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PROGRESS REPORT

ON

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

BY

F. R. BAYSINGER, R. G. KLINE, P. J. RIEPPEL
and C. B. VOLDRICH

BATTELLE MEMORIAL INSTITUTE
Under Bureau of Ships Contract NObs-48015

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 Research Council
Washington, D. C.
October 1, 1951

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2101 CONSTITUTION AVENUE, WASHINGTON 25, D. C.

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OF THE
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

October 1, 1951

Chief, Bureau of Ships
Code 343
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Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-40 entitled "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships." This report has been submitted by the contractor as a Progress Report of the work done on Research Project SR-100 under Contract NObs-48015 (1773) between the Bureau of Ships, Navy Department 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, Navy Department and the National Academy of Sciences.

Very truly yours,

R. F. Mehl

R. F. Mehl, Chairman
Committee on Ship Steel

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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REPORT

on

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

to

BUREAU OF SHIPS,
NAVY DEPARTMENT

by

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

CONTRACT NObs-48015 (1773)
INDEX NO. NS-011-067

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ABSTRACT

This report covers work done during the period of July 1, 1949, to October 15, 1950.

This program was requested by the Project Committee and the Committee on Ship Steel to secure a true appraisal of the notched-bead bend test as a test for evaluating performance of ship steels in large welded structures. It was throught that a determination of the fracture mechanism should accomplish this by showing if welding makes the steel in the heat-affected zone of the weld more susceptible to brittle failure or if some feature of the fracture process makes the test unsuited to that purpose.

This investigation covers crack initiation and propagation in Kinzel-type specimens made from "Br" and "C" steels. It also covers miscellaneous

studies of fracture in Lehigh specimens; in special Kinzel-type specimens taken from "C" steel weldments of the kind being investigated by Case Institute of Technology (SSC Project SR-99)[10*], and specimens of a steel containing 0.33 per cent carbon and 0.88 per cent manganese.

Crack Initiation

In unwelded and welded Kinzel-type specimens of "B_r" and "C" steels, small discontinuous cracks or surface tears were present in the root of the notch after the specimens were deflected by the small amount of 0.050 inch at midspan, at temperatures either above or below the transition range. In welded specimens, these cracks or surface tears occurred across the entire width of the specimen in the weld metal, heat-affected zone, and unaffected base metal. In unwelded specimens, they also appeared all across the width of the specimen. These superficial tears are inconsequential and are discussed here only for the sake of completeness, although one of them, favorably situated by chance, initiates the crack that develops into the fracture.

Crack Propagation

In any given specimen cross section, it was found that one of the small cracks or tears usually grew faster than the others, and on further deflection, actual propagation was confined to it. This tear elongated and ultimately united with others to form the continuous crack.

In welded specimens of "Br" and "C" steels, a crack propagated in the weld metal almost immediately after 0.050 deflection. In unwelded specimens, the crack did not propagate until much larger deflection, though

* Superscripts indicate references listed in the Bibliography.

the initial tears opened up in the midwidth area of the specimens. The test temperature appeared to have but little effect on the deflection at which cracks began to propagate in both the welded and unwelded specimens.

The significant feature here is the finding that the crack initiated in the welded specimen in the deposited weld metal at a very slight deformation, whereas, the crack of the unwelded specimen was delayed until a much greater deflection had been produced. This related to the behavior in and above the transition range. Specimens which failed in a cleavage fashion could not be studied by the technique used.

Miscellaneous Crack Studies

Lehigh-Type Specimen

In a few "C" steel Lehigh-type specimens studied, cracks were found to initiate in the heat-affected zone. The crack behavior was similar to that described for Kinzel specimens.

Kinzel-Type Specimens of a 0.33 Carbon Steel

Kinzel-type specimens prepared from a 0.33 per cent carbon and 0.88 per cent manganese steel cracked first in the heat-affected zone.

Correlation with Studies at Case Institute of Technology

Special Kinzel-type specimens were made from double-vee butt-welded joints of "C" steel similar to those studied at the Case Institute of Technology (10). Case Institute has reported a zone of low notch ductility in the outer regions of the heat-affected zones of the welds when specimens from that locality were compared with specimens from adjacent regions. It was desired to determine if cracks would initiate in this area when it was tested simultaneously with other parts of the weld and heat-affected zones. Although surface tears were first observed in the heat-affected zone and zone of low notch ductility in specimens tested at -40 F and -80 F, the cracks which propagated first were in weld metal.

INTRODUCTION

This is the fourth progress report on the investigation entitled "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships", being conducted for the Ship Structure Committee, under the Navy Department, Bureau of Ships, Contract NObs-48015, Index No. NS-011-067, Project SR-100.

The three previous reports have covered various phases of the investigation which are described briefly as follows: (a) a survey of published and unpublished reports which was made to appraise the various kinds of tests used in the past to study strength, ductility, and transition ranges of welded joints in structural steel (8), (b) tests made on the project steels (B_r, C, A, and W) with selected specimens and modifications thereof, in an attempt to duplicate the transition temperatures that were obtained for these steels from the full-scale hatch corner test specimens studied at the University of California (8, 9, 12), (c) a study of all-weld-metal bend specimens made with E6010 and E6020 electrodes (9), and (d) tests on "B_r" and "C" steels to determine the effect of preheat and postheat treatments on the transition ranges of Kinzel-type bend specimens.(12)

This report covers the detailed mechanism of crack initiation and propagation in Kinzel-type specimens of "B_r" and "C" steels. Welded and unwelded specimens were tested above and below the transition temperatures as determined by previous work. The principal objective of this phase of the investigation was to determine when and where cracks occurred, and how they propagated in the Kinzel-type specimen.

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 few tests were made with another steel which contained 0.33 per cent carbon. This steel will be discussed later in the report. The mechanical properties and chemical compositions of the "B_r" and "C" steels are given in Table 1.

Electrodes

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

SELECTION OF TEST SPECIMEN

The Kinzel-type specimen was selected for these crack studies in order to permit correlation with the results of earlier work with the Kinzel-type specimen on this project (8, 9, 12). Much was known about the effects of modified design and the use of various preheats on test results obtained with this specimen. It was planned that the information gained from the crack studies would be applied to the interpretation of the previous test data.

The weld bead is deposited on this specimen at a normal welding speed using a standard current and voltage for 3/16-inch E6010 electrode. This

TABLE 1. MECHANICAL PROPERTIES AND CHEMICAL COMPOSITION OF PROJECT STEELS "B_r" AND "C"

Steel Code Letter	Type of Steel	Steel Condition	Mechanical Properties (1) (2)					
			Yield Point, psi	Ultimate Strength, psi	Elongation in 2 In., %	Elongation in 8 In., %	Reduction in Area, %	Hardness, Rockwell B
B_r	Semikilled	As rolled	32,200 - 34,600	55,600 - 58,600	46-42	35-33	71-58	58-63
C	Semikilled	As rolled	34,500 - 37,600	61,500 - 68,500	43-35	32-28	63-50	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.

practice was believed desirable, since other tests, in which the welding is done under abnormal conditions, are not typical of normal production procedures. The 0.050-inch-deep notch in the Kinzel-type specimen imposes a stress concentration and, at the same time, leaves some weld metal below the notch.

Inasmuch as the notch subjects the weld metal, heat-affected zone, and base metal to the same stress condition when tested, it was believed that knowledge of which of these zones cracked first in free competition would be valuable in understanding why the Kinzel-type specimens behave as they do, and would give the clue to the correct interpretation of the results.

For comparison with welded specimens, unwelded Kinzel-type specimens of prime plate were included in the investigation.

PREPARATION OF TEST SPECIMEN

The details of the Kinzel-type specimen are shown in Figure 1. The coupons for the specimen were saw cut from the plates of "B_r" and "C" steels, and the surfaces were cleaned by grit blasting. The direction of rolling for all specimens was parallel to the longitudinal direction of the finished specimen.

For welded specimens, the weld beads were deposited on the coupons by automatic welding using the following schedule:

AWS electrode classification	E6010
Electrode diameter, inch	3/16
Amperes	175
Arc volts	27
Speed, inch/minute	6
Arc time, seconds	40
Length of weld bead, inches	4
Heat input, joules/inch	44,750

All of the specimens were welded at room temperature and cooled in air.

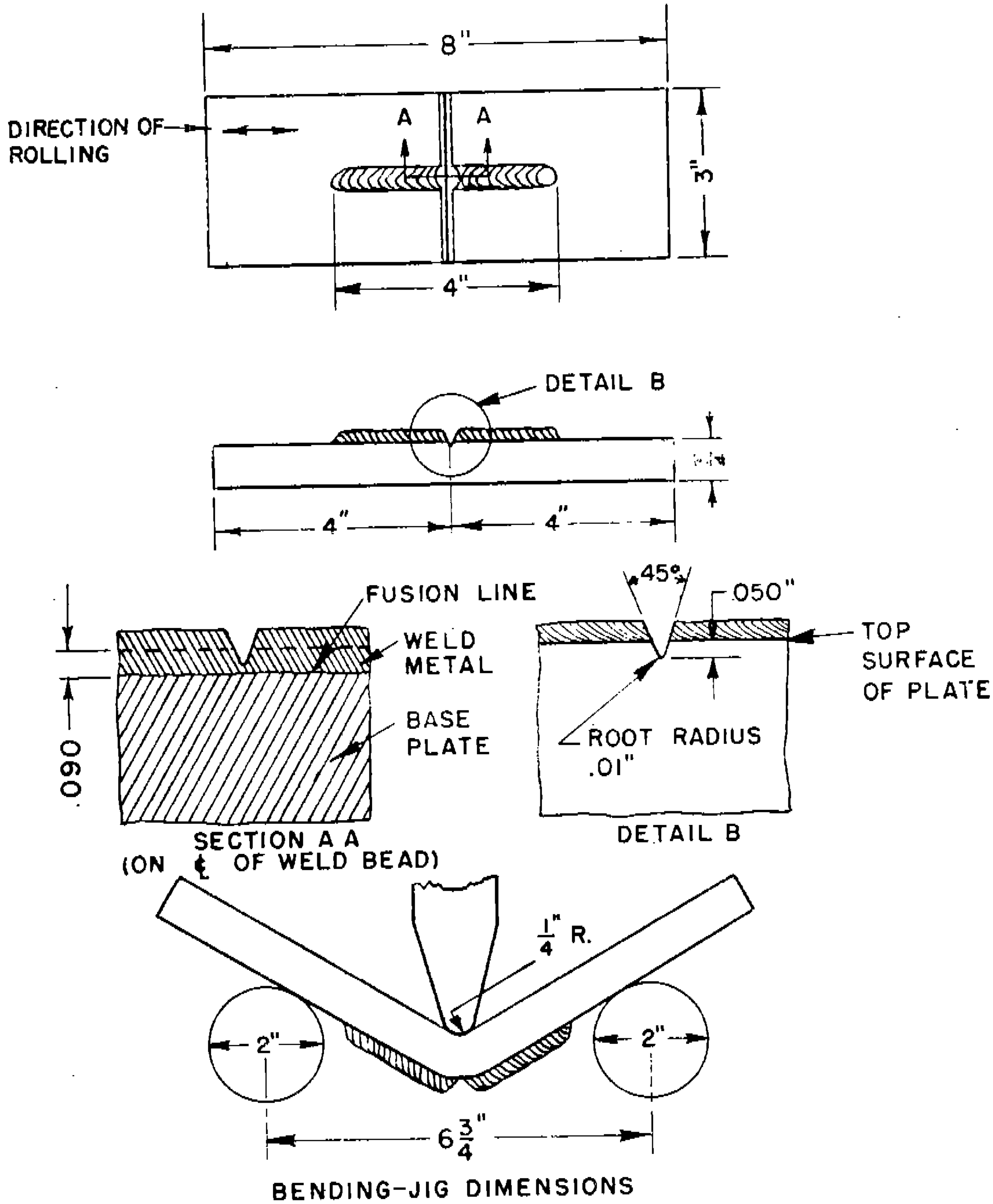

FIGURE 1. BEND SPECIMEN WITH LONGITUDINAL WELD BEAD AND TRANSVERSE NOTCH (KINZEL DESIGN)

The aging time for all specimens between welding and testing was eight days at room temperature. During the aging period, the final machining of the specimens was done according to the sketch shown in Figure 1. The sides of the specimens were finished by grinding and the notches were made with a fly cutter to accurately obtain the prescribed root radius.

