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PROGRESS REPORT

ON

EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

BY

R. W. BENNETT, P. J. RIEPPEL, AND C. B. VOLDRICH

Battelle Memorial Institute
Under Bureau of Ships Contract NObs-45543

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

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EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

to

BUREAU OF SHIPS
NAVY DEPARTMENT

by

R. W. Bennett, P. J. Rieppel, and C. B. Voldrich

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Preface

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals who were actively associated with the research work. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels."

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EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

to

Bureau of Ships
Navy Department

from

BATTELLE MEMORIAL INSTITUTE

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R. W. Bennett, P. J. Rieppel, and C. B. Voldrich

ABSTRACT

This report covers work done during the period June 25, 1947 to February 1, 1948.

A survey was made of published and unpublished reports to appraise the various kinds of tests used to study strength, ductility, and transition temperatures of welded joints in structural steels. On the basis of this survey, the Project Advisory Committee selected the tee-bend test, the longitudinally welded and transversely notched bead-bend tests (Kinzel and Lehigh types), and the transversely welded and transversely notched bead-bend tests (Naval Research Laboratory high constraint and Jackson types). These tests were used in a study of steels "B_r" and "C" and to correlate results obtained with them with results from the hatch corner tests made at the University of California. It was thought that if one of these tests were to give the same transition temperature for B_r and C steels that the hatch corner did with these steels, then that test would

be worthy of further study as a possible acceptance test of steel for ship plate.

The studies were made with project steels B_r and C because they previously exhibited a widely different behavior in the full-scale hatch corner and other tests. Class E6010, 5/32- and 3/16-inch diameter electrodes were used to make the samples for the initial tests. The specimens were tested at various temperature levels to determine the transition temperatures by means of the following criteria: absorbed energy, bend angle, lateral contraction, and fracture appearance.

The transition temperatures for the B_r and C steels showed that all the tests for both welded and unwelded specimens rated the two steels in the same qualitative order as indicated by the hatch corner tests. The variations in the actual transition temperatures were influenced by specimen design, welding conditions, and the various methods of evaluating transition temperature. It was also believed that the oriented discontinuities in the B_r steel, caused by large elongated complex sulphide inclusions, influenced fracture propagation, and hence the energy absorption, the total bend angle, and the fracture appearance of specimens made from this steel.

INTRODUCTION

This is the first progress report on Navy Department, Bureau of Ships, Project SR-100, authorized by Contract NObs-45543, entitled "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships".

The principal objective of this project is to evaluate the usefulness of various mechanical tests of small welded steel specimens for indicating the performance of large welded structures. Another objective is to study fundamental factors contributing to the performance of such welded laboratory specimens.

A survey was made of published and unpublished reports to appraise the various kinds of tests used to study strength, ductility, and transition temperatures of welded joints in structural steels. A summary of this survey and a bibliography are included in this report.

This report describes the details of the test specimens selected for use in studying the properties of project steels*, the welding and testing procedures used, and results obtained from the initial phases of the experimental work. Discussions of the influence of design on the transition temperatures of the specimens and of the criteria used for determining them are given. Results from limited tests of unwelded specimens are included and compared with those obtained from welded specimens.

MATERIALS

Steels

Two semi-killed, as-rolled, medium carbon ship steels, designated as B_r and C, were used in this phase of the investigation. These steels were selected for this work because they previously exhibited differing properties when used in the full-scale hatch corner and other tests to determine their mechanical properties. A supply of the two steels, 3/4 inch thick, was received from the University of California. The heat histories, mechanical properties, and chemical compositions of these steels are as follows:

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* The various heats of steel used in the investigations, sponsored by the Ship Structure Committee, have been designated alphabetically and are termed "project steels". These include the University of California tests.

Steel Code Letter	Type of Steel	Steel Condition	Mechanical Properties (1) (2)					
			Yield Point, psi	Ultimate Strength, psi	Elongation		Red. in Area, %	Hardness Rkw B
					in 2 In., %	in 8 In., %		
B_r	Semikilled	As rolled	32,200 - 34,600	55,600 - 58,600	42-45.7	32.5-35	58-71	58-63
C	Semikilled	As rolled	34,500 - 37,600	61,500 68,500	34.5-42.5	28-31.7	50-63	66-69

Steel Code Letter	Chemical Composition, % (1)											
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	Sn	N
B_r	0.18	0.73	0.07	0.008	0.030	0.03	0.05	0.006	0.07	0.015	0.012	0.005
C	0.24	0.43	0.05	0.012	0.026	0.03	0.02	0.005	0.03	0.016	0.003	0.009

(1) Boodberg, A., H. E. Davis, E. R. Parker, and G. E. Troxell, "Causes of Cleavage Fracture in Ship Plate - Tests of Wide Notched Plates", _Welding Journal_, April 1948

(2) The data for the mechanical properties are the lowest and highest values obtained for each steel.

Electrodes

The electrodes used throughout this phase of the investigation were 5/32- and 3/16-inch diameter Class E6010 electrodes. The welding schedules used for the various tests will be discussed later in this report.

PREPARATION OF TEST SPECIMENS

Plate Preparation

Plates 3 inches x 12 inches, were used for the bend specimens having longitudinal welds and transverse notches (Kinzel- and Lehigh-type specimens, shown by Figures 1 and 2). They were sawcut rather than flame cut so that no heat-affected metal would be along the edges of the specimens.

The plates for the tee-bend test and the bend specimens having a transverse bead and a transverse notch (Naval Research Laboratory High Constraint and Jackson-type specimens) were flame cut to the size shown in Figures 3, 5, and 6. The heat-affected metal along the edges of these specimens was removed by machining after welding.

The direction of rolling for all specimens was parallel to the longitudinal direction of the finished specimen, as shown in the figures.

The plate surfaces were grit blasted prior to welding to remove mill scale, rust, or other surface contaminators.

Welding Procedure

The investigators, who originated the various tests or who have done considerable recent work with them, were contacted to obtain the most recent welding and testing procedures for the various types of specimens before welding was started on any of the test specimens. A summary of the welding condition for each of the five types of test specimens is given in Table 1. Automatic welding was used for all specimens except those for the tee-bend test. Automatic welding has been used in the past by some investigators for making tee-bend specimens. On the basis of recent work, however, manual-arc welding was recommended to obtain better control of the conditions essential to the success of this test.

All specimens were welded at room temperature (75°F). After welding, they were set endwise on an asbestos pad and cooled in air to room temperature. All of the specimens were aged for exactly eight days at room temperature before testing. During this period, they were machined to the final dimensions for testing.

Machining

After welding, the test specimens were machined to the dimensions shown in Figures 1, 2, 3, 4, 5, and 6. The sides of the specimens were finished by grinding to aid in taking accurate lateral measurements before and after testing. The transverse notches in both the longitudinally welded and transversely welded bend specimens were made with a flycutter to accurately obtain the prescribed root radius.

The side notches on the Naval Research Laboratory-type specimen (Figure 5) were made by drilling a hole 1/16 inch in diameter to accurately index the width of notched weld metal. A 1/4-inch milling cutter having an 1/8-inch tooth radius was then used to cut in from the side until the drilled hole was contacted. The side notches were incorporated to impart higher constraint to the transversely welded and notched type of specimen.

In the weldment for the tee-bend test, the vertical leg was flame cut to size so that it would fit a standard bending-jig guide. To insure uniformity for this test, the weldment was sawcut with the crater from one weld increment and start of the next increment centered in the test specimen, as shown in Figure 4. After grinding the specimen to the final width of 1-7/8 inches, which is a proportionality dimension based on plate thickness, the tension corners were broken with a file and the specimen was tested in that condition.

TESTING PROCEDURE

It was necessary either to heat or to cool the test specimens to various temperature levels and to maintain the temperatures during testing to determine the temperature at which the specimens exhibited a transition from ductile to brittle behavior. Consequently, both the bending jig and the test specimen were immersed in an agitated liquid medium and maintained at the desired temperature for at least 15 minutes before applying the load. A mixture of alcohol and dry ice was used for all temperatures below about 80°F. Temperatures ranging from about 80°F to 200°F were attained by using water heated with resistance immersion coils. Above 200°F, a water-soluble quenching oil, having 350°F flash point, was used with the immersion heaters to attain the desired temperature.

The dimensions of the bending jigs used for testing the various types of specimens are schematically illustrated in Figures 1, 2, 4, 5, and 6.

The width of each specimen was measured with a micrometer. The specimen was then placed on the submerged jig and brought to the desired temperature. An Amsler hydraulic-type testing machine, using a loading rate of one inch per minute free displacement of the movable platen, was used for all of the tests. The load was usually applied until the specimen fractured, but, if the specimen did not fail, loading was continued until the load reached a maximum and then dropped to 6,000 pounds (2,000 pounds for the Naval Research Laboratory specimen), or until the limit of the testing apparatus had been reached.

A load-deflection curve was made (Figure 7) and the maximum load applied was recorded for each test. The contour of this curve after reaching maximum load, the angle of bend at maximum load, and the fracture appearance were used as the immediate criteria for selecting the temperature at which subsequent specimens would be tested.

Calibration curves were made for the various types of specimens tested in jigs having different dimensions. The bend angle of the tested specimens was obtained from these curves by measuring the displacement of the movable platen, as shown on the load-deflection curves.

CRITERIA USED FOR EVALUATING TRANSITION TEMPERATURE

The term "transition temperature" designates the temperature (or temperature range) at which the fracture behavior of the test specimen changes from ductile to brittle. This transition, in many cases, occurs over a temperature range rather than at a definite temperature and the test results may show considerable scatter. For the more precise determination of the transition temperature, statistical methods to determine the transition-temperature curve contour, supplemented by the use of the parallelogram method, have provided a mathematical solution (Reference 142, Appendix C). The average curve method, however, is most commonly used. For average curves, the transition temperature is usually designated as being: (a) the point of inflection; (b) the upper or lower limit of the transition range; (c) the point on the curve represented by half the difference between the upper and lower limits of the curve; (d) the point on the curve represented by half of the maximum measured value obtained; or (e) the temperature at which the fracture changes from a fibrous ductile to a bright crystalline (brittle) structure, though it seemed appropriate here to use a different point.

The transition curves in this report represent averages of the slow-bend test data and show the complete transition-temperature ranges obtained for welded and unwelded B_r and C steel specimens. The "transition temperature" for any test included in this report is defined as the highest temperature at which the first significant decrease (or wide discrepancy) occurred in the measured property (absorbed energy, bend angle, lateral contraction, etc.). Consequently, this point is generally located at, or slightly above, the inflection point.

The criteria used to evaluate the change in behavior of bend-test specimens made from B_r and C steels are discussed in the following pages.

<u>Absorbed Energy</u>

The amount of energy absorbed by each specimen up to the point of failure, or by bending to the limit of the jig, was determined by measuring the area under the load-deflection curves obtained for each specimen during testing. Schematic diagrams of typical load-deflection curves are shown in Figure 7. The energy absorbed by a specimen up to the maximum load included the area under the curve to a deflection indicated by the dimension "M". The energy absorbed after maximum load, which either broke the specimen or bent it to the capacity of the jig, was determined by measuring the area under the curve from the point of maximum load to the point of failure or where the load dropped to 6,000 pounds (2,000 pounds for the Naval Research Laboratory-type specimens), as indicated by dimension "N". The total energy, T, was determined by measuring the total area under the curve, or "M" + "N".

The shape of the curve after maximum load, usually indicated the type of the fracture surface that resulted. If the slope was relatively flat, smooth, and regular, the specimen usually bent to the capacity of the jig and had a ductile-type fracture surface. A sharp decline in the curve was usually accompanied by varying degrees of brittleness.

The energy-absorption values for the various types of test specimens were based on total energy and the energy absorbed after maximum load. The curves of the "energy absorbed to maximum load versus temperature" for the various test specimens had about the same relative contour as the curves showing total energy absorbed and energy absorbed after maximum load and indicated similar transition temperatures for the two steels. This is shown in Figure 8 for the Lehigh specimen. Other tests showed the same condition to exist, consequently only the data for total energy and energy absorbed after maximum load are given in this report.

Bend Angle

The deflection of a specimen at maximum load and at the point where failure occurred, or at the maximum deflection allowed by the jig, was measured from the load deflection curve (Figure 7). The amount of linear deflection was then converted to bend-angle degrees from calibration curves for the given type of specimen tested and bending jig used for that type specimen.

Lateral Contraction

The lateral contraction of the test specimens was obtained by measuring the width of the ground specimens in the test area with a micrometer before and after bending. The amount of contraction of the specimens, which were tested at different temperature levels, was expressed on a percentage basis to eliminate any variation that existed between the initial width of the specimens.

The widths of specimens, having a longitudinal weld bead and transverse notch (Lehigh and Kinzel specimens), were measured at about 1/32 inch below the root of the notch before testing. After testing, the width of the test specimen was measured at about the same point adjacent to the fracture.

The lateral contraction of specimens exhibiting a brittle- or transition-type (part brittle and part ductile) fracture was relatively easy to measure. The contraction measurements for the more ductile specimens, tested above the transition temperature, were less accurate and more difficult to make because of the excessive tearing and unevenness in the fractured surface and edges of the specimens. Since the need for accuracy is most essential for specimens tested at about the transition temperature, it is evident that the relative inaccuracy of lateral contraction measurements for 100 per cent ductile fractures is of little importance for a proper appraisal of the over-all test results.

Lateral contraction measurements for the Jackson-type specimens were made in essentially the same way as previously mentioned.

It is more difficult to make lateral contraction measurements for the tee-bend test specimens than for the Kinzel and Lehigh-type specimens. Measurements of the width of the specimen were made on both sides of the fracture at points A and B, and on the unfractured side at a point C, as shown in Figure 9. This latter point was determined by the intersection of a line through the toe of the fillet parallel to the stem and a line parallel to and about 1/16 inch below the plane of the joint. The point C, then, was located in the heat-affected zone where maximum contraction, without failure, usually took place. A comparison of lateral contraction measurements at points A, B, and C versus temperature is shown in Figure 10. These measurements did not show correlation of sufficient accuracy to warrant further consideration as a criterion for evaluating transition temperature for the tee-bend specimen.

Accurate measurements could not be obtained on the Naval Research Laboratory-type specimen after testing because the deep-side notches made it necessary to use special micrometers that were not available at the time the tests were completed. Consequently, this criterion was not considered for this test.

Fracture Appearance

The results obtained by different people using the fracture appearance as a criterion of the ductile to brittle transition of a steel are arbitrary. Confusion arises from the differences in fracture appearance that are probably caused by variations in the chemical composition, mechanical properties, processing history of the steel, and testing procedures. Employment of the terms "cleavage" and "shear" fractures may also be misleading because the true mode of failure cannot always be detected macroscopically.

In order to clarify the use of fracture appearance in this report as a criterion for determining ductile to brittle transition, a ductile fracture is defined as being a progressive failure, dark gray in color, with a woody or cokey appearance. A brittle fracture is defined as an abrupt failure having a bright, crystalline-appearing surface. Typical fractures are illustrated in Figures 16 and 17.

The transition temperature of the tee-bend specimens was not determined on the basis of fracture appearance, because variations in the fracture characteristics could not be accurately appraised. Specimens having ductile properties, either deformed to the capacity of the testing equipment, or had incomplete failure as shown in Figures 18 and 19. Brittle fractures obtained at lower testing temperatures showed the typical crystalline-appearing surface. An intermediate structure that would be representative of the transition range was not apparent. Consequently, the appearance of fractured tee-bend specimens was not used as a criterion for evaluating transition temperature.

Energy Ratio

This criterion for transition temperature was used only for the tee-bend test. Its application for evaluating transition temperature will, therefore, be discussed in a later section of this report.

RESULTS AND DISCUSSIONS

The tabulated data obtained from testing the various welded and unwelded specimens made of B_r and C steels are contained in Tables 3 through 13, Appendix A.

The transition temperatures for welded B_r and C steels obtained from the various tests are compared in Table 2. The data obtained from the five types of bend tests are shown by graphs in Figures 11 through 15. In these graphs, absorbed energy, bend angle, lateral contraction, and fracture appearance are plotted versus testing temperature.

The data in Table 2 and the transition-temperature curves based on various criteria shown in Figures 11 through 15 indicate that all five of the tests rated the two steels in the same order as the hatch corner tests and other types of tests made by different investigators; i.e., the B_r steel had a lower transition temperature than the C steel. However, none of the small tests gave the same transition temperatures for the two steels that were obtained from the hatch corner specimens. In general, the transition temperature for the B_r steel hatch corners was higher than the average temperature shown by the notched specimens having either a longitudinal or transverse weld bead. For the C steel, this relation was reversed, so that the transition temperature of the hatch corners was lower than for the small bend specimens. The transition-temperature curves for the tee-bend tests, however, were below the transition of the hatch corners for both the B_r and C steels. This relationship would be advantageous if the tee-bend specimens were modified in an attempt to raise their respective transition temperatures to correspond with those given by the hatch corners.

<u>The Relation of Specimen Design to Transition Properties.</u>

The test results and the shape of the transition curves obtained with the specimens used (Figures 1 through 6) varied with the design of the specimen. The difference in notch details and welding schedule between the Lehigh and Kinzel specimens had no apparent effect on the scatter of test data nor the shape of the transition-temperature curve. The curves determined by plotting the various criteria versus testing temperature showed only a small amount of scatter and a well defined ductile to brittle transition. The difference in the measured values between the upper and lower knees of the transition range was of sufficient magnitude so that a transition temperature could be ascertained with reasonable accuracy.

The low transition temperature of the Lehigh specimens made from B_r steel could have been influenced either by the specimen design and/or by the inherent properties of the steel. Future studies may help to clarify this point.

In addition to giving well defined transition curves of the steels tested, the Lehigh- and Kinzel-type test specimens are easy to weld, machine, and test. A further possible advantage of the Kinzel specimen is the extra depth of weld metal that remains below the root of the notch. The influence of this weld metal on the test results, however, has not yet been investigated. A possible disadvantage of both specimens is that they are purely test specimens and are not necessarily representative of a welded structure.

The tee-bend test (Figures 3 and 4) is the only test in this series that employs a specimen that is representative of typical welded joints used in ship building and structural welding. The specimens are also easily machined and tested. These factors, along with the sharply defined transition range determined by measuring the bend angle (Figure 12B) and absorbed energy (Figure 11B), and the small amount of scatter in the plotted data comprise the chief advantages for this test. The transition temperatures for the B_r and C steels are both lower than the respective hatch corner transition temperatures by about the same amount (Table 2). This suggests that a modification of this type of specimen should be attempted to duplicate the hatch corner transition temperatures.

The most apparent disadvantage of the tee-bend test is the difficulty in adhering to the welding requirements and the amount of discard lost after machining. Furthermore, the criteria for determining the transition temperature are limited to absorbed-energy and bend-angle measurements. The inadequacy of lateral contraction and fracture appearance appraisals from these specimens will be discussed later in this report.

The specimen, designed by the Naval Research Laboratory having a transverse weld bead with a machined notch and also notches cut into the specimen edges to increase the constraint (Figure 5), also proved to be a satisfactory test for determining transition temperature. Figures 11C and 12B indicate that complete transition data were not obtained with this type specimen for the C steel, because adequate tests were not made at higher temperatures. The transition curves for B_r steel, however, show that the bend angle at maximum load is not significant. Although the plotted data for absorbed energy and bend angle at maximum load have a limited amount of scatter and define a ductile to brittle transition, the differences in the amounts of energy and of bending between the upper and lower limits of the curve are considerably smaller than are shown by other tests. This condition would reduce the sensitivity essential for an accurate rating of steels that had properties between those shown by the B_r and C steels. Although other investigators using the side-notched high-constraint type of bend specimen have made satisfactory lateral contraction measurements, this criterion for evaluating transition temperature was not used because of the need for special micrometers that were not available for these measurements. In addition to the disadvantages apparent from the aforementioned discussion, the difficulty and cost of machining are the most pronounced detriment to the use of this specimen. The only apparent advantage is the relatively high transition temperature which obtains compared with those from the other types of specimens.

The Jackson-type specimens, having a transverse weld bead with a machined notch (Figure 6), were made to check the actual influence that side notches might have on transition temperature, as shown by the high-constraint specimen. Consequently, tests were only made on B_r steel. The plotted data in Figures 11C, 12B, and 13 show some scatter and were not satisfactory for defining a transition curve. It is apparent from these plotted data that this type specimen is the least desirable of the five types of tests used for evaluating the relative properties of steel on the basis of transition temperature.

Evaluation of the Criteria for Determining Transition Temperatures

Absorbed Energy. The procedure used to determine the amount of energy required to produce failure in the bend specimens or bend them to the limit of the jigs was described on page 9. The transition curves for the B_r and C steels based on absorbed energy are given in Figures 11A, 11B, and 11C. A survey of these curves indicates that this criterion sharply defines the ductile to brittle transition for all the tests except the Jackson type. The transition temperatures obtained by the absorbed-energy method compare favorably with the transition temperatures obtained for the steels by other criteria for a given test (Table 2).

Bend Angle. The degrees of bending of a specimen up to maximum load and to the point where the specimen broke (or reached the bending capacity of the equipment) were calculated from the deflection shown on the load-deflection curves. This procedure is more fully described on page 10. The transition curves for the B_r and C steels based on bend-angle measurements are given in Figures 12A and 12B. From these curves, it appears that the total bend angle provides a more accurate transition than the bend angle at maximum load. The transition temperature for each specific test determined on the basis of total bend angle compared favorably with the transition temperature evaluated by other criteria.

Lateral Contraction. The measurement of lateral contraction of a bend-test specimen as a criterion for determining the behavior of steels during loading to failure was advocated by Dr. A. B. Kinzel in his 1947 Campbell Memorial Lecture. This criterion was included during the course of this investigation as another method for evaluating the relative properties of welded steels.

The procedure used for measuring lateral contraction is described on page 10. The transition curves for the B_r and C steels based on lateral contraction measurements are presented in Figure 13.

The results of these tests indicated that the use of lateral contraction measurements for evaluating transition temperatures is most useful for the specimens having a longitudinal bead and transverse notch, i.e., the Lehigh- or Kinzel-type specimens. Lateral measurements for these specimens are easy to make and are accurate as long as the fractures are relatively sharp and the ductility is relatively low. When the fracture is ductile and very irregular, it is extremely difficult to make an accurate lateral measurement. Transitions from ductile to brittle failure for the Lehigh and Kinzel tests were well defined and compared closely to the transitions of B_r steel, as shown by other criteria. For the C steel, however, the transition temperatures were lower than shown by the other criteria which are given in Table 2.

Although the lateral contraction measurements were obtained for the Jackson-type test, they did not clearly define the transition temperature.

The inadequacy of using contraction for evaluating the transition temperature of tee-bend specimens by measuring the contraction at the fracture is apparent from Figure 10.

On the basis of the data obtained from these tests, the use of lateral contraction measurements is most practicable for the Lehigh- and Kinzel-type specimens.

Fracture Appearance. "Fracture appearance" has been used extensively by many investigators for comparing the relative physical and metallurgical properties of steels. The results obtained by this method depend to a great extent upon the interpretation of the fracture made by each person who examines it. The procedure used for evaluating the percentage of ductile fracture in this work was discussed on page 12.

The transition-temperature curves based on fracture appearance versus testing temperature are shown in Figure 14. The fracture appearance of the tee-bend specimens was not used as a criterion for evaluating transition temperature. The reasons have been previously discussed on page 12. The transition temperatures for B_r and C steels on the basis of fracture appearance are essentially the same as those shown by other criteria for a specific test specimen containing a weld.

