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SERIAL NO. SSC-45

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FINAL REPORT

ON

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

BY

F. R. BAYSINGER, P. J. RIEPPEL AND C. B. VOLDRICH

BATTELLE MEMORIAL INSTITUTE

Under Bureau of Ships Contract NObs-48015
(Index No. NS-011-067)

Transmitted through

NATIONAL RESEARCH COUNCIL'S

COMMITTEE ON SHIP STEEL

Advisory to

SHIP STRUCTURE COMMITTEE

under

Bureau of Ships, Navy Department
Contract NObs-50148

Division of Engineering and Industrial Research
National Academy of Sciences - National Research Council
Washington, D. C.
December 20, 1951

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OF THE
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December 20, 1951

Dear Sir:

Attached is Report Serial No. SSC-45 entitled "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships." This report has been submitted by the contractor as a Final Report of work completed for the Ship Structure Committee on Research Project SR-100 under Contract NObs-48015 (1773) between the Bureau of Ships, Department of the Navy and Battelle Memorial Institute.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Steel, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Department of the Navy and the National Academy of Sciences.

Very truly yours,

Peter E. Kyle

P. E. Kyle, Chairman
Committee on Ship Steel

FINAL REPORT

on

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

to

BUREAU OF SHIPS
NAVY DEPARTMENT

Summarizing Work Completed on Project SR-100 Under Contract NObs-45543, and Contract NObs-48015 (1773) Index No. NS-011-067

by

F. R. Baysinger, P. J. Rieppel, and C. B. Voldrich

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PREFACE

The Navy Department through the Bureau of Ships is distributing this report for the SHIP STRUCTURE COMMITTEE to those agencies and individuals who were actively associated with the research work. This report represents results of part of the research program conducted under the Ship Structure Committee's directive to "improve the hull structures of ships by an extension of knowledge pertaining to design, materials and methods of fabrication".

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FINAL REPORT

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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

by

F. R. Baysinger, P. J. Rieppel, and C. B. Voldrich

Summarizing Work Completed on Project SR-100 Under Contract NObs-45543, and Contract NObs-48015 (1773) Index No. NS-011-067

INTRODUCTION

This is the final report on Navy Department, Bureau of Ships, Project SR-100, authorized by Contract NObs-48015 (1773) Index No. NS-011-067, entitled"Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships". This report summarizes work done during the period June 25, 1947, to December 30, 1950. Progress Reports* prepared under this contract are Ship Structure Committee Reports Serial Nos. SSC-23, Mar. 30, 1949; SSC-33**, Nov. 15, 1949; SSC-36, Dec. 20, 1950; SSC-40, Oct. 1,1951; and SSC-41, Oct. 1, 1951.

*A paper "Evaluation of Tests for Steels for Welded Structures", by P. J. Rieppel, R. G. Kline and C. B. Voldrich, Welding Journal, Vol. 25, April, 1950, pp. 195S-216S, also describes work completed under this contract.
**An extensive Bibliography appears in Appendix "C" of this report.

This project had three objectives. The principal objective was to evaluate the usefulness of various mechanical tests of small welded steel specimens for indicating the probable performance of large welded structures. Another objective was to study the fundamental factors contributing to the performance of such welded laboratory specimens. The last objective was to evaluate the underbead crack sensitivity of a series of steels made to American Bureau of Shipping specifications.

Work done toward finding a test for evaluating steels for large welded structures started with a literature survey* of tests used previously to study the qualities of welds in steel and the weldability of steels. From the results of the survey, five types of tests which seemed most promising for further study were selected. Of the five types of tests selected and studied, the Kinzel test using notched weld-bead specimen was used for the major part of the work, particularly to determine the transition-temperature ranges of project steels "B_r", "C", "A", and "W" and to determine the micromechanism of fracture initiation and propagation as a guide to the interpretation of the results.

At the start, a premise was set up for this investigation that, if the transition-temperature range which had previously been determined for the full-scale hatch-corner specimen was matched by that of a small specimen of the same steels, the small specimen would be useful in predicting the performance of steels in large welded structures in general. To this end, various modifications were made in the design of the Kinzel-type specimen and in testing procedure.

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* See Ship Structure Committee Report, Serial No. SSC-33, Nov. 15, 1949.

A detailed study was made of crack initiation and propagation in Kinzel-type specimens to obtain fundamental information on factors contributing to the performance of the test. It was also desired to determine why welded Kinzel-type specimens always gave poorer performance than unwelded Kinzel-type specimens of the same steels.

On the third objective, work included a study of forty-one heats of ABS Classes B and C steels using the Battelle underbead cracking test. Nine of these steels were used in large tee joints designed to simulate ship-welding conditions. The effects of various test modifications on cracking in these tee joints were studied.

The work done toward these objectives is summarized in this report under the following headings:

1. Evaluation of tests for rating steels.
2. Studies with standard and modified Kinzel-type specimens.
3. Crack initiation and propagation studies of Kinzel-type specimens.
4. Crack-sensitivity tests and tee-joint tests of ABS Classes B and C steel.

EVALUATION OF TESTS FOR RATING STEELS

A survey was made of the published literature and unpublished reports to uncover the various kinds of test specimens that had already been developed to study properties of weld joints in steel and the weldability of steels, and to determine their applicability to the current*

*See Ship Structure Committee Report Serial No. SSC-33, Nov. 15, 1949.

investigation. In choosing a test for evaluating the effect of welding on medium-carbon hull steels and predicting the behaviour of the welded structure under service loads, a number of factors had to be considered. The specimen employed in this test 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, electrodes, preheating, postheating, etc., must also be reflected by the response of the specimen during testing. The service conditions of a weldment, such as rigidity, loading, and temperature variations, should also be simulated by constraint developed by the geometry of the specimen, rate of loading, and testing the specimens at different temperature levels. Therefore, the only tests considered during this survey for further study were those in which the test specimens contained the components of a weldment, that is, weld metal, heat-affected metal caused by welding, and base metal.

The types of tests were roughly divided into the following five groups:

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

The tests of Group 4, the cracking or restraint-type test, were excluded from further consideration, because, in general, they were 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 of Group 5 were also excluded because they did not appear applicable to the investigation. While fatigue might play a part in some ship failures, it was held to be subordinate to the sudden brittle type of failure.

The impact types of tests in Group 3 were considered for various aspects of the investigation, such as studying the transition-temperature range 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, this type of test was not included.

To further classify the bend and tension tests, they were separated into two types, those using notched and unnotched test specimens. The bend tests using specimens without a machined notch or stress raiser included such tests as the guided bend, free bend, and single and double tee-joint bend.

Of these, the single-tee-joint bend test was considered satisfactory for this investigation because the test specimen was judged most representative of a typical welded structure found in ship construction, and because other investigators had found that the test was practical for rating the welding quality of steels.

The bend specimens, containing machined notches of various types to impart a higher degree of constraint to the specimens, had been used extensively 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 and the specimen having a transverse bead and transverse notch seemed to be most in line with the stated objective of this research.

Unnotched tension specimens were given little consideration because most of these tests were used only for evaluating weld-metal strength efficiency. However, one notched tension specimen was used to a limited extent in the project.

On October 1, 1947, the various types of tests reviewed by the 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-bond test, representing a typical welded ship joint, should be further investigated over a range of testing temperatures to evaluate the strengrh, ductility, types of fractures, and transition-temperature ranges of the "B_r" and "C" ship steels. It was the thought of the committee that, if one of these tests were to give the same transition-temperature ranges 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 a steel for ship plate. The compositions of project steels are given in Table B-2, Appendix B.

The specific specimens included were the tee-bend, the Kinzel-type, Lehigh-type, Naval Research Laboratory high-constraint, Jackson-type, and notched tension specimens. The specimen designs are given in Appendix A, Figures A-1 through A-9. The welding schedules are given in Appendix B, Table B-1. Each of the specimens will be discussed briefly in the following sections except the Kinzel-type specimen, which is discussed in a separate section of this report.

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-temperature ranges for the steels. The transition-temperature ranges were determined by the following criteria: absorbed energy, bend angle, lateral contraction, and fracture appearance. Of these, only data on absorbed energy will be presented in this report to conserve space and since it has proved to be the most useful of the criteria listed above.

Tests With Tee-Bend Specimen

The main advantage of the tee-bend test is that it represents a typical welded joint used in ship building and structural welding. The specimens are easily machined and tested. The most apparent disadvantage of this test is the difficulty in adhering to the welding requirements and the amount of discard of specimen lost after machining. Details of the specimen are shown in Appendix A, Figures A-1 and A-2.

The standard tee-bend specimen was used to study "B_r" and "C" steels. Curves for absorbed energy vs. temperature for this test are shown in Figure 1. For both steels, the transition-temperature ranges were lower than those for the hatch-corner tests for the respective steels. Therefore, modifications of the tee-bend specimen were made in an attempt to match the hatch-corner results.

* DeGarmo, Paul E., "Tests of Various Designs of Welded Hatch Corner for Ships", Welding Journal, Vol. 27, February, 1948, pp. 50s-58s, also Ship Structure Committee Report Serial No. SSC-5, Oct. 23, 1946.

The first modification made in the tee-bend test was in the welding procedure used to make the specimens. A 3/16-inch-diameter electrode was used instead of a 5/32-inch-diameter electrode, and a welding schedule was set up to deposit a 3/16-inch fillet with slightly less heat input per inch of weld than with the smaller electrode. It was expected that this change in welding procedure would influence the transition-temperature ranges of the steels being tested. However, tests showed that the change in welding schedule had only a minor influence on transition range, as shown in Figure 1.

As the desired increase in transition-temperature range was not attained, it was decided to use the modified welding schedule on tee-bend weldments for tee-bend specimens of different widths. The standard 1-7/8-inch width was increased to 3 inches. The tests of the wider specimens indicated a slight increase in the transition ranges, with the "C" steel being affected more than the "B_r" steels, as shown by Figure 1. No further modifications were studied.

Tests with Lehigh-Type Specimen

Design details of the Lehigh-type specimen are shown in Appendix A, Figure A-3. Absorbed energy vs. temperature curves for "B_r and "C" steels obtained with the Lehigh-type specimen are shown in Figure 2a. The Lehigh specimen gave well-defined transition-temperature ranges for the two steels, but these temperatures were lower than those indicated by the hatch-corner test. This specimen was easy to weld, machine, and test. However, no further work was done with it, because slightly better results were obtained with the Kinzel-type specimen which was similar in many respects to the Lehigh specimen.

Tests With Naval Research Laboratory Specimen

The specimen designed by the Naval Research Laboratory is shown in Figure A-4 of Appendix A. Complete data for C steel were not obtained with this specimen, but from the "B_r" steel data in Figure 2b, it was found that there was not enough difference between the upper and lower limits of the curve to make the test very sensitive for an accurate rating of steels. Therefore, no further work was done with this specimen, since other tests gave somewhat better performance.

Tests With Jackson-Type Specimen

The Jackson-type specimens, having a transverse weld bead with a machined notch, as shown in Figure A-5 of Appendix A, were made to check the effect of side notches on the transition-temperature range. Consequently, tests were only made on "B_r" steel. Data are shown in Figure 2b. No further testing was done with this specimen, since it appeared to have no advantage over other bead-on-plate specimens such as the Lehigh and Kinzel which were easier to prepare.

Tests Using Notched Tension Specimen

Tension specimens ranging in width from 3 to 72 inches, and over, had been used by investigators to determine the transition ranges of various ship steels. It was believed that the tension test was more representative of the condition of loading found in a ship's hull or hatch corner than were the short-span notched-bend-type tests. Therefore, it was decided that the transition-temperature ranges of welded and unwelded "B_r" and "C" steel should be determined by using notched tension specimens similar in design to those used for the bend tests, and the results compared with the bend-test results and the hatch-corner test results.

The notched-tension specimens used were of the same design as the Kinzel-type specimens, except that the width was reduced to 2-3/4 inches to accommodate the testing equipment and to prevent the possibility of failure away from the notched section. Adapter bars were welded to the ends of the specimens to save the project steel. Refer to Figures A-6 and A-7, Appendix A.

Results of this test are shown in Figure 2c. The transition-temperature ranges were lower than shown by the other types of specimens studied and lower than the hatch-corner results. However, the qualitative order was the same; in other words, the tests always rated "C" steel as being inferior to "B_r" steel.

The main disadvantage of the notched-tension test was the low temperatures required to obtain the transition-temperature data for the steels tested.

Discussion of Results from Evaluation Studies on Test Specimens

With all test specimens, the "C" steel had a higher transition-temperature range than the "B_r" steel. This observation correlated directly with results from full-scale hatch-corner tests made on these two steels.

Of the specimens studied, the transition-temperature ranges obtained from the Kinzel specimen for "B_r" and "C" steels were a little closer to those obtained by the hatch-corner specimens than the transition-temperature ranges obtained by other specimens. For this reason, and because the Kinzel specimen was easy to weld, machine, and test, it was selected for further studies and evaluation.

STUDIES WITH STANDARD AND MODIFIED KINZEL-TYPE SPECIMENS

The Kinzel-type specimen gave generally well-defined transition-temperature ranges for the steels studied at temperatures not too difficult to obtain in testing. The welding on the specimen was done at currents and travel speeds which are normally used with 3/16-inch E6010 electrodes in actual welding on large structures. When the specimen was notched, about half of the weld metal was left under the root of the notch. For those reasons, it was believed that this specimen was more representative of actual welds than some of the other specimens studied. The specimen details are shown in Appendix A, Figure A-8.

Therefore, this specimen was selected for use in further studies of other steels. Various modifications of the specimen were made in an attempt to more closely match the transition-temperature of the hatch-corner specimens and study factors contributing to the performance of welded laboratory specimens.

Evaluation of Project Steels

The original work with the Kinzel-type specimen was to rate "B_r" and "C" project steels, along with the other type specimens previously discussed. At the December, 1948, meeting of the Project Advisory Committee, it was decided that "A" and "W" steels also be studied with the Kinzel-type specimen to compare with the results obtained for "B_r" and "C" steels.

A welded and an unwelded series of each of the project steels "B_r", "A", "W", and "C" were tested through a range of temperatures.

Absorbed-energy data for these tests were plotted, and are shown in Figure 3. These tests rated the steels in order of increasing transition-temperature ranges as follows: "B_r", "W", "A", and "C". The transition-temperature ranges for unwelded "W" and "A" steels were very similar to the range for "B_r" steel, as shown by Figure 3A. In the welded condition, the transition-temperature ranges for "W" and "A" steels fall between transition-temperature ranges for "B_r" and "C" steels. The welded "B_r" steel absorbed much more energy than the "W", "A", and "C" steels.

The results obtained with the Kinzel specimen on these four steels were compared with the results of studies made on them with several other specimens, such as the Navy tear test, Charpy keyhole, Charpy vee-notch, and 72-inch center-notched plate specimens. The Kinzel specimen rated the steels in the same general order as other welded and unwelded specimens.

Variations from Standard Kinzel-Type Specimens

Various modifications of the Kinzel-type specimen were used in attempts to find conditions by which transition-temperature ranges obtained from the hatch-corner tests could be more closely duplicated with this type of test specimen, and to obtain more information regarding the factors which influenced the performance of the specimen. The modifications used included use of E6020 electrodes instead of E6010, a change from 3-inch-wide specimens to 1-1/2 and 6-inch-wide specimens, a change in notch depth from 0.050 inch to 0.090 inch deep, and the use of various thermal treatments. These will be discussed in turn.

Influence of E6020 Electrodes on Transition Range

A series of Kinzel-type specimens was made using E6020 electrodes, to determine if the transition range would be changed from that obtained when E6010 electrodes were used. The heat input per inch of deposited weld metal was made as nearly as possible the same for specimens welded with the two types of electrodes. This variable was controlled as closely as possible so that any changes resulting in transition-temperature range could be attributed to differences in type of weld metal.

