square break" type.

COMPARISON OF PARTIAL PENETRATION AND SHARP CRACK DEFECTS

This investigation is part of a broad program of evaluation of the relative severity of weld defects on the performance of weldments which was instituted by the Ship Structure Committee. Six E6010 weldments of 3/4-in. ABS-B ship plate were prepared by the Philadelphia Naval Shipyard. Three of these weldments were of conventional full penetration VV butt type, and three were of partial penetration type featuring a 5/16-in. gap at the center of the butt weld. One of the full penetration weldments was damaged by the application of arc strikes as will be described.

Figure 7 illustrates the results of the various tests which were conducted. Two partial penetration welds and two full penetration welds were bulge tested at 55°F. The partial penetration welds withstood 8--9% T.R. (thickness reduction of plate) prior to failure; one of the full penetration welds withstood 31% T.R. prior to failure; and the other withstood only 8% T.R. due to the presence of weld porosity. These results indicate a decrease in performance of approximately equal magnitude due to partial penetration and weld porosity. From a practical viewpoint of the performance of conventional ship structures, neither defect may be construed to be critical, since relatively drastic deformation (8% thickness reduction) was required to produce failure.

Following these tests, the effect of the presence of arc strikes was investigated. Material was removed from the sides of a bulge test sample (as denoted by the dotted area A and B shown in Figure 7), and arc strikes were applied using a carbon-arc technique. This method produces reproducible crack conditions adjacent to the arc strike crater. The use of conventional E6010 electrodes to produce arc strikes may also result in cracks but not reproducibly, i.e., the arc strikes which result may or may not be associated with sharp cracks. The next step was to determine the critical temperature below which deformation is not possible in the presence of the sharp cracks associated with arc strikes. This temperature may be determined from the Charpy V transition curve (below 10 ft-lb) or more expeditiously by means of the drop-weight technique. Based on the previously described drop-weight tests of ABS-B steel, it was suspected that the critical temperature was approximately 20°F; accordingly, sections A and B were drop-weight tested at 20°F. The resulting fractures indicated that this temperature was appropriate for the comparisons intended. Figure 8 (bottom) illustrates the type of cracks which are obtained with arc strikes and the fractured drop-weight specimens A and B (top).