In addition to determining fracture types empirically, there are other considerations which indicate that a macroexamination of the fracture might be misleading for evaluating the transition from ductile to brittle behavior of a steel. Other investigators have suggested that a failure classed as "shear" or "cleavage" on the basis of macroappearance is often erroneous. Basic studies have indicated that some ductile-appearing shear failures have deformed plastically along slip planes, but terminal fracture has taken place along a cleavage plane or in the grain boundaries.

The most apparent feature of the fractures for the B_r and C steels for all types of specimens is the difference in the appearance of the ductile-type fractures which were obtained from the specimens tested at the highest temperature for each series. The B_r steel shows a fibrous woody type of ductile fracture which usually terminated part way across the specimen and then propagated along a longitudinal plane, as shown in the fractured Kinzel-type specimen, Fig.16, specimen 22-5. As the testing temperature was lowered, the ductile portion of the fracture gradually decreased. The remaining portions of the fractures in these cases had a bright crystalline appearance which characterized brittle fracture at the lower testing temperatures.

The ductile fractures of the C steel specimens did not show the woody fibrous structure characterized by the B_r steel. Instead, failures propagated across the entire specimen producing a corduroy or dark-appearing rough surface, as shown in Figure 17. Unless the approximate transition temperature were known, it was not uncommon to interpret this type of fracture as being of a brittle nature. When the tests were made at relatively high temperatures and oil was used for the heating medium, the dark oily surface further added to the confusion of accurate fracture interpretation. The transition, and low-temperature brittle fractures appeared about the same as those shown by the corresponding fractures of B_r steel.

The longitudinally welded and transversely notched specimens (Lehigh and Kinzel type) exhibited an elliptical-appearing fracture pattern in the transition-temperature range, as shown in Figures 16 and 17. The dark-appearing structure was considered to be ductile and the bright structure was termed brittle. It is also of interest to note that where the ductile vein reached the notched surface, there was a pronounced ductile distortion in the plate surface. The actual cause for this structure appearance has not been definitely determined. It is possible, however, that the stress conditions and loading characteristics, the outer heat-affected zone of the weld, or the inherent properties of the steel, might have been influencing factors.

Figures 18 and 19 show representative fractures of tee-bend specimens made of B_r and C steels, respectively, and tested at different temperature levels. Figure 18 illustrates a ductile-type fracture in B_r steel that has broken part way across the specimen and then changed direction so that the fracture continued longitudinally along a segregation or large inclusion. Figure 19 shows that the direction of ductile fracture of C steel proceeds across the thickness of the plate.

A factor that creates suspicion as to the validity of this criterion is shown graphically in Figure 20B. From a comparison of the transition curves on the basis of fracture appearance for welded and unwelded Kinzel-type specimens, it appears that the transition occurs at the same temperature for both specimens. This holds for each steel. The figure also shows that a trend exists in which the transition temperature for the unwelded specimens is higher than for the welded specimens. This condition is not consistent with the curves shown for the other criteria.

It is apparent from this brief discussion that more fundamental understanding of fractures and their occurrence is essential before an accurate appraisal can be made by this method on various steels tested under varying conditions.

<u>Energy Ratio</u>. Other investigators who have used the tee-bend test found that a convenient method for rating the performance of a welded steel specimen is to compare the amount of energy it absorbs during testing with the amount of energy absorbed by a steel selected as a standard (Reference 43, Appendix C). A medium-carbon steel standard is used which has a tensile strength close to 60,000 psi and bends to the maximum capacity of the testing jig without any indication of failure. From tee-bend tests on this steel, it has been found that the standard total energy absorbed for 3/4-inch plate having a 5/16-inch fillet is 42,700 inch-pounds. The transition curves for B_r and C steels based on the

energy-absorption ratio obtained from tee-bend specimens, tested at the various temperature levels and expressed as per cent, are shown in Figure 15. The contour of these curves and the transition temperatures indicated by them are the same as shown by the energy-absorption curves shown in Figure 11B. It is possible that a rating system of this type can be applied to ship steels after a positive criterion has been established and the procedure proven.

Bend Tests of Unwelded Specimens

A series of bend tests was made on unwelded specimens of B_r and C steels with a transverse notch (Kinzel type, Figure 2), to compare the transition temperatures of welded and unwelded plates. The testing procedure used for the unwelded specimens was the same as for the welded specimens previously described. The tabulated data for these tests are given in Tables 12 and 13, Appendix A. Figures 20A and 20B graphically show that the unwelded specimens have a lower transition temperature than the respective welded steels. Also, the absorbed energy, bend angle, and lateral contraction measurements on a specimen at a given testing temperature are higher for the unwelded specimens than for the welded ones. These results are in line with those obtained by other investigators on other steels (Reference 131, Appendix C).

The transition temperatures for the unwelded B_r and C steels on the basis of fracture appearance are essentially the same as those shown by the welded specimens. These results indicate that fracture appearance might not be an accurate criterion for comparing the transition properties of welded and unwelded specimens. Further detailed discussion relating to the subject has been presented on page 19 of this report.

Metallurgical Observations

Microsections were made to determine the direction of rolling for the B_r and C steels and to compare their cleanliness. Fig. 21 gives a typical comparison of the size and shape of the inclusions found in the two steels. The large stringers of complex sulphide inclusions shown in the B_r steel were of sufficient magnitude to produce magnaflux indications along the ground edges of the specimens. The planes of these discontinuities, which are shown in Fig. 21(a), influenced the propagation of fracture and thus the amount of energy absorption, bend angle, etc., required to break the specimen. It was observed on many fractured specimens made of B_r steel, that the fracture through the notch and into the plate would stop abruptly and propagate by tearing along the longitudinal plane of the plate, as shown by Fig. 16, Specimen 22-5. The best comparison of ductile-type fractures in B_r and C steels based on this hypothesis is illustrated by the tee-bend specimens shown in Figures 18 and 19. When the specimens were tested below the transition temperature, this longitudinal tearing was not apparent.

The inclusions in the C steel were small, round, and uniformly distributed in the steel. The directional properties of the inclusions were so obscure that it was difficult to determine the rolling direction of the steel.

On the basis of these limited observations, it is possible that large inclusions of the type in the B_r steel probably reduce the rate of fracture propagation.

It is further apparent from the foregoing discussion that the inherent properties and structure of the steel have an influence on the mode of fracture of the specimen and the resulting appearance of the broken surface.

The macrographs in Figures 22 and 23 show the relative difference between the size of the weld bead and the depth of the heat-affected zone that obtains when the welding speed is increased from 6 inches per minute for the Kinzel specimen to 10 inches per minute for the Lehigh specimen. The depth of notch, cut transverse to the bead, is also indicated on the photographs. Dr. Stout has shown that with all conditions constant, the transition temperature of a given steel is raised as the welding speed is increased

(Reference 131, Appendix C). In this investigation, the welding speed, notch design, and notch depth varied for the Lehigh and Kinzel tests. The Kinzel specimen indicated a higher transition than the Lehigh specimens regardless of the slower welding speed and more shallow notch. This indicated that the sharper notch more than offset the effect of the other two variables which tended to lower the transition temperature.

The photographs further show that the Kinzel specimens have more weld metal below the root of the notch as well as a wider heat-affected zone. The exact influence that this weld metal has on transition temperature has not been fully determined. There is some indication, however, that the weld metal and heat-affected zone have a transition temperature independent of that exhibited by the base metal. Further work is contemplated along these lines.

SUMMARY

1. A survey was made of published and unpublished reports to appraise the various kinds of tests used to study strength, ductility, and transition temperatures of welded joints in structural steel. On the basis of this survey, the Project Advisory Committee selected the tee-bend test, the longitudinally welded and transversely notched bead-bend tests, and the transversely welded and transversely notched bead-bend tests, for study and correlation with the hatch-corner tests made at the University of California.

2. The transition temperatures of welded and unwelded bend specimens of B_r and C steels tested during this investigation, are in the same qualitative order as those indicated by the full-scale, hatch-corner, wide-plate, and notched-bar tests. (See Summary Table 2, page 28).

3. Bend tests of unwelded Kinzel-type specimens of B_r and C steel had a lower transition temperature than the respective welded steels. Also, the absorbed energy, bend angle, and lateral contraction at a given testing temperature were higher for the unwelded specimens than for the welded ones.

4. There are indications that the metallurgical properties and structure of the steel have an influence on the mode of fracture, the appearance of the broken surface, and the absorbed-energy and bend-angle measurements of the specimen. This observation was most apparent when specimens of B_r steel were tested at or above the transition temperature. In the B_r steel, the large stringers of complex sulphide inclusions observed by microexamination were of sufficient magnitude to produce magnaflux indications along the ground edges of the specimens.

5. The different criteria (absorbed energy, bend angle, lateral contraction, etc.) used for evaluating the transition temperatures for the B_r and C steels were more practicable for some bend specimens than others.

   a. Total absorbed energy and total bend angle obtained from load-deflection curves showed an abrupt and well-defined transition for all specimens except the Jackson type.

   b. Lateral contraction measurements were most applicable to the specimens having a longitudinal weld and transverse notch, (Kinzel and Lehigh types).

   c. The use of fracture appearance as a criterion for evaluating transition temperatures is open to question. An understanding and interpretation of the mechanics of fracture of a given type specimen with a specific grade of steel seem necessary before the fracture will give an accurate appraisal of the change from the ductile to the brittle type of fracture.

6. The variations in the designs of the five specimens influenced the transition temperatures in different ways.

   a. The data from the longitudinally welded and transversely notched Kinzel and Lehigh specimens and the tee-bend specimens gave clear-cut transition curves.

   b. The transversely welded and transversely notched Naval Research Laboratory High-Constraint and Jackson-type specimens showed a small difference in magnitude of the measured criteria between the upper and lower limits of the transition range.

   c. The side notches added constraint to the Naval Research Laboratory specimen which raised the transition temperature of the steel above that shown by the other specimens.

FUTURE WORK

On February 26, 1948, the Advisory Committee for Project SR-100, Contract NObs-45543, "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships", met to review the progress of the work being conducted at Battelle Memorial Institute. The information contained in this report, describing work authorized by the Committee on October 1, 1947, was presented for the Committee's approval.

After the current work had been thoroughly discussed, the following program for future work at Battelle Memorial Institute was discussed and approved by the Advisory Committee.

Item 1. Modified specimens of the Lehigh or Kinzel type are to be developed and tested in an attempt to obtain a specimen that will give the same transition temperatures for B_r and C steels that they show in the hatch-corner tests. Specimens having a notch deep enough to eliminate the effect of weld metal are to be included in these tests.

Item 2. Tension tests are to be made at various temperatures using a specimen similar in design to that developed in Item 1. The transition curves, determined for specimens made from B_r and C steels, will be compared with the bend test and hatch-corner transition curves.

Item 3. A series of tests on the specimen developed from Item 1 to determine the relative transitions of several steels and different steel conditions. The test conditions are to be as follows:

a. Steels to be tested - A, B_r, C, D_n, and E.

b. Specimens to be preheated to 400° F prior to welding. Tests to be made on B_r and C steels.

c. Specimens to be postheated (stress relieved) to 1100° F after welding. Tests to be made on C steel only.

d. Make specimens using the water-quenching technique employed by Dr. Bagsar. These tests are to be made on both welded and unwelded specimens. The type steel will be determined by the investigators.

Item 4. A. A limited study to determine more fundamental information on the causes, start, and appearance of fractures will be conducted concurrently with the foregoing items.

B. A series of tests will be made, to determine the transition temperature of the weld metal.

C. Limited tests will be made to determine the effect of ageing on the specimen developed from Item 1. Unless some pronounced ageing effect is apparent, the ageing time of 8 days used for previous tests will be maintained.

Data given in this report are recorded in Battelle Laboratory Book No. 3240.

RWB:PJR:CBV:vm:cs
January 25, 1949

TABLE 1. WELDING CONDITIONS USED FOR THE BEND TEST SPECIMENS

Welding Details	Type Test: Lehigh	Kinzel	Tee Bend	Naval Res. Lab. High Constraint	Jackson Transverse Notched Bead Bend
Electrode Class	E6010	E6010	E6010	E6010	E6010
Electrode Diameter, In.	3/16	3/16	5/32	3/16	3/16
Avg Welding Current, Amps	175	175	145	175	175
Avg Arc Volts	27	27	25	27	27
Avg Welding Speed, In./Min.	10	6	2.8	6	6
Length of Weld Bead, In.	10	4	2.7	6	6
Length of Electrode per Inch of Weld	.78	1.4	3.6	1.4	1.4
Initial Plate Temp, F	75	75	75	75	75
Cooling Medium	Air	Air	Air	Air	Air

TABLE 2. COMPARISON OF TRANISITION TEMPERATURES[1], DEGREES F, FOR WELDED B_R AND C STEELS, FROM VARIOUS TESTS

Type of Test	Fig. No.	(A) Absorbed Energy: Total	(B) Absorbed Energy: Max. Load to Failure	(C) Bend Angle: Total	(D) Bend Angle: At Max. Load	(E) Lateral Contraction	(F) Appearance of Fracture
Steel B_R							
Lehigh	1	-20	-20	-20	-30	-30	-20
Kinzel	2	20	20	20	0	20	20
Tee-Bend	3,4	0	0	0	?	-	-
Naval Res. Lab.	5	30	30	30	?	?	30
Jackson	6	?	?	-10	?	?	10
Hatch corner[2]		40	-	-	-	-	-
72"-Wide Plate (Internal Notch[3])		30	-	-	-	-	-
Standard Keyhole Notched Bar[4]		-30	-	-	-	-	-
Steel C							
Lehigh		150	140	150	160	110	150
Kinzel		150	150	150	140	120	160
Tee-Bend		100	100	80	40	-	-
Naval Res. Lab.		180?	180?	180	?	?	160
Hatch corner[2]		120	-	-	-	-	-
72"-Wide Plate (Internal Notch)		90	-	-	-	-	-
Standard Keyhole Notched Bar[4]		15	-	-	-	-	-

? Transition temperature is not apparent.

(1) The transition temperature as used for tests included in this report is defined as the highest temperature at which the first significant decrease (or wide discrepancy) occurred in the measured properties.

(2) DeGarmo, E.P., and A. Boodberg, "Causes of Cleavage Fracture in Ship Plate: Hatch Corner Design Tests", University of California, Report No. SSC-16, December 4, 1947.

(3) Davis, H.E., G.E. Troxell, E.R. Parker, A. Boodberg, and M.P. O'Brien, "Causes of Cleavage Fracture in Ship Plate; Flat Plate Tests and Additional Tests on Large Tubes", University of California, Report No. SSC-8, January 17, 1947.

(4) Gensamer, M., E.P. Klier, T.A. Prater, F.C. Wagner, J.O. Mack, J.L. Fisher, "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests", Pennsylvania State College, Report No. SSC-9, March 19, 1947.

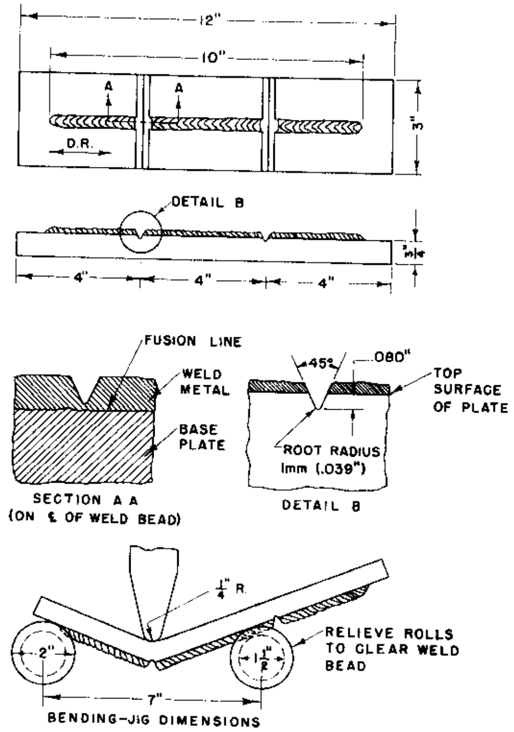


FIGURE 1. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCHES (LEHIGH DESIGN)

WELDING SCHEDULE GIVEN IN TABLE 1.

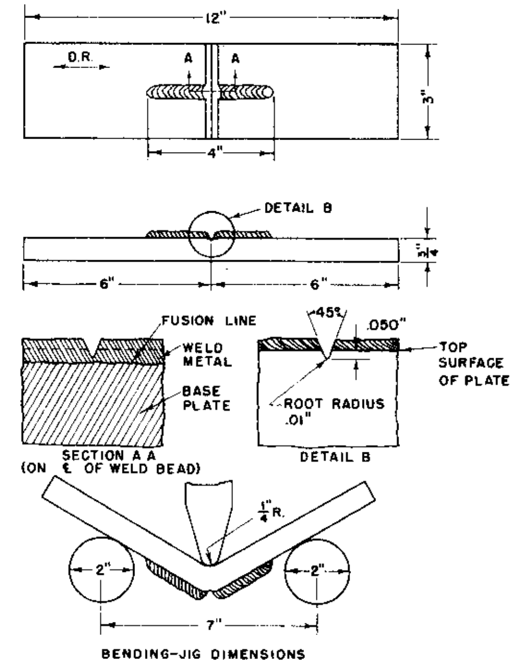


FIGURE 2. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN)

WELDING SCHEDULE GIVEN IN TABLE 1.

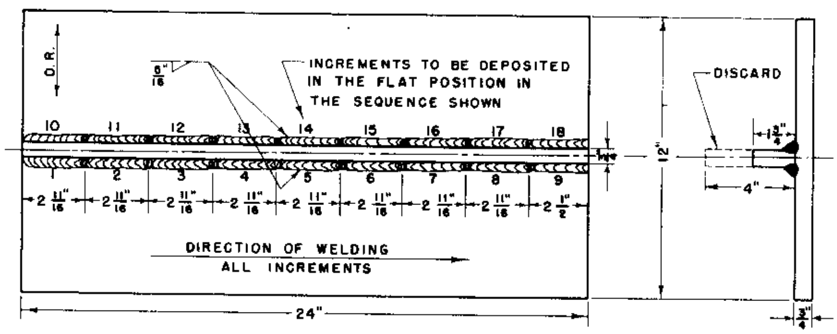


FIGURE 3. WELDING DETAILS FOR TEE-BEND SPECIMEN MADE FROM 3/4" PLATE

WELDING SCHEDULE GIVEN IN TABLE 1.

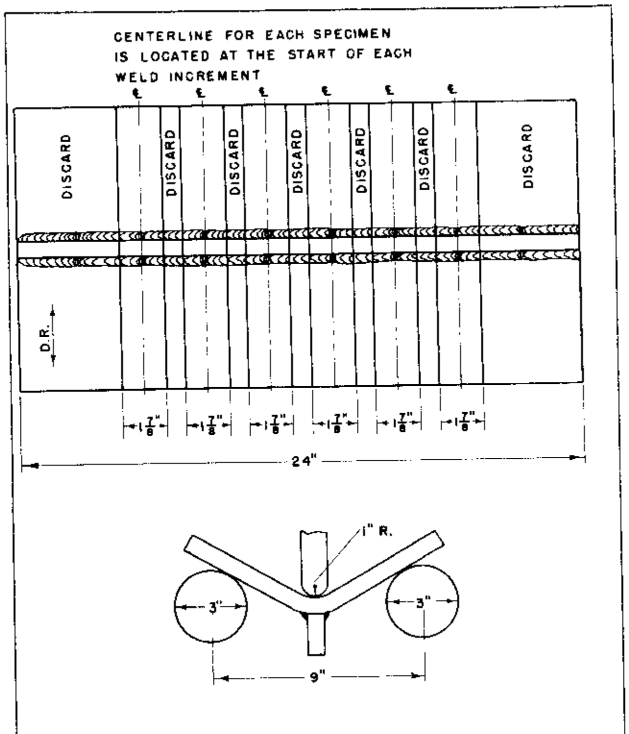


FIGURE 4. MACHINING AND TESTING DETAILS FOR TEE-BEND SPECIMEN

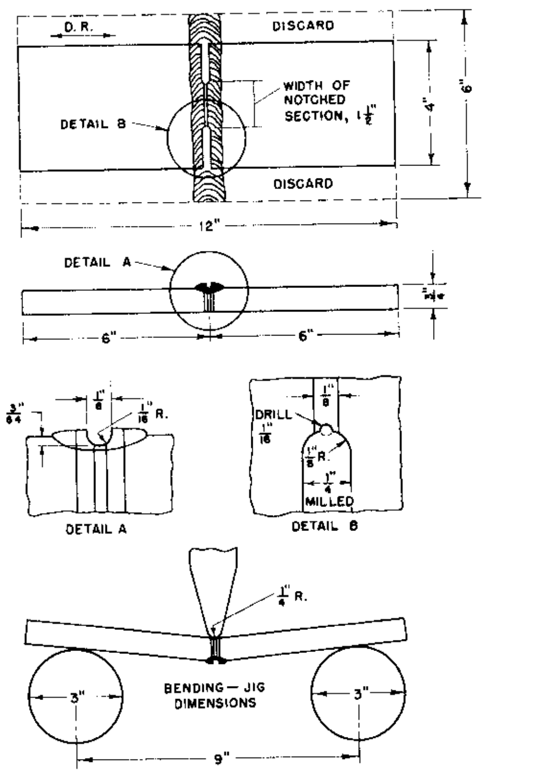


FIGURE 5. BEND SPECIMEN WITH TRANSVERSE NOTCHED WELD BEAD AND EDGE NOTCHES. (NAVAL RESEARCH LABORATORY DESIGN)

WELDING SCHEDULE GIVEN IN TABLE I.