Absorbed-energy data for these tests are shown in Figure 4. As can be noted, the change in electrodes had little effect on the transition temperature range, although the energy values were not so high as those of the specimens welded with E6010 electrodes. Tests were not made with "C" steel because of the small influence of E6020 weld metal on the transition range of "B_r" steel, and because of a shortage of "C" steel.

Influence of Specimen Width on Transition-Temperature Range

Two series of modified Kinzel-type specimens were prepared and tested to determine the influence of variations in specimen width on transition-temperature range. The specimens of one series were 1-1/2 inches wide and the others were 6 inches wide. Absorbed-energy data for the 1-1/2-inch-wide specimens of "B_r" steel are shown in Figure 4. The decrease in width lowered the transition range slightly. For the 6-inch-wide specimens, the transition range was the same, but energy values were nearly double those of the standard specimens (these data were not included in Figure 4.). No tests were made on "C" steel with modifications in width of specimen.

Influence of Notch Depth on Transition-Temperature Ranges

Standard Kinzel-type specimens of "B_r" and "C" steels having a notch depth of 0.090 inch were prepared. It was desired that these specimens have a notch sufficiently deep to eliminate the weld metal, but not to penetrate below the fusion line at the bottom of the bead and into heat-affected zones at the bottom of the weld. Macrosections of several typical welds indicated that a notch depth of 0.090 inch below the plate surface would eliminate the weld metal and leave only heat-affected base metal in the weld area of the specimen.

Absorbed-energy data for "B_r" steel specimens with 0.090-inch notch depth are shown in Figure 4, and for "C" steel, in Figure 5. Energy values were lowered, and the transition-temperature ranges for both steels were slightly raised.

Effect of Thermal Treatments on Kinzel-Type Specimens of "B_r" and "C" Steels

The effect of several thermal treatments on the behavior of Kinzel-type specimens of "B_r" and "C" steels was studied to determine if the performance of the specimen would be improved in the same manner that hatch-corner performance was improved by stress-relieving treatments. The thermal treatments included:

a. The use of 10F, 70F, 150F, 250F, 400F, and 500F preheats on "B_r" and "C" steels.

b. The use of 70F preheat and a postheat of 1150F for one hour on "B_r" and "C" steels.

c. The use of 400F preheat and a postheat of 1150F for one hour on "B_r" steel.

Cooling rates were recorded for each condition of preheat, and hardness surveys were made to determine the effects of the various thermal treatments on both steels.

Effect of Preheats and Postheat on "B_r" Steel. Absorbed-energy data for "B_r" steel Kinzel-type specimens given various preheats are shown in Figure 7. A preheat of 10F had no effect on the transition-temperature range of "B_r" steel. Preheats of 150F, 250F, 400F, and 500F successively lowered the transition range, but were within the range of values shown for 400F preheat in Figure 7. Specimens welded with preheats of 70F and 400F, and postheated for one hour at 1150F, gave similar values. The transition ranges were not lowered below that of the 400F preheat, but the absorbed-energy values were higher. In general, these thermal treatments improved the performance of the specimen in the same manner that stress-relieving treatments improved hatch-corner performance.

Effects of Preheats and Postheat on "C" Steel. Based on absorbed energy, 10F and 150F preheats had little effect on the transition temperature range of "C" steel, although absorbed-energy values were lower. Preheats of 250F, 400F, and 500F, however, successively lowered the transition range, with the 500F preheat being the most effective. Absorbed-energy data for 10F, 70F, 500F preheats, and 70F preheat and 1150F postheat on "C" steel are shown in Figure 6. The postheat treatment did not lower the transition range below that of 500F preheat, but the maximum absorbed energy was increased about 3000 inch pounds over that obtained with 500F preheat, as shown by Figure 6.

The cooling rates for each preheat were measured by means of a Chromel-Alumel thermocouple flash welded into a small hole drilled in the bottom side of the specimen. Average cooling curces for the various preheats are shown in Figure 8. An examination of these cooling curves shows that the rate of cooling changed with preheat. For a preheat of 10F, the cooling rate was much faster than the rate for 500F preheat. In sixty seconds' cooling time, the end temperatures for 10F, 70F, 150F, 250F, 400F, and 500F preheats were 350F, 450F, 500F, 550F, 700F, and 800F, respectively, illustrating the effect of preheat in slowing the cooling rate.

Hardness surveys, using a Vickers hardness tester, were made on samples of "B_r" and "C" steels welded at the various preheats and postheats. In general, as the preheating temperature was increased, the hardness was decreased in both the weld and the heat-affected zones of "B_r" and "C" steels. The postheat treatment further decreased hardness in both steels. This decrease in hardness appears to correlate with the lowering of the transition ranges with increased preheat temperature. However, there may have been other changes in the weld metal and heat-affected zone which accompanied the preheating which was responsible for the lowering of the transition ranges of the specimens. For example, the thermal treatments may have permitted hydrogen to escape from the weld metal and heat-affected zones of the welds and thereby improved the properties of this area of the specimens and hence the over-all performance of the specimens.

CRACK INITIATION AND PROPAGATION STUDIES OF KINZEL-TYPE SPECIMENS

At this point, the work on interpretation of the test results of the Kinzel-type specimens was started.* This consisted of precise determinations of the initiation of the fracture and its propagation through the cross section.

Welded and unwelded Kinzel-type specimens were prepared according to standard procedure. Test temperatures selected were 80F and 0F for "B_r" steel specimens, and 180F and 40F for "C" steel specimens. Two or three specimens were bent at each of several deflections ranging from 0.05 to 0.250 inch at midspan for welded specimens, and from 0.05 to 1.25 inch for unwelded specimens. Following deformation, all specimens were cut and sectioned transverse to the notch, and depth of cracks was measured. In welded specimens, cracks were identified by the zone in the notch root in which they originated. In unwelded specimens, cracks were identified by location, as center or edge sections. Average crack-depth data were tabulated and plotted against deflection. Figure 9 summarizes the crack-depth data for these series of specimens.

Crack Initiation

At 0.050-inch deflection at midspan of "B_r" and "C" steel specimens, both welded and unwelded, small surface tears were observed

*See Ship Structure Committee Report Serial No. SSC-40, October 1, 1951.

in the notch-root radius. These tears were from 0 to 9 in number, and were generally observed all across the width of the specimen. In welded specimens, these tears were observed in all zones, that is, weld metal, heat-affected zone, and in base metal. There were no significant differences in the tears observed in specimens tested above and below the transition range.

Crack Propagation

As the deflection at midspan of the Kinzel-type specimens was increased beyond 0.050 inch, one of the several discontinuous cracks or tears that were present at 0.050 inch increased in depth, or propagated. The increase in propagation occurred at different deflections. An arbitrary depth of 0.005 inch was chosen to define a crack. The deflections at which cracks had attained a depth of 0.005 inch were measured, as follows:

Deflection in inches at Which Cracks Were 0.005 Inch Deep

	"B_r" Steel		"C" Steel	
	80F	0F	180F	40F
Welded	0.15	0.15	0.10	0.06
Unwelded	0.77	0.82	0.52	0.55

From these data, it was quite apparent that cracks started to propagate beyond 0.005 inch depth in the welded specimens almost immediately, while the unwelded specimens underwent considerable deflection before cracks propagated. It was also observed that the "C" steel cracked at lower deflections than the "B_r" and that temperature differences appeared to have very little effect on when cracks started to propagate.

To demonstrate how cracks propagated, isometric graphs were prepared, as shown in Figures 10 and 11 for welded and unwelded "C" steel at 180F. These figures demonstrate the early fracture of the weld area of the welded specimens, as compared with the unwelded specimens. They are typical of all the curves obtained from welded and unwelded "B_r" and "C" steels tested at the temperatures shown above.

<u>Interpretation of the Behavior of Kinzel-Type Specimens</u>

The crack-propagation data explained the inferiority of welded Kinzel-type specimens compared with unwelded specimens. The energy absorbed-vs.-temperature data, which were used to study transition ranges, were originally obtained from the area under the load-deflection curves for the test specimens. By dividing the energy absorbed by the specimens into (a) energy absorbed before cracking, and (b) energy absorbed after start of cracking, it is possible to quantitatively determine what has the greatest effect on energy values.

In Figure 12, energy absorbed to maximum load of Kinzel-type specimens of "B_r" and "C" steels is shown. This energy is divided into energy absorbed before and after cracking. Figure 13 compares the energies absorbed after cracking. If the energies absorbed prior to cracking for welded specimens versus unwelded specimens are compared at any temperature, it is found that there are large differences between the two, and that the welded specimens absorb very little energy up to the start of cracking. If the energies after cracking are compared, it can be observed that the differences between the welded and unwelded specimens are much less than the differences in energies before cracking for the two series of specimens. In other words, the early fracture of the weld area in welded specimens contributed most to the low energy values of welded Kinzel-type specimens, as compared to unwelded Kinzel-type specimens tested at the same temperature.

In the cases in which preheating and postheating improved the performance of Kinzel-type specimens, this improvement probably resulted directly from improvements in weld metal and the heat-affected zone. The improvement in weld metal presumably allowed more deformation before the crack started and thus better performance was obtained at lower temperatures than with specimens not having the benefit of preheat or postheat treatments.

CONCLUDING STATEMENTS CONCERNING SMALL WELDED TEST SPECIMENS AND FACTORS CONTRIBUTING TO THEIR PERFORMANCE

At the start of the project, the only specific data available on the performance of large welded structures was that obtained from testing full-scale welded hatch corners made of several ship steels at the University of California.* In the initial planning, it was desired to determine if a test using a small welded specimen would give the same transition-temperature ranges as those obtained by the full-scale hatch-corner specimens on the same steels and electrodes. It was believed that if such a test were found the small welded specimen might be useful in predicting the performance of other steels of the same grade when used in large welded structures.

*See Ship Structure Committee Reports Serial Nos. SSC-5, Oct. 23, 1946 and SSC-27, Aug. 19, 1949.

The work done toward finding a specimen for predicting the performance of steels was as follows:

1. A literature survey and study of many tests employing small specimens was made. On the basis of results from this survey, five small welded bend specimens and one tension specimen were selected for further study to determine if one or more of them would show the same qualities in steels that were brought out by hatch-corner tests of the same steels.

2. Two steels, "B_r" and "C", were used in evaluation of five selected bend tests and one tension test.

The chief results and conclusions from these studies are summarized as follows:

1. The transition-temperature ranges of "B_r" and "C" steels, as determined by the Kinzel specimen, matched those obtained by the hatch-corner specimens. However, it was concluded from the over-all study that it is probably too much to expect that any one small welded specimen will give the same transition temperature for a series of steels that would be obtained from a series of large weldments of various designs made from the same steels.

2. Much more important was the fact that all of the small test specimens showed that "B_r" steel gave a better performance at low temperatures than "C" steel, the same as was shown by the hatch-corner specimens. This was true whether the specimens contained welds or not. That is, specimens of prime plate showed the same trend in differences between "B_r" and "C" steels. This difference between "B_r" and "C" steels has been shown by several other investigations in which tests (Navy tear test, 72-inch-wide plate, 3-inch edge-notched specimen, Charpy V-notched bar, Charpy keyhole-notched bar, etc.)* of prime plate were used.

3. It appears, then, that any one of several specimens (welded or prime plate) could be used to compare steels of these grades for use in large welded structures. However, it would be necessary to correlate test results for many steels of varying quality with service results of weldments made with the steels in order eventually to build up background information for evaluating the test results.

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*a. Kahn, N.A., and Imbembo, E.A., "Further Study of Navy Tear Test", the Welding Journal, 29 (2), Research Suppl. pp. 84s to 96s (1950).
b. See Ship Structure Committee Report Serial No. SSC-8, Jan. 17, 1947.
c. See Ship Structure Committee Report Serial No. SSC-9, March 19, 1947.

4. None of the welded test specimens showed conclusively that either "B_r" or "C" steel was more weldable than the other. However, the welded specimens always gave poorer performance than specimens of the same type of prime plate.

With the selection of the Kinzel-type specimen as the most suitable welded specimen for predicting the performance of steels, the crack behavior of the specimens was studied to determine why welded Kinzel-type specimens gave poorer performance than unwelded specimens. The results and conclusions were as follows:

1. Results of the investigation on the initiation and propagation of cracks in Kinzel-type specimens of "B_r" and "C" steels showed that fractures in these specimens propagated first in the weld metal. The behavior of these specimens was controlled primarily by the cracking of the weld metal at a very low bend angle as the specimens were tested.

2. It was concluded that, although the Kinzel-type specimen could be used to rate steels, more work is indicated before the specimen could be used as a weldability test. It is believed the specimen could be used to study weld-metal properties and, with modifications, could also be used to study the effects of the heat of welding upon steels.

CRACK-SENSITIVITY TESTS AND TEE-JOINT TESTS OF ABS CLASS B AND C STEEL

The final phase of work on this project was distinct and separate from the original objective of finding a test specimen suitable for rating steels.* The objective of this phase of the investigation was to determine the underbead crack sensitivity of forty-one heats of steel made to new American Bureau of Shipping specifications for Class B and C steel. A second objective was to determine whether the more crack-sensitive heats would give trouble in service, as measured from cracking in large

*See Ship Structure Committee Report Serial No. SSC-41, Oct. 1, 1951.

tee-joint specimens which simulated ship-welding conditions.

Underbead Crack-Sensitivity Tests

The forty-one heats of steel studied for crack sensitivity included one heat of ABS Peening Project*steel, eight heats of Class B steel from David Taylor Model Basin, thirty-two heats of Class B and C steels directly from two steel mills. A control steel, designated as Z-13, was used throughout this investigation. The control steel was known to be crack sensitive.

The standard Battelle underbead cracking specimen was used in determining crack sensitivity of the steels. The underbead cracking specimen consisted of a 2-inch by 3-inch block, on which a weld bead was deposited by automatic welding, according to the following schedule:

AWS electrode classification	E6010
Electrode diameter, inch	1/8
Amperes	96-100
Volts	24-26
Travel speed, inches/minutes	10
Length of bead, inches	1-1/2
Weld time, seconds	9

Following welding, specimens were aged for 24 hours then stress relieved to stop further underbead cracking. The specimens were sectioned down the longitudinal centerline of the weld bead, polished, and transfers made of Magnaflux indications. These indications were measured, and recorded. Average per cent underbead cracking was obtained from the ten specimens used for each heat of steel.

Of the forty-one heats tested, only three steels had values of underbead cracking more than 7 per cent. These three were Class C

*Project under the Welding Research Council of the American Welding Society.

steels which cracked 16, 15 and 36 per cent.

Two additional series of underbead cracking tests were made, using the 36 per cent cracking steel. One series was prepared from blocks which had been homogenized at 2350F for 6 hours and normalized at 1600F. Another series was welded using low-hydrogen lime-ferritic electrodes. The homogenized series gave 5 per cent cracking, while use of the low-hydrogen electrodes reduced cracking to 1 per cent. These tests confirmed the belief that the underbead cracking in these steels was a result of microsegregations of manganese rich areas parallel with the direction of rolling.

Tee-Joint Tests

At this point, it was not known whether a steel such as the one which gave 36 per cent underbead cracking would give trouble in service. It was decided to test some of the steels under simulated ship-welding conditions, in the form of tee-joint specimens. Originally, three steels were picked for tee-joint tests which gave 36, 16 and 0 per cent underbead cracking. Later, six other heats of steel were tested in tee-joints. The additional steels were used to determine if, in cracking, tee-joints could be produced in any Class B or C hull steel, regardless of underbead crack sensitivity. A series of tests using various brands of low-hydrogen electrodes was made on the steel which gave 36 per cent underbead cracking. Tests were also made with low-hydrogen-type electrodes dried at 600F, and electrodes which conformed to Department of Defense Specification MIL-E-986(Ships), specifying 0.4% maximum coating moisture content. Other tests were made to determine the effect of preheat, homogenization, and a balanced welding sequence on cracking in tee-joints.