Unwelded specimens of the same dimensions were machined from prime plate.

Criteria and Method Used in Determining Testing Temperatures Above and Below the Transition Temperature

As the modes of fracture above and below the transition temperature are shear and cleavage, respectively, it was decided to look for differences in crack initiation and propagation characteristics for these two test conditions as nearly as possible. It would have been desirable to study specimens for a range of temperatures, but the time and budget allotted for this work limited the studies to one temperature above and one temperature in or below the transition range for each steel.

No problem was encountered in the selection of a test temperature above the transition range, which was known from previous work. Specimens will behave ductilely as long as the temperature at which they are tested is above the transition range. However, the selection of a test temperature for brittle fracture was more difficult. If the temperature selected was much below the transition range, the specimens would break abruptly in the bending jig after a small amount of deflection, and make it impossible to study the progress of the fracture. However, it was believed that if a low-test temperature in the transition range were used, the origin of cracking could occur without complete brittle failure of the specimen.

Test temperatures chosen for "Br" steel were 0 F and 80 F for both welded and unwelded specimens. In Figure 2 are shown absorbed energy and fracture appearance curves for "B_r" steel, from data previously reported(12) on this project. The test temperatures are indicated by dotted lines. The 0 F temperature is close to the transition range of welded specimens but much above that of the unwelded specimens. Had a temperature below the transition range of the unwelded specimens been chosen, the welded specimens would have failed completely by cleavage and no fracture data could have been obtained. As a result, the data for unwelded "B_r" steel specimens were nearly identical for both test temperatures, these temperatures being in the ductile range for both cases.

For "C" steel, the test temperatures chosen were 40 F and 180 F for welded and unwelded specimens. As shown in Figure 3, the lower test temperature of 40 F was at the bottom of the transition ranges of both the unwelded and welded specimens. In fact, some of the welded specimens failed by cleavage at this temperature.

It was observed in this study that differences in crack initiation of specimens tested above and below the transition range are negligible. Temperature apparently had more influence on how cracks propagated in these specimens. This compares with similar observations made previously by another investigator(6). However, as will be discussed later, it is more pertinent to consider the difference between absorbed energy values for welded and unwelded specimens at a given temperature. This study has given information which can

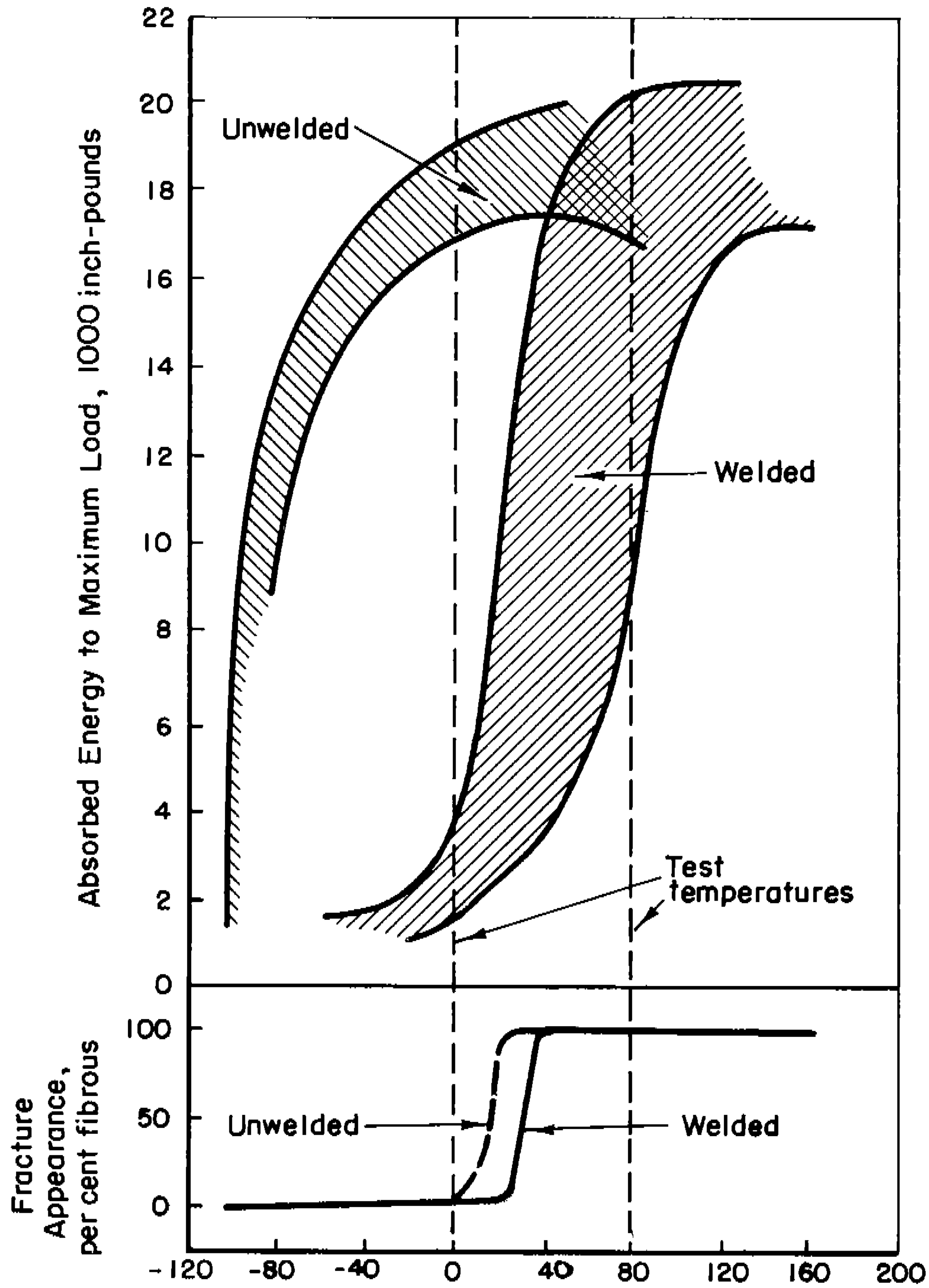

FIGURE 2. ABSORBED ENERGY AND FRACTURE APPEARANCE CURVES FOR WELDED AND UNWELDED "Br" STEEL KINZEL-TYPE SPECIMENS, SHOWING TEST TEMPERATURES USED IN FRACTTURE STUDIES.[12]

0-17069

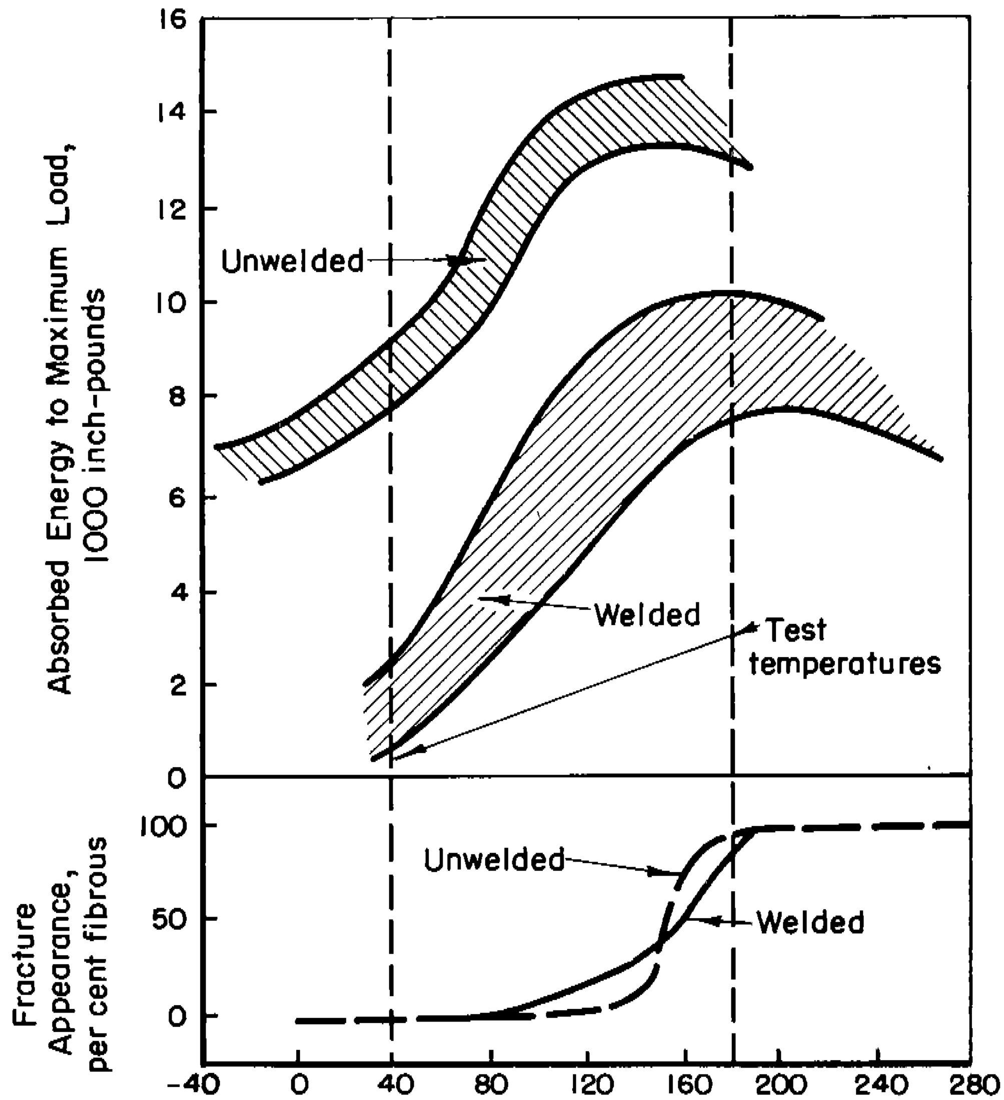

FIGURE 3. ABSORBED ENERGY AND FRACTURE APPEARANCE CURVES FOR WELDED AND UNWELDED "C" STEEL KINZEL-TYPE SPECIMENS, SHOWING TEST TEMPERATURES USED IN FRACTURE STUDIES.[12]

0-17070

be used to explain the lower absorbed energy values for the welded specimens as compared with unwelded specimens. In this light, then, the importance of differences observed between specimens at two temperatures becomes secondary to the ability to interpret why welded specimens are inferior at a given test temperature.