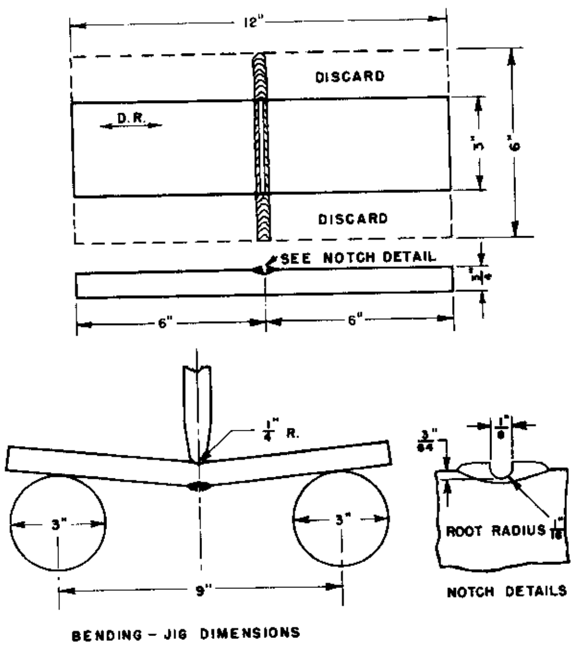
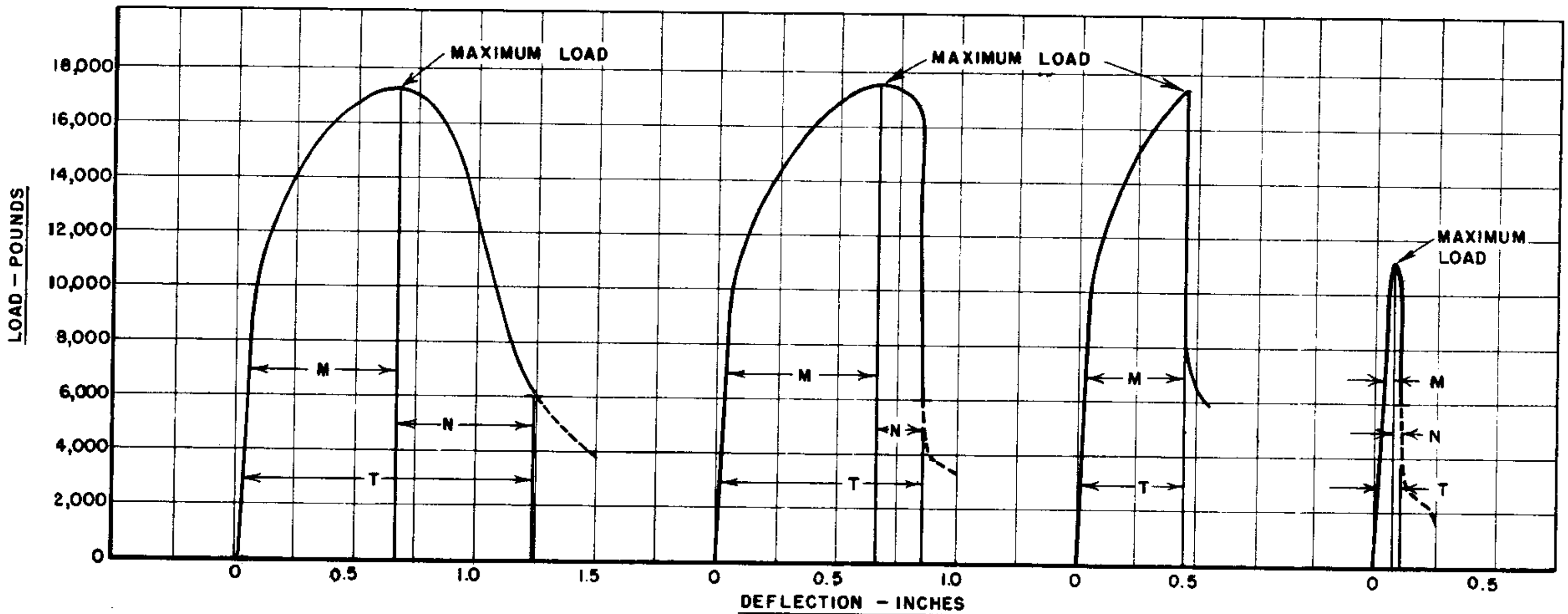


FIGURE 6. BEND SPECIMEN WITH TRANSVERSE WELD BEAD AND TRANSVERSE NOTCH (JACKSON—TYPE SPECIMEN) 58529

WELDING SCHEDULE GIVEN IN TABLE I.

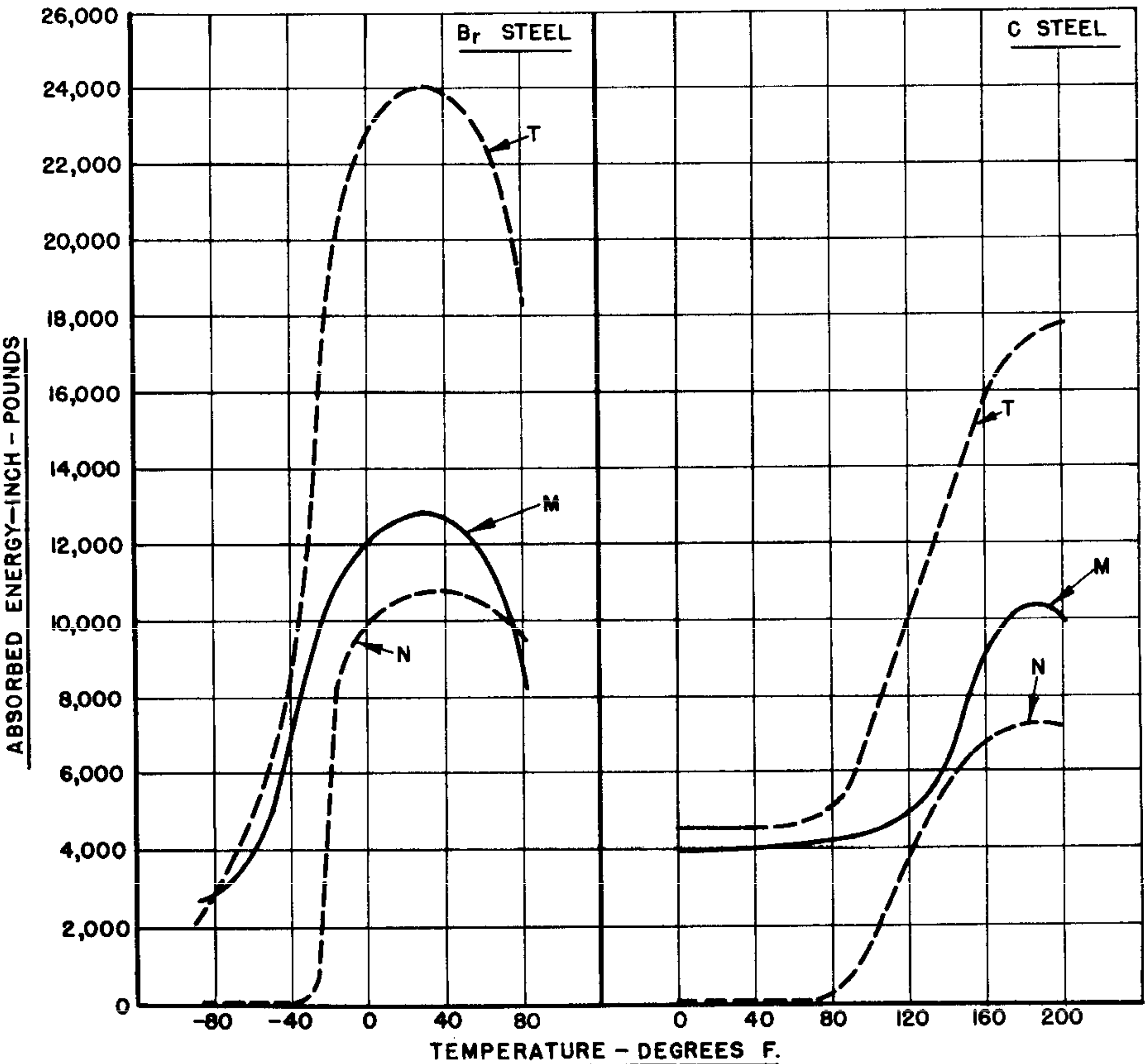


T - TOTAL ENERGY ABSORBED

M - ENERGY ABSORBED TO MAXIMUM LOAD

N - ENERGY ABSORBED AFTER MAXIMUM LOAD

FIGURE 7. SCHEMATIC DIAGRAMS OF TYPICAL LOAD-DEFLECTION CURVES



T — TOTAL ENERGY ABSORBED
M — ENERGY ABSORBED TO MAXIMUM LOAD
N — ENERGY ABSORBED AFTER MAXIMUM LOAD

FIGURE 8. TRANSITION-TEMPERATURE CURVES OF LEHIGH-TYPE SPECIMENS BASED ON ABSORBED ENERGY AS SHOWN BY DIFFERENT PORTIONS OF THE LOAD-DEFLECTION DIAGRAM. REFER TO FIGURE 7.

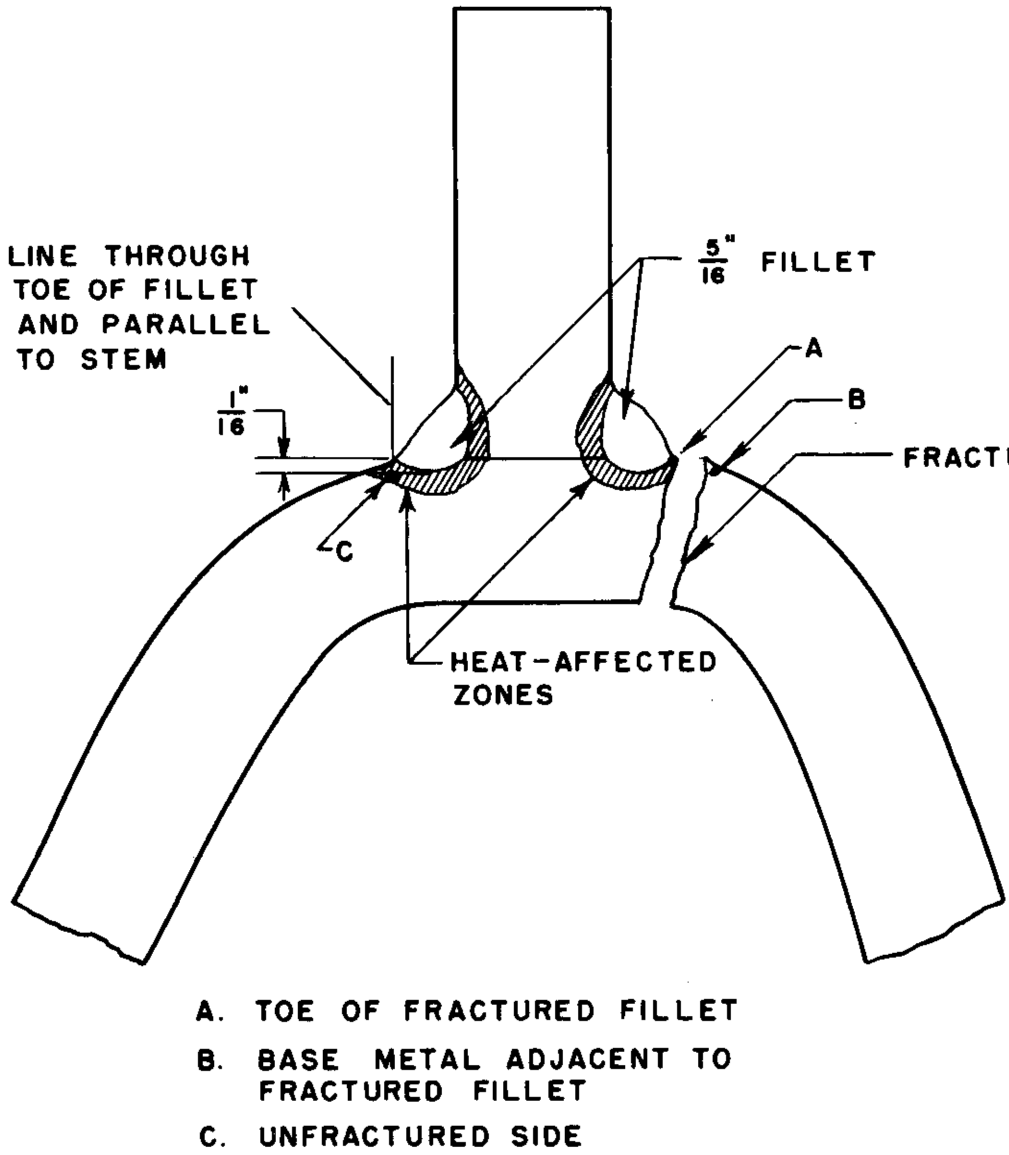


FIGURE 9. LOCATION OF POINTS FOR LATERAL CONTRACTION MEASUREMENTS ON TESTED TEE-BEND SPECIMENS.

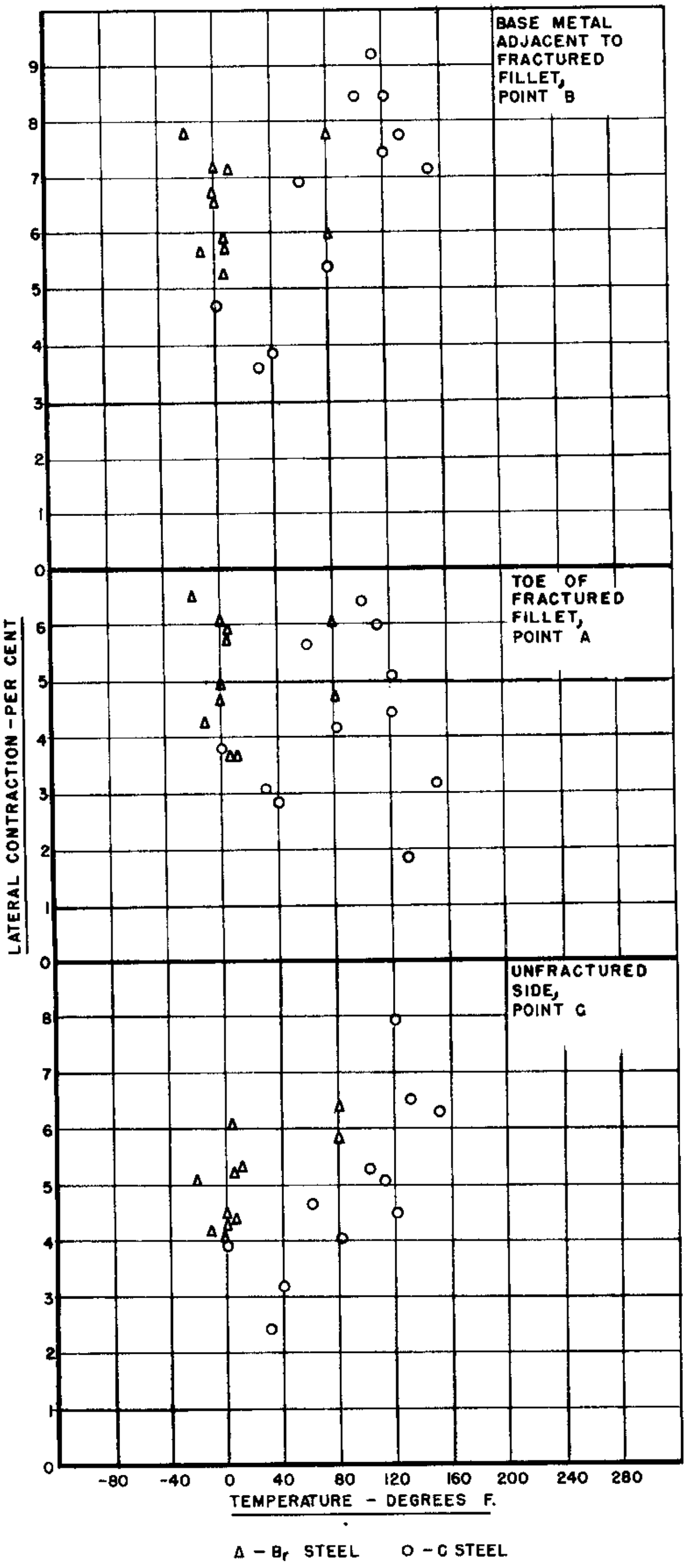


FIGURE 10. A COMPARISON OF LATERAL CONTRACTION MEASUREMENTS AT THREE LOCATIONS ON THE TEE-BEND SPECIMENS. REFER TO FIGURE 9.