Tee-Joint Specimen and Procedure

The original tee-joint specimens consisted of a base plate 12 inches wide and 36 inches long, to which was welded a 36-inch by 4-inch bar for the leg of the tee. The connecting weld was a 45-degree double-bevel weld, with a 3/16-inch root opening and no land. The specimen design and welding sequence are given in Appendix A, Figure A-9. In subsequent tests, the specimen length was reduced to 24 inches in order to conserve material.

The welding schedule used was as follows:

AWS electrode class	E6010	E7015
Size of electrode, inch	3/16	3/16
Root pass: amperes	160	160
Volts	25	25
Other passes: Amperes	180	200
Average speed, inches/minute	6	7
Number of passes	6	9

Following welding, sections were taken transverse to the weld, polished, and Magnaflux inspected. Cracks found in these specimens started at the root of the welds below the fusion line and propagated down into the heat-affected zone in a stepwise path, apparently following banded structure. Maximum crack depth was measured as the projected transverse depth of crack, excluding weld overlap. Average crack depth was determined by dividing the sum of crack depths of the sections in the joint, by the total number of sections of the joint.

Results of tee-joint tests are summarized in the bar graph of Figure 14.

Relation Between Underbead Crack Sensitivity and Cracking in Tee-Joints

Steels with high underbead cracking cracked more in the tee-joint than steels with low underbead cracking. Those steels with 0 per cent underbead cracking had a maximum tee-joint crack 0.3 inch deep, compared to 0.7-inch deep for the 36 per cent steel.

Relation Between Electrode Types and Cracking in Tee-Joints

Steel 66P193-1 gave only 1 per cent underbead cracking when low-hydrogen electrodes were used, compared to 36 per cent cracking which resulted when E6010 electrodes were used. It was believed, therefore, that less cracking would result if low-hydrogen electrodes were used on tee-joints. However, it was found that tee-joint cracking was increased by the use of the low-hydrogen electrodes.

With the E7015 electrodes with different coating moisture content used on Heat 66P193-1, there was no relation between the amount of moisture and cracking. Brand A electrodes, with 1.03 per cent coating moisture gave 0.40-inch maximum crack depth, while brand B, with but 0.27 per cent coating moisture, gave 0.68-inch maximum crack depth. The latter was the deepest crack observed in the 24-inch-long tee-joint specimens.

Effect of Homogenization and Preheat on Cracking in Tee-Joints

A homogenizing heat treatment (2350F for 5 hours, normalized at 1600F) prior to welding reduced the maximum crack depth in Heat 66P193-1 (36 per cent underbead cracking) from 0.46 inch to 0.11 inch, and the average crack depth from 0.33 inch to 0.03 inch. These results compare with the reduction from 36 to 5 per cent in underbead cracking which accompanied the homogenization of the steel. A 400F preheat also produced a marked decrease in this type of cracking.

Effect of Balanced Welding Sequence on Cracking in Tee-Joints

Four tee-joints were made using a balanced welding sequence on Heats 21P169-1 and 71Y354, which gave 16 and 15 per cent underbead cracking, respectively. By this sequence, the root weld and the second pass were made on one side of the joint, and then the other side of the joint was completed, after which the first side was completed. No cracking was found in any of the four tee-joints made.

Additional Tests to Study Cracking in the Joints

Additional studies were made in an effort to explain the difference in cracking between the steels. It was felt that some weakness in the "Z" direction might be the cause of the cracking observed in the joints. Specially prepared 0.505-inch tensile specimens were made to test several steels normal to the plate surface. No correlation was found between cracking in the tee-joints and the properties of the steels in the "Z" direction.

Keyhole Charpy bars were made to test the notch sensitivity of several of the steels. The specimens were located so that the notch was parallel with the longitudinal direction of the tee-joints, so that stress would be applied in the same direction as in the tee-joints. All of the steels gave high impact values above -100F.

Discussion of Results

Definite causes for tee-joint cracking are not known. If stress alone were the cause, then the tee-joint cracking would not have been reduced by preheat and homogenization. On one hand, tee-joint cracking appears to be influenced by the same mechanism as underbead cracking, because homogenization reduced the cracking in both; and tee-joint cracking increased with an increase in the underbead crack sensitivity of the steels. On the other hand, the use of low-hydrogen electrodes with low moisture content which produce no underbead cracks increased, rather than decreased, the amount of tee-joint cracking.

It is believed that the cracking is somehow associated with bending in the steels. However, more work of a fundamental nature is needed to definitely determine the causes of this type of cracking.

CONCLUDING STATEMENTS CONCERNING UNDERBEAD CRACKING AND TEE-JOINT CRACKING

The following conclusions were drawn concerning underbead cracking and tee-joint cracking:

1. On the basis of the test results, it appears that there is little danger from underbead cracking in the ABS Class B steels. Cracking can occur under some welding conditions in some heats of ABS steels which are on the high side of the chemistry range. Most heats should give no trouble under any normal welding conditions.

2. If a balanced welding sequence is used with proper inspection and chipping of root welds, it appears that root weld cracking in tee-joints made in both ABS Class B and C steels can be controlled.

RECOMMENDATIONS FOR FURTHER RESEARCH ON TEE-JOINT CRACKING

A study of the results show that the future work in tee-joints should be divided into two phases with objectives as follows:

Phase I - Study the practical adjustments that can be made immediately in steel chemistry and welding practices to eliminate this type of cracking in ABS steel of present quality.

Phase II - Study fundamental mechanisms of this type of cracking.

The following work was proposed for Phase I:

1. Determine the effect on cracking of a 150F preheat and interpass temperature. A steel which gives relatively high cracking would be used with E6010 and E7015 electrodes.

2. Determine at what time in the welding sequence (first, second, third pass, etc.) the cracking starts. A steel which gives relatively high cracking, and one which gives low cracking would be used with E6010 or E7015 electrodes.

3. Determine the effect on cracking in tee joints of welding with E6010 or E7015 electrodes at 0F and cooling at that ambient temperature. (The same steel used in (1) and (2) would be used.)

4. Study the effects of normalization of plates before welding tee joints on cracking. (Use the same steel as in (1), (2), and (3), with E6010 or E7015 electrodes.)

5. Make large tee joints with E6010 and E7015 using large fillets instead of 100 per cent penetration welds to determine if cracking results. (Use the same steels as in (1), (2), (3), and (4).)

6. Compare a crack-sensitive steel and a noncrack-sensitive steel by the nick-break to determine if this test might be useful for checking steels for this type of crack sensitivity.

7. Study the crack tendencies of an ABS Class A steel by using the tee-joint specimen with E6010 and E7015 electrodes.

The following work was proposed for Phase II:

1. It is proposed that composition gradients in banded steels be determined by some suitable method (microradiography, electron microscope, etc.), and the correlation of the composition gradients in the bands of the steels with their tendency to crack in large tee-joint specimens be attempted.

2. It is also proposed that exhaustive studies of the nonmetallic inclusions in the steel be made to determine if cracking correlates with the presence of certain concentrations of nonmetallic inclusions. Along with this study, fractional vacuum tests, deep etch, strain aging tests, etc., would be run to determine the metallurgical properties of the steels.

Data given in this report are recorded in Battelle Laboratory Books

Numbers 3240, 3856, 4698, and 5390.

FIGURES

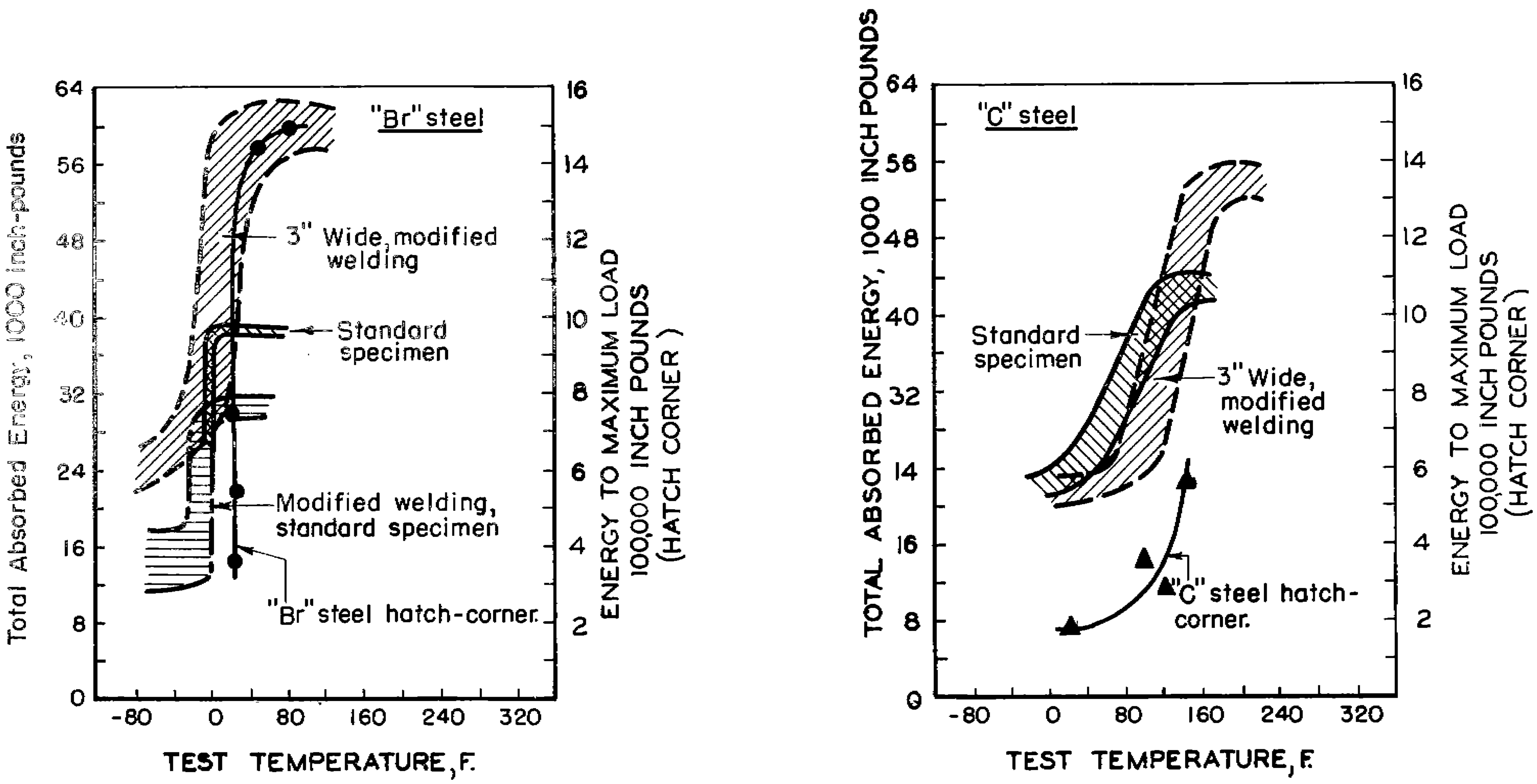

FIGURE I. TRANSITION TEMPERATURE RANGES FOR "Br" AND "C" STEELS OBTAINED BY STANDARD AND MODIFIED TEE-BEND SPECIMENS.

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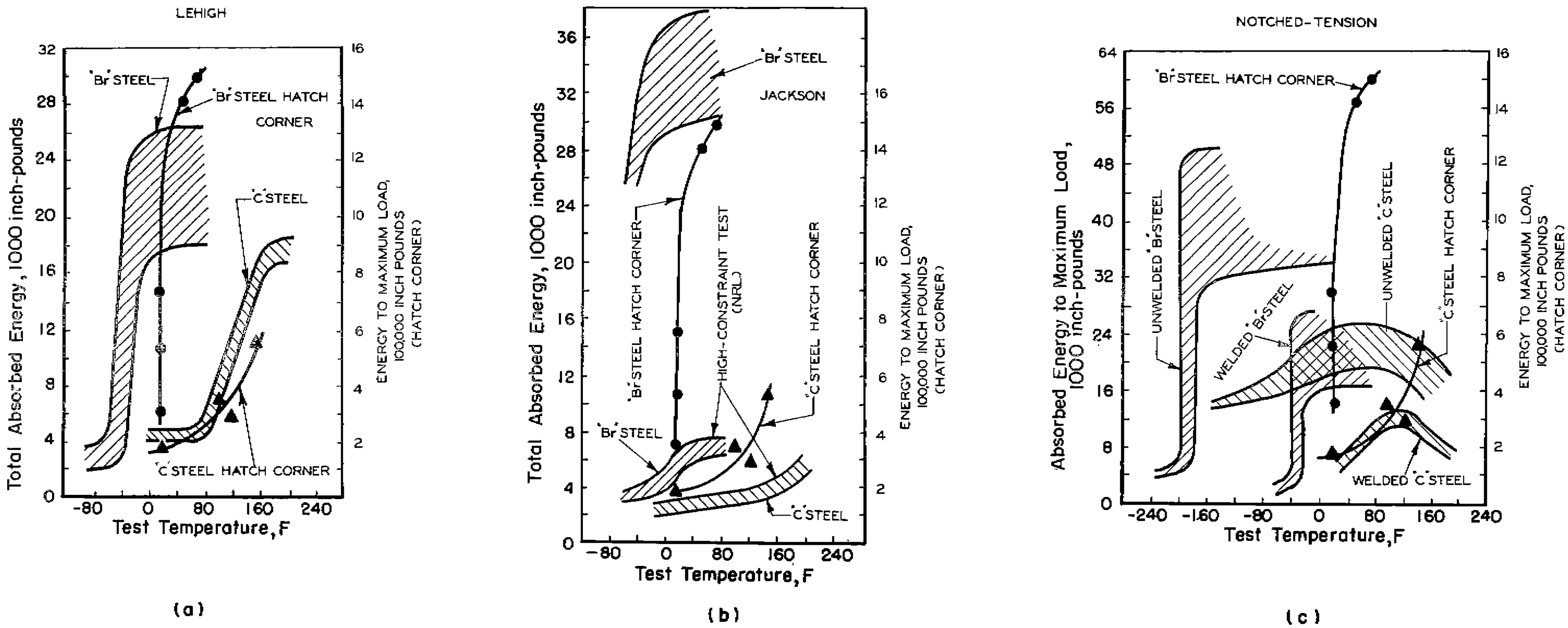

FIG. 2. ABSORBED ENERGY VS. TEMPERATURE CURVES FOR "Br" AND "C" STEELS DETERMINED BY VARIOUS TEST SPECIMENS. HATCH-CORNER CURVES ARE SHOWN FOR COMPARISON.

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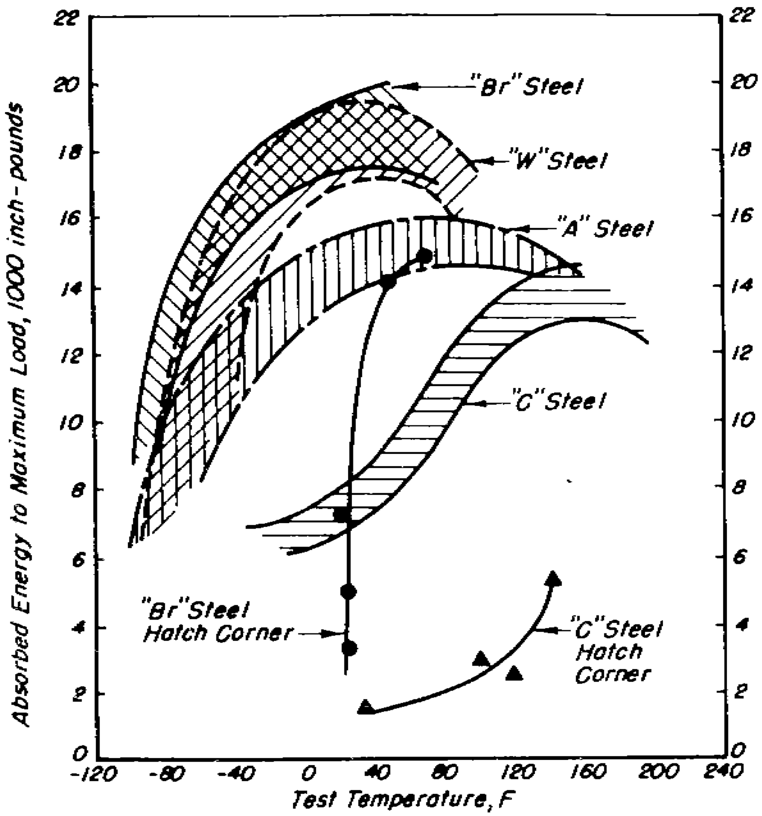

FIGURE 14. COMPARISON OF ENERGY VALUES FOR UN-WELDED KINZEL SPECIMENS OF "Br", "W", "A", AND "C" STEELS. HATCH-CORNER DATA ARE INCLUDED FOR COMPARISON OF TRANSITION-TEMPERATURE RANGES.