TESTING AND EXAMINATION OF SPECIMENS FOR FRACTURE INITIATION AND PROPAGATION STUDIES

The test specimens were bent to various deflections in the standard bend jig (see Figure 1), the load was removed, and the specimens were sectioned and examined in detail to determine where the cracks started and how they propagated.

Testing Procedure

Test specimens and bending jig were immersed in a liquid medium at testing temperatures for at least five minutes before applying the load. Temperatures above the transition temperatures were obtained by using water heated with resistance immersion coils. A mixture of methyl cyclchaxane and dry ice was used when specimens were tested below the transition temperature.

All specimens were preloaded to 1000 pounds manually in an Amsler hydraulic-type testing machine, and then an Ames Dial Gauge "88", located at the center of the specimens, was set at zero to measure deflection during later loading. After preloading, the specimens were bent at a rate of approximately 0.075-inch-per-minute displacement of platen. A load-deflection curve was made, and the load applied to produce the desired deflection was recorded for each specimen tested.

Four series of "B_r" steel specimens and four series of "C" steel specimens were tested at deflections ranging from 0.050 inch to 1.25 inch. The deflections used for each series of specimens tested are listed in Table 2. One series each of welded and unwelded "B_r" steel specimens was tested at 80 F (above the transition temperature) and 0 F (below the transition temperature). Similar groups of "C" steel specimens, both welded and unwelded, were tested at 180 F (above the transition temperature) and 40 F (below the transition temperature). For any given deflection, three specimens were tested to allow for possible scatter in the test results. The deflections are given in inches and bend angle, as shown in Table 2.

Sectioning Specimens

After bending, the notched section of the specimen, including about 1/8 inch of material on each side of the notch, was removed from the specimen by saw cutting. Sections were then cut transversely to the notch by means of a small power hack saw using thin blades. An adjustable screw stop attached to the saw made it possible to cut sections of varying thickness.

For welded specimens, the first section was cut in the base plate at a distance of approximately 0.10 inch from one edge of the weld. Successive cuts were made every 0.10 inch across the weld bead and to 0.10 to 0.30 inch into the base plate on the opposite side of the weld bead. Each section was approximately 0.050 inch in thickness and roughly 0.050 inch was removed by the saw cut. The method of sectioning is shown in Figure 4.

Unwelded specimens were sectioned at approximately 1/2-inch intervals across the 3-inch specimen width. Six sections were obtained from each specimen,

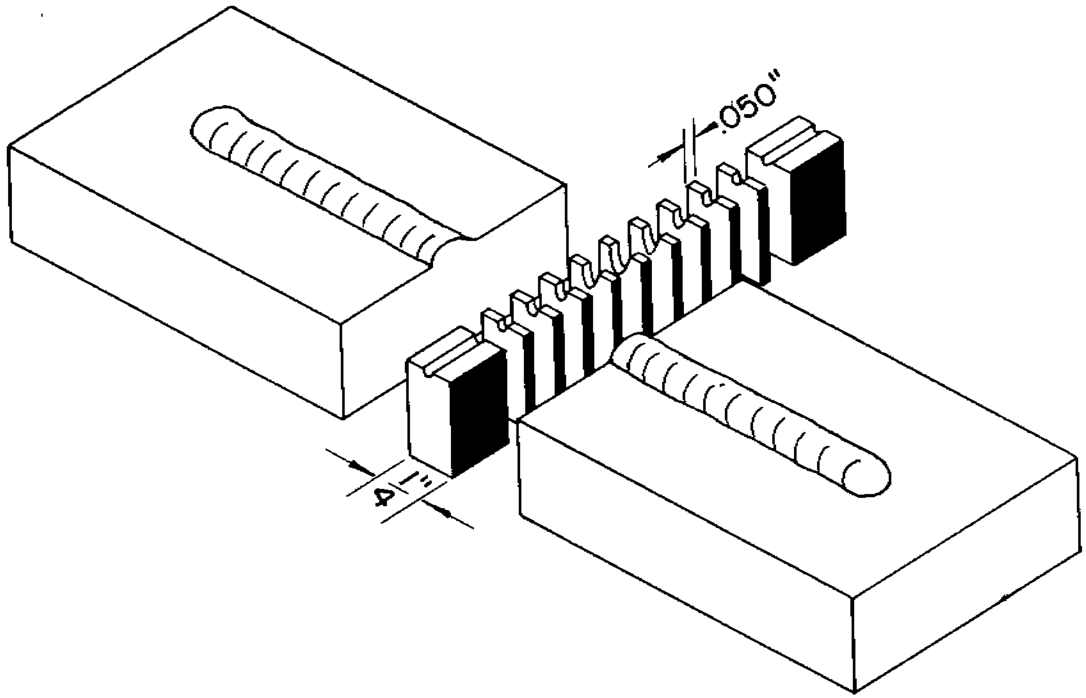

FIGURE 4. CUTTING AND SECTIONING DETAILS FOR WELDED KINZEL-TYPE SPECIMENS

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TABLE 2. DEFLECTION AT WHICH EACH SERIES OF KINZEL-TYPE SPECIMENS WAS STUDIED

Deflection		Number of Specimens Tested							
		"B" Steel				"C" Steel			
		Welded		Unwelded		Welded		Unwelded	
Inches	Bend Angle, Degrees	80 F(1)	0 F(2)	80 F(1)	0 F(2)	180 F(1)	40 F(2)	180 F(1)	40 F(2)
0.050	1°42'	3	3	3	3	3	3	3	3
0.075	2°32'	2	3	3	3	3	3	3	3
0.100	3°24'	3	3	--	--	3	3	--	--
0.125	4°14'	--	--	3	3	--	--	3	3
0.150	5°06'	3	3	3	3	3	4	3	3
0.200	6°48'	--	--	--	--	3	2	3	3
0.250	8°30'	3	3	3	3	3	--	3	3
0.300	10°12'	--	--	--	--	--	--	3	3
0.400	13°32'	--	--	--	--	--	--	3	3
0.500	16°50'	--	--	3	3	--	--	3	3
0.600	20°10'	--	--	--	--	--	--	3	3
0.700	23°26'	--	--	3	3	--	--	--	--
0.750	25°04'	--	--	3	3	--	--	--	--
0.900	29°59'	--	--	3	2	--	--	--	--
1.250	43°20'	--	--	2	2	--	--	--	--

(1) Above transition temperature.
(2) Below transition temperature.

as shown in Figure 5. The last section which contained the machined surface of the specimen was discarded because the lateral contraction, brought about by bending of the specimen, caused the notch to be deformed and it was believed this condition would give erroneous results in the fracture studies of the specimen. Each section was marked with specimen number and section number so as not to lose its identity.

Polishing

All sections cut from welded specimens were mounted in Bakelite before polishing. Sections cut from unwelded specimens were mounted when the specimen had been deflected only a small amount. Sections from specimens deflected larger amounts were left unmounted. All sections from both welded and unwelded specimens were polished through 600-grit size. A final wet polish was given all sections with Type B Linde polishing compound on billiard cloth. After polishing, each section was given a light etch with 2 per cent nital. Sections made from welded specimens were grouped together, according to steel, specimen number, test temperature (i.e., above or below the transition temperature), and deflection. Unwelded specimens were grouped together in the same manner. All sections were stored in desiccators to preserve the polished surface.

Inspection and Record of Cracks

All sections were examined under a microscope at 100X and 400X, starting with those specimens tested at the lowest deflection. The magnification of 400X was used for measuring crack depth, since all cracks were clearly visible at this magnification. Throughout this investigation, only the deepest crack appearing in each section was measured by means of a micrometer eye piece. The depth (1 unit = 0.000352 inch) and location of the crack was recorded

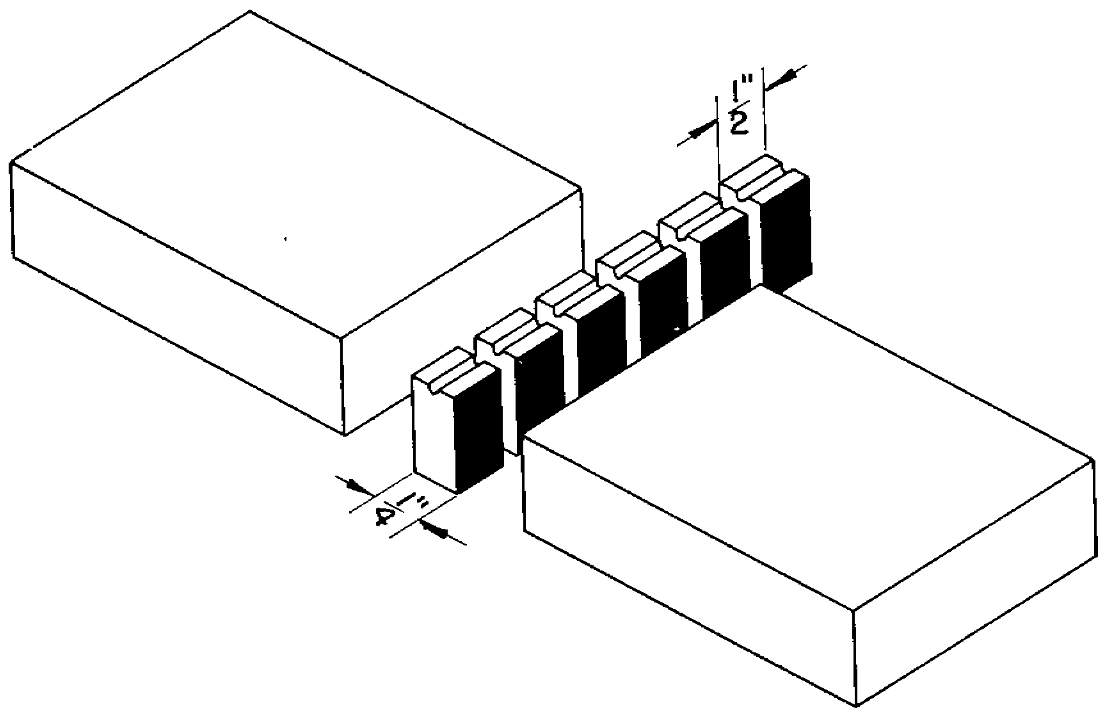

FIGURE 5. CUTTING AND SECTIONING DETAILS FOR UNWELDED KINZEL-TYPE SPECIMEN

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on especially prepared record sheets, as shown in Figure 6. Also recorded were the locations of other cracks appearing in the notch radius, location of heat-affected zone with respect to the notch, and the zones in which cracks were located. The record sheets were used for both welded and unwelded specimens; however, information pertinent to welded specimens only was deleted when unwelded specimens were examined.