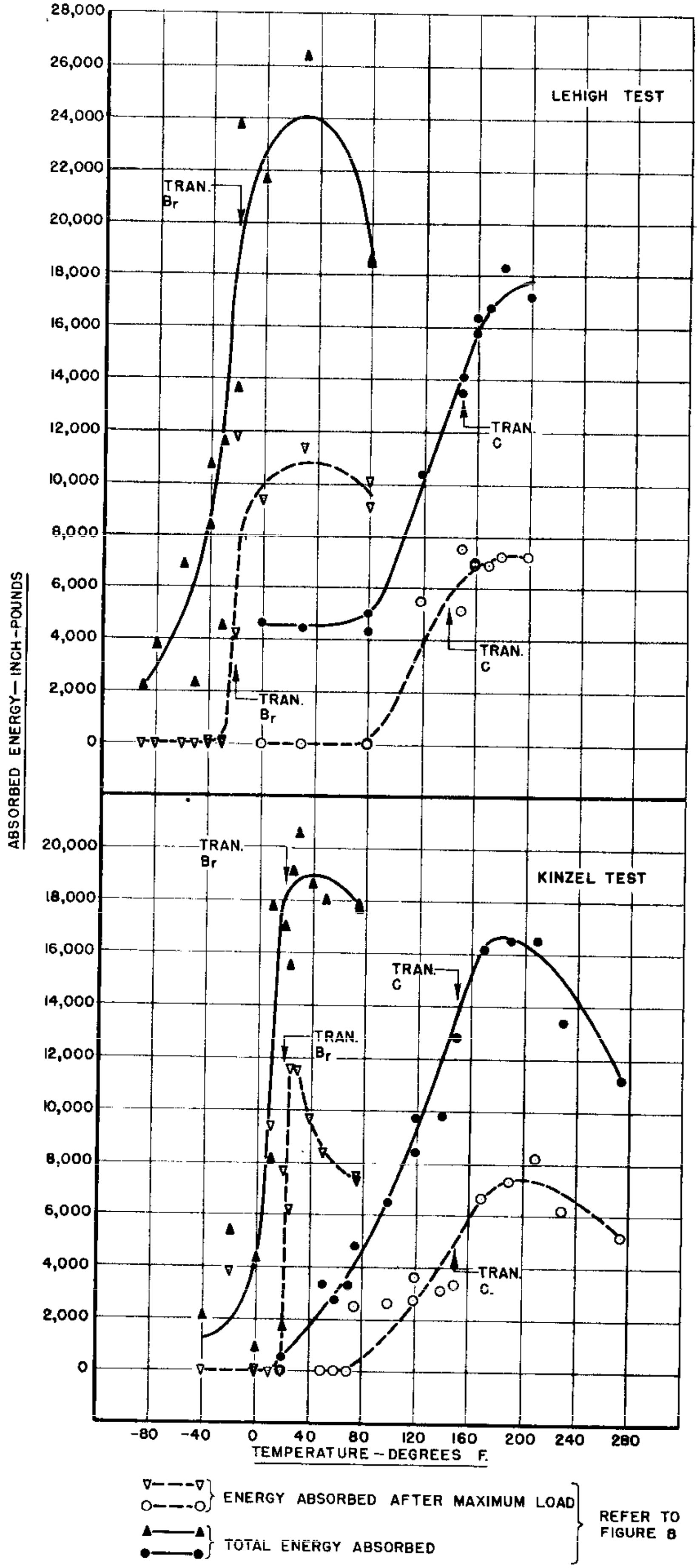


FIGURE 11 A. TRANSITION-TEMPERATURE CURVES FOR B_r AND C STEELS BASED ON ABSORBED ENERGY

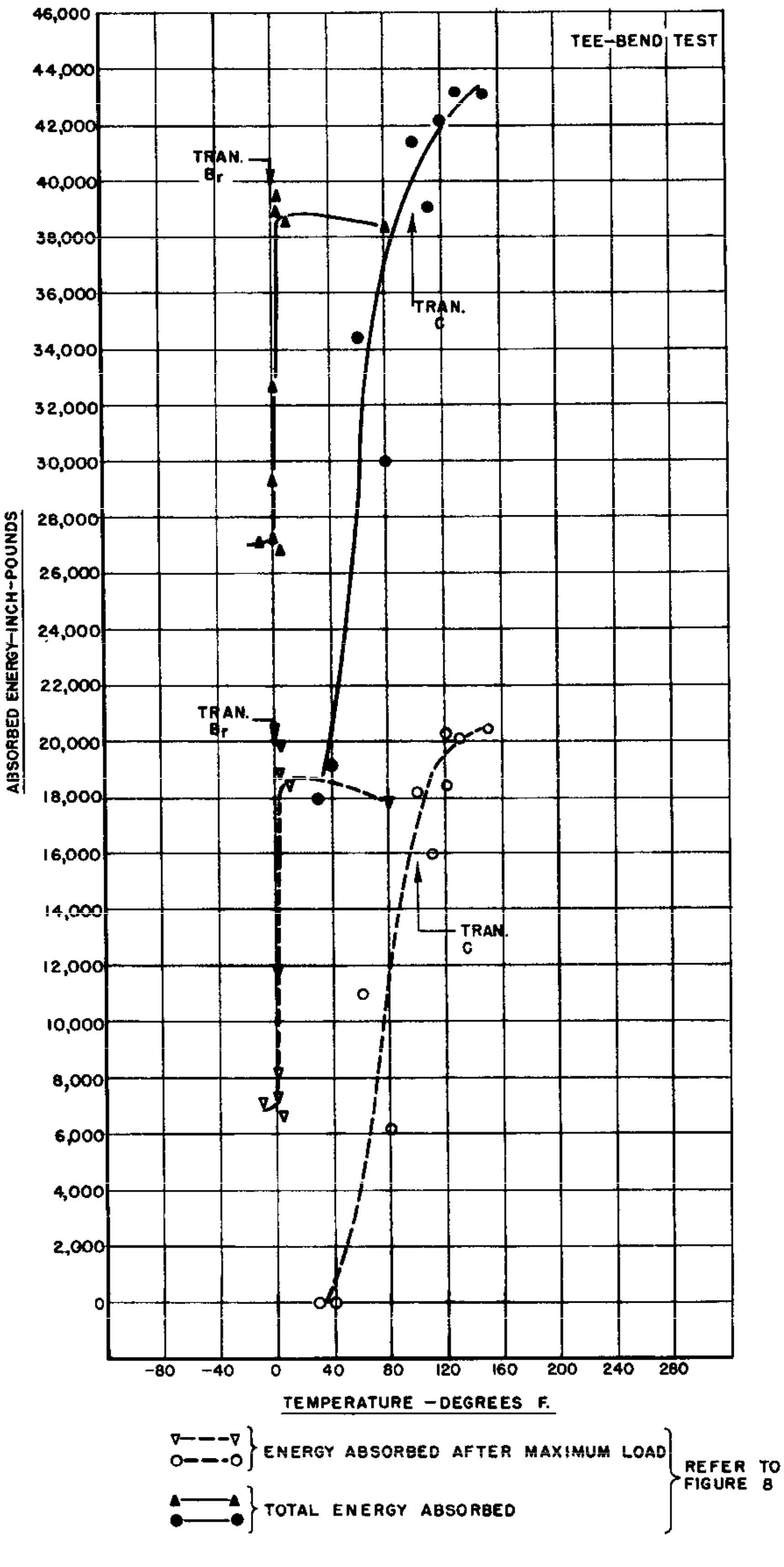


FIGURE 11 B. TRANSITION-TEMPERATURE CURVES FOR B_r AND C STEELS BASED ON ABSORBED ENERGY

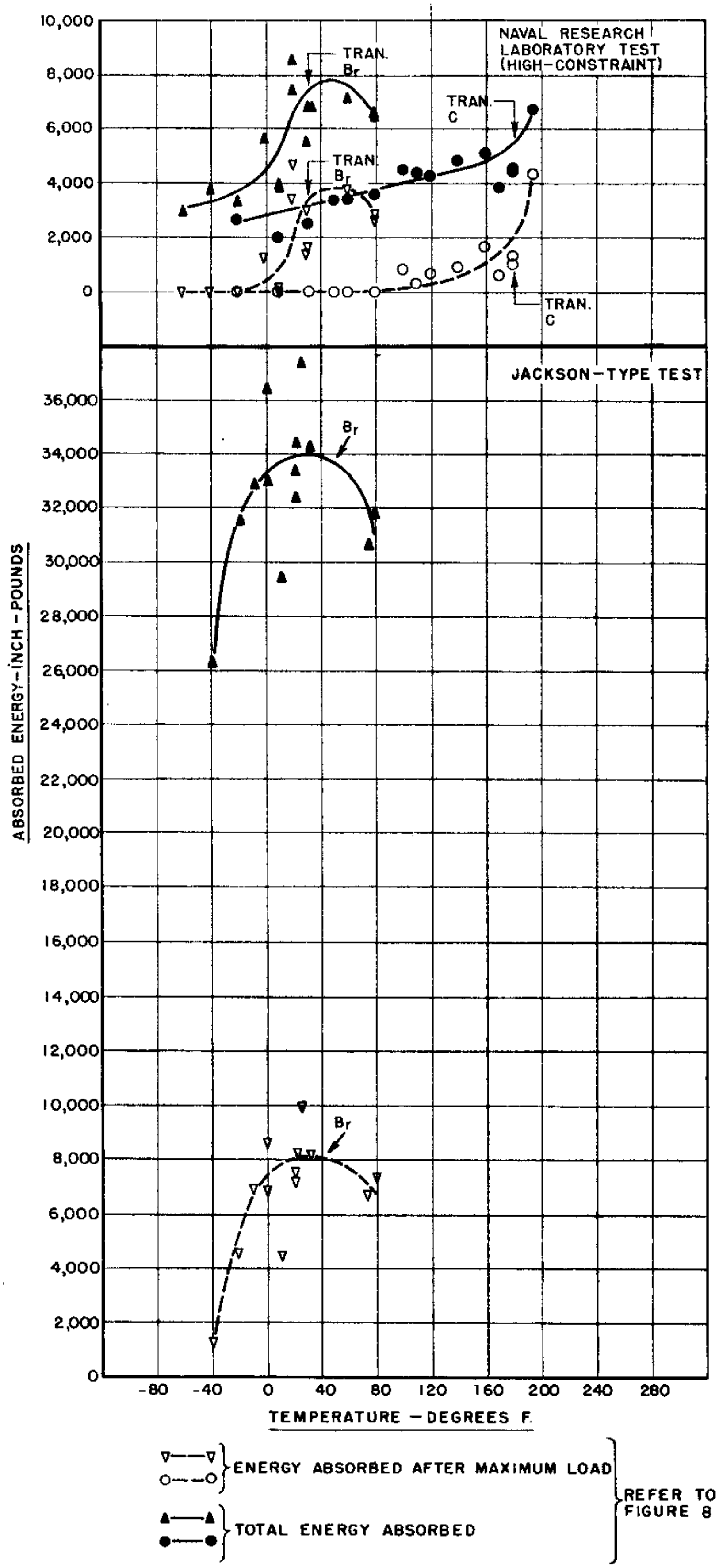


FIGURE II C. TRANSITION-TEMPERATURE CURVES FOR B_r AND C STEELS BASED ON ABSORBED ENERGY

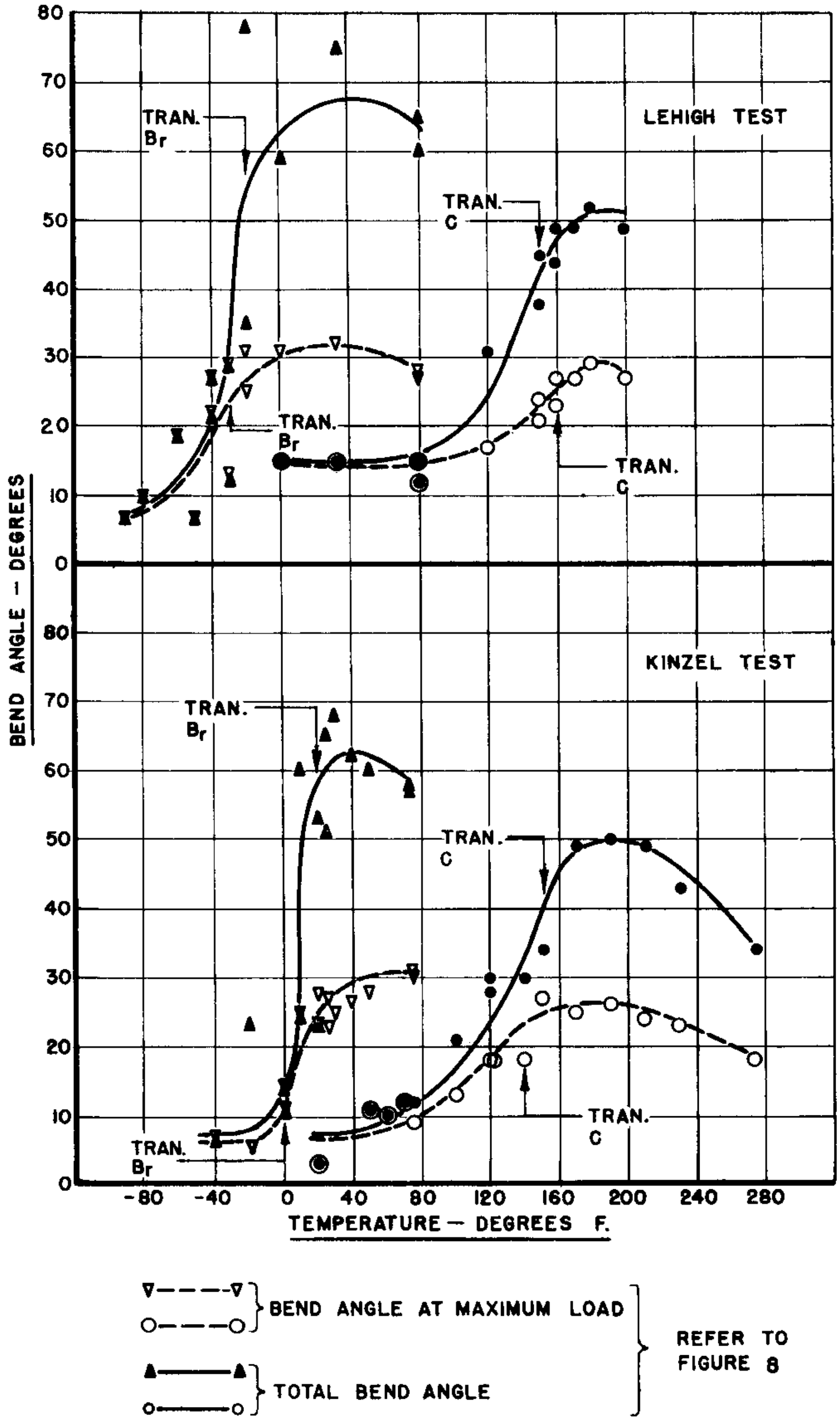


FIGURE 12 A. TRANSITION-TEMPERATURE CURVES FOR B_r AND C STEELS BASED ON BEND-ANGLE MEASUREMENTS

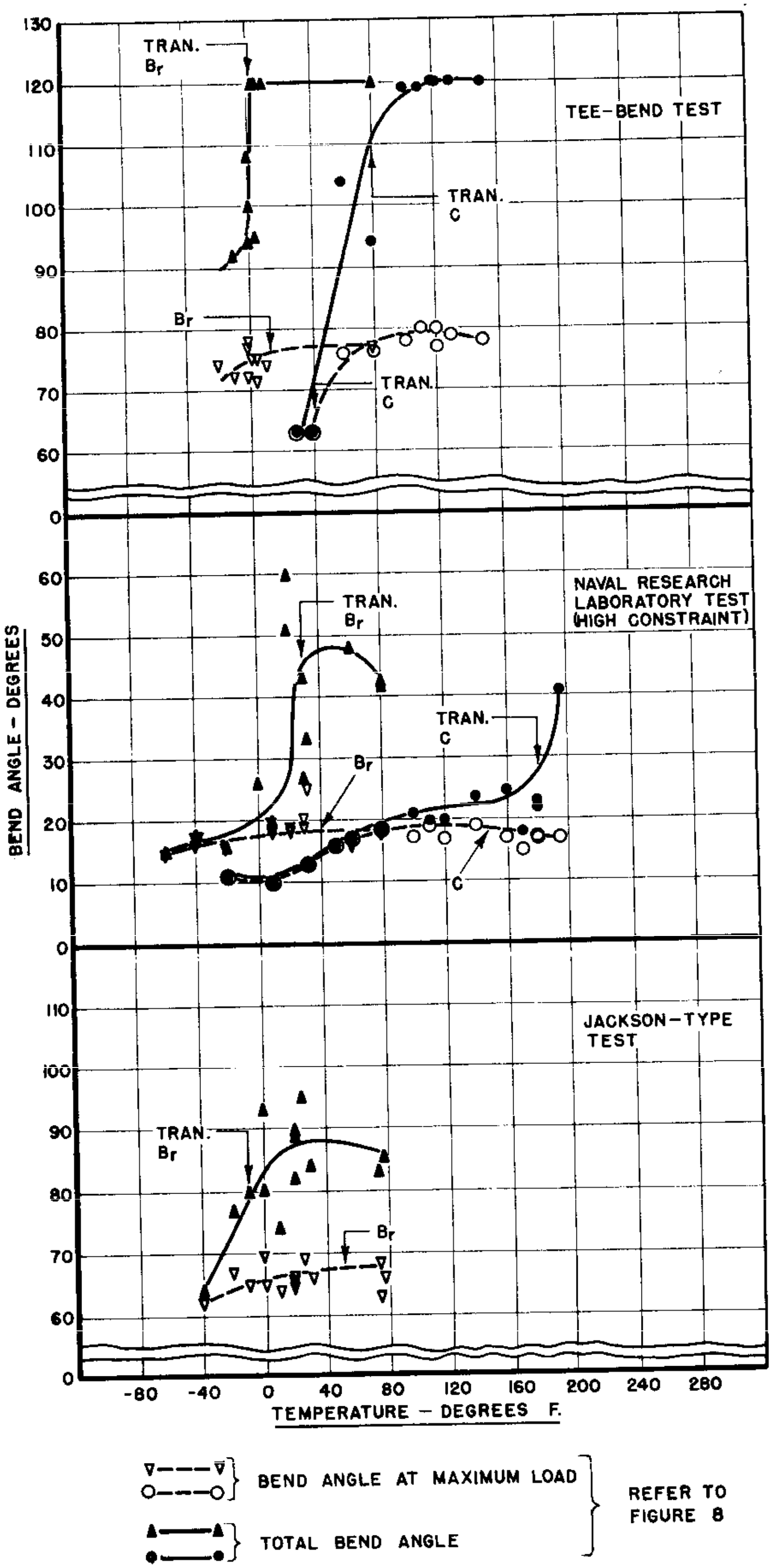


FIGURE 12 B. TRANSITION-TEMPERATURE CURVES FOR Br AND C STEELS BASED ON BEND-ANGLE MEASUREMENTS.

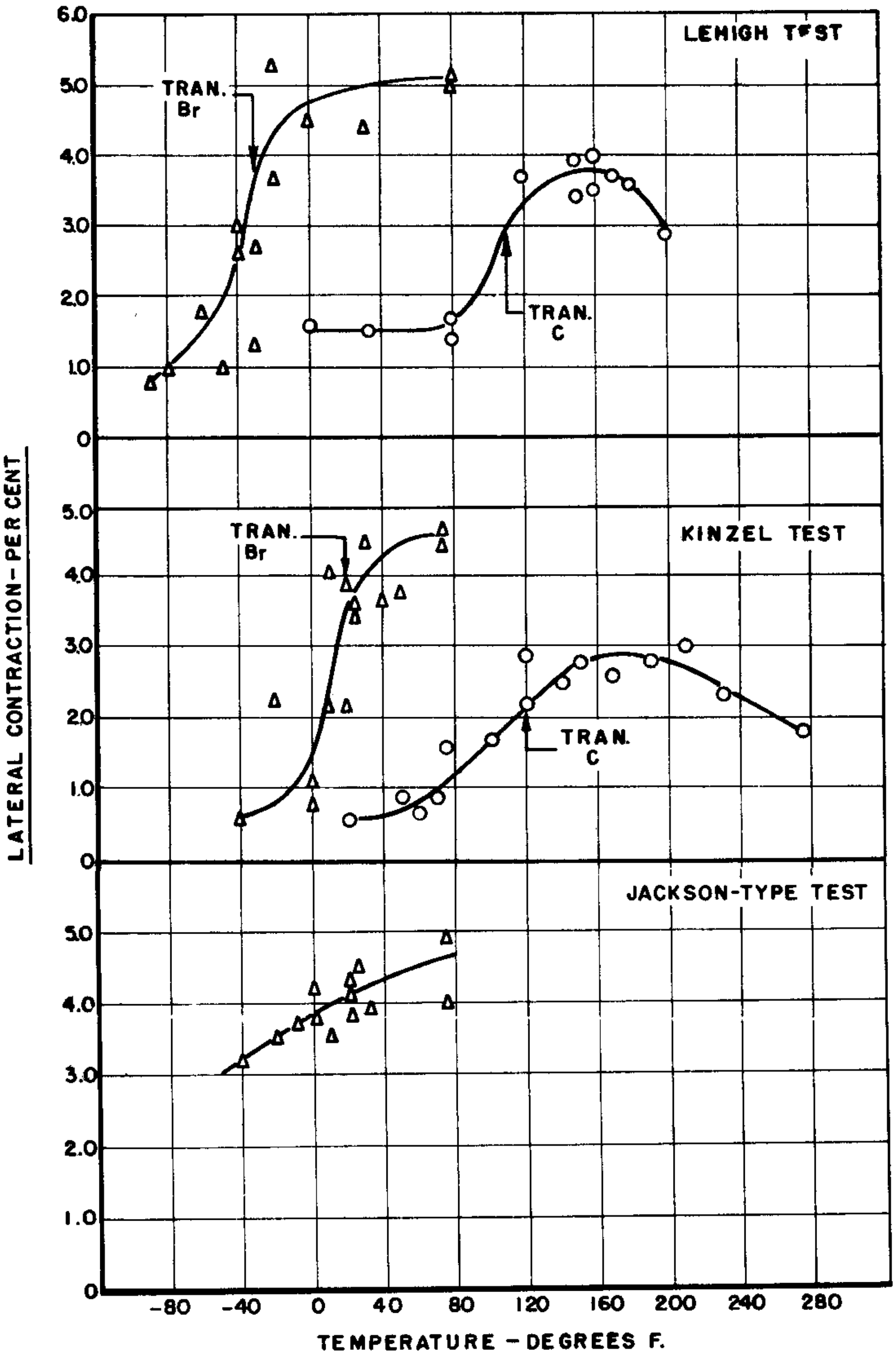


FIGURE 13. TRANSITION-TEMPERATURE CURVES FOR Br AND C STEELS BASED ON LATERAL-CONTRACTION MEASUREMENTS

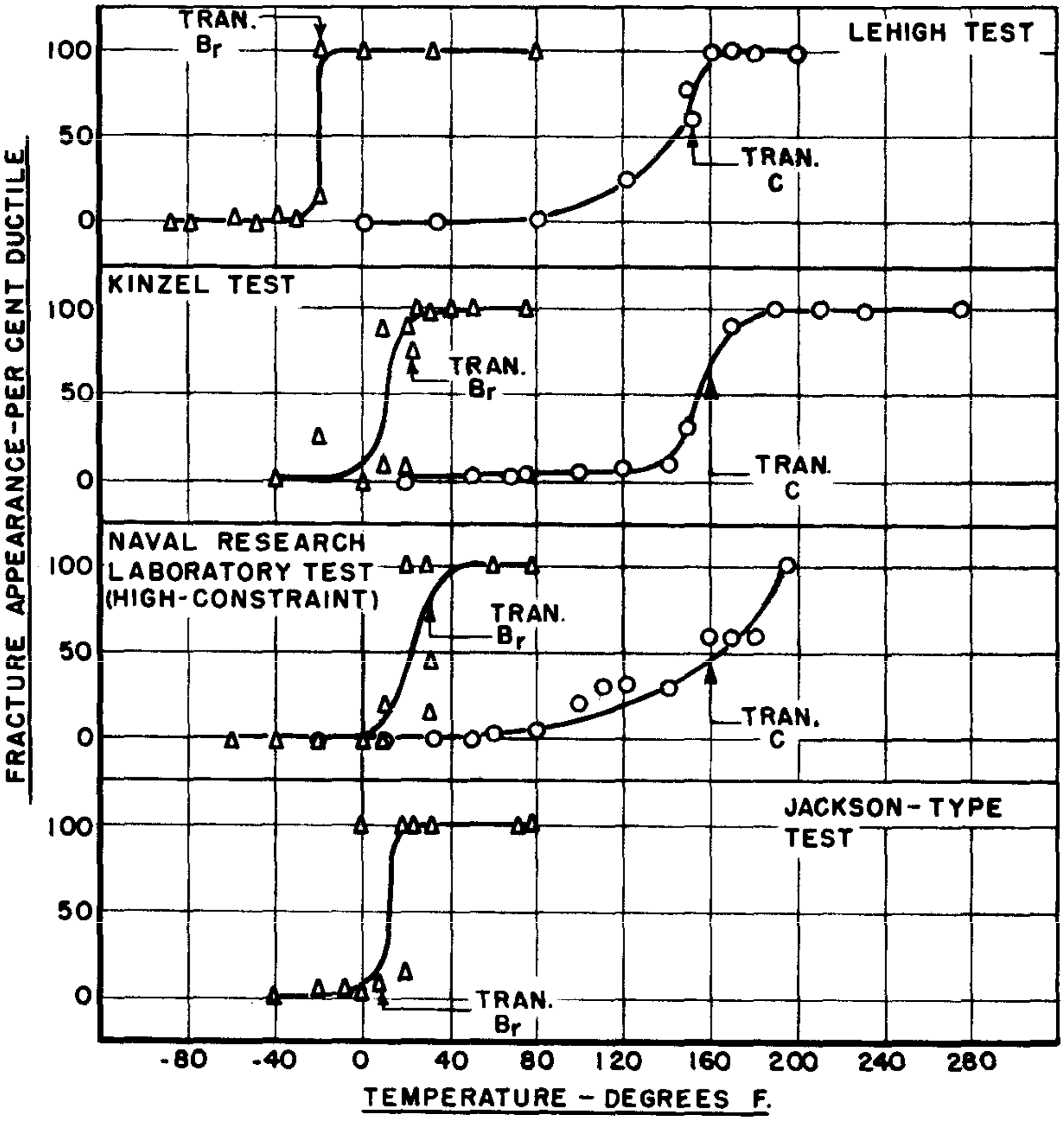


FIGURE 14. TRANSITION-TEMPERATURE CURVES FOR B_r AND C STEELS BASED ON FRACTURE APPEARANCE

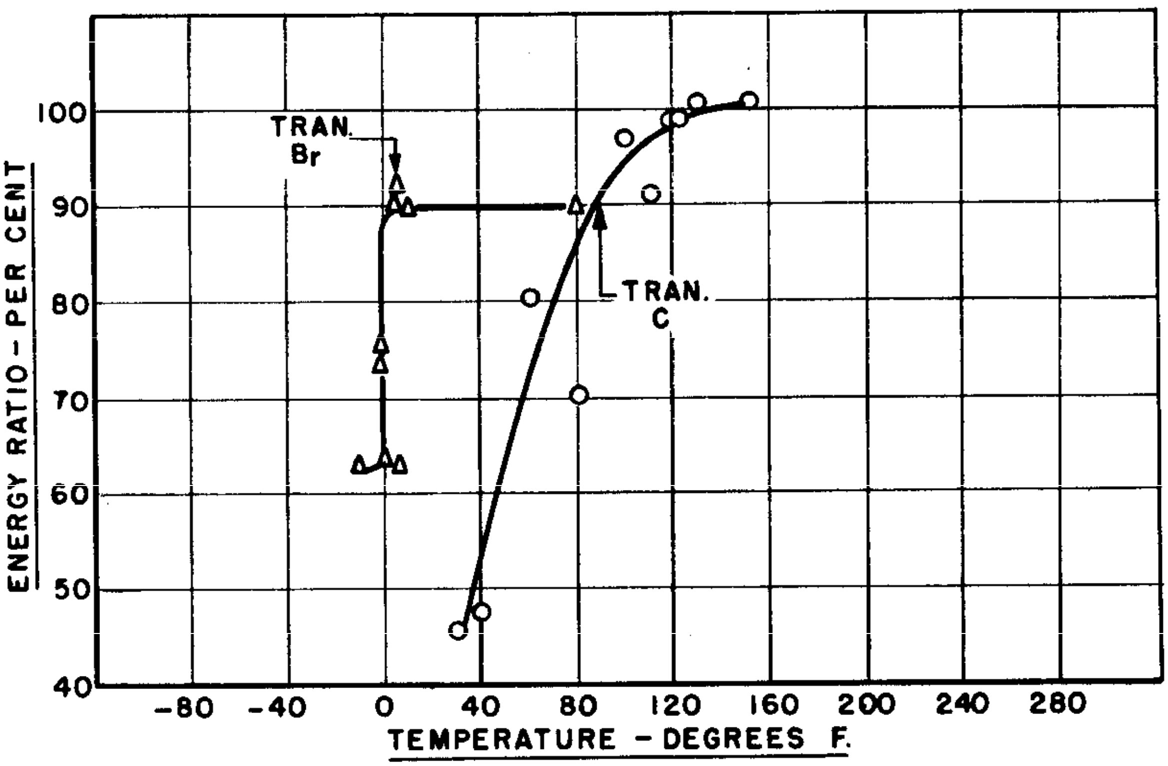
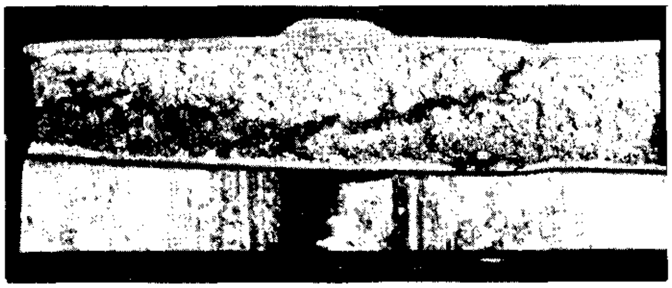


FIGURE 15. TRANSITION-TEMPERATURE CURVES FOR Br AND C STEELS BASED ON THE ENERGY ABSORPTION RATIO OBTAINED FROM TEE-BEND TESTS

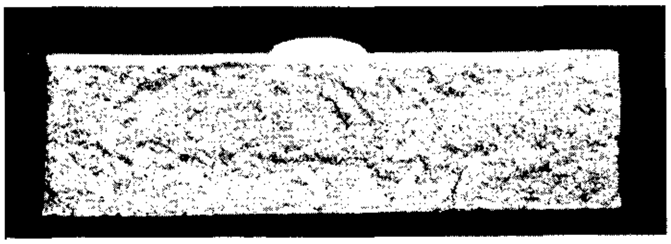
Ductile
Fracture

Specimen 22-5 53780
Testing temperature 40 F



Transition
Fracture

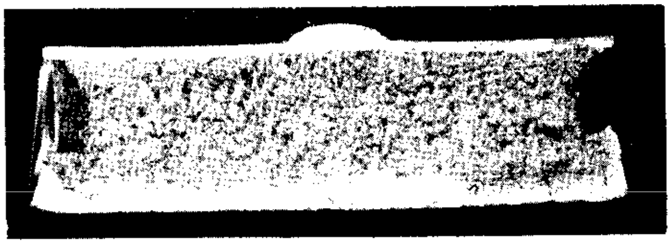
Specimen 22-6 53783
Testing temperature -20 F



Brittle
Fracture

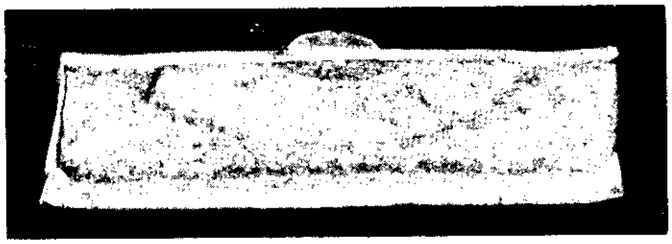
Specimen 22-4 53754
Testing temperature -40 F