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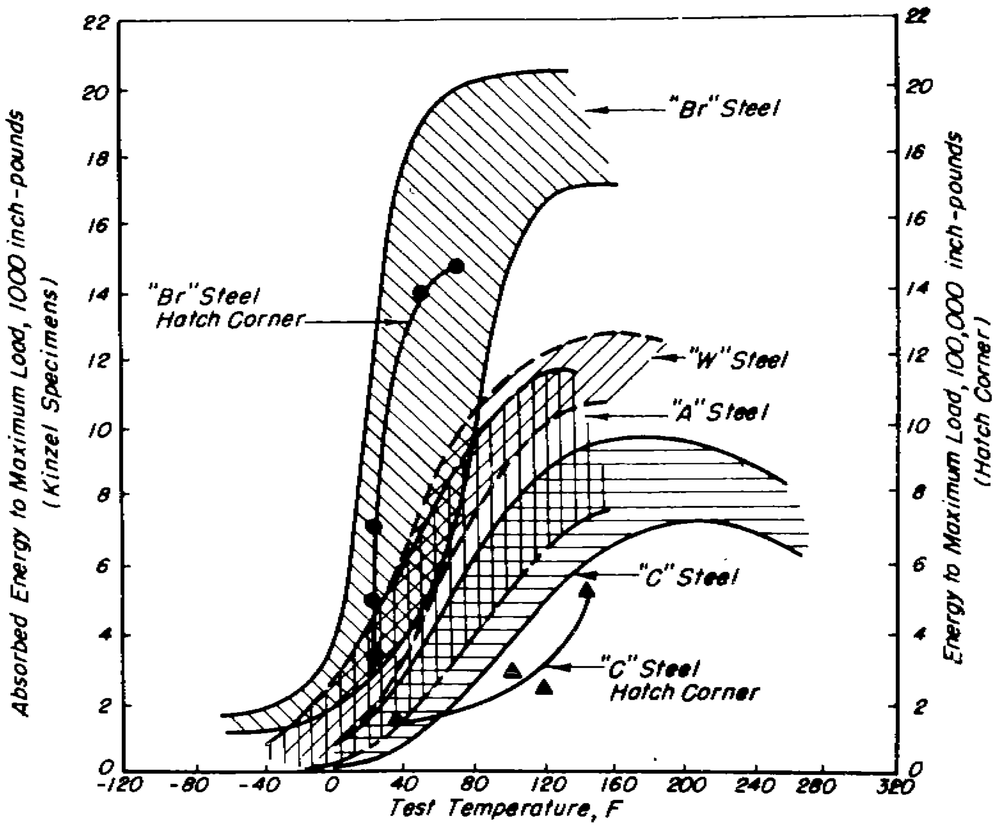

COMPARISON OF ENERGY VALUES FOR WELDED KINZEL SPECIMENS OF "Br", "W", "A" AND "C" STEELS. HATCH-CORNER DATA INCLUDED FOR COMPARISON OF TRANSITION-TEMPERATURE RANGES.

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FIGURE 3.

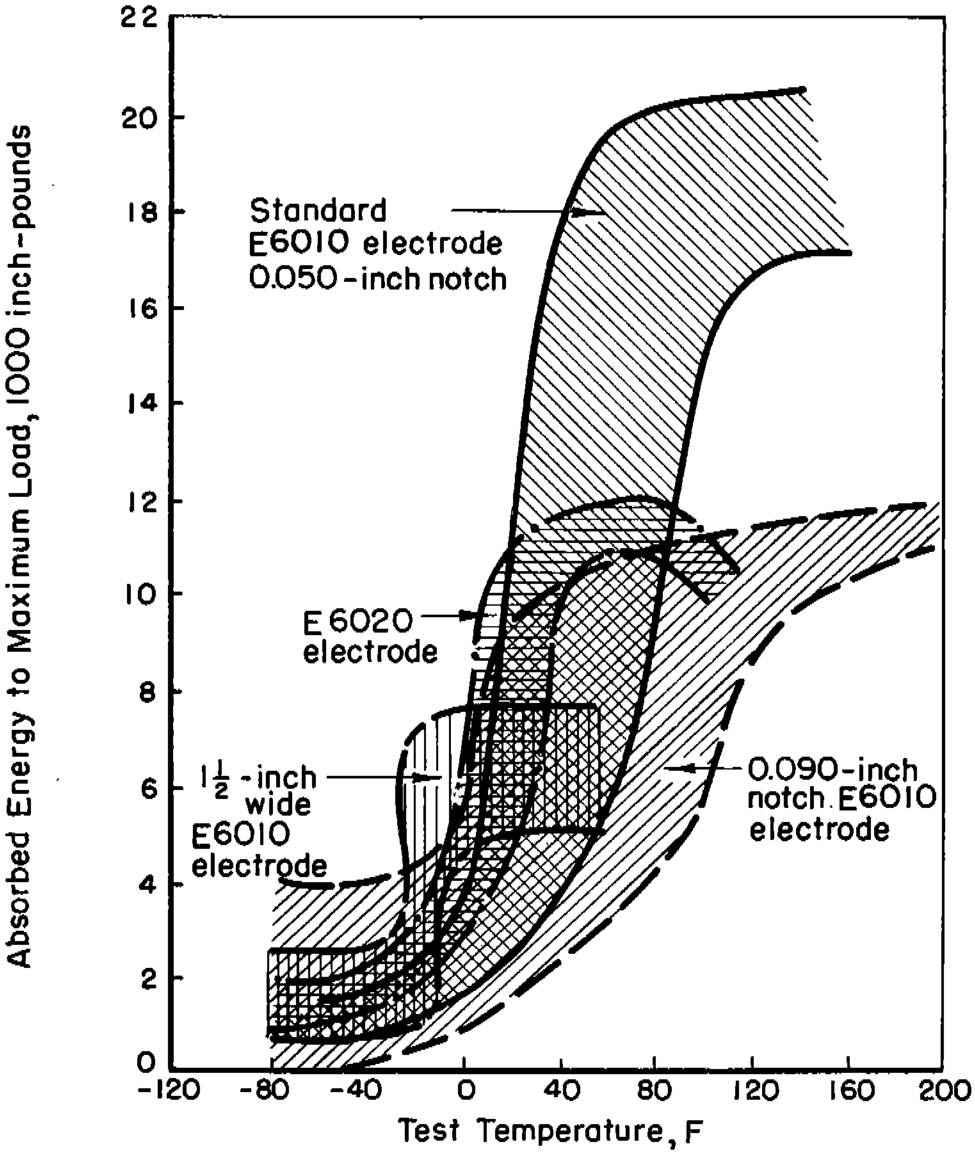


FIGURE 4. ABSORBED ENERGY VS. TEMPERATURE CURVES SHOWING THE EFFECTS OF MODIFICATIONS OF WELDED "Br" STEEL KINZEL-TYPE SPECIMENS ON THE TRANSITION TEMPERATURE RANGE.

0-17136

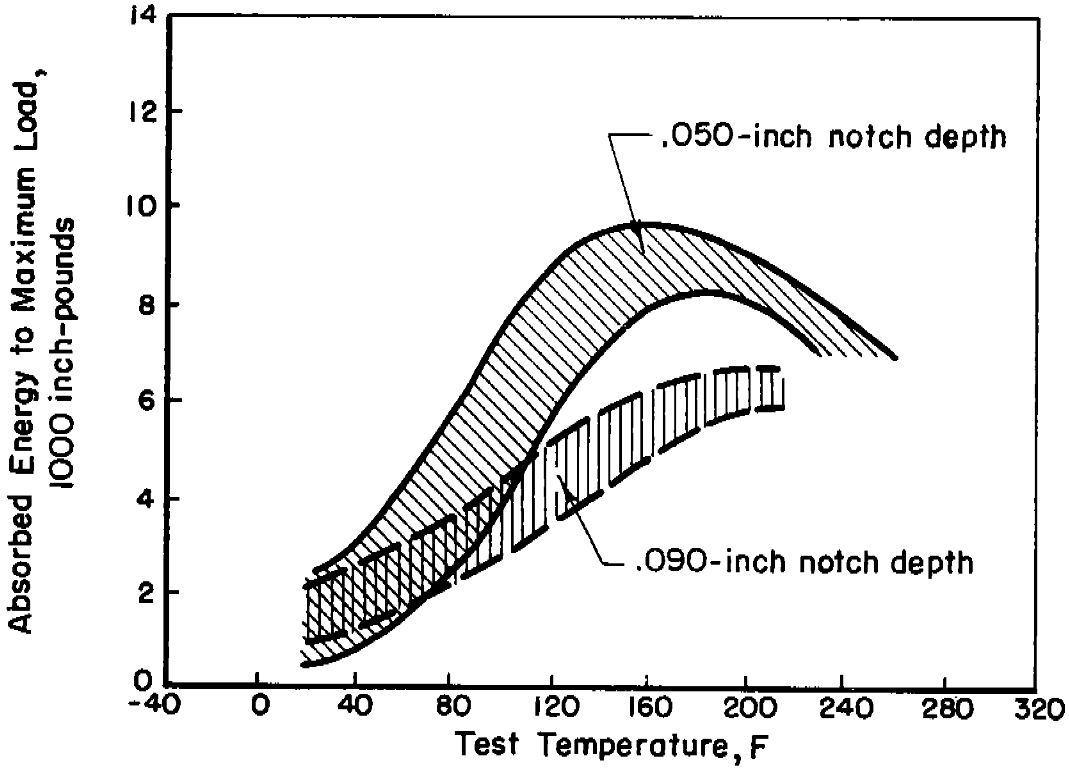


FIGURE 5. EFFECT OF NOTCH DEPTH ON TRANSITION TEMPERATURE RANGE OF WELDED "C" STEEL KINZEL-TYPE SPECIMENS.

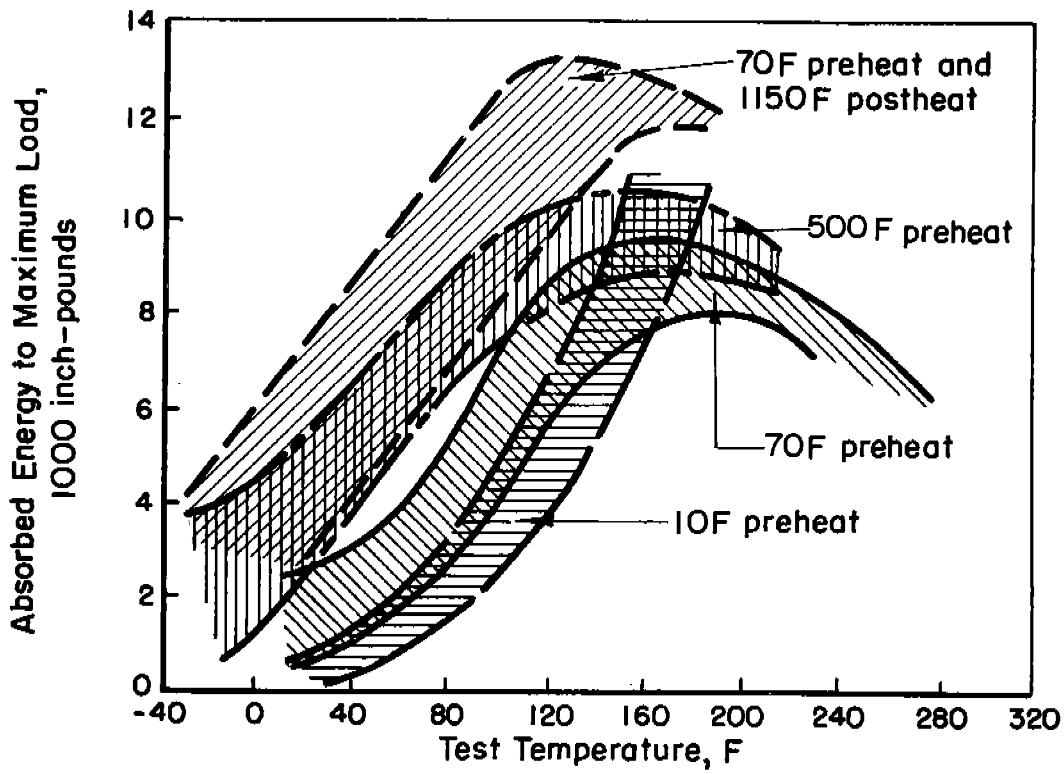


FIGURE 6. EFFECT OF PREHEAT AND POSTHEAT ON TRANSITION TEMPERATURE RANGE OF WELDED "C" STEEL KINZEL-TYPE SPECIMENS.

0-17138

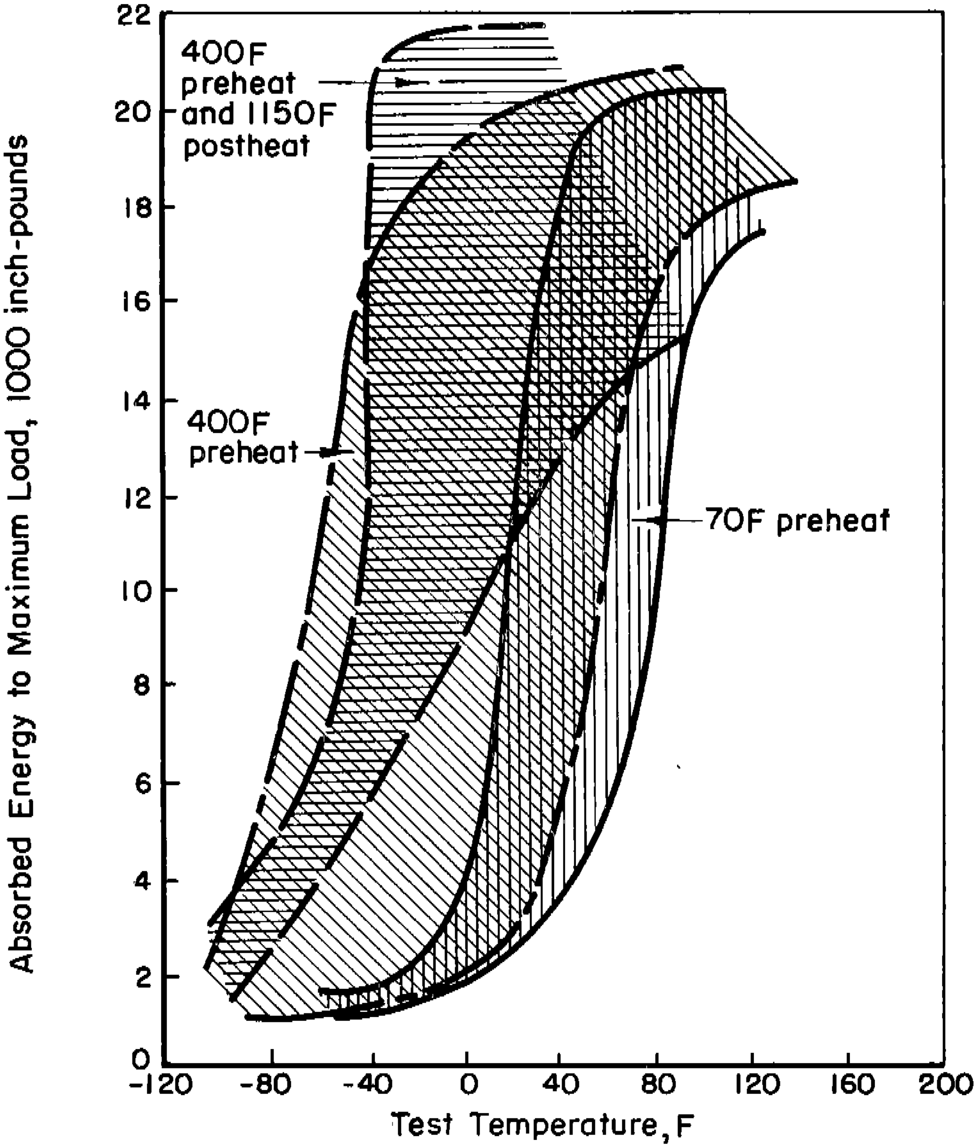


FIGURE 7. EFFECT OF PREHEAT AND POSTHEAT ON TRANSITION TEMPERATURE RANGES OF WELDED KINZEL-TYPE SPECIMENS OF "Br" STEEL.