Master tables for welded and unwelded specimens were made from the record sheets for each series of specimens tested. A typical example of a master table for unwelded samples is shown in Table A-1 of Appendix A. A typical table for welded specimens is shown in Table A-5 of Appendix A. Separate tables were made for specimens tested above and below the transition temperature.

In the tables for unwelded specimens, as shown in Table A-1, records were made of the specimen number, deflection of specimen, test load on specimen, section number, average crack depth of middle three sections of specimen (Sections 2, 3, and 4), and average crack depth for edge sections (Sections 1 and 5).

Record tables for welded specimens were similar to those for unwelded specimens, as shown in Table A-5 of Appendix A. However, additional columns were included for recording the zone of the specimen in which cracks were found, i.e., weld metal, heat-affected zone, and unaffected base metal. Average crack depth was computed on the basis of zones of the specimens, instead of by sections, as in the unwelded specimens. From the average data in these tables, graphs were made in which crack depth for various parts of the specimens was

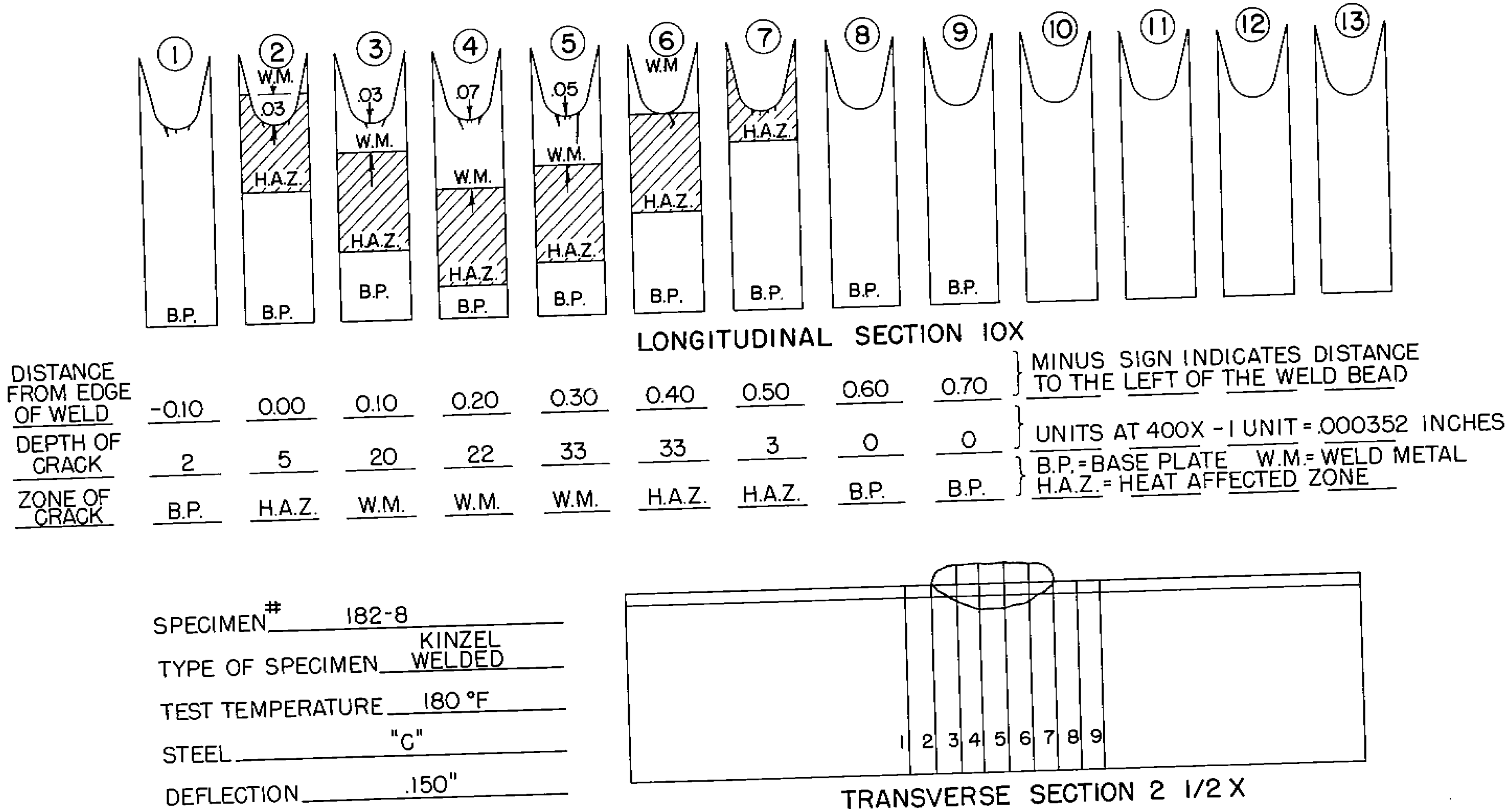


FIGURE 6. SAMPLE RECORD SHEET USED FOR RECORDING FRACTURE INITIATION AND PROPAGATION DATA FOR KINZEL-TYPE SPECIMENS

68439

plotted against deflection of the specimen.

TEST RESULTS

The results were studied to determine: (a) where and when the initial cracks occurred; and (b) how cracks propagated.

Crack Initiation

In unwelded and welded specimens of both "B_r" and "C" steels, tested above and below the transition temperatures of the steels, small cracks or surface tears were present in the root of the notch after 0.050-inch deflection of the center of the specimens. In both the unwelded and welded specimens, these cracks occurred across the entire width of the specimen.

A typical example of these cracks or surface tears is shown in Figure 7. As shown in this figure, several of these cracks were often found in the root of one cross section. It may be held that these are not cracks, but are surface tears, which precede the true fracture. They occur in these specimens in the superficial work-hardened layer caused by machining. However, cracks of similar appearance have also been observed in specimens whose notches were carefully lapped to a depth that was designed to go well below the work-hardened layer. It has not been possible to perform a more rigorous study of these small, irregular, and superficial cracks. While they undoubtedly play a role in the fracture of these test bars, it is thought to be a minor one.

A 400X magnification, some of the cracks, that is, those present after the specimen was deflected 0.050 inch, were quite wide, as shown in Figures 8 and 9, and showed evidence that plastic deformation had taken place. Some cracks were also sharp (Figure 7) and comparatively deep. However, at the

300X 68462

FIGURE 7. TYPICAL CRACKS APPEARING IN WELD METAL OF A "B_r" STEEL SPECIMEN DEFLECTED 0.050 INCH AT THE CENTER

400X 68463

FIGURE 8. TYPICAL CRACKS OR TEARS APPEARING IN THE HEAT-AFFECTED ZONE OF A "B_r" STEEL SPECIMEN DEFLECTED 0.050 INCH

lower deflection, there was usually evidence of ductility and the cracks resembled tears in the metal surface, as shown in Figures 8 and 9. Very often, as the specimens were deflected further, the cracks opened up at the sides of the notch-root radius instead of in the center as might be expected. Figure 10 is a good illustration.

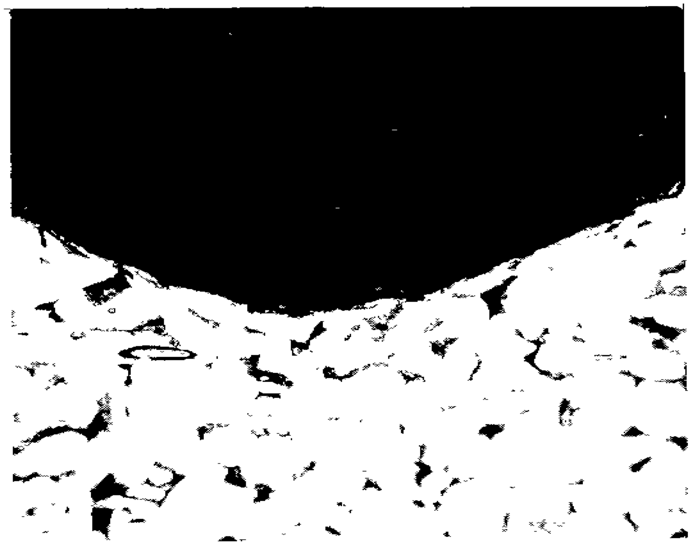
In each of Figures 7, 8, and 9, there is evidence that a very thin surface layer of metal at the root of the notch was cold worked by machining. This is shown better in Figure 11, which is the cross section of a specimen that was not bent or deformed in any way after machining. At this time, it was believed that this thin layer of cold-worked metal contributed to the early initiation of cracks or surface tears. However, since all previous specimens were tested as machined, this condition was normal for all. The layer might have been removed by lapping the root of the notch, but, since this investigation was concerned with a normal Kinzel-type specimen, it was decided to leave the surface of the notch in the normal as-machined condition.

In unwelded "B_r" steel specimens, all of which were tested above the transition temperature, there were only a few discontinuous cracks or surface tears when the specimens were deflected 0.050 inch.

The unwelded "C" steel specimens deflected 0.050 inch behaved about the same as the unwelded "B_r" steel specimens, but the frequency of cracking was somewhat greater in tests above the transition temperature than below. Average values, as shown in Appendix A, Tables A-9 and A-10, for each series of unwelded "B_r" and "C" steel specimens showed that small surface cracks or tears occurred

400X 68463

FIGURE 8. TYPICAL CRACKS OR TEARS APPEARING IN THE HEAT-AFFECTED ZONE OF A "B_r" STEEL SPECIMEN DEFLECTED 0.050 INCH

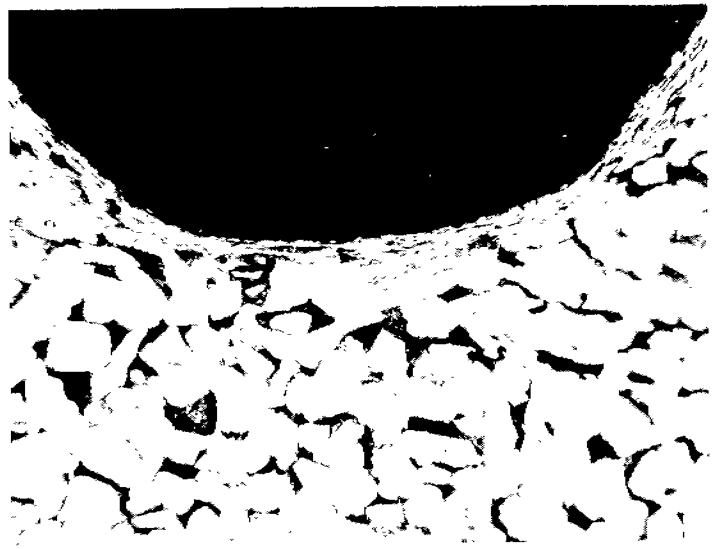


300X 68464

FIGURE 9. TYPICAL CRACKS OR TEARS APPEARING IN THE UNAFFECTED BASE METAL OF A "B_r" STEEL SPECIMEN DEFLECTED 0.050 INCH

150X 65759

FIGURE 10. TYPICAL CRACK THAT HAS PROPAGATED WITH INCREASE IN DEFLECTION BEYOND 0.050 INCH. THIS IS A WELDED "B_r" STEEL, AT 0.150 INCH DEFLECTION



300X 68465

FIGURE 11. APPEARANCE OF A TYPICAL NOTCH-ROOT RADIUS OF AN UNBENT KINZEL-TYPE SPECIMEN

In welded specimens of "B_r" and "C" steels deflected 0.050 inch, the initial cracks were similar to those observed in unwelded specimens. However, there appeared to be more cracks in the welded specimens, especially in the weld metal and heat-affected zone. No significant difference was observed when comparing the number of cracks in specimens tested above and below the transition temperature for either series of specimens. The "B_r" steel specimens contained more cracks or tears than the "C" steel specimens, but this difference was small.