FIGURE 16. FRACTURED KINZEL-TYPE SPECIMENS MADE FROM B_r STEEL AND TESTED AT VARIOUS TEMPERATURES



Ductile
Fracture

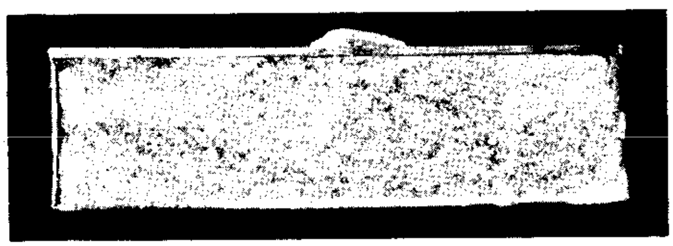
Specimen 23-7 53733
Testing temperature 275 F



Specimen 23-9 53734
Testing temperature 120 F

Transition
Fracture

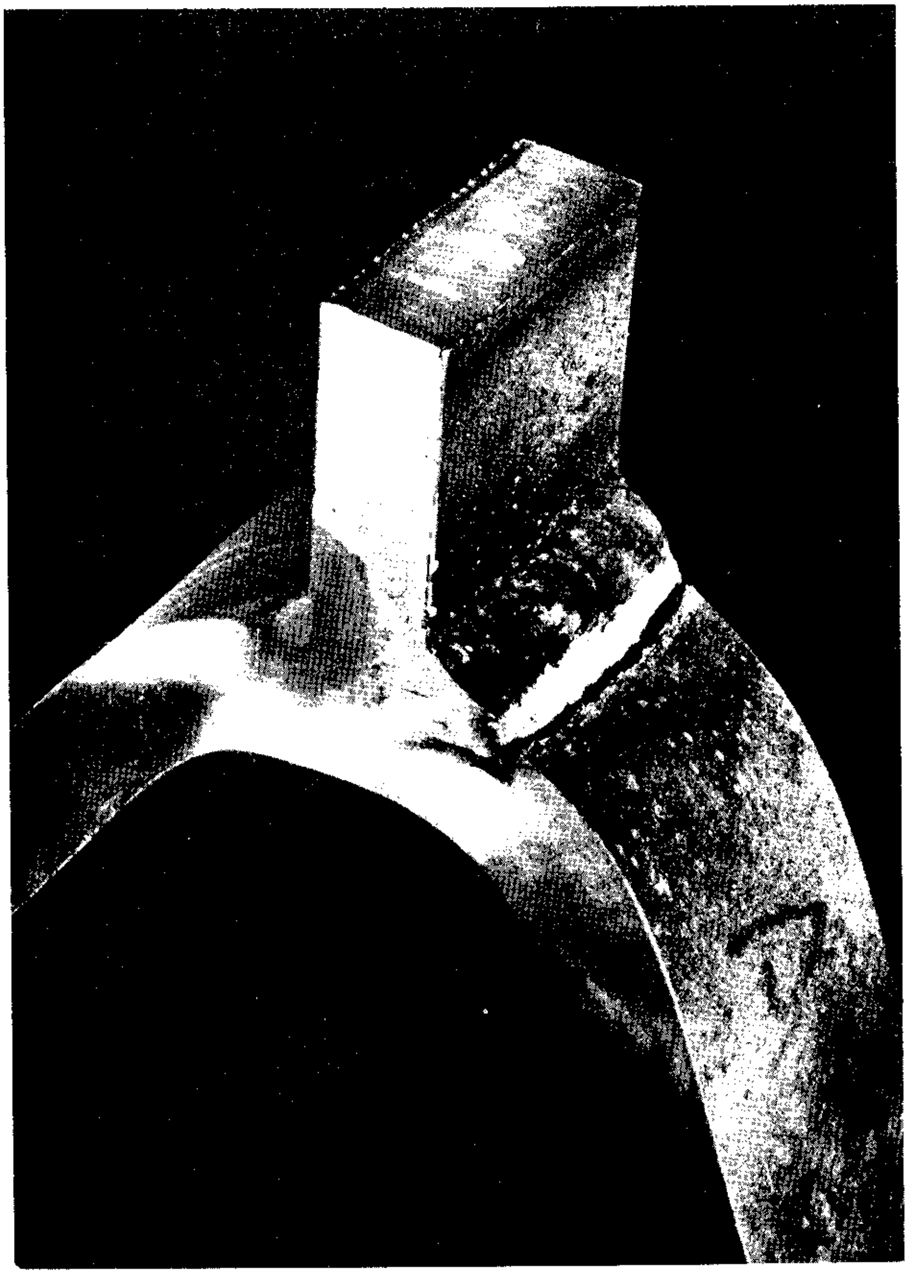
Specimen 23-12 53753
Testing temperature 100 F



Brittle
Fracture

Specimen 23-11 53750
Testing temperature 20 F

FIGURE 17. FRACTURED KINZEL-TYPE SPECIMENS MADE FROM C STEEL AND TESTED AT VARIOUS TEMPERATURES



Specimen 20-1 53756
Testing temperature 80 F

FIGURE 18. TEE-BEND SPECIMEN MADE FROM B_r STEEL

Specimen 18-4 53759
Testing temperature 150 F

FIGURE 19. TEE-BEND SPECIMEN MADE FROM C STEEL

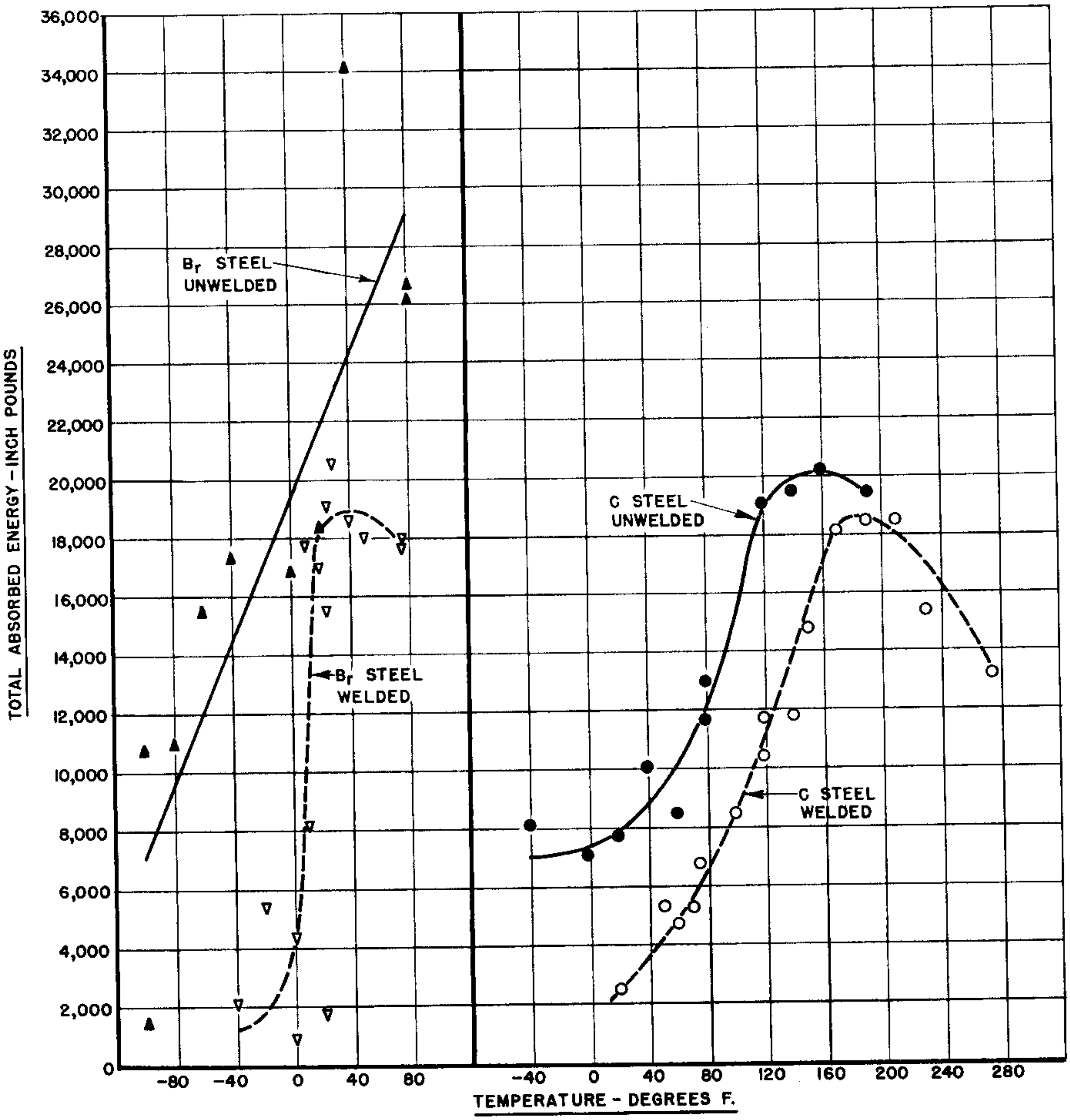


FIGURE 20 A. A COMPARISON OF TRANSITION CURVES FOR WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF B_r AND C STEELS.

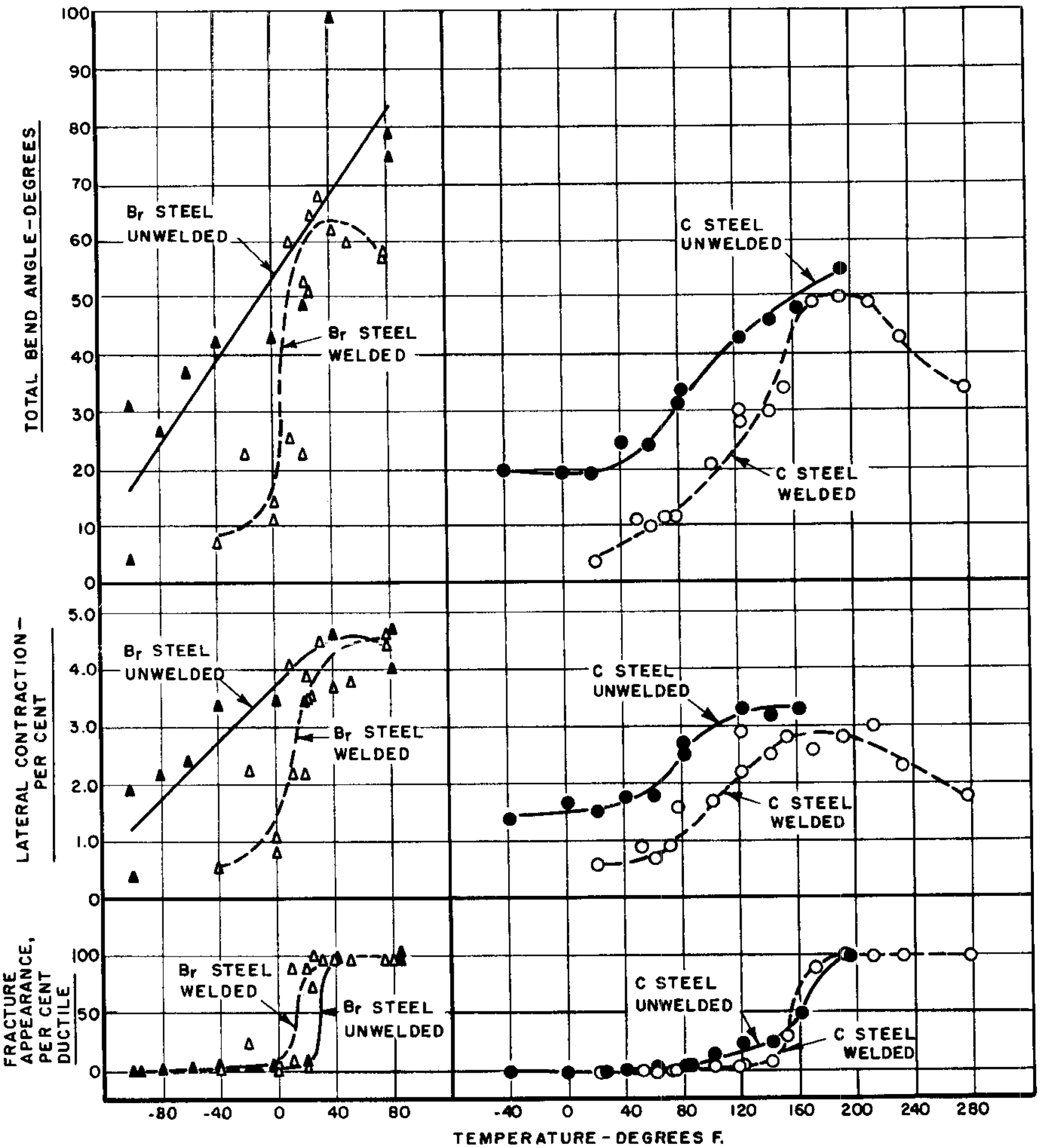
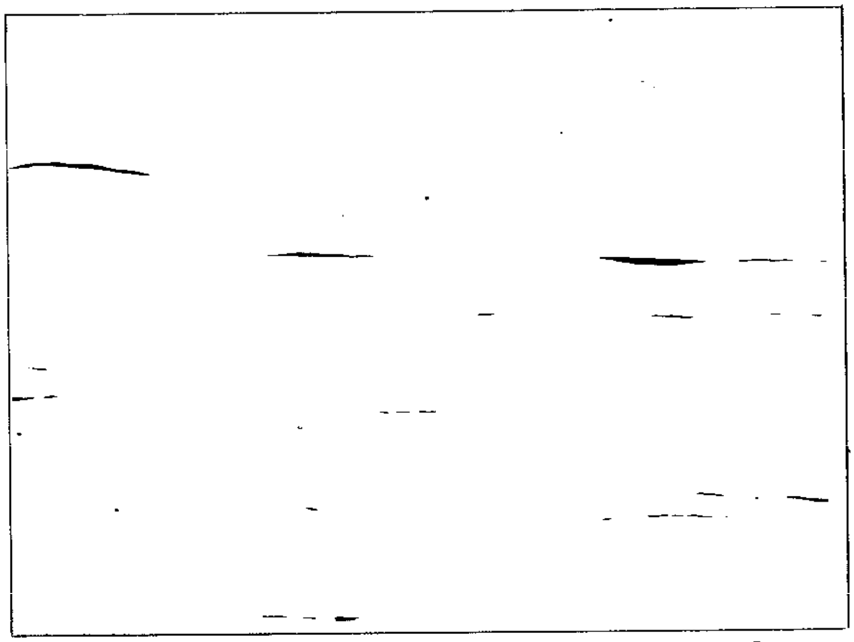
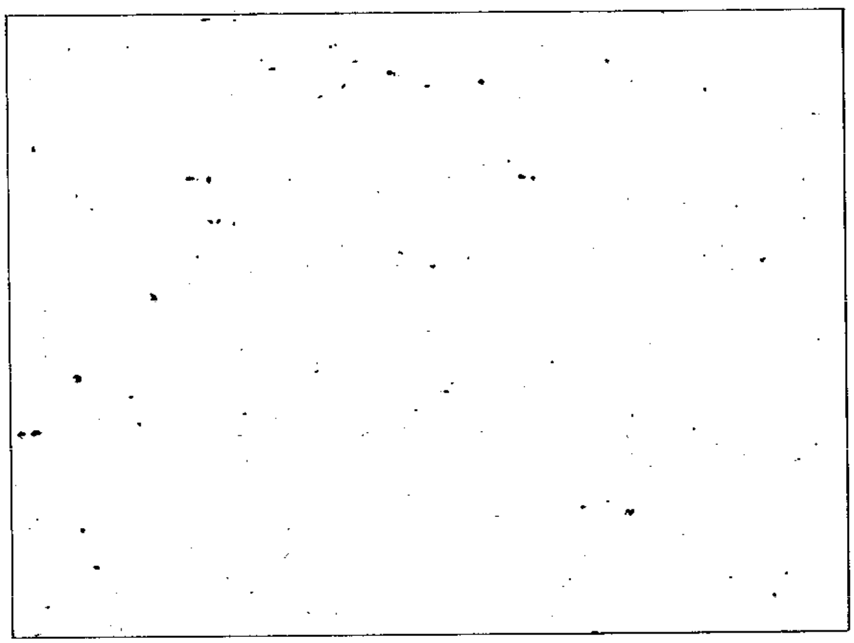


FIGURE 20 B A COMPARISON OF TRANSITION CURVES FOR WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF Br AND C STEELS.



100X 54019

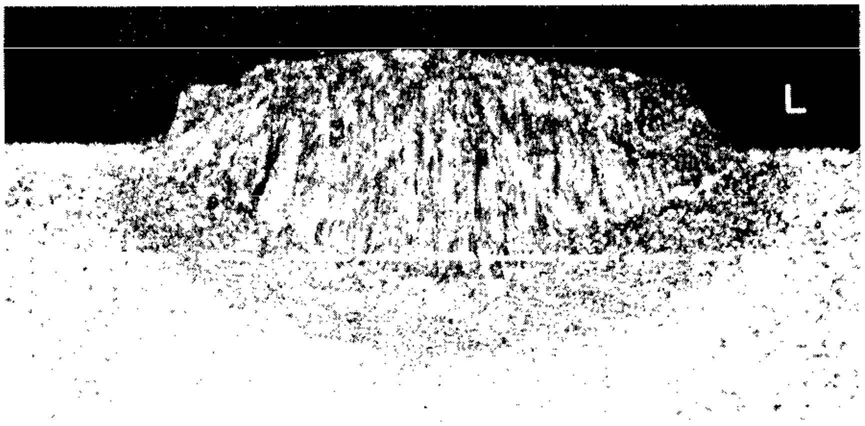
(a) B_r Steel



100X 54023

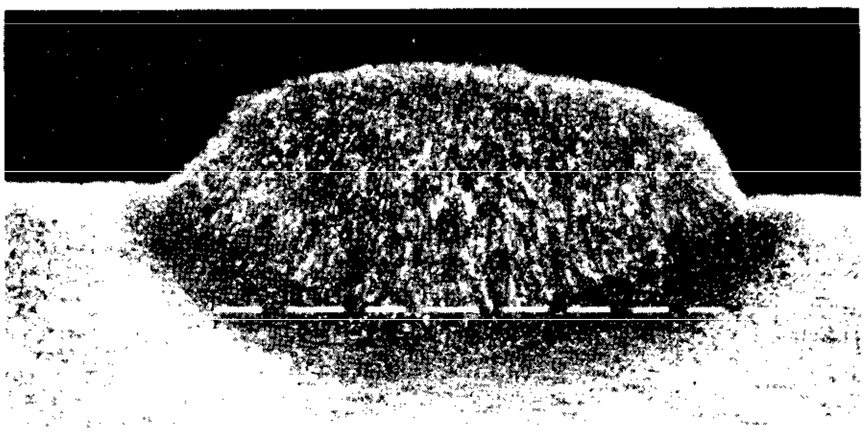
(b) C Steel

FIGURE 21. POLISHED UNETCHED SECTIONS OF B_r AND C STEELS SHOWING THEIR CLEANLINESS AND THE MAGNITUDE OF THE INCLUSIONS



7-1/2X 54017

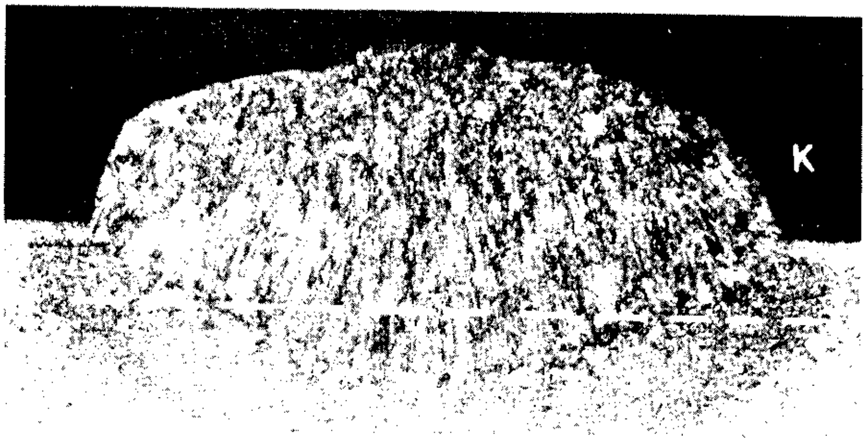
(a) B_r Steel



7-1/2X 54018

(b) C Steel

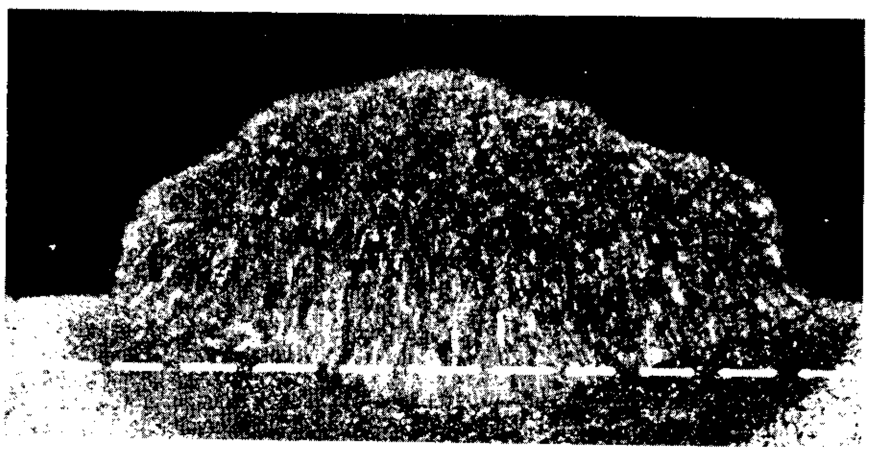
FIGURE 22. SECTIONS OF LEHIGH-TYPE SPECIMENS MADE FROM B_r AND C STEELS SHOWING THE POSITION OF THE NOTCH ROOT WITH RESPECT TO THE FUSION ZONE OF THE WELD



7-1/2X

54016

(a) B_r Steel



7-1/2X

54014

(b) C Steel

FIGURE 23. SECTIONS OF KINZEL-TYPE SPECIMENS MADE FROM B_r AND C STEELS SHOWING THE POSITION OF THE NOTCH ROOT WITH RESPECT TO THE FUSION ZONE OF THE WELD

A P P E N D I X A

APPENDIX A

Detailed Tabulated Data

Tables 3 through 13 in this Appendix contain the tabulated data from testing various welded and unwelded specimens made of B_r and C steels.