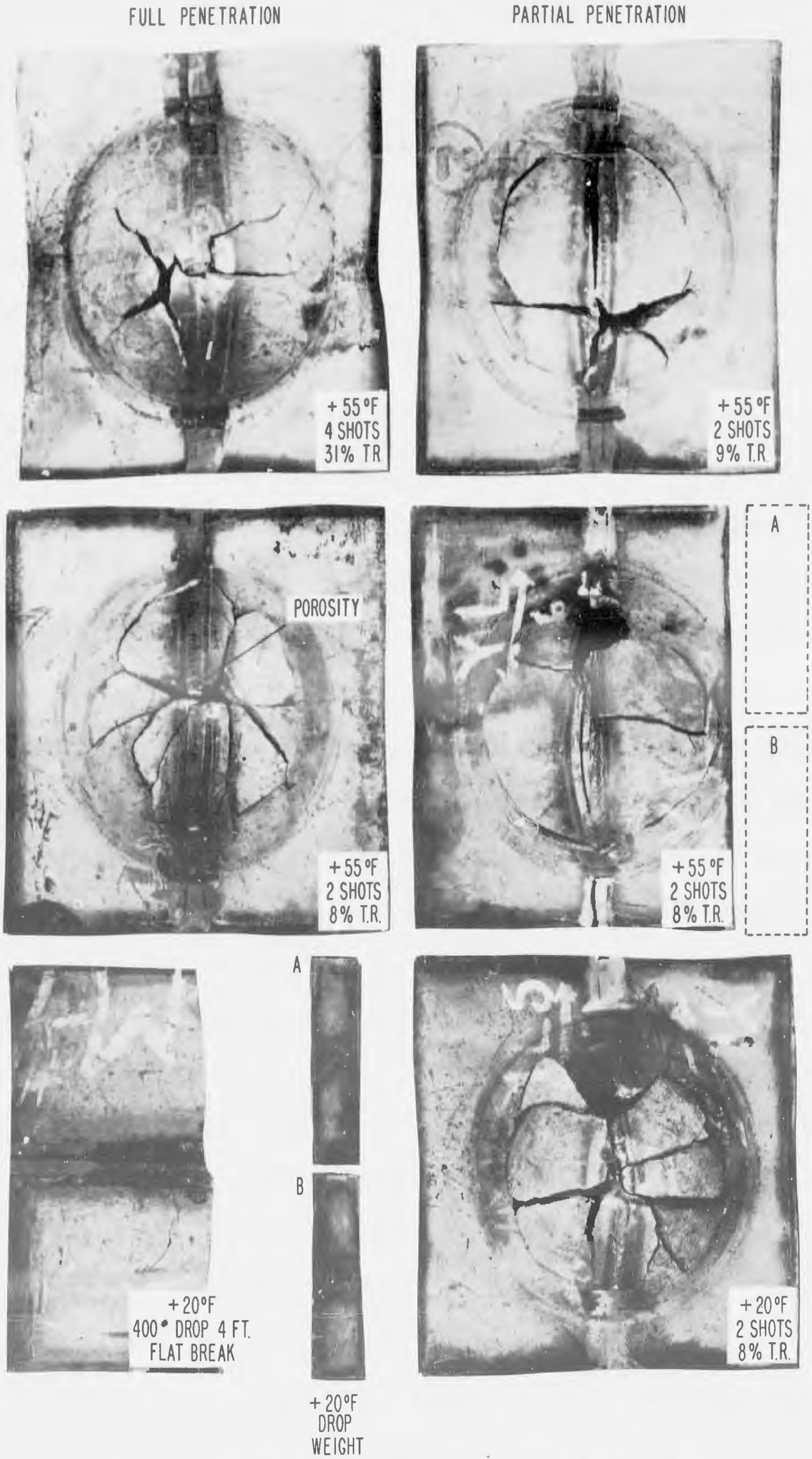


Fig. 7. Result of Tests Illustrating the Relative Severity of Arc Strikes and Partial Penetration Welds.

Fig. 8. Top - "A" and "B" Drop Weight Test Pieces with Arc Strike Defects (See Fig. 7)
Center - Arc Strike Origin of Fracture in 20" x 20" Weldment.
Bottom - Cracks Associated with Arc Strikes; the Crater is Approximately 1/8" x 1/4" actual size.

The last remaining partial penetration weld was Explosion Bulge tested at 20°F and withstood 8% T.R. prior to failure indicating similar performance as at +55°F. The last remaining full penetration weldment was damaged with carbon arc strikes and tested at 20°F in the laboratory by dropping a 400# weight from a height of four feet. The weldment was supported at two ends, and the weight impacted on the center of the span. Figure 7 (bottom left) illustrates the brittle break (no visible bending deformation) which resulted due to the presence of the arc strikes. Figure 8 (center) illustrates the fracture characteristics in detail; the arc strike which initiated the failure of the full penetration weldment may be observed at a position approximately 1 in. to the right of the weld. Actually, the presence of the weld (partial or complete penetration) was of no consequence inasmuch as the arc strike was located away from the weld, i.e., the same result could have been obtained by using prime plate.

This comparison shows clearly that the defects to be feared in welded structures are those of sharp crack-like nature and that size of defects is not an index of severity. Arc strikes have been shown to be responsible for a number of ship failures. NBS Ship No. 52, for example, failed at 35°F (Charpy V of source plate 6--8 ft-lb) due to the presence of an arc strike. Drop-weight tests of the source plate from this ship resulted in fractures to +50°F (Charpy V 10 ft-lb)[6].

## COMPARISON OF E6010 AND G180 WELDMENTS

Standard 20-in. by 20-in. VV butt weldments of E6010 and G180 welds were prepared by the Philadelphia Naval Shipyard. Explosion Bulge tests were conducted with the conventional 15-in. diameter circular die. The weldments were tested with the weld reinforcement intact. Temperature control was obtained by refrigerating in cold temperature boxes of the dry-ice vapor type. The test temperatures are considered accurate to ±5°F. The explosive charge was 4 lb. of Pentolite positioned at 15 in. from the plate. Unbroken test plates were returned to the cold cabinets for temperature re-equalization following each shot. Testing was discontinued after the fourth shot inasmuch as thickness reductions* of 14% were attained for plates which resisted four shots without fracture.

Figure 9 illustrates the bulge ductility transitions for the prime plate and for the weldments. The prime plate develops a sharp ductility transition in the range of -60° to -80°F. Figure 10 illustrates a typical fracture originating at the center of the bulge area and the anomalous off-center fracture of plate P-8 which was out of line with the remainder of the test series. The off-center point of fracture initiation indicates that a flaw condition was responsible for the poor performance of this plate. The nature of the flaw was not evident from a visual examination of the fracture.

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*Thickness reduction of the plate measured at the center of the bulge 1 1/2 in. from the weld.