Crack Propagation

With an increase in deflection of the Kinzel-type specimens beyond 0.050 inch, one of the several discontinuous cracks or tears that were present at 0.050-inch deflection increased in depth, or propagated. Two things were characteristic of crack propagation: first, the cracks began to propagate at different deflections, and, second, once started, the cracks propagated at different rates. When and how cracks propagate will be discussed separately.

When Cracks Propagate

Graphs of crack depth versus deflection were prepared for the several series of tests. These are presented in Appendix B, Figures B-1 through B-24. In order to determine when cracks began to propagate, it was necessary to distinguish between surface tears and true cracking.

It was necessary to define the depth to which a surface tear must propagate before it could be considered a crack. An arbitrary depth of 0.005 inch was chosen to define a true crack for convenience in measuring when cracks start to propagate. In Figures B-1, B-2, B-4, B-5, B-9, B-10, B-14, B-15, and B-16, Appendix B, the deflections at which the 0.005-inch abscissa intercepted the crack-depth curves were measured. These deflections were as follows:

Deflection at Which Cracks Started to Propagate, Inch

	"B_r" Steel		"C" Steel	
	80 F	0 F	180 F	40 F
Welded Specimens				
Weld metal	0.15	0.15	0.10	0.06
Heat-affected zone	0.18	0.17	0.17	0.08
Unaffected base metal (adjacent to weld area)	--	--	0.25	0.13
Unwelded Specimens				
Center sections	0.77	0.82	0.52	0.55
Edge sections	0.86	0.94	0.57	0.60

It can be observed that in the welded specimens of both "B_r" and "C" steel, cracks started to propagate at a much lower deflection than in the unwelded specimens. The use of this observation will be discussed in a later section.

The cracks propagated sooner in welded "C" steel specimens than welded "B_r" steel specimens, although the difference in deflection was small. Cracks in unwelded "C" steel specimens started to propagate at 0.52- and 0.55-inch deflection, compared with 0.77- and 0.82-inch deflection for the "B_r" steel specimens.

Except in the case of welded "C" steel specimens, the temperature of testing appeared to have but little effect on when the cracks began to propagate. It appears that temperature must have more effect on how cracks propagate after they start.

How Cracks Propagate

In the Kinzel-type specimens, where the cracks initiate in a line of surface tears along the notch root radius, the cracks must, in some manner, propagate from those line origins down into the specimens. In order to show how these cracks propagated through the specimens, the isometric graphs of Figures 12 through 15 were prepared, using data from Tables A-9 through A-12, Appendix A.

A few words of explanation should make their interpretation easier. Refer to Figure 12A. The X-axis on the graph corresponds to the notch root of the specimen projected in true length. The crack depth scale in the Y direction is magnified 100 times true depth. On the X-Y plane, the weld, heat-affected, and base metal zones are indicated in order to show in what zones the crack lies at any deflection. Deflections are indicated on the Z-axis.

Numbers on the graph refer to planes which cut the notch root transversely. The plane cutting through weld metal in the notch root is identified as (1). Similarly, (2) refers to planes cutting the heat-affected zone, and (3) planes cutting the base metal. Cracks are identified by the zone or number of the transverse plane in which they lie. A crack in plane (1) which started in the weld zone had propagated into the heat-affected zone beneath it when it reached the depth of 0.04, the depth of the weld metal at that section. Similarly, a crack in plane (2) starting in the heat-affected zone, propagated into base metal at a depth of approximately 0.10 inch.

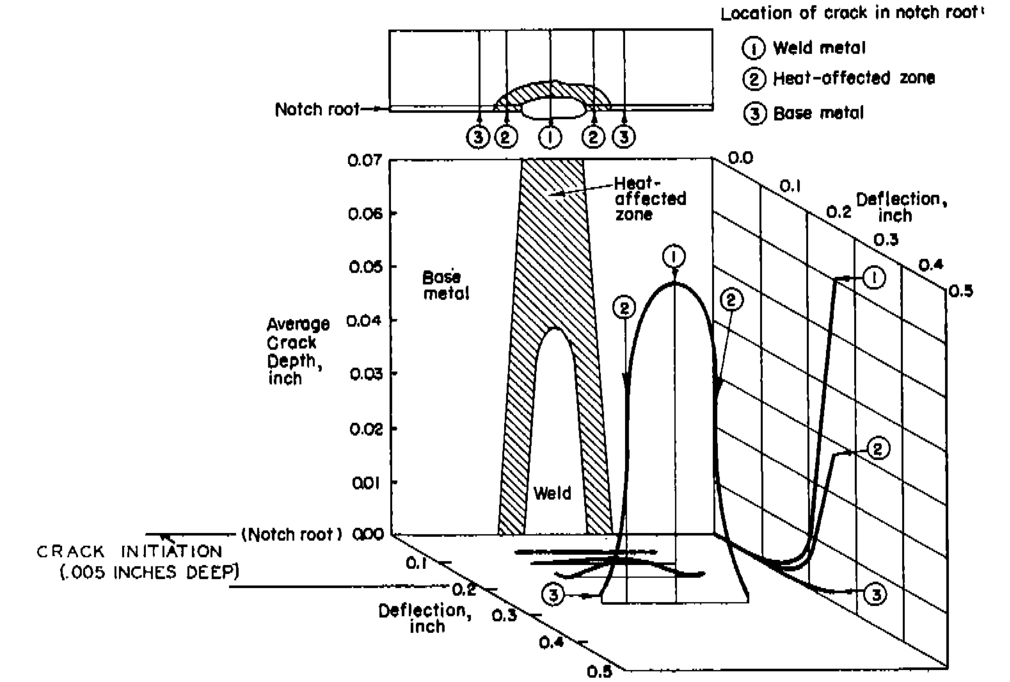


FIG. 12 A. CRACK INITIATION AND PROPAGATION IN WELDED "Br" STEEL KINZEL-TYPE SPECIMENS TESTED AT 0 F

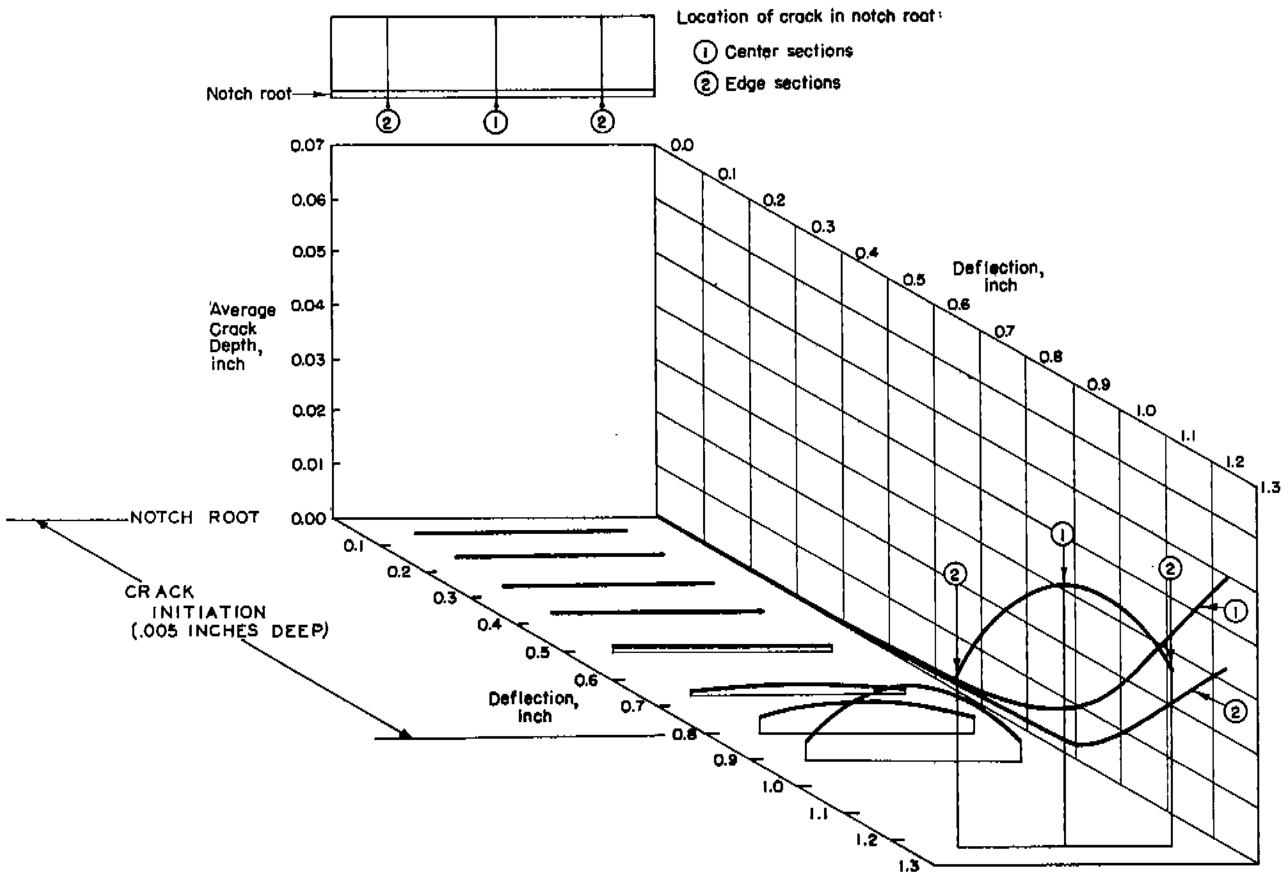


FIGURE 12 B. CRACK INITIATION AND PROPAGATION IN UNWELDED "Br" STEEL KINZEL-TYPE SPECIMENS. CURVES ARE SIMILAR FOR SPECIMENS TESTED AT 80F AND 0 F