TABLE 3. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM BR STEEL AND HAVING A LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (LEHIGH DESIGN)

Specimen Number	Testing Temp., F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at Fracture (1)	Absorbed Energy (2): Breaking Energy (3), Sq In.	Absorbed Energy (2): Breaking Energy (3), In.-Lb	Absorbed Energy (2): Total Energy (3), Sq In.	Absorbed Energy (2): Total Energy (3), In.-Lb	Average Lateral Contraction (4), Inch	Average Lateral Contraction (4), Per Cent	Fracture Appearance, Per Cent Shear
9-1A	80	15,500	27	65	4.53	10,100	8.24	18,500	0.138	5.0	100
-1B	80	16,300	28	60	4.14	9,200	8.20	18,500	0.141	5.1	100
-2A	32	18,400	32	75	6.05	13,400	11.17	26,400	0.133	4.4	100
-2B	0	18,900	31	59	4.18	9,400	9.65	21,700	0.137	4.5	100
-3A	-20	18,100	31	78	5.25	11,800	10.57	23,800	0.152	5.3	100
-7A	-20	18,100	25	35	1.87	4,200	6.08	13,700	0.113	3.7	15
-6B	-30	19,500	29	29	0	0	5.15	11,600	0.084	2.7	2
-7B	-30	16,700	13	12	0	0	2.00	4,500	0.041	1.3	2
-3B	-40	18,000	22	22	0	0	3.74	8,400	0.076	2.6	5
-6A	-40	19,700	27	27	0	0	4.78	10,700	0.091	3.0	2
-5B	-50	15,400	7	7	0	0	1.02	2,300	0.031	1.0	0
-5A	-60	18,300	19	19	0	0	3.07	6,900	0.056	1.8	2
-4A	-80	16,900	10	10	0	0	1.64	3,700	0.032	1.0	0
-4B	-90	16,400	7	7	0	0	1.00	2,200	0.026	0.8	0

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS
(3) REFER TO FIGURE 7
(4) MEASUREMENT MADE AT POINT OF MAXIMUM CONTRACTION (USUALLY 1/32 INCH BELOW THE NOTCH ROOT) ON BOTH SIDES OF FRACTURE WITH POINTED MICROMETERS.

TABLE 4. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM C STEEL AND HAVING A LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (LEHIGH DESIGN)

Specimen Number	Testing Temp., F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at Fracture (1)	Absorbed Energy (2): Breaking Energy (3), Sq In.	Absorbed Energy (2): Breaking Energy (3), In.-Lb	Absorbed Energy (2): Total Energy (3), Sq In.	Absorbed Energy (2): Total Energy (3), In.-Lb	Average Lateral Contraction (4), Inch	Average Lateral Contraction (4), Per Cent	Fracture Appearance, Per Cent Shear
10-5B	200	18,100	27	49	3.20	7,200	7.65	17,200	0.088	2.9	100
-5A	180	18,200	29	52	3.22	7,200	8.15	18,300	0.111	3.6	100
-7A	170	17,900	27	49	3.07	6,900	7.48	16,800	0.111	3.7	100
-7B	160	17,900	23	44	3.12	7,000	7.00	15,800	0.106	3.5	100
-6A	160	17,700	27	49	3.06	6,900	7.30	16,400	0.121	4.0	100
-6B	150	16,800	24	38	2.26	5,100	6.00	13,500	0.102	3.4	60
-3B	150	16,900	21	45	3.33	7,500	6.28	14,100	0.114	3.9	80
-3A	120	15,900	17	31	2.43	5,500	4.60	10,400	0.106	3.7	25
-1A	80	17,300	15	15	0	0	2.22	5,000	0.052	1.7	2
-1B	80	16,800	12	12	0	0	1.91	4,300	0.043	1.4	2
-2A	32	15,700	15	15	0	0	1.96	4,400	0.043	1.5	2
-2B	0	16,300	15	15	0	0	2.05	4,600	0.043	1.6	<2

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS
(3) REFER TO FIGURE 7
(4) MEASUREMENT MADE AT POINT OF MAXIMUM CONTRACTION (USUALLY 1/32 INCH BELOW THE NOTCH ROOT) ON BOTH SIDES OF FRACTURE WITH POINTED MICROMETERS.

TABLE 5. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM BR STEEL AND HAVING A LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN).

Specimen Number	Testing Temp. F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at (1) Fracture	Absorbed Energy (2): Breaking Energy (3) Sq In.	Breaking Energy (3) In.-Lb	Total Energy (3) Sq In.	Total Energy (3) In.-Lb	Average Lateral Contraction (4) Inch	Average Lateral Contraction (4) Per Cent	Fracture Appearance, Per Cent Shear
22-1	75	16,100	30	58	3.34	7,500	7.95	17,900	0.134	4.6	100
-2	75	16,000	31	57	3.23	7,300	7.90	17,800	0.127	4.4	100
-11	50	16,200	28	60	3.83	8,400	8.00	18,000	0.111	3.8	100
-5	40	16,300	27	62	4.30	9,700	8.30	18,700	0.108	3.7	100
-7	30	16,700	25	68	5.10	11,500	9.14	20,600	0.131	4.5	98
-9	25	16,500	23	65	5.15	11,600	8.50	19,100	0.102	3.5	100
-10	25	16,300	27	51	2.75	6,200	6.87	15,500	0.105	3.6	75
-8	20	16,500	23	23	0	0	0.76	1,700	0.065	2.2	5
-15	20	16,400	28	53	3.40	7,700	7.54	17,000	0.114	3.9	90
-12	10	15,900	25	60	4.17	9,400	7.90	17,800	0.119	4.1	90
-13	10	16,600	24	24	0	0	3.60	8,100	0.064	2.2	10
-3	0	15,400	14	14	0	0	1.91	4,300	0.034	1.1	2
-14	0	15,000	11	11	0	0	0.40	900	0.024	0.8	0
-6	-20	13,400	6	23	1.70	3,800	2.39	5,400	0.068	2.3	25
-4	-40	14,300	7	7	0	0	0.93	2,100	0.019	0.6	0

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS
(3) REFER TO FIGURE 7
(4) MEASUREMENT MADE AT POINT OF MAXIMUM CONTRACTION (USUALLY 1/32 INCH BELOW THE NOTCH ROOT) ON BOTH SIDES OF FRACTURE WITH POINTED MICROMETERS.

TABLE 6. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM C STEEL AND HAVING A LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN).

Specimen Number	Testing Temp. F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at (1) Fracture	Absorbed Energy (2): Breaking Energy (3) Sq In.	Breaking Energy (3) In.-Lb	Total Energy (3) Sq In.	Total Energy (3) In.-Lb	Average Lateral Contraction (4) Inch	Average Lateral Contraction (4) Per Cent	Fracture Appearance, Per Cent Shear
23-7	275	18,100	18	34	2.27	5,100	4.99	11,200	0.052	1.8	100
-6	230	16,800	23	43	2.72	6,100	5.96	13,400	0.067	2.3	100
-5	210	18,000	24	49	3.65	8,200	7.35	16,500	0.088	3.0	100
-4	190	17,500	26	50	3.25	7,300	7.30	16,500	0.083	2.8	100
-3	170	17,300	25	49	2.98	6,700	7.19	16,200	0.076	2.6	90
-2	150	17,800	27	34	1.45	3,300	5.67	12,800	0.082	2.8	30
-8	140	18,500	18	30	1.37	3,080	4.36	9,800	0.074	2.5	10
-9	120	17,000	18	30	1.60	3,600	4.30	9,700	0.084	2.9	5
-10	120	17,800	18	28	1.20	2,700	3.73	8,400	0.065	2.2	5
-12	100	15,600	13	21	1.14	2,600	2.87	6,500	0.049	1.7	5
-1	75	14,700	9	12	1.10	2,500	2.13	4,800	0.047	1.6	2
-15	70	15,500	12	12	0	0	1.47	3,900	0.026	0.9	2
-14	60	14,800	10	10	0	0	1.20	2,700	0.022	0.7	2
-13	50	15,400	11	11	0	0	1.47	3,300	0.027	0.9	2
-11	20	11,300	3	3	0	0	0.26	500	0.019	0.6	0

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS
(3) REFER TO FIGURE 7
(4) MEASUREMENT MADE AT POINT OF MAXIMUM CONTRACTION (USUALLY 1/32 INCH BELOW THE NOTCH ROOT) ON BOTH SIDES OF FRACTURE WITH POINTED MICROMETERS.

TABLE 7. RESULTS OF SLOW-BEND TESTS OF TEE-BEND SPECIMENS MADE FROM BR STEEL

SPECIMEN NUMBER	TESTING TEMP. F	MAXIMUM LOAD, POUNDS	BEND ANGLE DEGREES AT		ABSORBED ENERGY (2)				LATERAL CONTRACTION, PER CENT (4)			ENERGY RATIO, PER CENT (5)
					BREAKING ENERGY (3)		TOTAL ENERGY (3)		UNFRACTURED SIDE	FRACTURED SIDE		
			MAX LOAD	(1) FRACTURE	SQ IN.	IN.-LB	SQ IN.	IN.-LB		TOE OF FILLET	BASE METAL	
20-1	80	13,000	-	-	-	-	-	-	5.86	4.75	7.84	-
21-5	80	11,900	77	120	7.93	17,800	17.06	38,400	6.45	6.04	6.02	90
20-4	10	12,300	74	120	8.16	18,400	17.15	38,600	5.33	3.68	7.15	91
20-6	5	12,300	72	120	8.78	19,800	17.55	39,500	6.08	5.76	5.76	93
21-1	5	12,200	75	120	8.35	18,800	17.34	39,000	5.28	5.87	5.87	91
20-5	5	12,000	75	95	2.96	6,700	11.98	26,900	4.37	3.73	5.33	63
20-2	0	12,700	77	108	4.80	10,800	14.54	32,700	4.32	4.95	6.77	77
21-3	0	12,600	72	94	3.25	7,300	12.16	27,300	4.10	4.70	6.72	64
21-4	0	12,500	77	100	3.58	8,100	13.05	29,400	4.42	6.15	7.20	69
21-2	-10	12,300	72	92	3.14	7,100	12.05	27,100	4.21	4.32	5.70	64
20-3	-20	12,300	74	-	-	-	-	-	5.12	6.56	7.84	-

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD

(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS

(3) REFER TO FIGURE 7

(4) MEASUREMENTS MADE WITH POINTED MICROMETERS, REFER TO FIGURE 9

(5) ENERGY RATIO = $\frac{\text{TOTAL ENERGY}}{42,700}$ X 100 = PER CENT. REFER TO PAGE 44

TABLE 8. RESULTS OF SLOW-BEND TESTS OF TEE-BEND SPECIMENS MADE FROM C STEEL

SPECIMEN NUMBER	TESTING TEMP. F	MAXIMUM LOAD, POUNDS	BEND ANGLE DEGREES AT		ABSORBED ENERGY (2)				LATERAL CONTRACTION, PER CENT (4)			ENERGY RATIO, PER CENT (5)
					BREAKING ENERGY (3)		TOTAL ENERGY (3)		UNFRACTURED SIDE	FRACTURED SIDE		
			MAX LOAD	(1) FRACTURE	SQ IN.	IN.-LB	SQ IN.	IN.-LB		TOE OF FILLET	BASE METAL	
18-4	150	13,300	78	120	8.97	20,200	19.16	43,100	6.30	3.15	7.15	101
-3	130	13,300	79	120	8.90	20,000	19.20	43,200	6.50	1.87	7.75	101
-2	120	13,200	80	120	8.17	18,400	18.80	42,300	4.48	5.12	8.44	99
-5	120	13,400	77	120	9.00	20,200	18.76	42,200	7.95	4.42	7.46	99
-6	110	13,200	80	119	7.10	16,000	17.30	39,000	5.12	6.03	9.28	91
-1	100	14,400	78	119	8.10	18,200	18.36	41,400	5.28	6.40	8.44	97
17-6	80	14,200	76	94	2.77	6,200	13.35	30,000	4.05	4.16	5.40	70
-1 (6)	75	13,300	79	116	6.50	12,400	16.97	38,200	4.80	4.47	7.46	90
-5	60	14,100	76	104	4.90	11,000	15.30	34,400	4.69	5.65	6.93	81
-4	40	14,000	63	63	0	0	8.50	19,100	3.20	2.83	3.78	48
-2	30	13,700	63	63	0	0	8.00	18,000	2.45	3.09	3.63	46

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD HAS DROPPED TO 6000 POUNDS AFTER PASSING MAXIMUM LOAD

(2) ABSORBED ENERGY=MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250=INCH-POUNDS

(3) REFER TO FIGURE 7

(4) MEASUREMENTS MADE WITH POINTED MICROMETERS, REFER TO FIGURE 9

(5) ENERGY RATIO = $\frac{\text{TOTAL ENERGY}}{42,700}$ X 100 = PER CENT. REFER TO PAGE 44

(6) SPECIMEN WAS TESTED AT A VERY SLOW RATE OF LOADING TO DEVELOP A BEND ANGLE VS. DISPLACEMENT CALIBRATION CURVE. THESE DATA WERE NOT PLOTTED ON THE TRANSITION TEMPERATURE CURVES

TABLE 9. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM BR STEEL AND HAVING A TRANSVERSE NOTCHED WELD BEAD AND EDGE NOTCHES (NAVAL RESEARCH LABORATORY, HIGH+CONSTAINT-TYPE SPECIMEN)

SPECIMEN NUMBER	TESTING TEMP, F	MAXIMUM LOAD, POUNDS	BEND ANGLE		ABSORBED ENERGY (2)				FRACTURE APPEARANCE, PER CENT SHEAR
					BREAKING ENERGY (3)		TOTAL ENERGY (3)		
			MAX LOAD	(1) FRACTURE	SQ IN.	IN.-LB	SQ IN.	IN.-LB	
11.1	80	7,500	18	42	1.30	2,900	2.85	6,400	100
.2	80	7,600	19	42	1.20	2,700	2.85	6,400	100
.5	60	7,600	16	48	1.70	3,800	3.17	7,100	100
.9	32	8,000	25	33	.70	1,600	3.0	6,800	15
.11	30	8,000	20	27	.60	1,400	2.42	5,500	45
.15	30	7,900	19	43	1.32	3,000	3.0	6,800	100
.12	20	7,900	19	60	2.08	4,700	3.78	8,500	100
.14	20	7,800	19	51	1.53	3,400	3.30	7,400	100
.10	10	8,100	19	19	0	0	1.75	3,900	0
.3	10	8,000	19	19	0	0	1.69	3,800	20
.7	0	7,900	20	26	.57	1,300	2.48	5,600	0
.13	-20	8,200	16	16	0	0	1.47	3,300	0
.6	-40	8,400	17	17	0	0	1.65	3,700	0
.8	-40	8,300	17	17	0	0	1.65	3,700	0
.4	-60	8,300	15	15	0	0	1.32	3,000	0

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD DROPPED TO 2000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY-MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250-INCH-POUNDS
(3) REFER TO FIGURE 7

TABLE 10. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM C STEEL AND HAVING A TRANSVERSE NOTCHED WELD BEAD AND EDGE NOTCHES. (NAVAL RESEARCH LABORATORY, HIGH-CONSTRAINT-TYPE SPECIMEN)

SPECIMEN NUMBER	TESTING TEMP, F	MAXIMUM LOAD, POUNDS	BEND ANGLE		ABSORBED ENERGY (2)				FRACTURE APPEARANCE, PER CENT SHEAR
					BREAKING ENERGY (3)		TOTAL ENERGY (3)		
			MAX LOAD	(1) FRACTURE	SQ IN.	IN.-LB	SQ IN.	IN.-LB	
12.7	194	7,900	17	41	1.90	4,300	2.98	6,700	100
.4	180	7,800	17	23	.57	1,300	2.05	4,600	60
.14	180	7,800	17	22	.45	1,000	2.00	4,500	60
.13	170	8,100	15	18	.27	600	1.75	3,900	60
.15	160	7,900	17	25	.77	1,700	2.27	5,100	60
.10	140	8,200	19	24	.40	900	2.15	4,800	30
.6	120	7,900	17	20	.30	700	1.90	4,300	30
.11	110	8,300	19	20	.15	300	1.95	4,400	30
.2	100	8,200	17	21	.40	900	2.00	4,500	20
.1	80	8,200	18	18	0	0	1.60	3,600	5
.5	60	8,300	17	17	0	0	1.50	3,400	2
.8	50	8,700	16	16	0	0	1.50	3,400	0
.9	32	8,200	13	13	0	0	1.10	2,500	0
.12	10	7,900	10	10	0	0	0.88	2,000	0
.3	-20	8,500	11	11	0	0	1.15	2,600	0

(1) IF THE SPECIMEN DID NOT FAIL, THIS MEASUREMENT WAS TAKEN AT THE POINT ON THE LOAD-DEFLECTION CURVE WHERE THE LOAD DROPPED TO 2000 POUNDS AFTER PASSING MAXIMUM LOAD
(2) ABSORBED ENERGY-MEASURED AREA UNDER THE LOAD-DEFLECTION CURVE TIMES 2,250-INCH-POUNDS
(3) REFER TO FIGURE 7

TABLE 11. RESULTS OF SLOW-BEND TESTS OF SPECIMENS MADE FROM B_R STEEL AND HAVING A TRANSVERSE WELD BEAD AND TRANSVERSE NOTCH (JACKSON-TYPE SPECIMEN).

Specimen Number	Testing Temp., F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at Fracture (1)	Absorbed Energy (2): Breaking Energy (3) Sq In.	Breaking Energy (3) In.-Lb	Total Energy (3) Sq In.	Total Energy (3) In.-Lb	Average Lateral Contraction (4) Inch	Average Lateral Contraction (4) Per Cent	Fracture Appearance, Per Cent Shear
19-2	78	15,000	66	86	3.2	7,200	14.15	31,800	0.122	4.0	100
-14 (5)	75	15,300	68	-	-	-	-	-	0.149	4.9	100
-13 (5)	75	15,100	63	83	2.98	6,700	13.62	30,700	0.117	3.8	100
-10	30	15,400	66	84	3.60	8,100	15.20	34,200	0.119	3.9	100
-11	25	15,400	69	95	4.40	9,900	16.60	37,400	0.136	4.5	100
-8	20	15,500	66	89	3.65	8,200	15.30	34,400	0.130	4.3	100
-12	20	15,500	66	89	3.25	7,300	14.88	33,500	0.125	4.1	100
-9	20	15,400	65	82	3.30	7,400	14.40	32,400	0.117	3.8	15
-7	10	15,500	64	74	2.00	4,500	13.20	29,700	0.106	3.5	10
-1	0	15,800	70	93	3.80	8,600	16.20	36,400	0.129	4.2	100
-6	0	15,700	65	80	3.00	6,800	14.67	33,000	0.117	3.8	5
-5	-10	15,600	65	80	3.05	6,900	14.60	32,900	0.112	3.7	5
-4	-20	15,800	67	77	1.98	4,500	14.00	31,500	0.107	3.5	5
-3	-40	16,200	62	64	0.60	1,300	11.70	26,300	0.097	3.2	0

(1) If the specimen did not fail, this measurement was taken at the point on the load-deflection curve where the load has dropped to 6000 pounds after passing maximum load
(2) Absorbed Energy=Measured area under the load-deflection curve times 2,250=inch-pounds
(3) Refer to Figure 7
(4) Measurement made at point of maximum contraction (usually 1/32 inch below the notch root) on both sides of fracture with pointed micrometers
(5) Specimen was tested at a very slow rate of loading to develop a bend angle vs. displacement calibration curve. These data were not plotted on the transition-temperature curves.

TABLE 12. RESULTS OF SLOW-BEND TESTS OF UNWELDED B_R STEEL SPECIMENS HAVING A TRANSVERSE KINZEL-TYPE NOTCH.

Specimen Number	Testing Temp., F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at Fracture (1)	Absorbed Energy (2): Breaking Energy (3) Sq In.	Breaking Energy (3) In.-Lb	Total Energy (3) Sq In.	Total Energy (3) In.-Lb	Average Lateral Contraction Inch	Average Lateral Contraction Per Cent	Fracture Appearance, Per Cent Shear
24-1	80	19,100	47	79	3.97	8,900	11.83	26,700	0.142	4.75	100
-2	80	19,200	47	75	3.70	8,300	11.64	26,200	1.220	4.05	100
-11	40	19,500	51	99	6.07	13,700	15.20	34,200	1.390	4.65	100
-12	20	20,000	47	47	0	0	8.16	18,400	0.112	3.74	5
-5	0	20,500	43	43	0	0	7.50	16,900	0.105	3.50	5
-6	-40	21,300	42	42	0	0	7.70	17,300	0.102	3.40	5
-10	-60	21,300	37	37	0	0	6.90	15,500	0.085	2.84	5
-7	-80	20,400	27	27	0	0	4.90	11,000	0.068	2.27	2
-8	-100	17,400	4	4	0	0	0.65	1,500	0.011	0.37	0
-9	-100	20,900	31	31	0	0	4.80	10,800	0.059	1.95	0

(1) If the specimen did not fail, this measurement was taken at the point on the load-deflection curve where the load dropped to 6000 pounds after passing maximum load
(2) Absorbed Energy=Measured area under the load-deflection curve times 2,250=inch-pounds
(3) Refer to Figure 7
(4) Measurement made at point of maximum contraction (usually 1/32 inch below the notch root) on both sides of the fracture with pointed micrometers.

TABLE 13. RESULTS OF SLOW-BEND TESTS OF UNWELDED C STEEL SPECIMENS HAVING A TRANSVERSE KINZEL-TYPE NOTCH.

Specimen Number	Testing Temp., F	Maximum Load, Pounds	Bend Angle Degrees at Max Load	Bend Angle Degrees at Fracture (1)	Absorbed Energy (2): Breaking Energy (3), Sq In.	Absorbed Energy (2): Breaking Energy (3), In.-Lb	Absorbed Energy (2): Total Energy (3), Sq In.	Absorbed Energy (2): Total Energy (3), In.-Lb	Average Lateral Contraction (4), Inch	Average Lateral Contraction (4), Per Cent	Fracture Appearance, Per Cent Shear
25.10	190	18,800	33	55	3.28	7,400	8.68	19,500	-	-	100
.6	160	21,100	33	48	2.96	6,700	9.00	20,300	0.100	3.33	50
.11	140	20,600	37	46	1.90	4,300	8.69	19,500	0.097	3.23	25
.5	120	21,400	35	43	1.97	4,400	8.48	19,100	0.100	3.33	25
.1	80	20,000	31	31	0	0	5.20	11,700	0.074	2.47	5
.2	80	20,800	33	33	0	0	5.75	13,000	0.081	2.70	5
.9	60	18,800	24	24	0	0	3.80	8,500	0.055	1.83	2
.3	40	19,600	25	25	0	0	4.50	10,100	0.056	1.87	0
.12	20	19,000	19	19	0	0	3.45	7,800	0.045	1.50	0
.4	0	19,200	19	19	0	0	3.15	7,100	0.050	1.67	0
.7	-40	19,300	20	20	0	0	3.60	8,100	0.042	1.40	0

(1) If the specimen did not fail, this measurement was taken at the point on the load-deflection curve where the load dropped to 6000 pounds after passing maximum load

(2) Absorbed energy = Measured area under the load-deflection curve times 2,250 = inch-pounds

(3) Refer to Figure 7

(4) Measurement made at point of maximum contraction (usually 1/32 inch below the notch root) on both sides of fracture with pointed micrometers

APPENDIX B

APPENDIX B

Literature Survey

The objective of this research program is to evaluate the usefulness of various small mechanical tests for indicating the performance of large welded structures. A survey was made of the published literature and unpublished reports to uncover the various kinds of test specimens that have already been developed, and to determine their applicability to the current investigation.

Many test specimens and testing procedures have been developed during the past decade in an attempt to provide designers and engineers with a method for selecting the proper material and welding procedures for use in welded structures. The specimens illustrated in this Appendix have been successfully used for determining (1) the effects of welding on the ductility and susceptibility of a steel to cracking, (2) the mechanical properties and over-all efficiency of welded joints, (3) the strength and soundness of weld metal, and (4) the expected service life of a structure under different conditions of loading and temperature. A large majority of the tests was, therefore, considered not applicable to the present problems.