0-17137

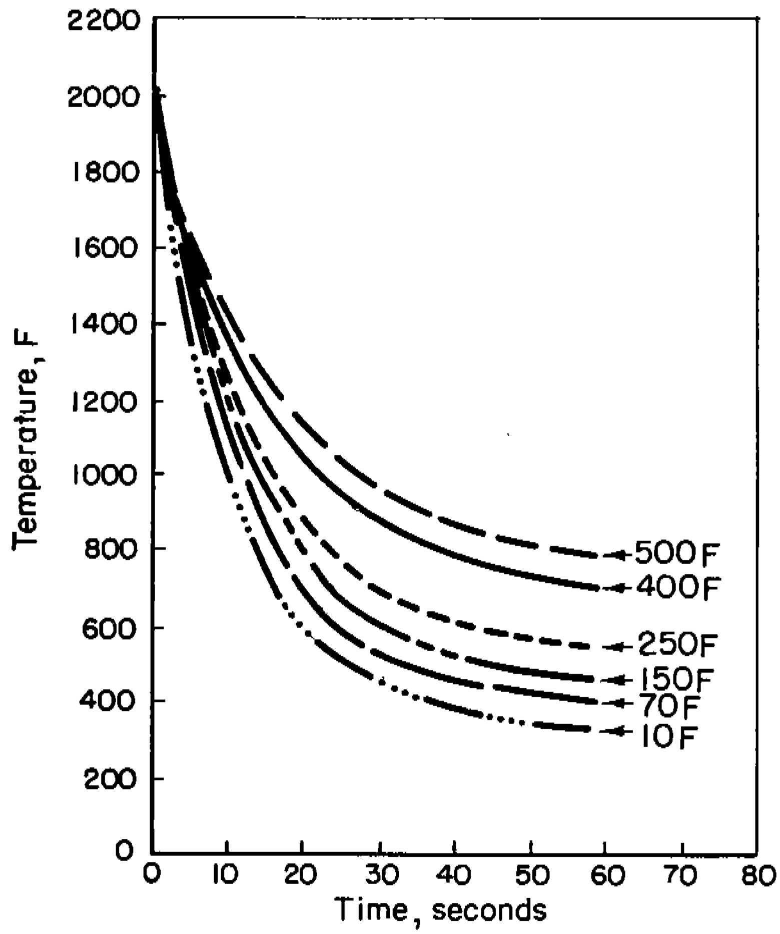


FIGURE 8. AVERAGE COOLING CURVES ON KINZEL-TYPE SPECIMENS USING 10, 70, 150, 250, 400 AND 500F PREHEATS.

0-17139

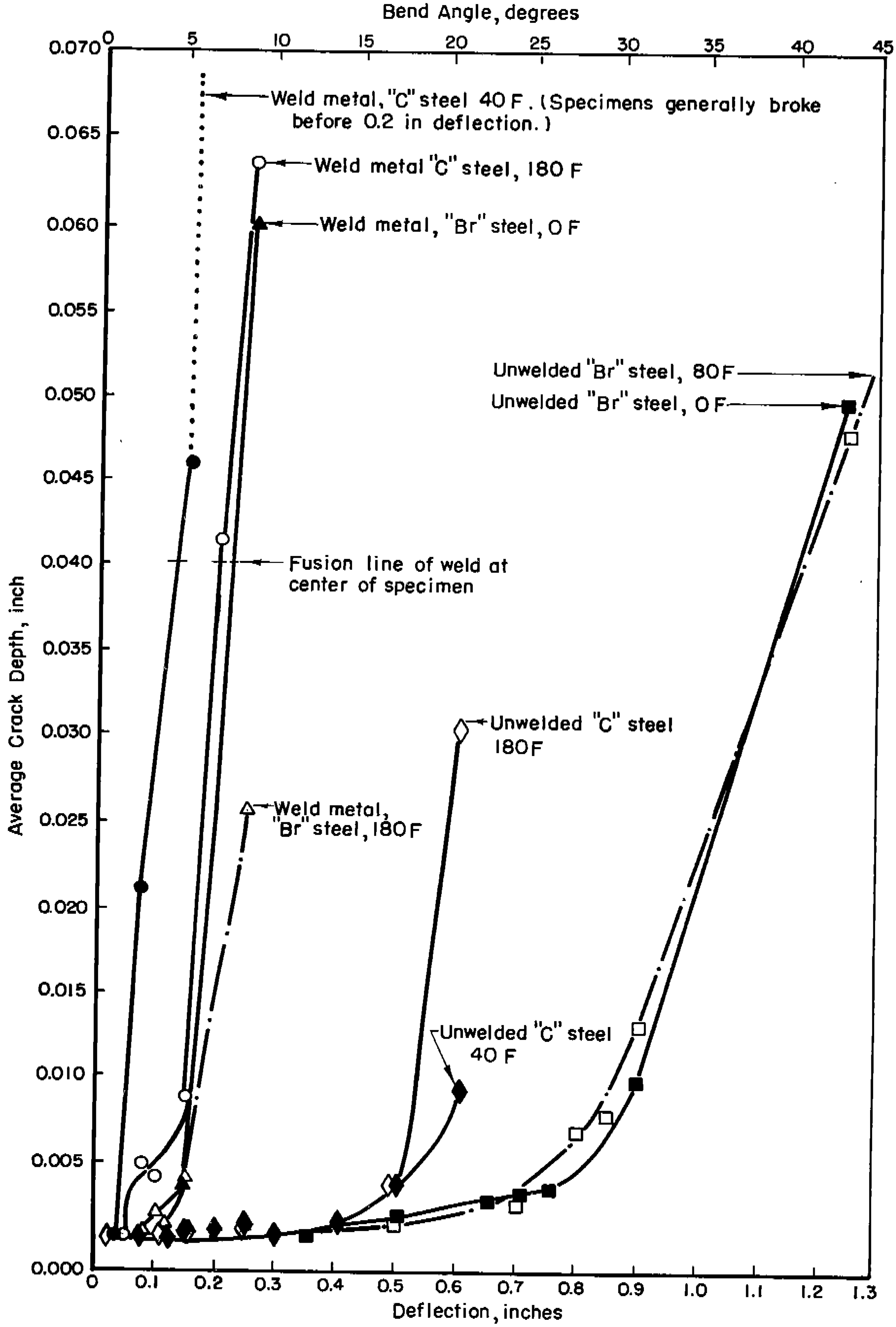


FIGURE 9. DEPTH OF CRACKS IN WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEEL, TESTED AT VARIOUS TEMPERATURES, AND VARIOUS DEFLECTIONS AT MID-SPAN.

O-17140

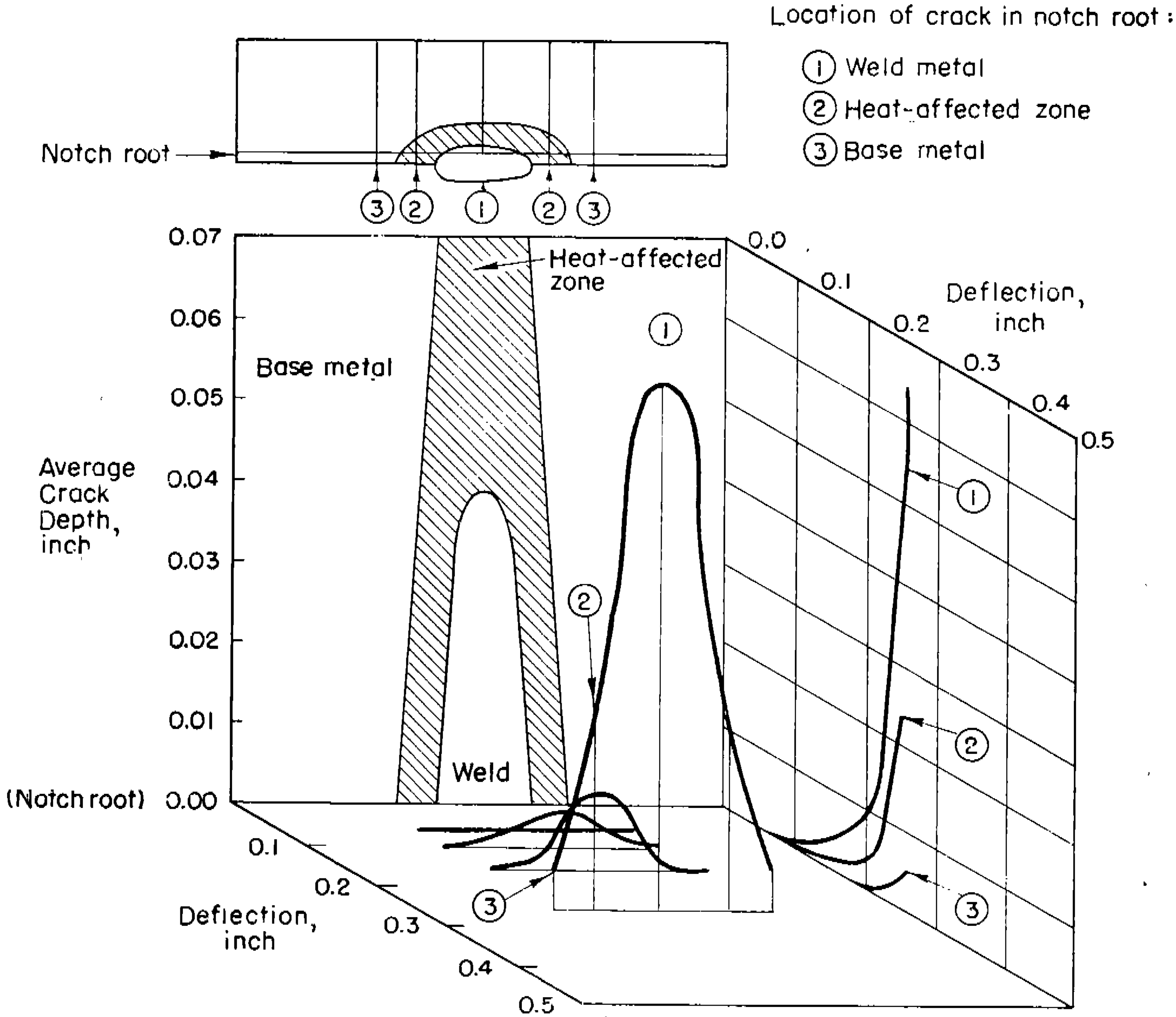


FIGURE 10 CRACK PROPAGATION IN WELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 180 F.

NOTE: THICKNESS OF WELD AND HEAT AFFECTED ZONE IS MAGNIFIED 100 TIMES AS SHOWN.

0-17076

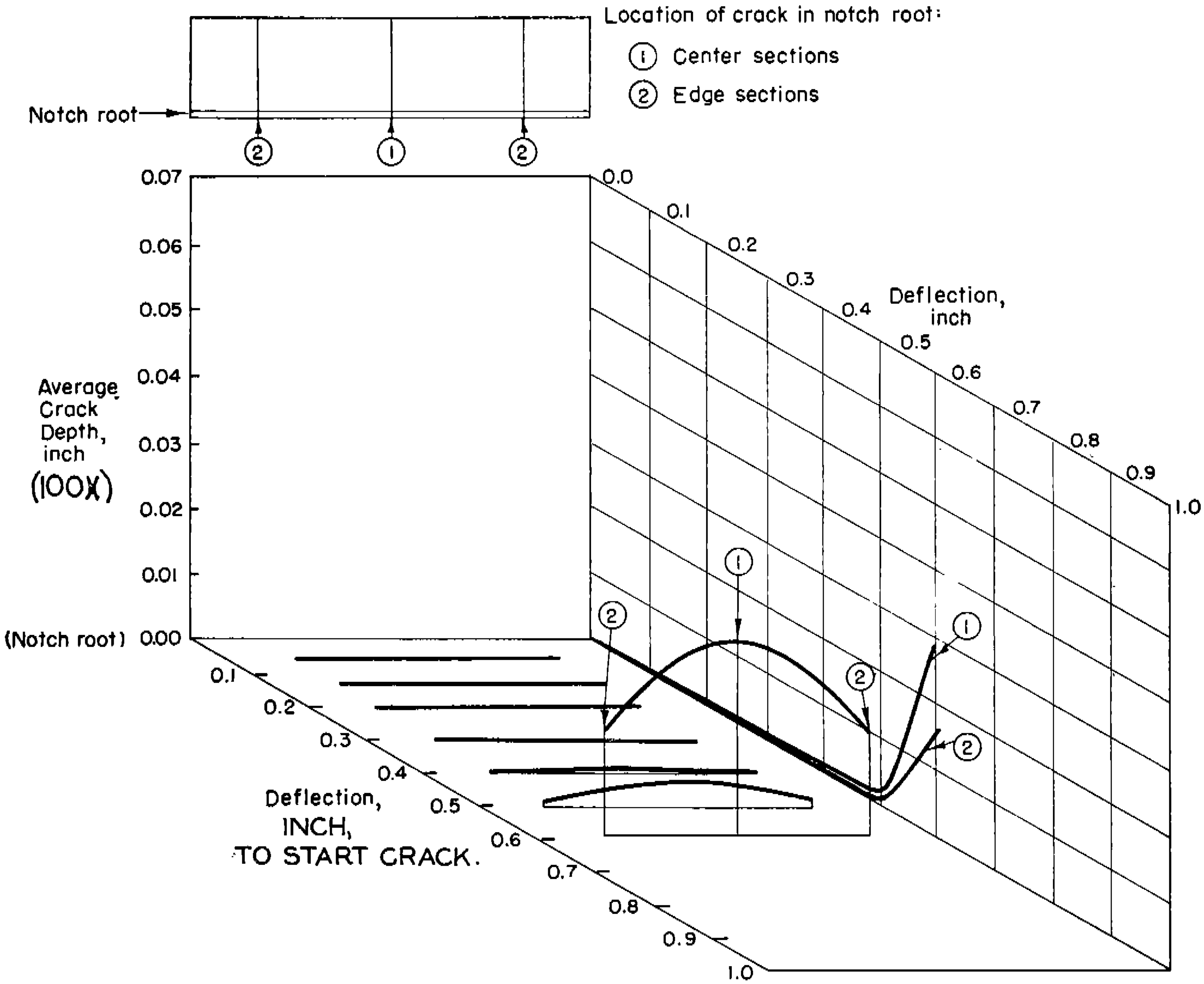


FIGURE 11. CRACK PROPAGATION IN UNWELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 180 F.