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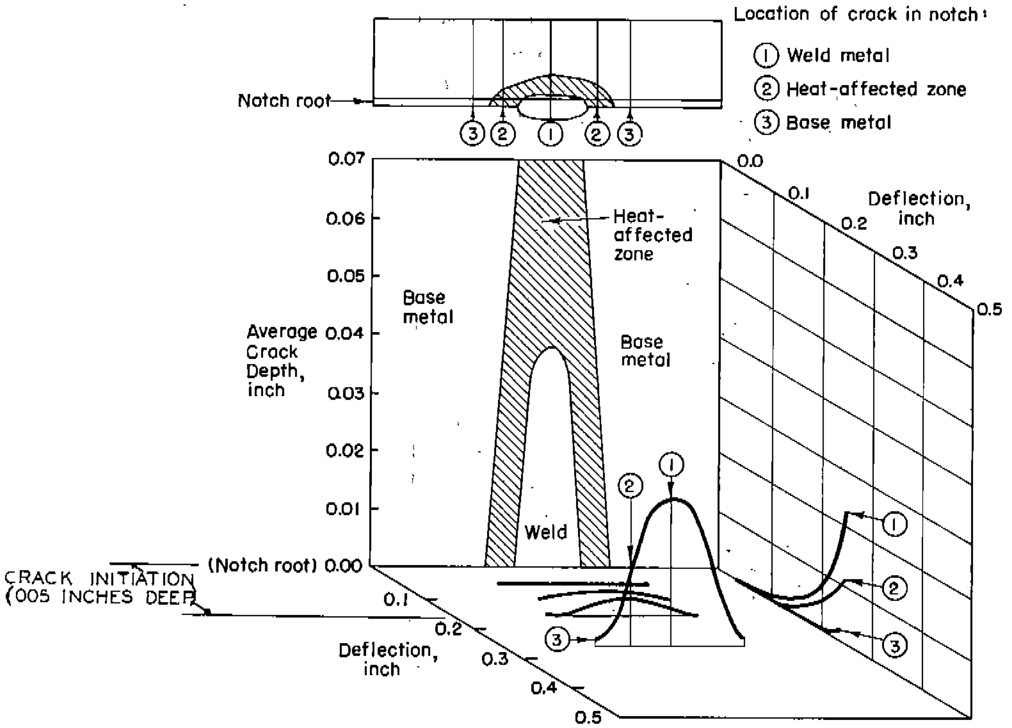


FIGURE 13. CRACK INITIATION AND PROPAGATION IN WELDED "Br" STEEL KINZEL-TYPE SPECIMENS TESTED AT 80F.

0-17073

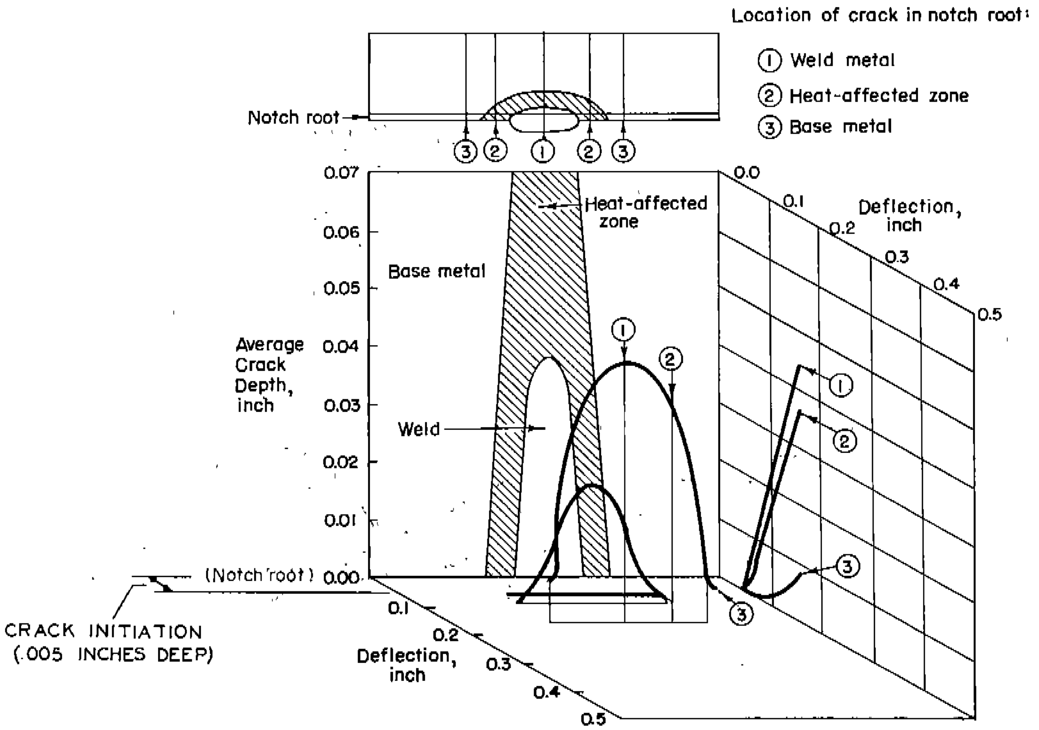


FIGURE 14A. CRACK INITIATION AND PROPAGATION IN WELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 40F.

0-17074

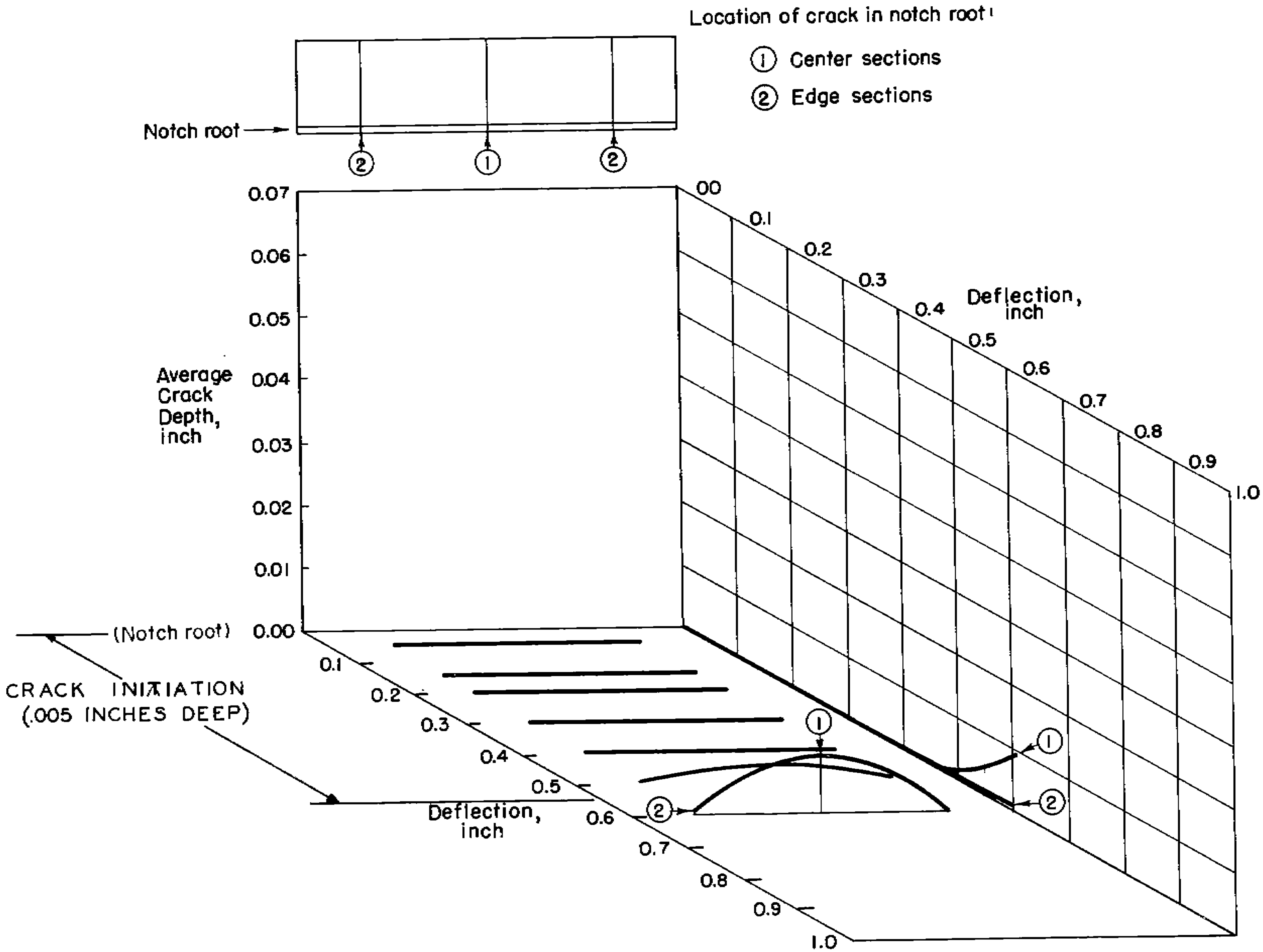


FIGURE 14B. CRACK INITIATION AND PROPAGATION IN UNWELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 40F.

0-17075

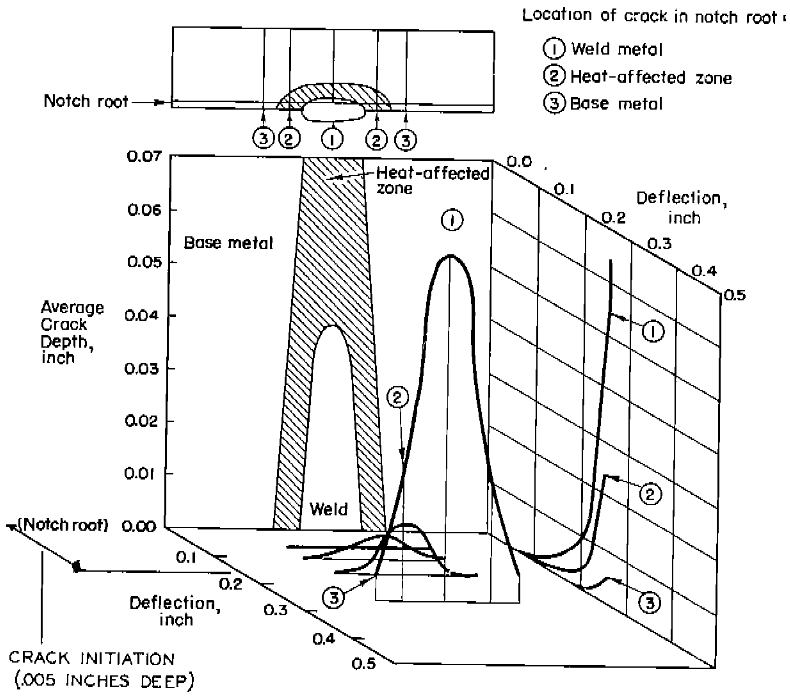


FIGURE 15A. CRACK INITIATION AND PROPAGATION IN WELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 180 F.