In choosing a specimen for quantitatively evaluating the effect of welding on medium-carbon hull steels and predicting the behavior of the welded structure under service loads, a large number of factors had to be considered. The specimen should be small, economical, and conducive to easy and rapid testing. The influence of manufacturing and fabrication variables, such as variations in steel analysis and processing, welding procedures, different sources and types of electrodes, preheating, postheating, etc., must also be reflected by the response of the specimen during testing. The service requirements of the weldment, such as rigidity, loading, and temperature variations, should also be simulated by constraint developed by the specimen, a predetermined rate of loading, and testing the specimens at different temperature levels. Therefore, the only specimens considered during this survey for further study were those that contained the components of a weldment, i.e., weld metal, heat-affected metal caused by welding and base metal.

Schematic and detailed drawings of representative types of specimens and testing details are shown in Figures 24 through 61. Most of the illustrated specimens have been welded and tested by varying procedures and using different thicknesses of material. For some tests, proportionality factors have been used to determine welding and testing requirements for correlating the properties of a given steel of any thickness of material. Since the steels to be used for this investigation were all 3/4 inch thick, all the drawings in this Appendix were dimensioned on that basis. It is also essential that the references for each specific test should be consulted for a more detailed explanation of the welding and testing procedures advocated by the various investigators. The reference numbers below the title on each drawing refer to the numbers of specific reports listed in the bibliography, which is contained in Appendix C.

The types of specimens contained herein can be roughly divided into the following five groups based on the method used for testing them:

1. Bend tests
2. Tension Tests
3. Rapid loading or impact-type tests
4. Cracking or restraint-type tests
5. Fatigue tests

The specimens under Group 4 and shown in Figures 54 through 59 were excluded from further consideration, because, in general, they are used for determining the susceptibility of a steel to cracking during or after welding and not for predicting the performance of a welded structure. The fatigue tests in Group 5 (Figures 60 and 61) were also excluded essentially because of the long time and excessive cost of testing.

The impact type of tests in Group 3 (Figures 50 through 53) were seriously considered for various aspects of the investigation, such as evaluating the transition properties of weld metal and selected heat zones. However, because of the extensive notched-bar tests made by investigators engaged in other phases of this research program, it was believed that this type of test need not be investigated here.

To further analyze the bend and tension specimens, they were separated into types having notches and those without notches. The bend specimens without a machined notch or stress raiser are shown in Figures 24 through 31. Of these, the tee-bend test (Figures 24 and 25) was considered applicable to this investigation because it was most representative of a typical fabricated welded structure found in ship construction and because other investigators have found that the test was practical for rating steels to be fabricated by welding.

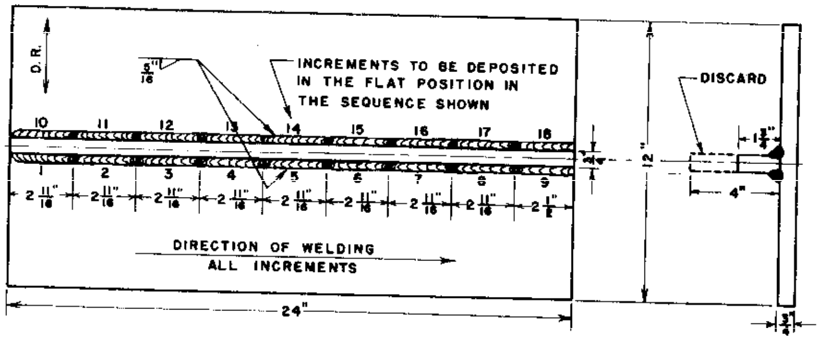
The bend specimens, containing machined notches of various types to impart a higher degree of constraint to a specimen, are shown in Figures 32 through 39. Most of these specimens have been extensively used by other investigators for evaluating the relative properties of various steels to be used for some specific type of weldment. The type of specimen having a longitudinal weld bead and transverse notch across the specimen (Figures 32 or 33) and the specimen having a transverse bead and transverse notch (Figures 34 and 35) were also considered as showing promise for achieving the objective of this research.

The unnotched tension specimens are shown in Figures 40 through 44. Since most of these tests are only useful for evaluating weld-metal efficiency alone, no further attention was given to them.

The notched tension specimens are shown in Figures 45 through 49. Of these tests, the specimen shown in Figure 45, or a modification of it, was considered to show possibilities which warranted additional study. The other specimens shown were excluded from further attention.

On October 1, 1947, the various types of tests uncovered by this literature survey were discussed with the SR-100 Project Advisory Committee. It was decided at this meeting that: (1) specimens having a longitudinal weld bead and transverse notch, (2) specimens having a transverse bead and transverse notch, and (3) the tee-bend test representing a typical welded ship joint, should be further investigated over a range of testing temperatures to evaluate the strength, ductility, types of fractures, and transition temperatures of the B_r and C types of ship steels.

Further details of the welding and testing procedures of the various specimens used for this investigation and the results obtained have been discussed in the body of the report.



58530

FIGURE 24. WELDING DETAILS FOR TEE-BEND SPECIMEN MADE FROM 3/4" PLATE

REFERENCES: 22, 24, 29, 31, 37, 42, 43, 47, 74, 98

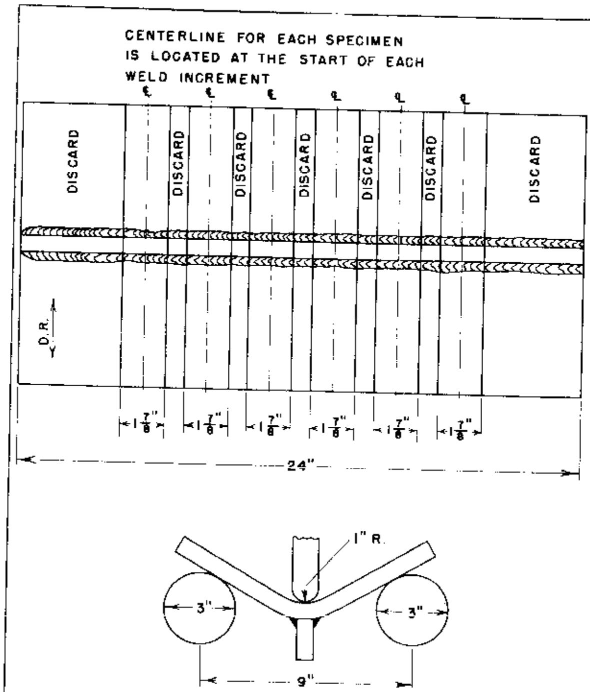


FIGURE 25. MACHINING AND TESTING DETAILS FOR TEE-BEND SPECIMEN. REFER TO FIGURE 24.

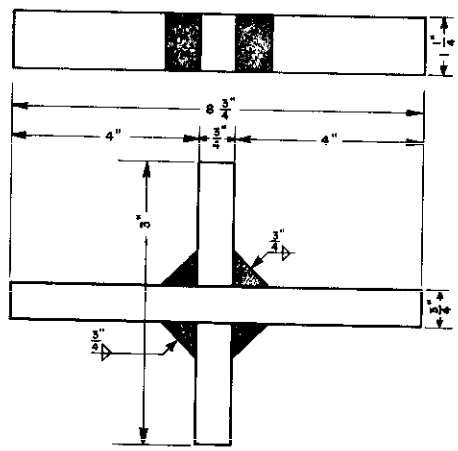


FIGURE 26. SPECIMEN FOR FILLET-WELDED DOUBLE-TEE JOINT BEND TEST.

REFERENCE: 29.

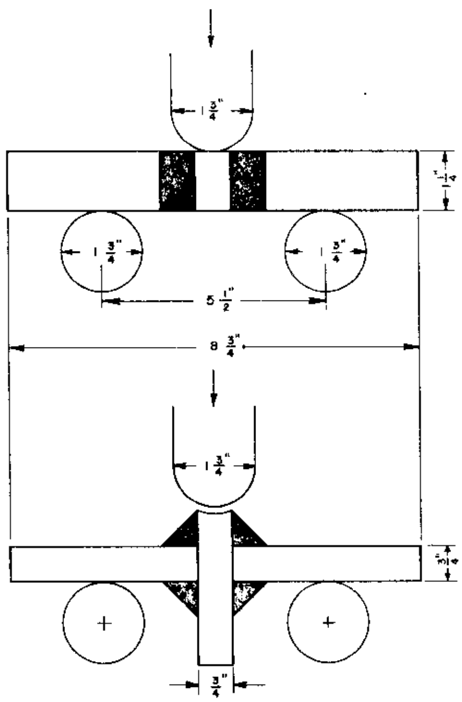


FIGURE 27. TESTING DETAILS FOR FILLET-WELDED DOUBLE-TEE JOINT BEND TEST. (SEE FIGURE 26.)

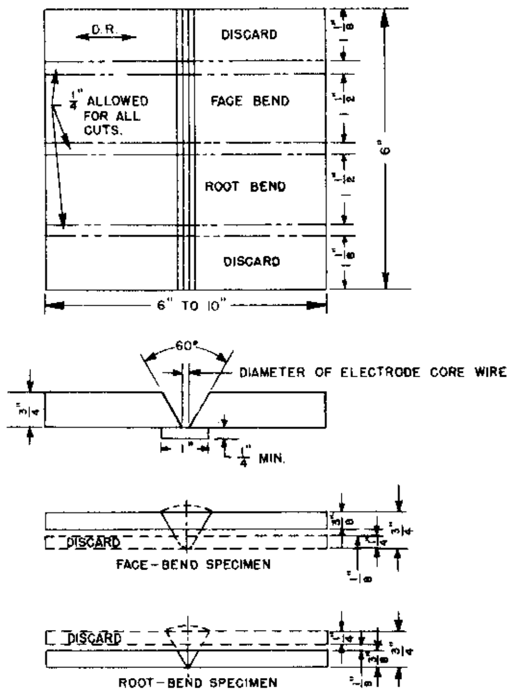


FIGURE 28. GUIDED-BEND SPECIMEN. SEE FIGURE 29 FOR TESTING DETAILS.

REFERENCES: 15, 24, 31, 98, 126.

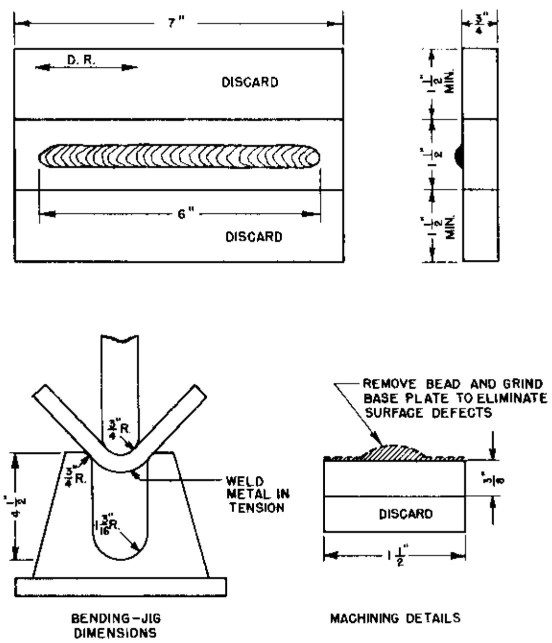


FIGURE 29. LONGITUDINALLY WELDED BEAD-BEND TEST.

REFERENCES: 24, 29, 41.

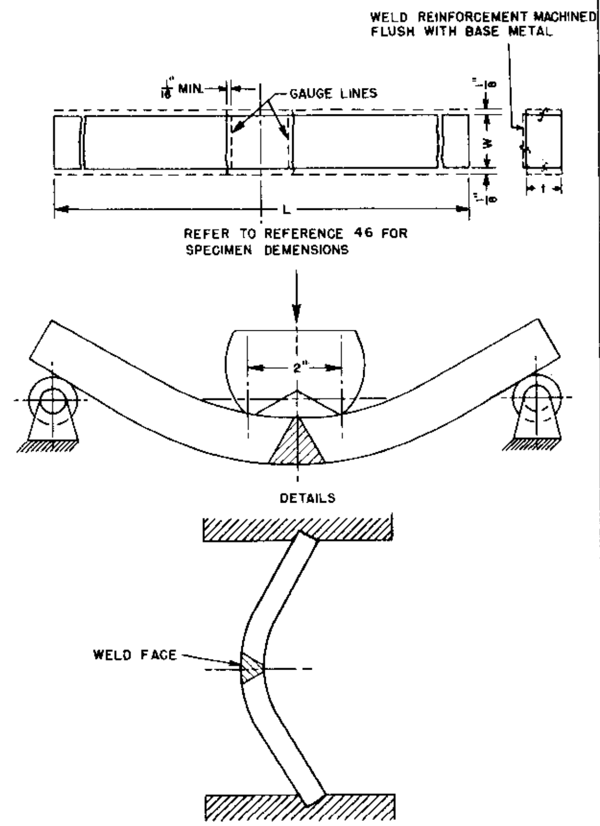


FIGURE 30. FREE-BEND SPECIMEN

REFERENCE: 15, 46.

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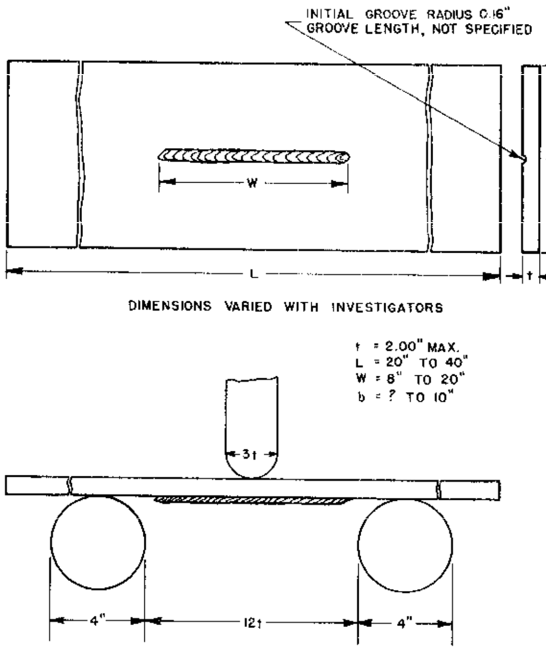


FIGURE 31. BEND SPECIMEN WITH LONGITUDINAL BEAD IN SHALLOW GROOVE.

REFERENCES: 29, 47, 56, 59, 73, 118, 125.

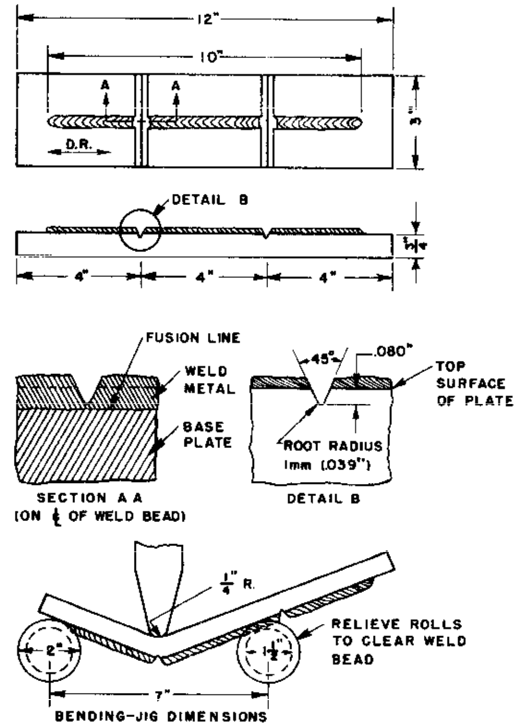


FIGURE 32. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCHES (LEHIGH DESIGN)

58532

REFERENCES: 88, 96, 117, 131

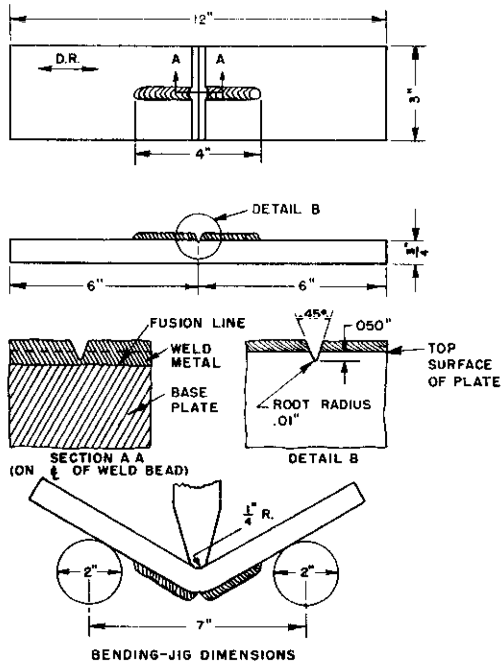


FIGURE 33. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN)

58533

REFERENCES: NOT PUBLISHED

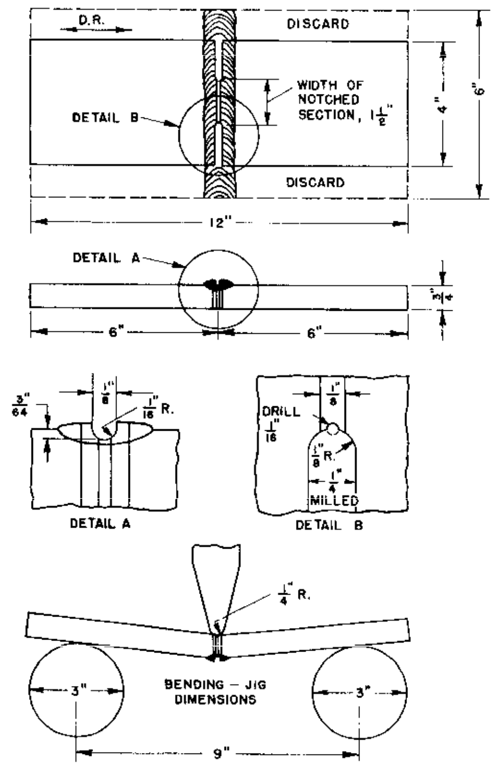


FIGURE 34. BEND SPECIMEN WITH TRANSVERSE NOTCHED WELD BEAD AND EDGE NOTCHES. (NAVAL RESEARCH LABORATORY DESIGN)

58534

REFERENCES: 98, 104, 105

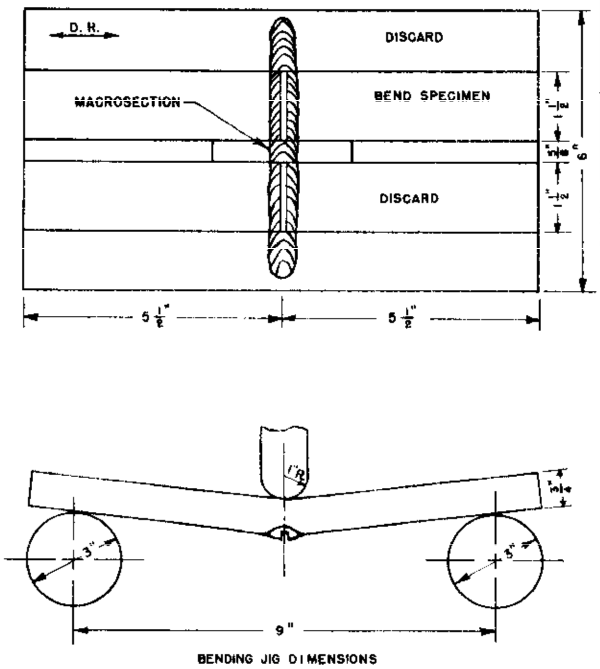


FIGURE 35. BEND SPECIMEN WITH TRANSVERSE WELD BEAD AND TRANSVERSE NOTCH. SEE FIGURE 36 FOR NOTCH DETAILS.

REFERENCES: 71, 81, 88, 92, 98, 105, 124.

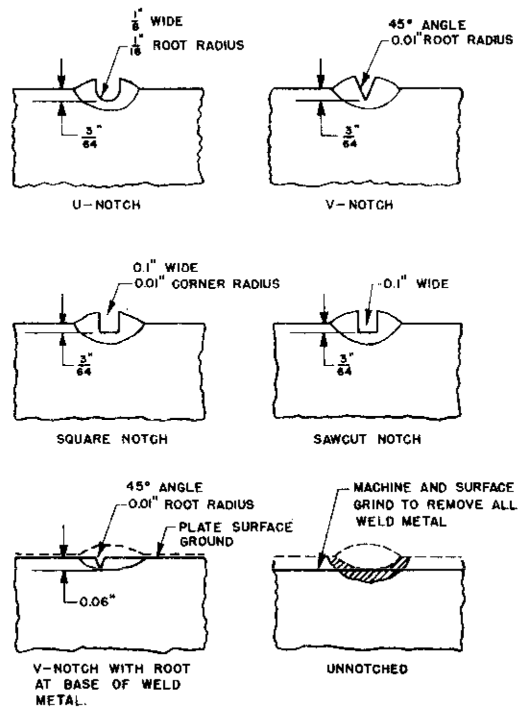


FIGURE 36. VARIOUS NOTCH DESIGNS USED WITH THE TRANSVERSE NOTCHED BEAD BEND SPECIMEN, FIGURE 35.

REFERENCES: 29, 42, 70, 71, 92, 98, 105, 124.

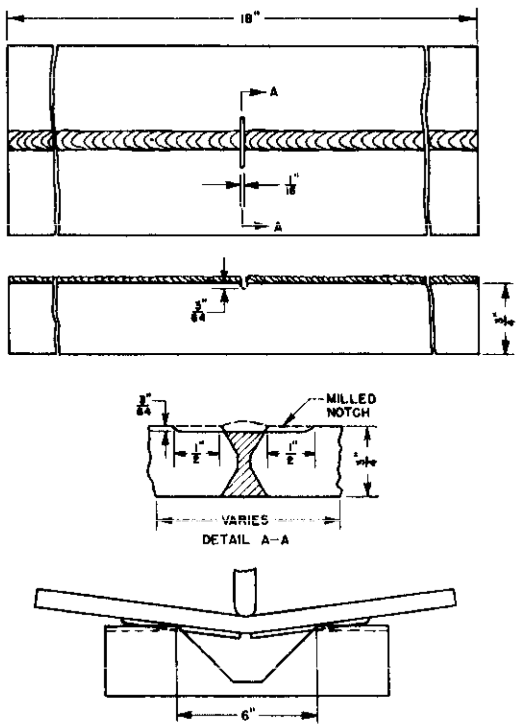
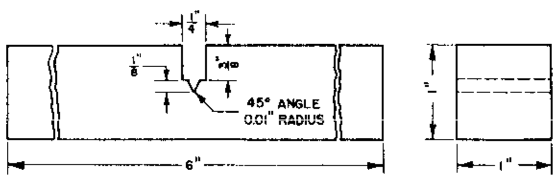


FIGURE 37. BEND SPECIMEN HAVING A LONGITUDINAL WELD AND A TRANSVERSE NOTCH.

REFERENCE: 89.



(MANY VARIATIONS IN NOTCH DETAILS AND LOCATION OF THE NOTCH WITH RESPECT TO THE WELD ARE SHOWN IN THE REFERENCES.)

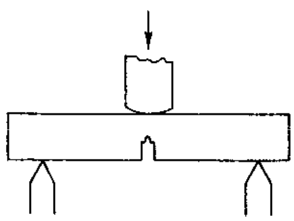


FIGURE 38. SPECIMEN FOR LOW-TEMPERATURE NOTCHED-BAR BENDING TEST.

REFERENCES: 97, 112, 116.