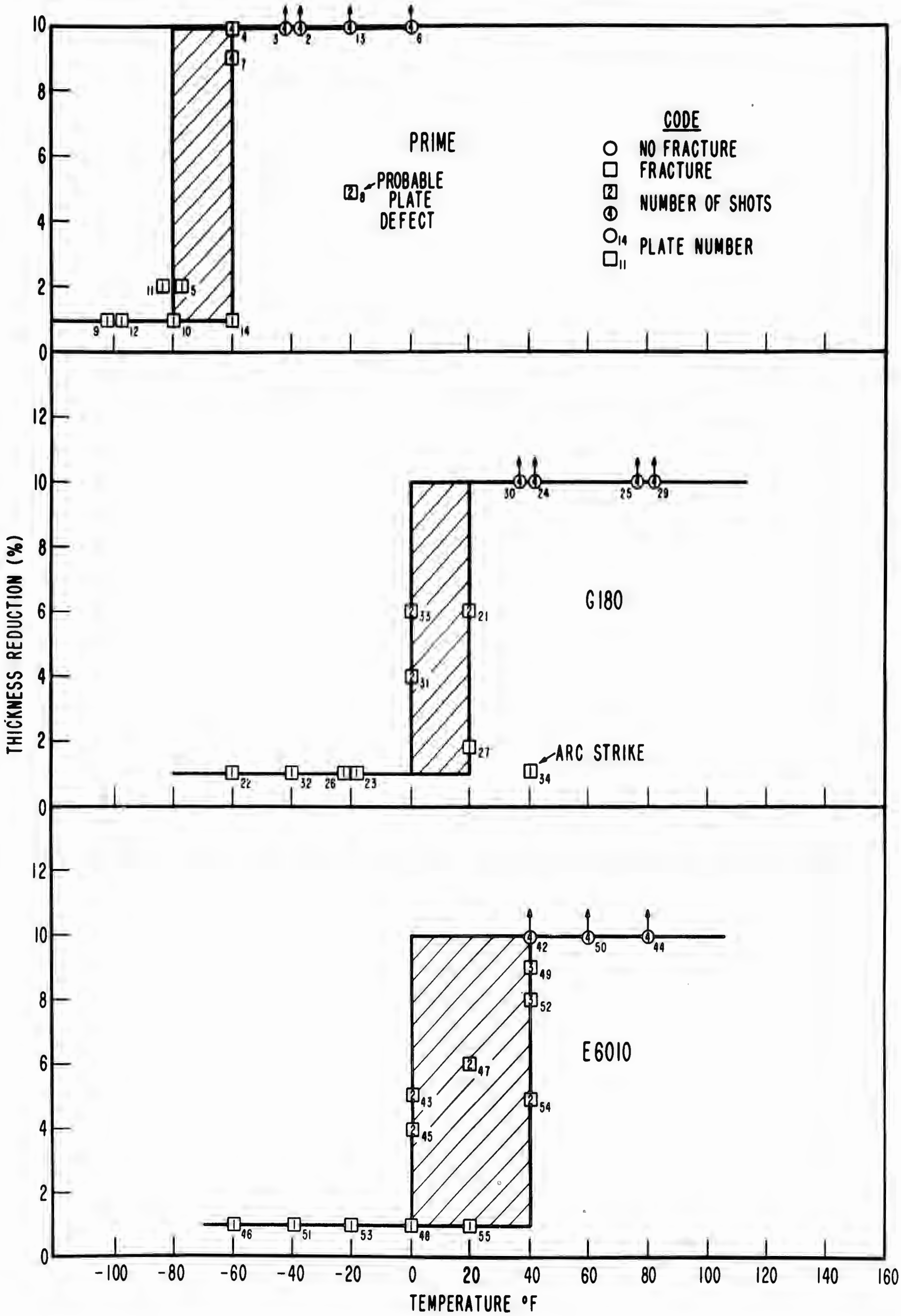


Fig. 9. Explosion Bulge Test Ductility Transitions of Prime Plate and Weldments.


Fig. 10. Fractures of Prime Plate Bulge Test Specimens.
(20" x 20" Plates).

The performance of the G180 weldments was essentially equivalent to that of the E6010 weldments at all temperatures except possibly 40°F. It is noted that two G180 weldments developed 14% thickness reduction (four shots without failure) at 40°F, while of four E6010 weldments only one equaled this performance; two of the E6010 weldments failed at three shots (8 and 9% T.R.) and one at two shots (5% T.R.).