0-17076

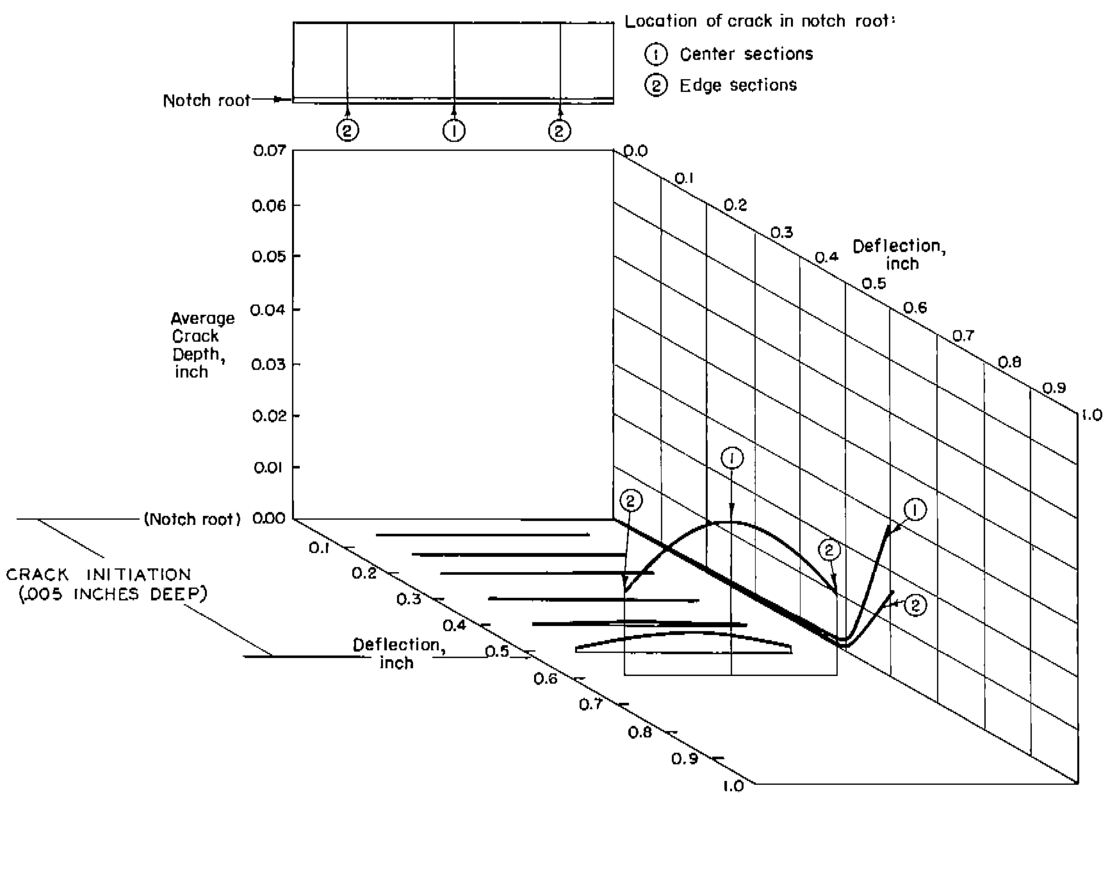


FIGURE 15B. CRACK INITIATION AND PROPAGATION IN UNWELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 180 F.

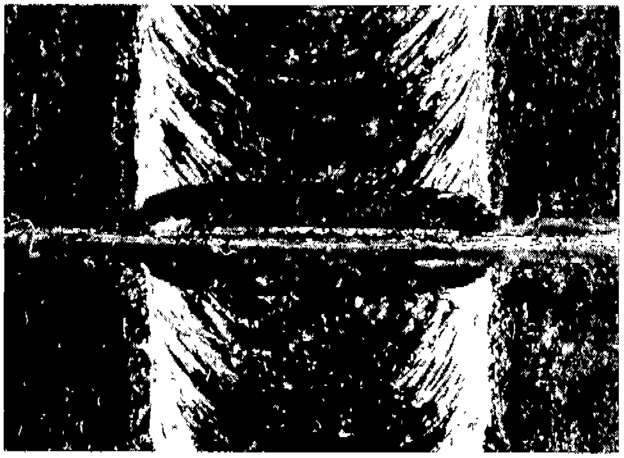
0-17077

As a further visual aid, the depth of cracks identified by number are plotted on a grid at the right. These lines would be generated by the transverse planes cutting the family of crack depth curves at the corresponding points. The curves on the grid represent the same curves that are plotted in Figures B-1 through B-24 in Appendix B.

Graphs for unwelded specimens are similar, except that instead of zones, points were plotted as center or edge sections. Figure 12-B is typical of the group.

Several things about how cracks propagate are demonstrated in Figures 12 through 15. The early cracking of the welded specimens, compared with the unwelded specimens, is evident. Cracks in the welded specimens propagate in the weld area, and not across the entire width of the specimen, as in unwelded specimens. Figure 16 is a photograph illustrating a typical crack in the weld area of a Kinzel-type specimen. In the unwelded specimens, the delay in crack propagation is evident. Cracks become deep in the center sections before they do in the edge sections.

Differences were observed in the depth of cracking between the specimens tested at the high and low temperatures. Welded "B_r" steel specimens tested at 0 F had deeper cracks than specimens tested at 80 F, at 0.250 inch which was the maximum deflection used. Unwelded "B_r" steel specimens tested at 0 F had deeper cracks than specimens tested at 80 F, at the maximum test deflection of 1.250 inch. Unwelded "C" steel specimens measured at a deflection of 0.600 inch showed deeper cracks in specimens tested at 180 F than in specimens tested at 40 F. Thus far, it would appear that unwelded "C" resisted better crack



2-1/2X 61010

FIGURE 16. CRACK IN A WELDED "C" STEEL KINZEL-TYPE SPECIMEN TESTED AT 190 F, AND DEFLECTED 0.200 INCH

propagation at 40 F. However, at slightly larger deflections, the 40 F specimens would fail by cleavage, while the 180 F specimen would continue to bend with a ductile crack.

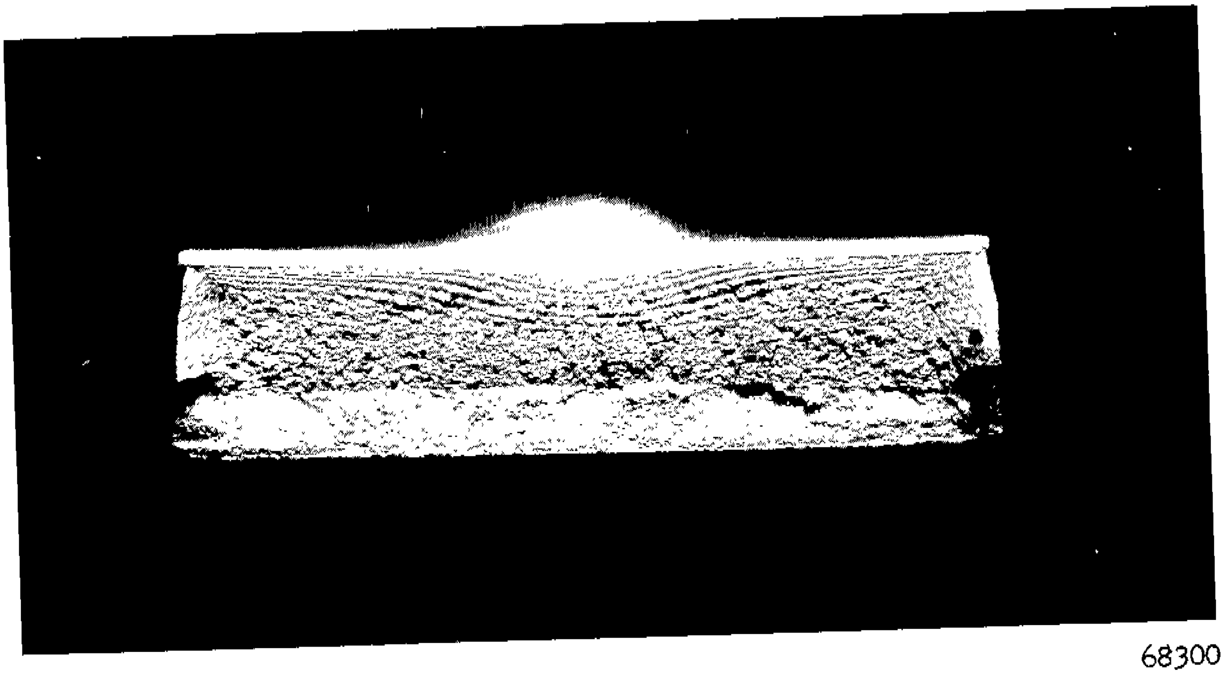
There were several differences between "B_r" and "C" steel which might explain why the "B_r" steel deflects more before cracks propagate. The carbon and nitrogen content of "B_r" steel are 0.18 and 0.005 per cent, respectively, compared with 0.24 and 0.09 per cent for "C" steel. The "C" steel is somewhat finer grained than the "B_r" steel. Perhaps the more important differences in structure are the slag stringers and laminations present in "B_r" steel, which act as crack arrestors.

General Observation on Crack Propagation

A few general observations were made in the study of fracture characteristics of Kinzel-type specimens. A typical pattern by which cracks propagated in welded specimens is shown in Figure 17. The step-like pattern appearing on the fractured surface represents progressive steps in crack propagation. The crack-pattern lines were deepest under the welds for the early stages of the cracking and decreased in depth on either side of the weld through the heat-affected zone and unaffected base metal.

In "B_r" steel specimens, cracks occasionally opened laminations, if present in the path of the fracture. Figure 19 shows a crack which opened a lamination for an interval, and then propagated across it. When severe lamination conditions were found, the specimen was not used in the crack-depth study.

In welded "C" steel specimens, cracks had a tendency to follow grain



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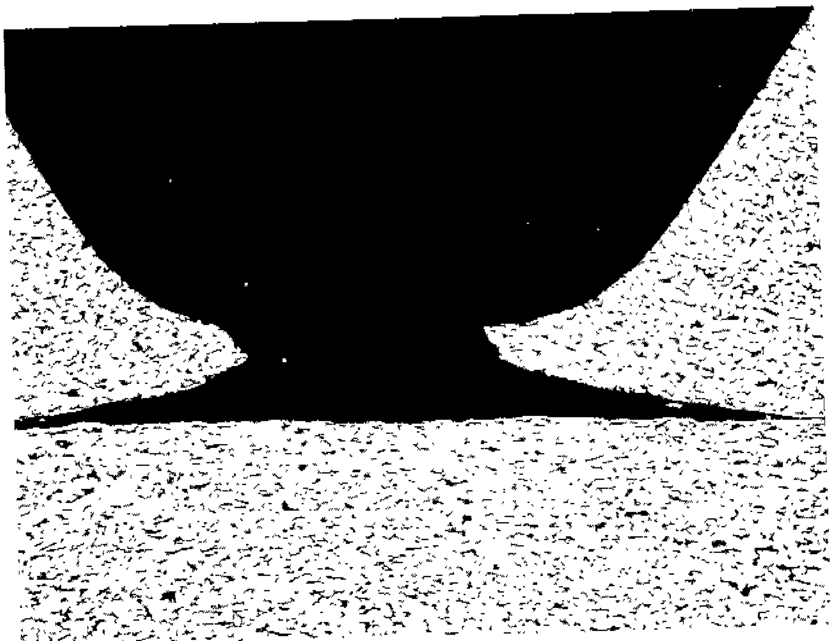
1-1/4X

FIGURE 17. PATTERN OF FRACTURE PROPAGATION IN A WELDED KINZEL-TYPE SPECIMEN



65757

50X

FIGURE 18. CRACK IN A "B_r" STEEL SPECIMEN THAT HAS FOLLOWED A LAMINATION BELOW THE NOTCH-ROOT RADIUS

50X 65758

FIGURE 19. CRACK IN A "B_T" STEEL SPECIMEN THAT FOLLOWS A LAMINATION AND THEN PROPAGATES THROUGH IT

50X 65761

FIGURE 20. CRACK IN A WELDED "C" STEEL SPECIMEN THAT HAS FOLLOWED THE GRAIN BOUNDARIES OF THE COARSE, HEAT-AFFECTED ZONE

boundaries in the coarse-grained part of the heat-affected zone, as shown in Figure 20. In welded "B_r" steel specimens, cracks in the heat-affected zone followed no pattern, with respect to grain boundaries. This might have been caused by the higher carbon content of "C" steel. Hardness surveys of the coarse, heat-affected zone of "C" steel show high hardness values[12]. It is believed the harder islands of bainite or fine pearlite found in "C" steel better resisted cracking, and cracks, therefore, followed the weaker ferritic grain boundaries.