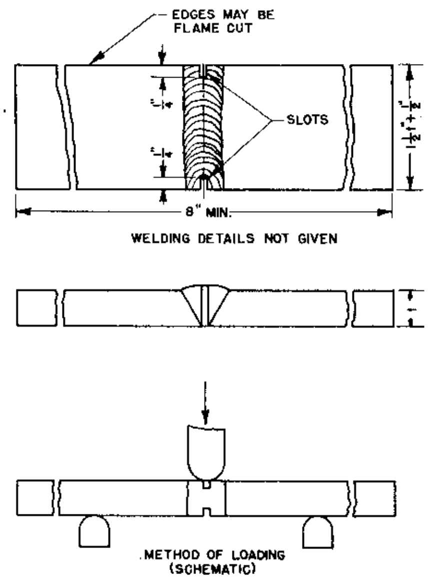


FIGURE 39. NICK-BREAK TEST OF WELDED JOINT.

REFERENCES: 26, 46.

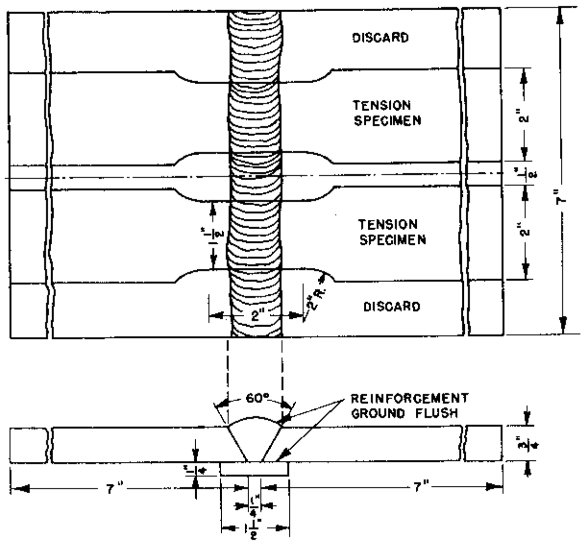


FIGURE 40. SPECIMEN FOR TRANSVERSE TENSION TEST OF WELDED JOINTS.

REFERENCE: 15.

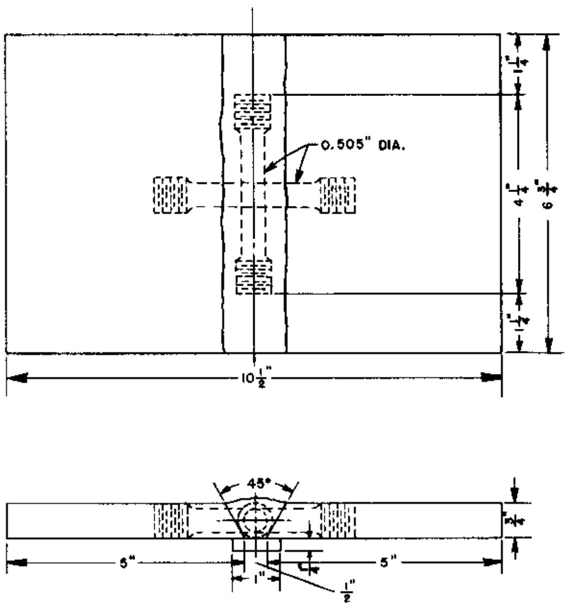


FIGURE 41. CYLINDRICAL ALL-WELD-METAL AND TRANSVERSE TENSION SPECIMENS.

REFERENCES: 2, 15, 21, 14.

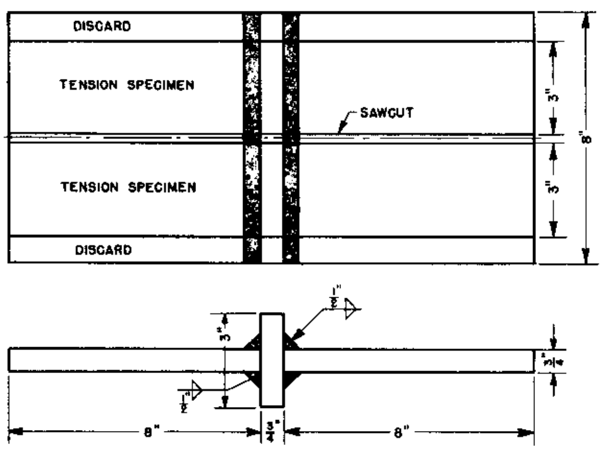


FIGURE 42. FILLET-WELDED DOUBLE-TEE JOINT SPECIMEN FOR TENSION TEST.

REFERENCES: 21, 32, 36, 40, 48.

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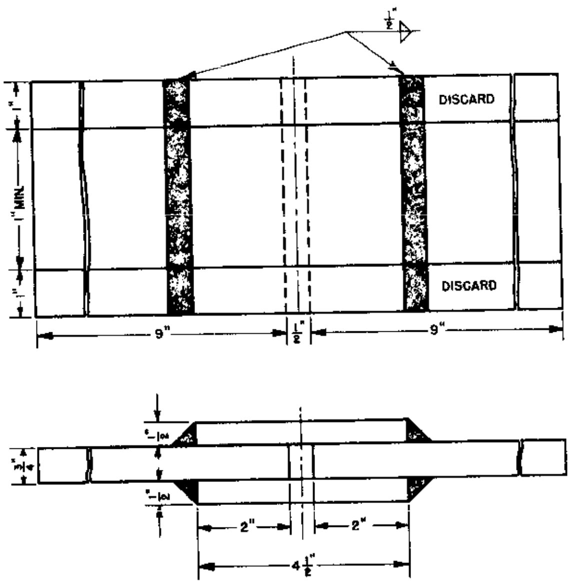


FIGURE 43. FILLET-WELD SPECIMEN FOR TRANSVERSE SHEAR TEST.

REFERENCES: 15, 21, 36, 40, 12.

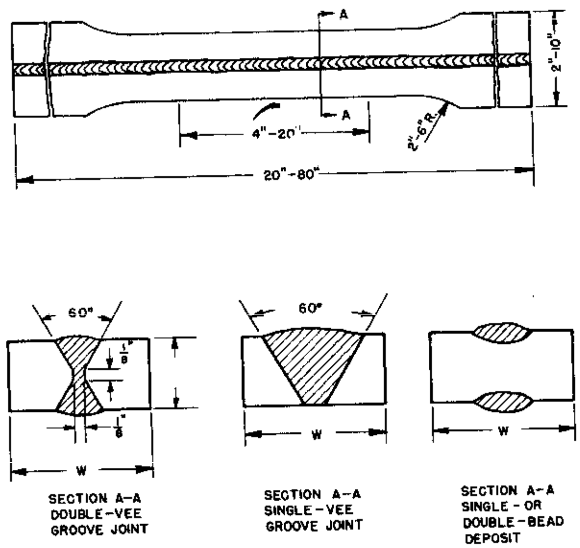


FIGURE 44. SPECIMEN FOR LONGITUDINALLY WELDED TENSION TEST.

REFERENCE: 32.

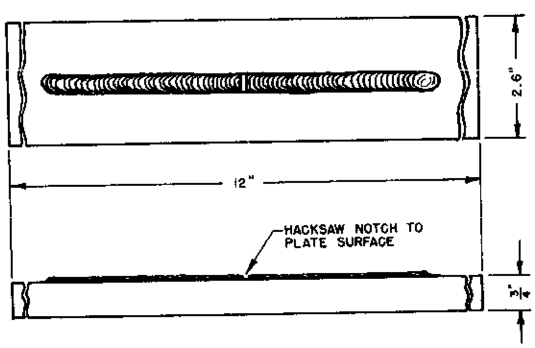


FIGURE 45. SPECIMEN FOR LONGITUDINALLY WELDED NOTCHED TENSION TEST.

REFERENCE: NOT PUBLISHED.

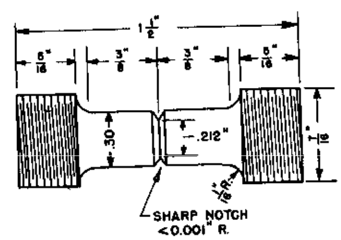


FIGURE 46. SPECIMEN FOR STATIC NOTCHED-BAR TENSION TEST.

REFERENCES: 127, 128.

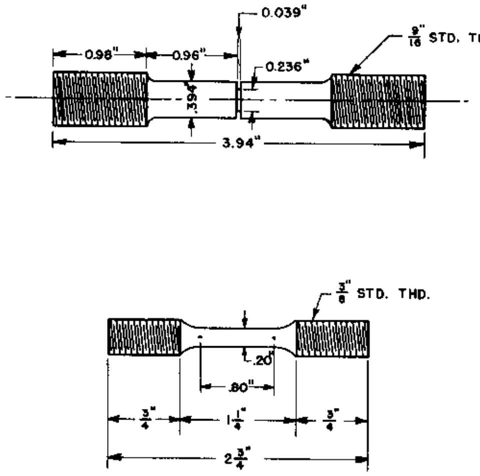


FIGURE 47. TYPICAL SPECIMENS FOR TENSION-IMPACT TESTS.

REFERENCES: 8, 138.

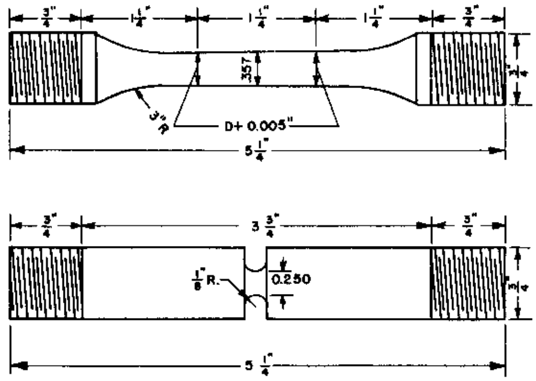


FIGURE 48. SPECIMENS FOR LOW-TEMPERATURE TENSILE TESTS.

REFERENCE: 87

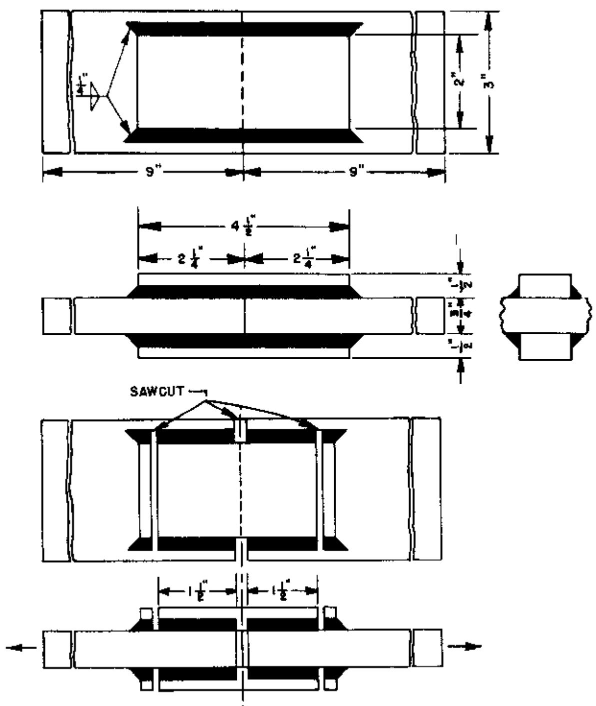


FIGURE 49. FILLET-WELD SPECIMEN FOR LONGITUDINAL SHEAR TEST.

REFERENCES: 13, 15, 21, 36, 40, 12.

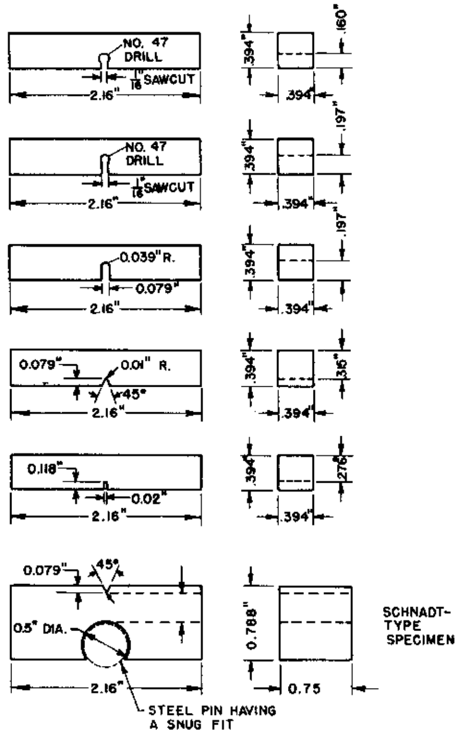


FIGURE 50. DETAILS OF VARIOUS SPECIMEN DESIGNS USED FOR NOTCHED-BAR TYPE TESTS.

REFERENCES: 16, 24, 29, 31, 105, 106, 125, 137.

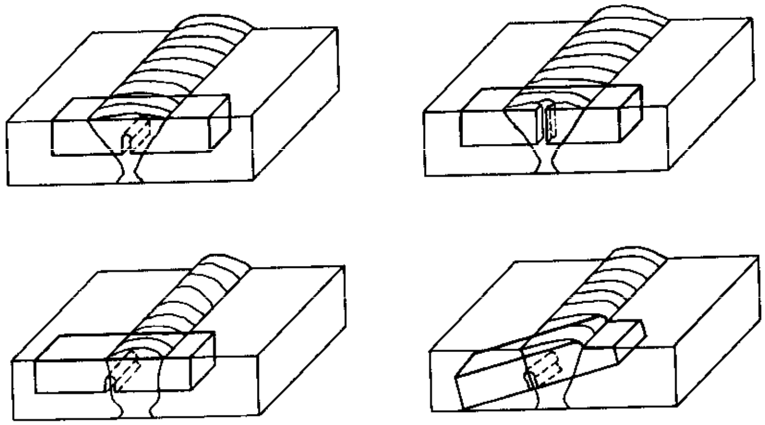


FIGURE 51. SCHEMATIC DIAGRAMS SHOWING THE VARIOUS LOCATIONS OF NOTCHED-BAR SPECIMENS MACHINED FROM WELDED GROOVE JOINTS. (REFER TO FIGURE 50 FOR NOTCH DETAILS.)

REFERENCES: 9, 16, 24, 29, 31, 105, 106, 125, 137.

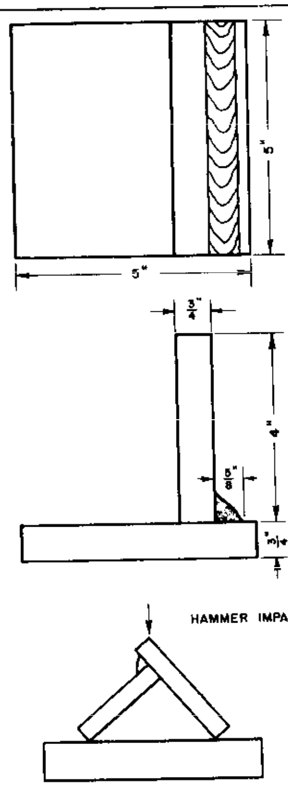


FIGURE 52. SPECIMEN FOR FILLET-WELD BREAK TEST.

REFERENCES: 46,147.

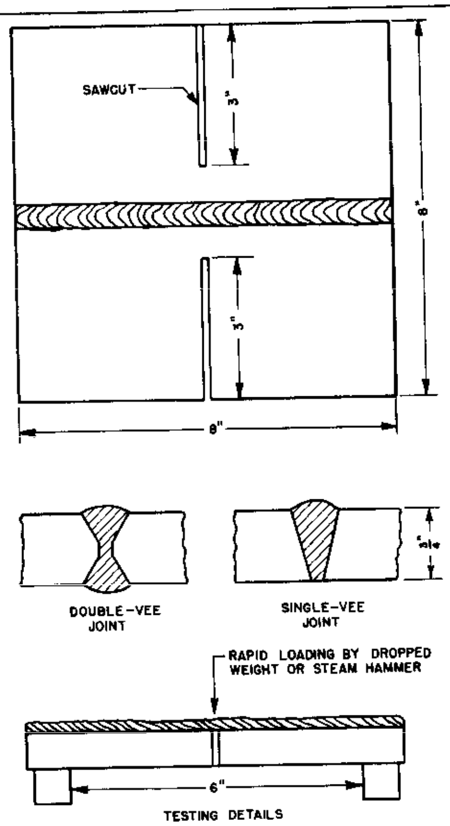


FIGURE 53. NICK-BREAK FRACTURE TEST.

REFERENCE: 78.

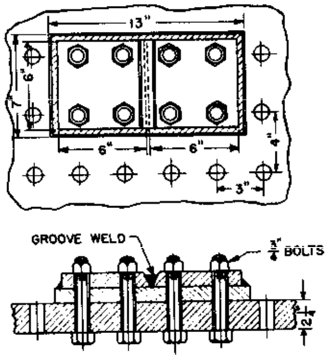


FIGURE 54. RESTRAINED SPECIMEN FOR CRACKING TEST.

REFERENCES: 47, 68, 73.

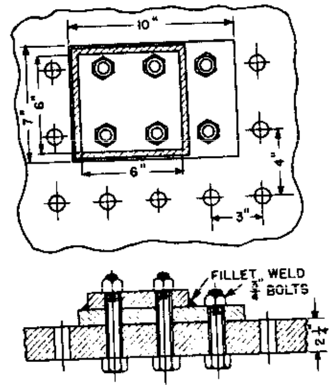


FIGURE 55. RESTRAINED FILLET-WELDED SPECIMEN FOR CRACKING TEST. (REEVE TEST).

REFERENCES: 23, 25, 47, 59, 68, 72, 73.

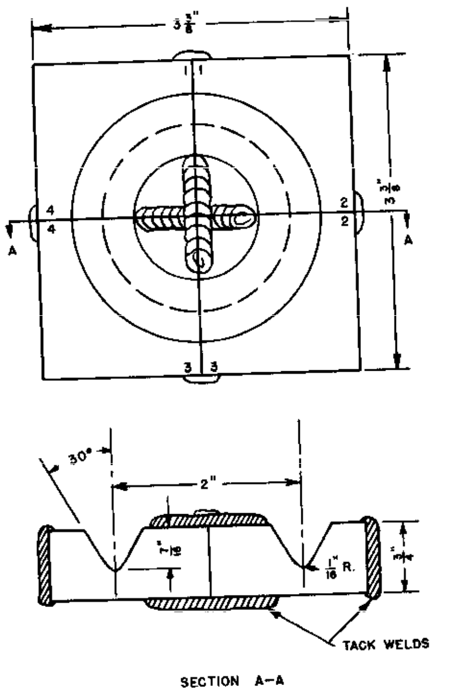


FIGURE 56. CIRCULAR GROOVE SPECIMEN FOR RESTRAINT-TYPE TEST.

REFERENCE: NOT PUBLISHED.

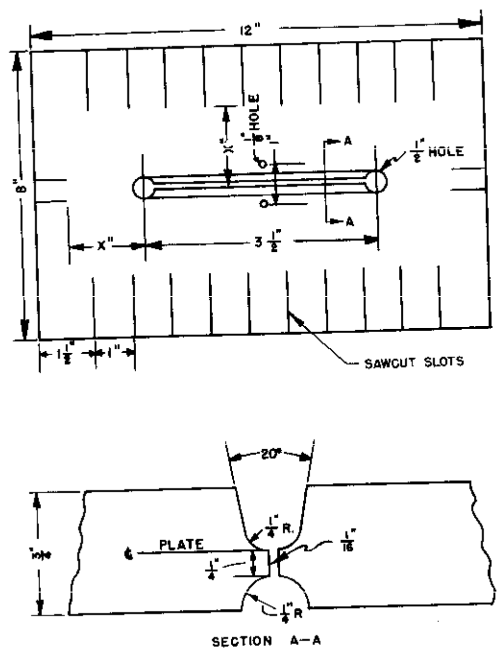


FIGURE 57. FIN SPECIMEN USED FOR RESTRAINT-TYPE TESTS.

REFERENCES: 98, 102, 130.

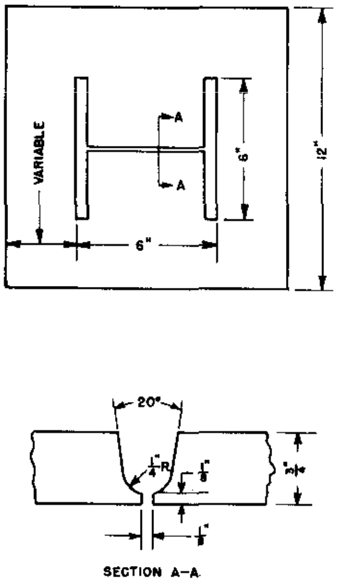


FIGURE 58. SPECIMEN FOR RESTRAINT-TYPE TEST

REFERENCE: 102.

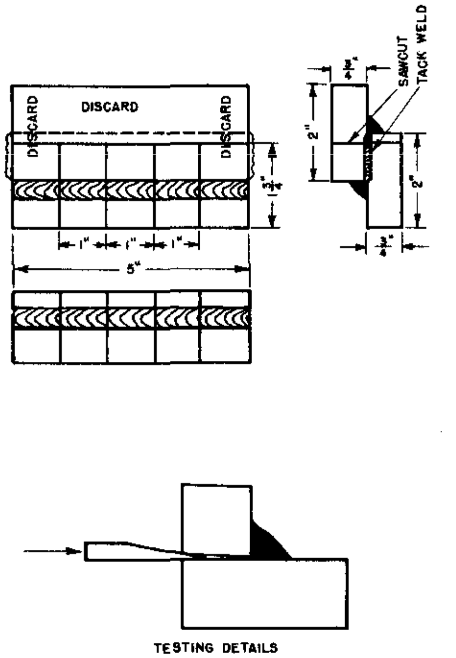
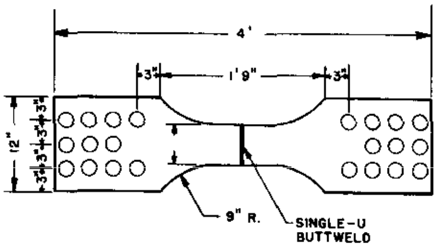


FIGURE 59. FILLET-WELD DUCTILITY TEST.

REFERENCE: 93.



VARIATIONS IN SPECIMEN DESIGN AND WELDING PROCEDURES ARE GIVEN IN THE REFERENCES.

FIGURE 60. SPECIMEN FOR PLATE BENDING FATIGUE TESTS.

REFERENCES: 28, 44, 45, 52, 58, 99.

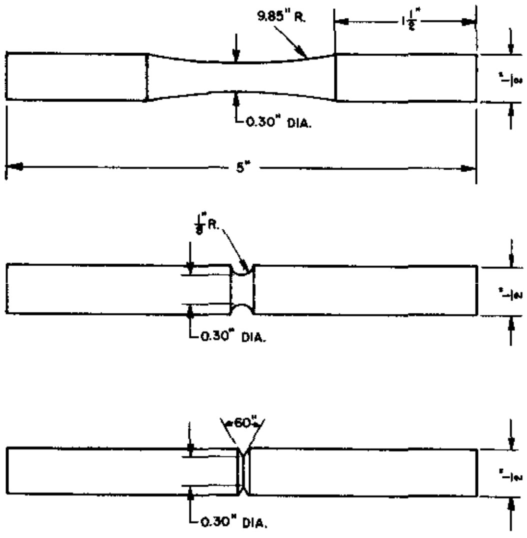


FIGURE 61. SPECIMENS FOR ROTATING BEAM FATIGUE TESTS.

REFERENCES: 34, 53.

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APPENDIX C

APPENDIX C

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