The one shot (1% T.R.) failure of P34, G180, at 40°F is explained by the nature of the failure shown in Figure 11, which shows no relation to the weld. The presence of an accidental arc-strike at the source of failure was responsible for this anomalous behavior. Several sharp, small cracks may be observed radiating from the arc strike which caused the initiation of failure. The arc strike was present in the weldment as received from Philadelphia Naval Shipyard and was not noticed prior to testing, despite critical X-ray and visual examination of all weldments on receipt at this Laboratory. This is another excellent example of the critical nature of minute, accidental imperfections when present on steel which is susceptible to brittle fracture at service temperatures. Unless the notch toughness of the ship steels are improved to an extent sufficient to develop insensitivity to the presence of such accidental defects, the benefits expected from high quality welds will not always be realized in service. This fact is illustrated by the excellent performance of G180

Fig. 11. Failure of P34, G180 Weldment Resulting from the Presence of an Accidental Arc Strike. The Insert Shows Small Cracks in the Arc Strike Region.

weldments at 40°F in the absence of on-the-plate defects.

The typical fracture characteristics of G180 and E6010 weldments are illustrated in Figures 12. The chevron markings indicated that the initiation of fracture occurred in the weld proper for the case of the E6010 weldments. In the case of the G180 the site of fracture initiation could not be established with certainty. In general the location indicated by the chevron markings was at fusion line area but without clear distinction as to weld or H.A.Z. side of this general area.

It should not be concluded on the basis of these tests that there is no advantage to the use of G180 low hydrogen electrodes over the E6010 cellulosic type. These data are specific to weldments prepared under laboratory conditions and indicate that the two weldments made under such optimum conditions are essentially equivalent. The low hydrogen electrodes were developed to mitigate fissuring and other crack-like defects which are developed when welding is performed with deviations from optimum conditions common to field use. The known effectiveness of low hydrogen electrodes in this respect commends their use, particularly when the steel to be welded is sensitive to the presence of crack-like defects (as demonstrated) at temperatures of service use.

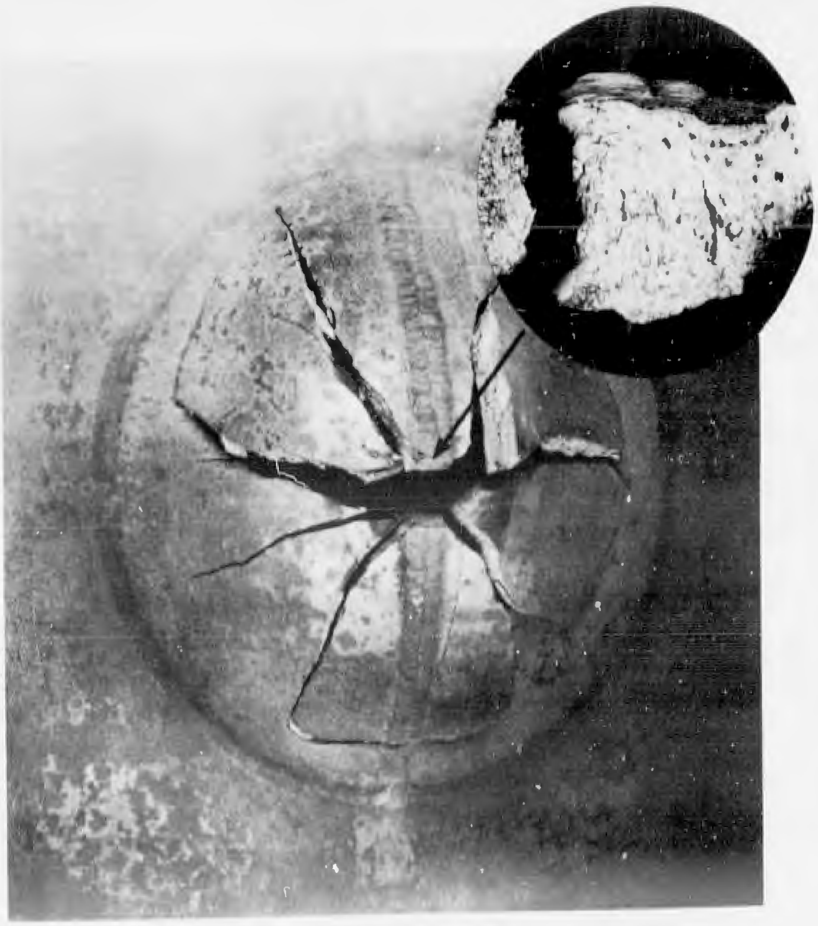

Fig. 12. Typical Fractures of E6010 Weldments (Top) and G180 Weldments (Bottom).

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