0-17077

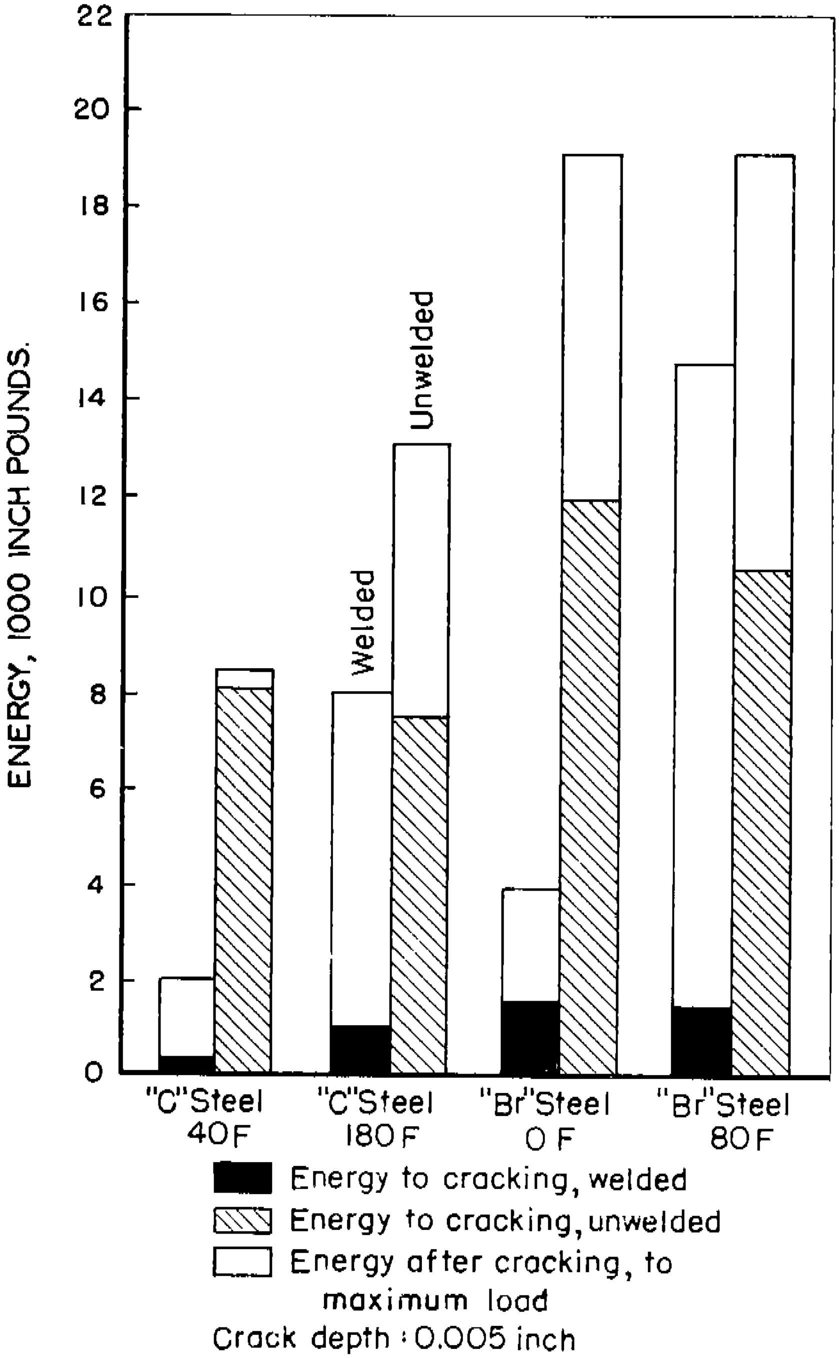


FIGURE 12. COMPARISON OF ENERGY TO CRACKING AND ENERGY AFTER CRACKING ABSORBED BY WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEELS.

0-17081

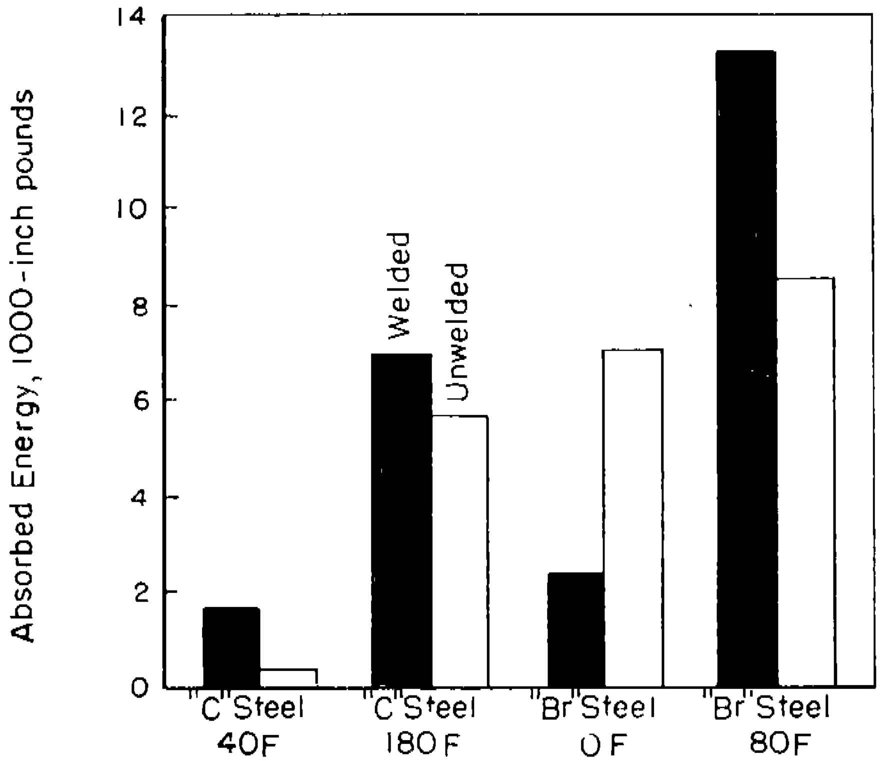
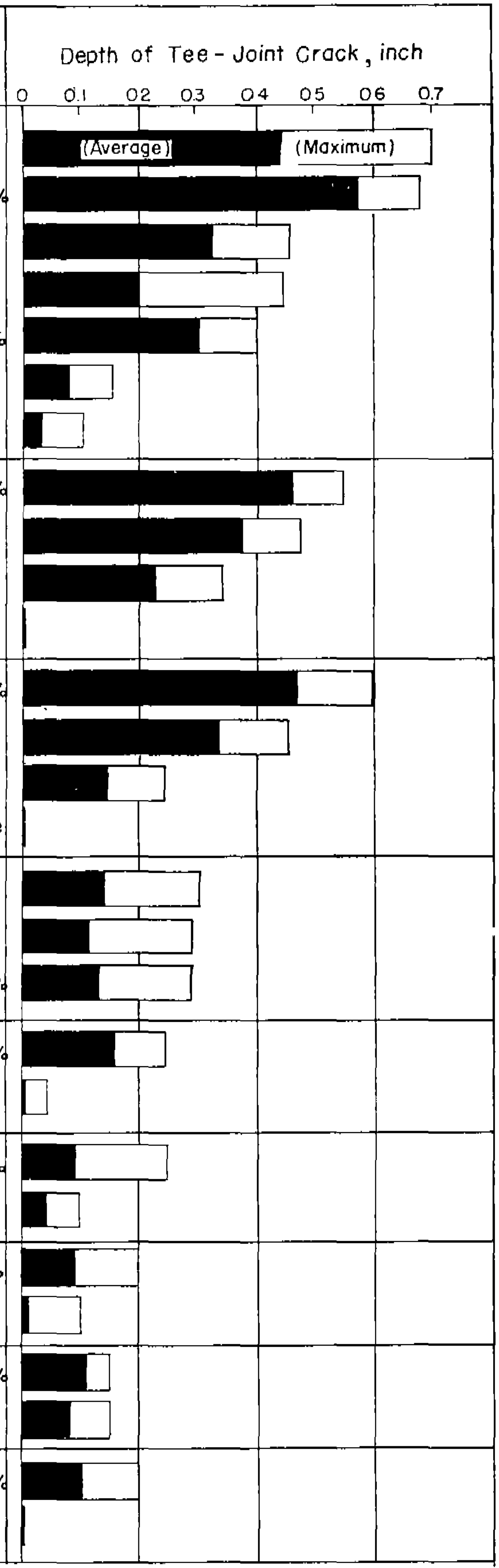


FIGURE 13. ENERGY AFTER CRACKING ABSORBED BY WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEELS.

O-17082

Heat No.	Test No	Electrode Class	Length of Tee, inches	Varied Test Condition
66P-193-1 (36%)(1) CLASS"C"	AC-214	E6010	36	Standard test
	AC-251	E7015	24	Brand B, moisture 0.27%
	AC-250	E6010	24	Standard test
	AC-252	E7015	24	Brand A, dried to 0.18 % moisture
	AC-233	E7015	24	Brand A, moisture, 1.03%
	AC-253	E6010	24	400 F preheat
	AC-250H	E6010	24	Homogenized
21P169-1 (16%)(1) CLASS"C"	AC-271	E7015(2)	24	Brand C, moisture < 0.4%
	AC-257	E6010	36	Standard test
	AC-263	E6010	24	Standard test
	AC-274 AC-276	E6010	24	Balanced weld sequence
71Y354 (15%)(1) CLASS"C"	AC-272	E7015(2)	24	Brand C, moisture < 0.4%
	AC-247	E6010	36	Standard test
	AC-284	E6010	24	Standard test
	AC-275 AC-277	E6010	24	Balanced weld sequence
71P200-1 (0%)(1) CLASS"C"	AC-256	E6010	36	Standard test
	AC-262	E6010	24	Standard test
	AC-270	E7015(2)	24	Brand C, moisture < 0.4%
71Y593 (0%)(1) CLASS"C"	AC-273	E7015(2)	24	Brand C, moisture < 0.4%
	AC-265	E6010	24	Standard test
24P266-1 (7%)(1) CLASS"B"	AC-267	E7015(2)	24	Brand C, moisture < 0.4%
	AC-259	E6010	24	Standard test
72P236-1 (1%)(1) CLASS"B"	AC-266	E7015(2)	24	Brand C, moisture < 0.4%
	AC-258	E6010	24	Standard test
83Y578 (1%)(1) CLASS"B"	AC-269	E7015(2)	24	Brand C, moisture < 0.4%
	AC-261	E6010	24	Standard test
66Y583 (0%)(1) CLASS"B"	AC-268	E7015(2)	24	Brand C, moisture < 0.4%
	AC-260	E6010	24	Standard test



(1) Underbead cracking
(2) Electrodes meet Department of Defense Specification MIL-E-986 (Ships)

FIGURE 14. SUMMARY OF TEE-JOINT TEST DATA, SHOWING HOW VARIATION IN TEST CONDITIONS AFFECTS DEPTH OF CRACKING IN TEE-JOINT SPECIMENS

O-17029

APPENDIX A

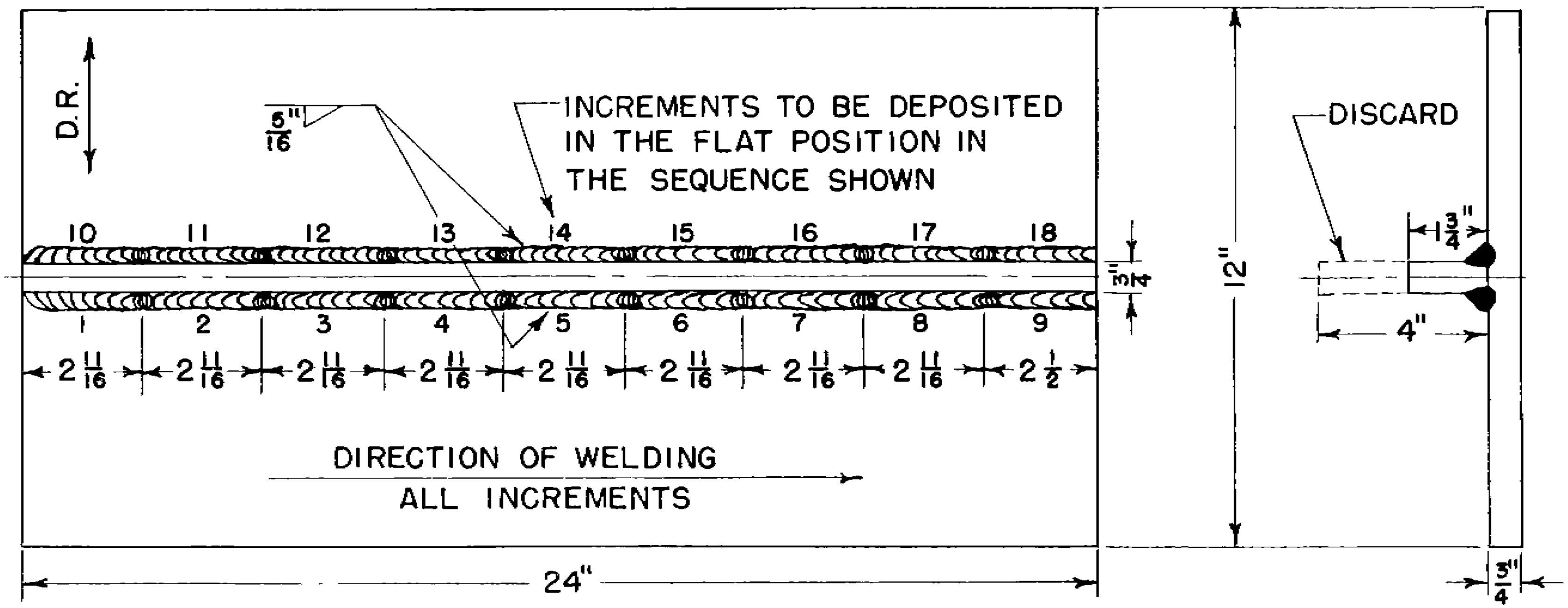
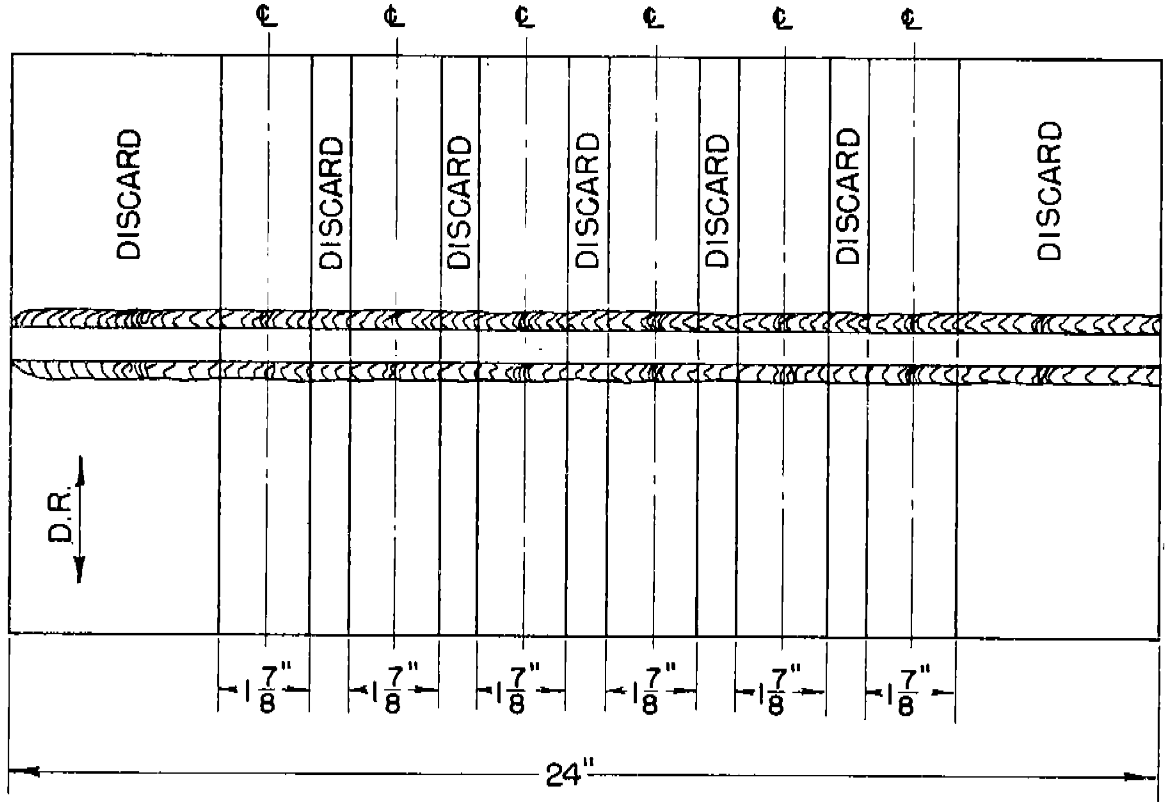


FIGURE A-1. WELDING DETAILS FOR TEE-BEND SPECIMEN MADE FROM 3/4" PLATE

0-8644

CENTERLINE FOR EACH SPECIMEN
IS LOCATED AT THE START OF
EACH WELD INCREMENT



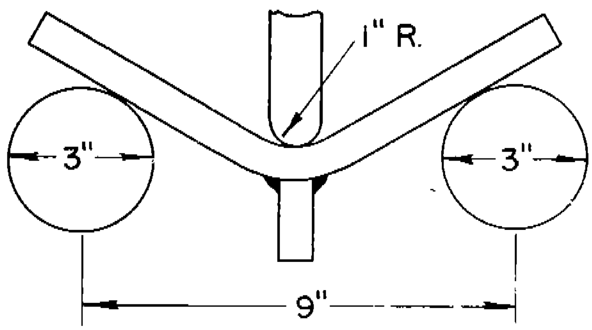


FIGURE A-2. MACHINING AND TESTING DETAILS FOR TEE-BEND SPECIMEN

0-8645

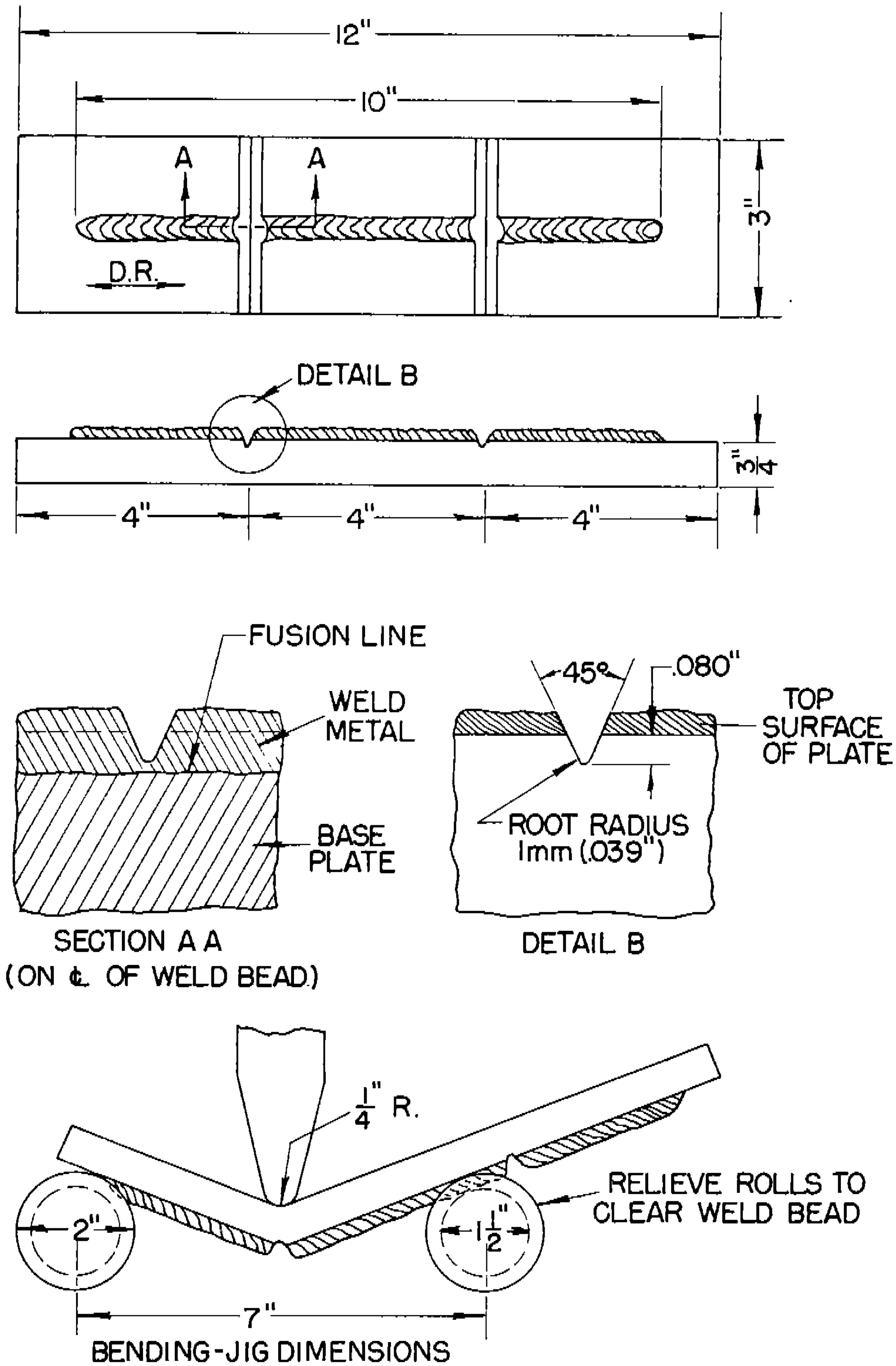


FIGURE A3. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCHES (LEHIGH DESIGN)

0-8642

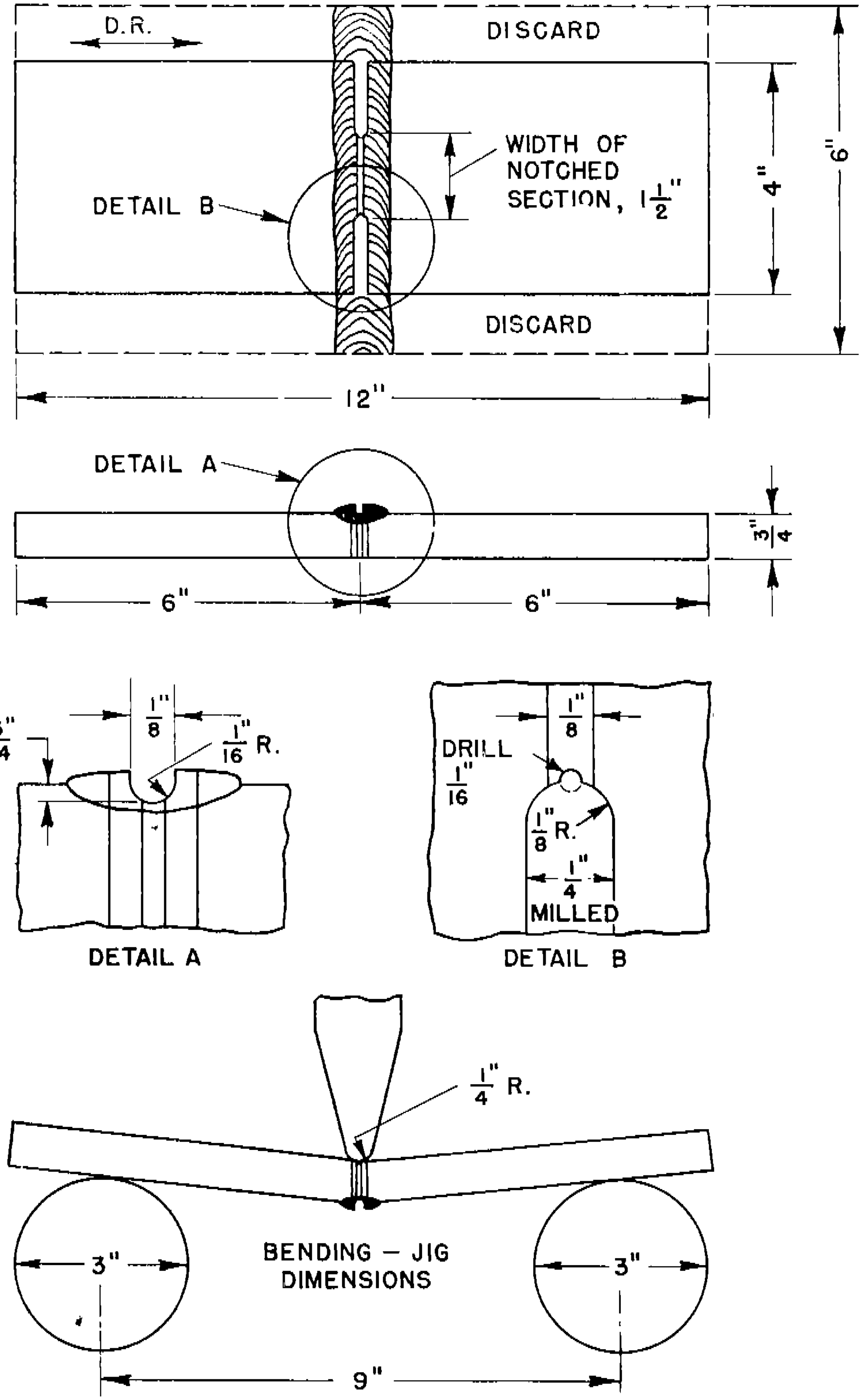


FIGURE A-4 BEND SPECIMEN WITH TRANSVERSE NOTCHED WELD BEAD AND EDGE NOTCHES (NAVAL RESEARCH LABORATORY DESIGN)

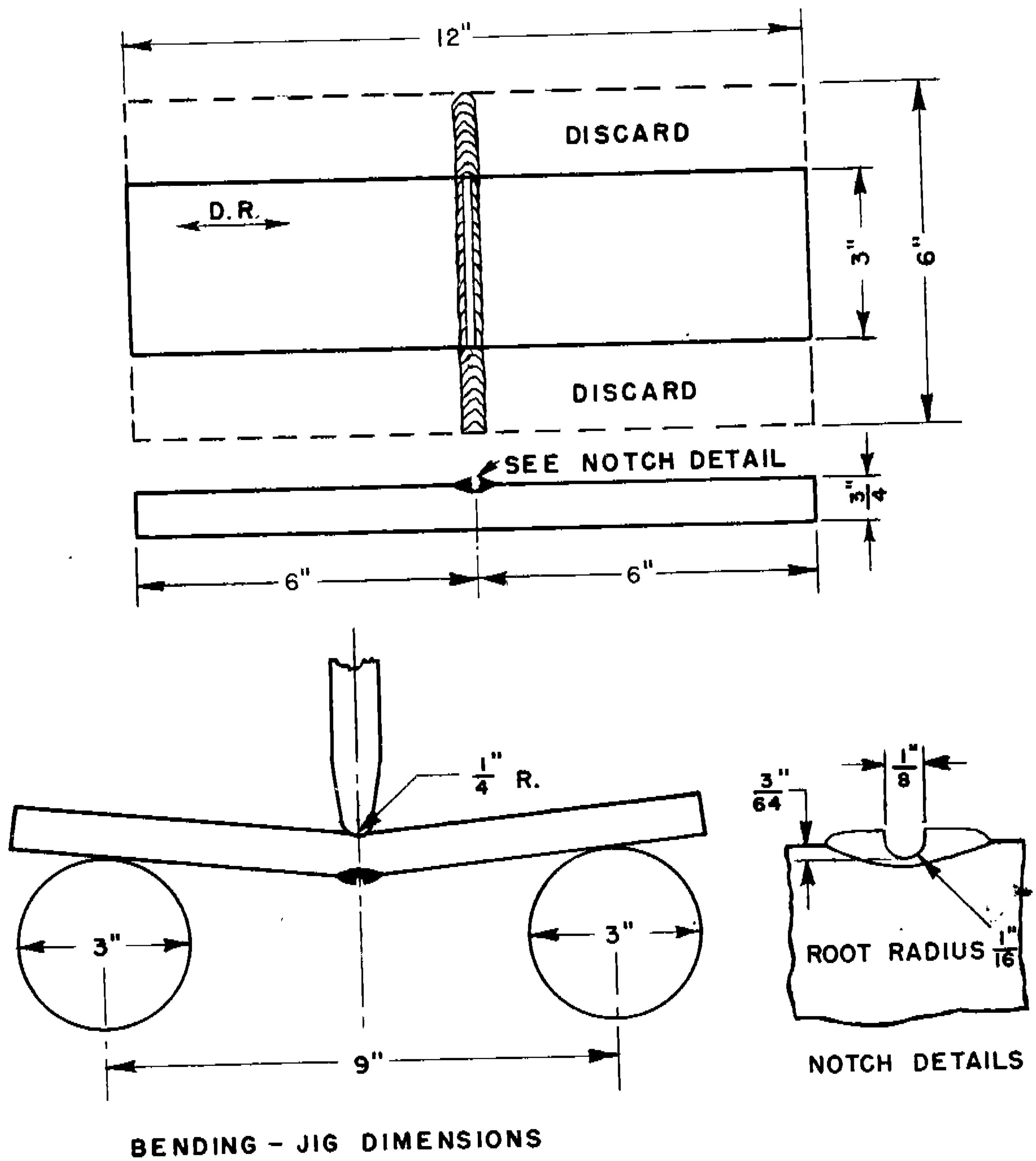


FIGURE A-5. BEND SPECIMEN WITH TRANSVERSE WELD BEAD AND TRANSVERSE NOTCH (JACKSON—TYPE SPECIMEN) 58529

WELDING SCHEDULE GIVEN IN TABLE B-1

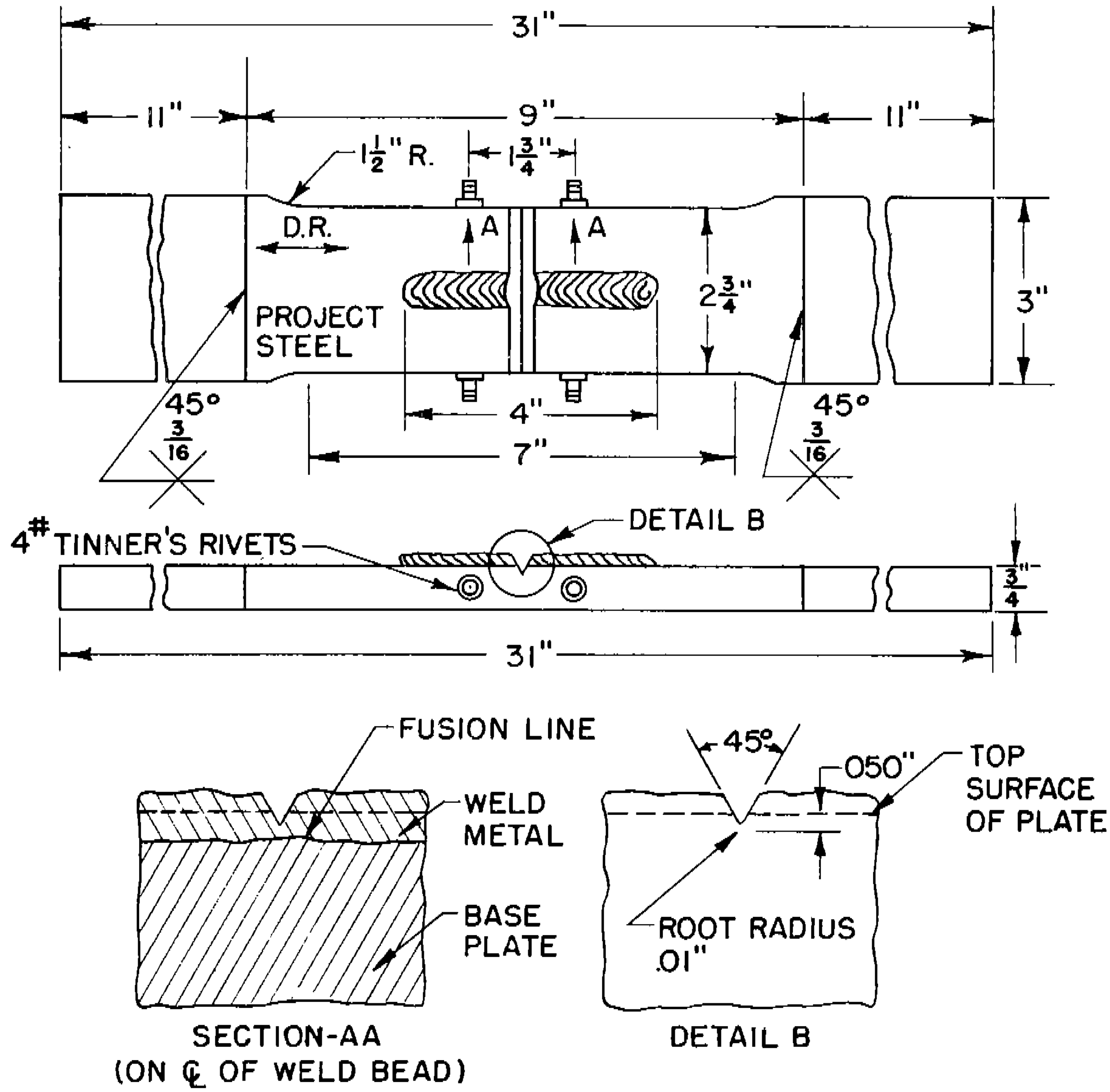


FIGURE A-6 TENSION SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH

O-12163

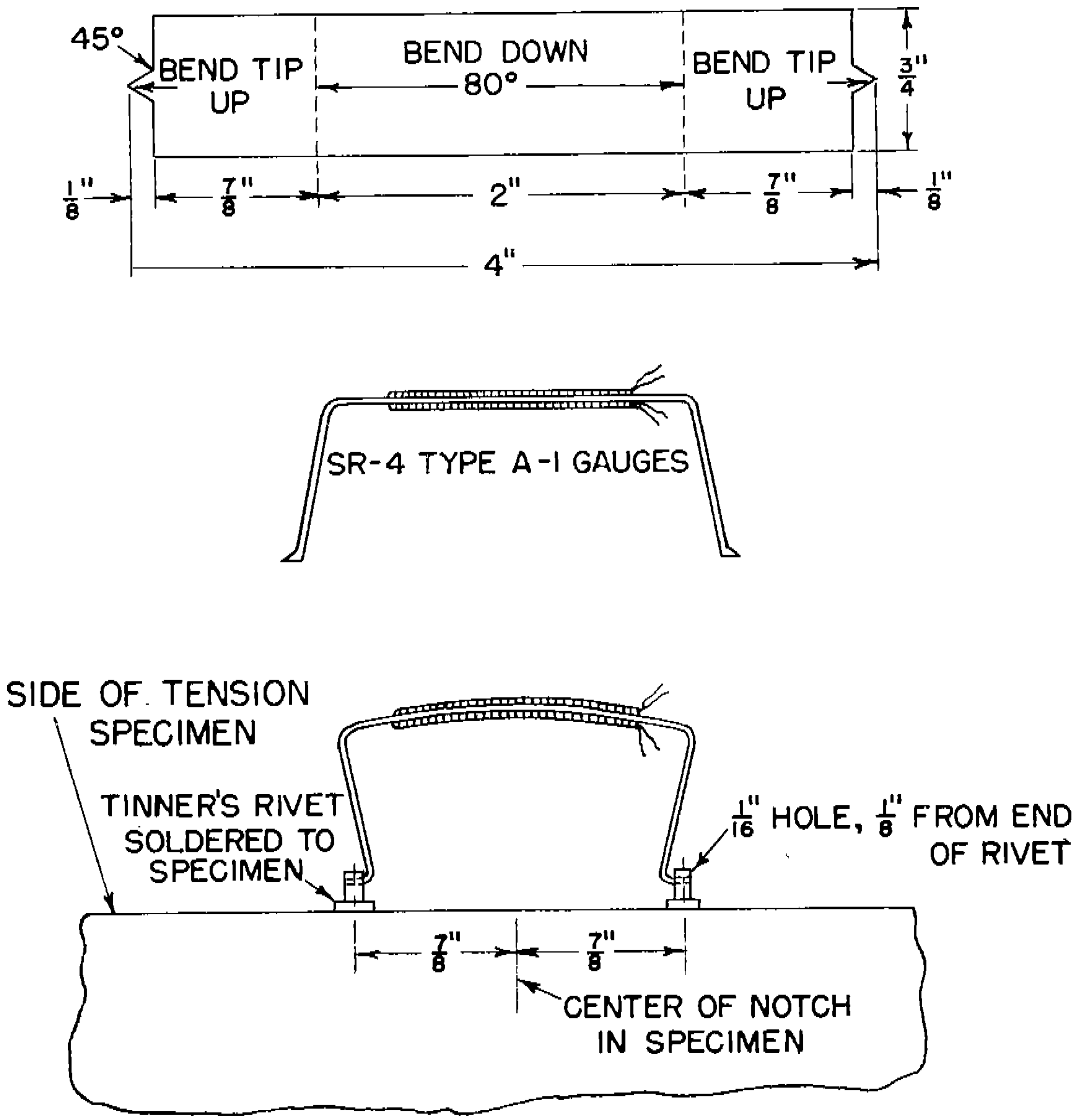


FIGURE A-7. DETAILS OF CLIP-TYPE COMPENSATING STRAIN GAUGE SHOWING ATTACHMENT TO TENSION SPECIMEN (DEVELOPED AT UNIVERSITY OF CALIFORNIA)

0-12164

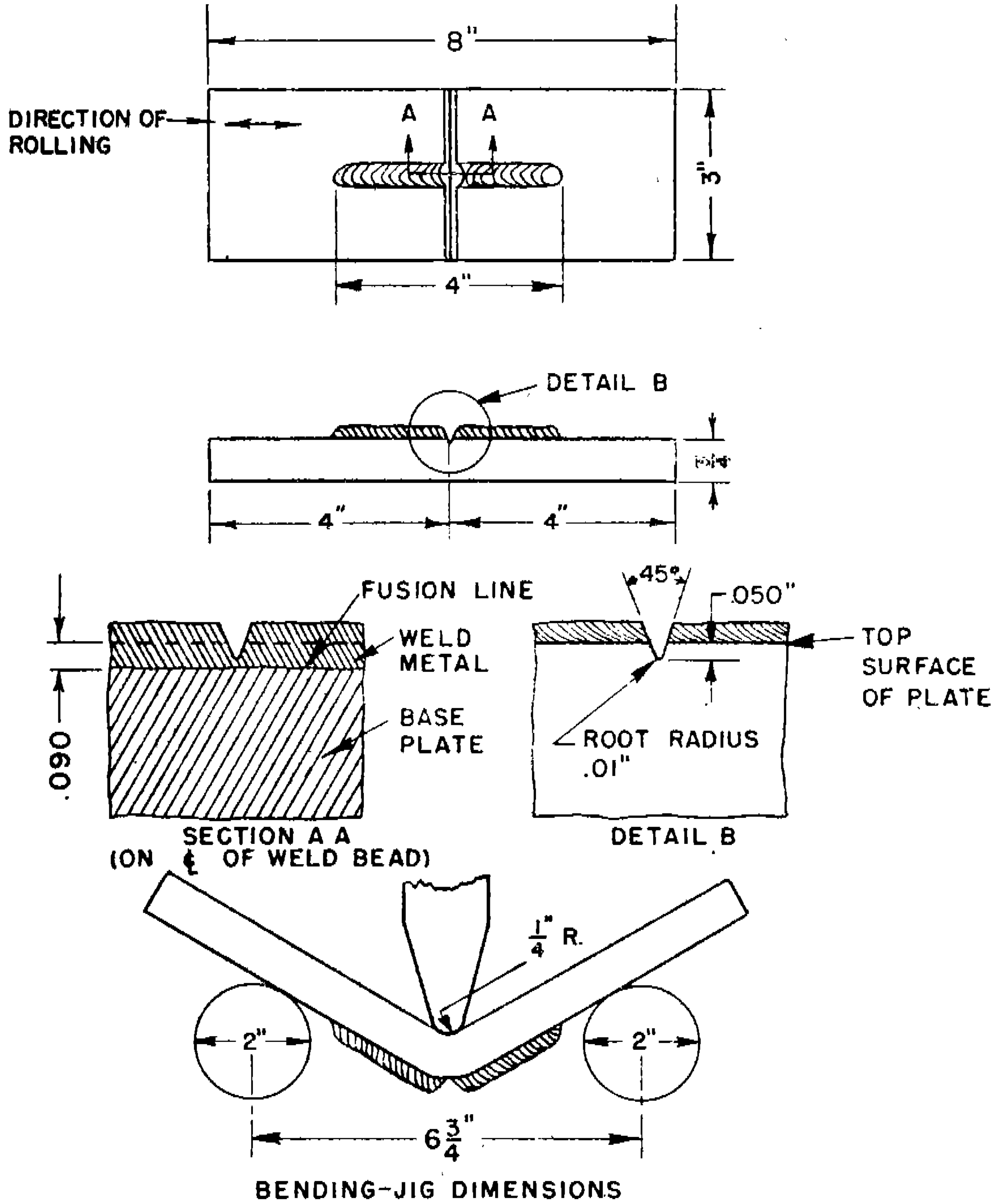


FIGURE A-8. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN)

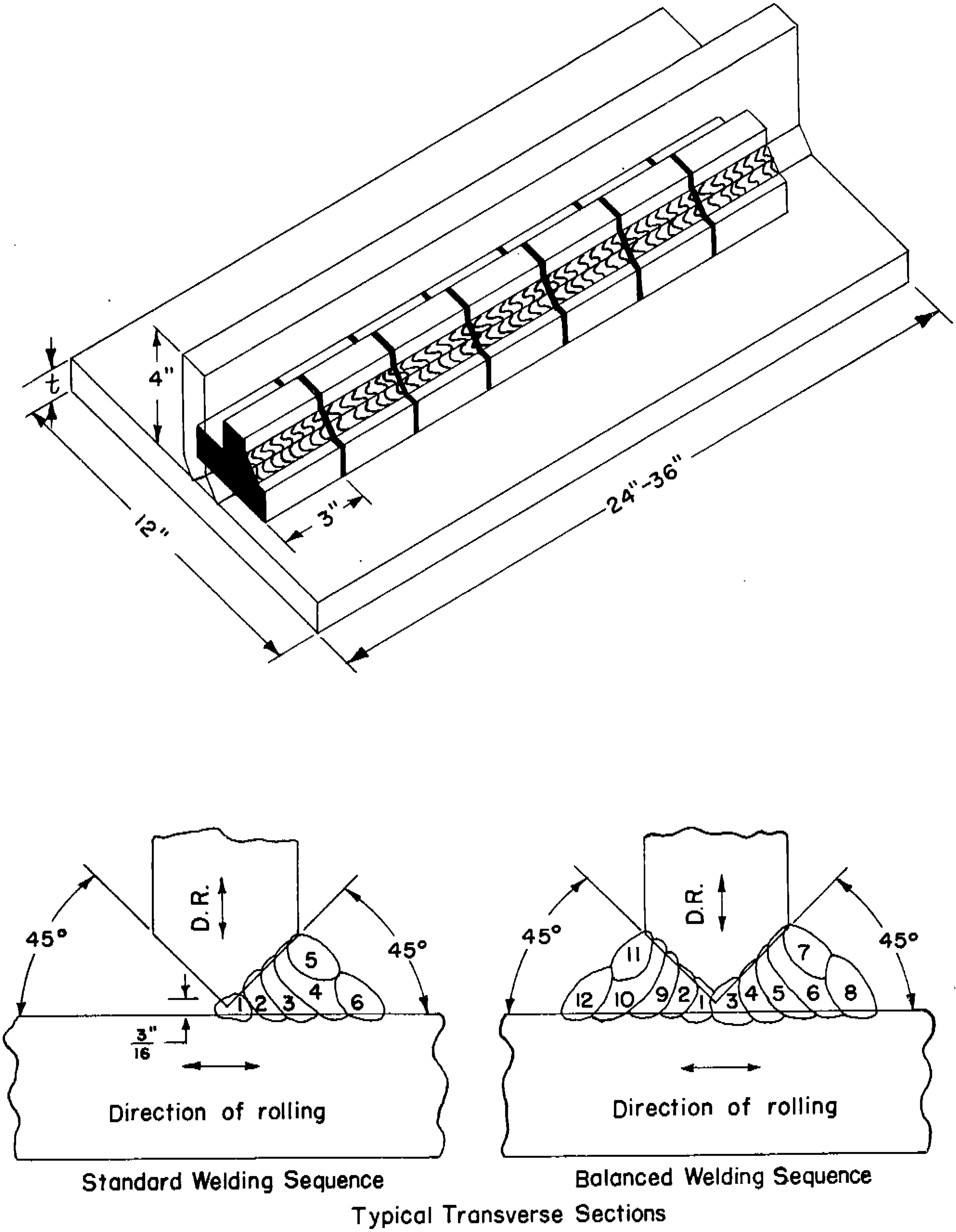


FIGURE A-9. DETAILS OF TEE-JOINT SPECIMENS SHOWING LOCATION OF SECTIONS

0-17028

A P P E N D I X B

TABLE B-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
Average welding current, amperes	175	175	145	175	175
Average arc volts	27	27	25	27	27
Average 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 temperature, F	75	75	75	75	75
Cooling medium	Air	Air	Air	Air	Air

TABLE B-2. MECHANICAL AND CHEMICAL PROPERTIES OF PROJECT STEELS "B_r", "C", "A", AND "W"

Steel Code Letter	Type of Steel	Thickness, In.	Steel Condition	Mechanical Properties: Yield Point, psi	Ultimate Strength, psi	Elongation in 2 In., %	Elongation in 8 In., %	Reduction in Area, %	Hardness Rockwell B
B_r(1)(2)	Semikilled	3/4	As rolled	32,200-34,600	55,600-58,600	43	33	71-58	58-63
C(1)(2)	Semikilled	3/4	As rolled	34,500-37,600	61,500-68,500	43-35	32	63-50	66-69
A(1)(2)	Semikilled	3/4	As rolled	35,400-36,700	57,600-62,900	45	37-32	62-53	58-62
W(3)	Killed	3/4	As rolled	37,200	62,500	-	30	-	-

Steel Code Letter	Chemical Composition, %: C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	Sn	N
B_r(1)	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(1)	0.24	0.43	0.05	0.012	0.026	0.03	0.02	0.005	0.03	0.016	0.003	0.009
A(1)	0.26	0.50	0.03	0.012	0.039	0.03	0.02	0.006	0.03	0.012	0.003	0.004
W(3)	0.20	0.52	0.23	0.013	0.010	0.07	0.10	0.010	0.17	0.006	0.035	0.005

(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.
(3) Kahn, N. A., and E. A. Imbembo, "Notch Sensitivity of Steel Evaluated by the Tear Test", Welding Journal, April 1949.