MISCELLANEOUS CRACK STUDIES

In addition to the main fracture program, other crack studies were made. Studies were made on a few Lehigh-type specimens, on Kinzel-type specimens made from a 0.33 carbon steel, and on Kinzel-type specimens from a weldment similar to one studied at Case Institute of Technology[10]. The results of these studies will be discussed in the following sections.

Lehigh-Type Specimen

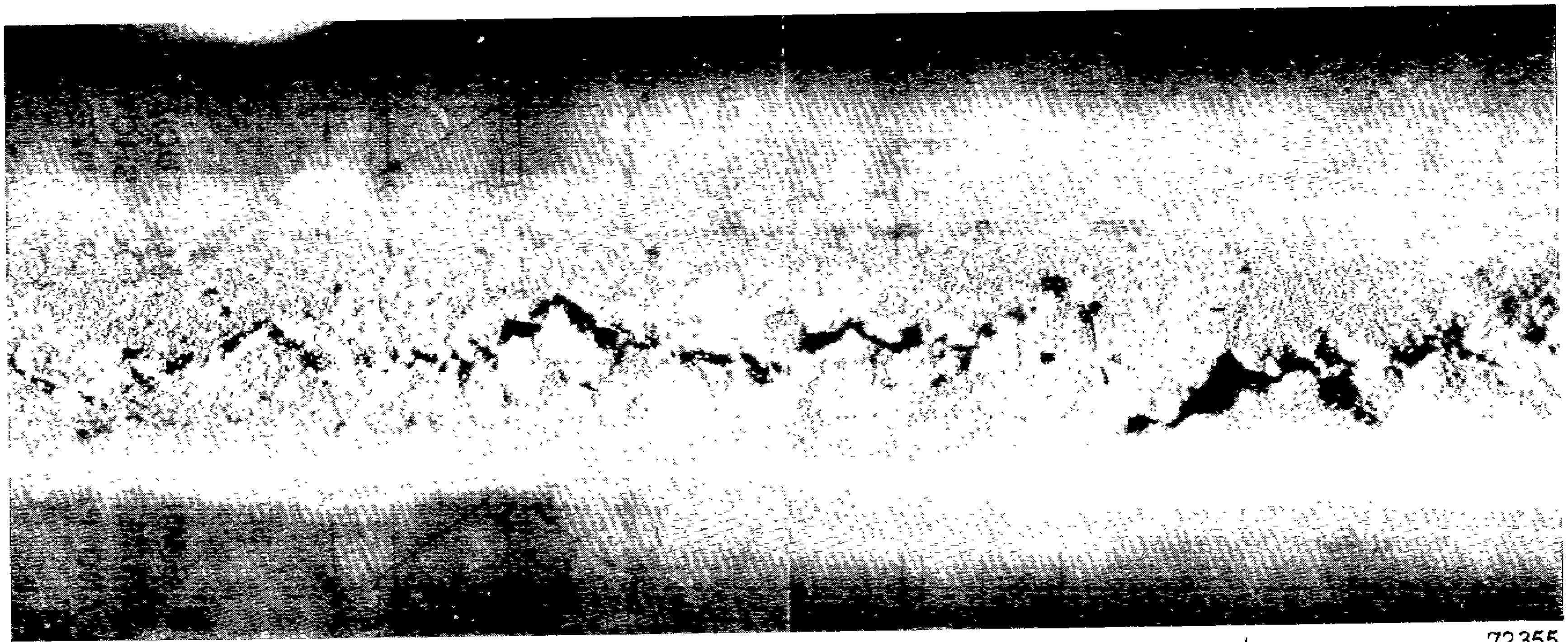
Previous to this work, Stout had examined Lehigh-type specimens of a 0.25 carbon steel and found that cracks initiated in the heat-affected zone[3,7]. To check this, a few Lehigh-type specimens of "C" steel were prepared and bent to 0.125 inch deflection. In the specimens tested, the original results were verified. The Lehigh-type specimen has but 0.015 inch average penetration of weld metal below the notch, compared to 0.05 inch for the Kinzel-type specimens. A greater proportion of heat-affected zone is exposed at the notch root, and this heat-affected zone is perhaps harder than that of the Kinzel-type specimen because of lower heat input and higher cooling rate. The removal of most the weld metal apparently shifts the initial crack to the heat-affected zone.

Kinzel-Type Specimens of a 0.33 Carbon Steel

To check the possibility that increasing the heat-affected zone hardness might change the crack origin from the weld metal to the heat-affected zone in the Kinzel-type specimen, three specimens were prepared from a 0.33 per cent carbon, 0.88 per cent manganese steel. These specimens were welded and machined with the standard procedure. The specimens were placed in a testing machine and deflected a small amount. The load was released, and the specimens were removed. The notch roots were examined with a low-power microscope for evidence of cracking. The specimens were successively bent to higher deflections and then examined until cracks were observed. Figure 21 shows the crack origin in the coarse-grain area of the heat-affected zone of one of these specimens. The crack follows boundaries of coarse grains.

Tests to Correlate Results of Studies at Case Institute of Technology With Results of Crack-Initiation Studies at Battelle

An investigation was made to determine if results of crack-initiation studies made at Battelle on Kinzel-type specimens correlated with the findings at Case Institute of Technology[10]. A region of low-notch ductility was found in the outer region of the heat-affected zone of a weldment consisting of a double-vee butt joint between two pieces of "C" steel, 10 inches wide and 24 inches long, made with E6010 electrodes, as shown in Figure 22. Results

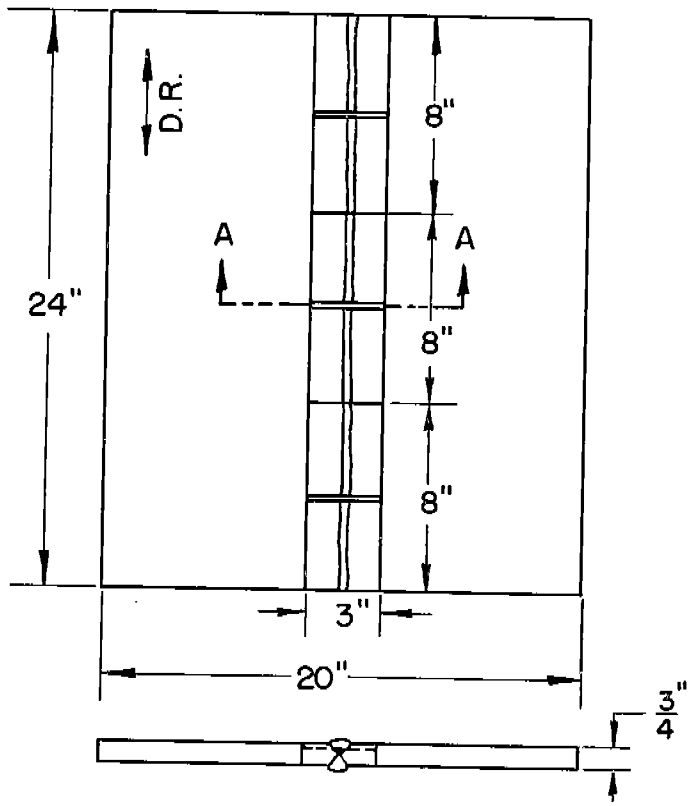


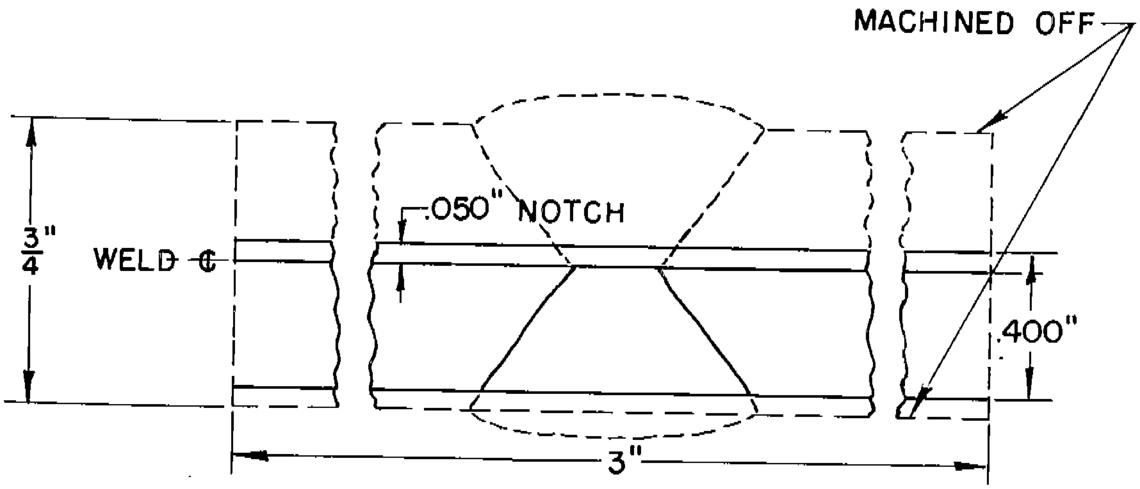
72355

75X

← Base Metal → | ← Heat-Affected Zone → | ← Weld Metal →

FIGURE 21. FRACTURE PATTERN IN THE HEAT-AFFECTED ZONE OF A KINZEL-TYPE SPECIMEN MADE FROM A STEEL CONTAINING 0.33 PER CENT CARBON AND 0.88 PER CENT MANGANESE





SECTION A-A

FIGURE 22. WELDMENT SIMILAR TO THOSE STUDIED AT CASE INSTITUTE OF TECHNOLOGY SHOWING LOCATION AND PREPARATION OF KINZEL-TYPE SPECIMENS

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of the research at Case showed the presence of a zone of heat-affected metal 0.3 inch from the center of the weld joint which had low-notch ductility. This metal had been heated below the lower critical temperature during the welding of the joint. The first specimens tested were taken from the mid-thickness, but these findings were later confirmed by tests of specimens at the surface position.

It was believed, since this zone had lower notch ductility than any other part of the weld joint, that it might fracture first if it was bent in free competition with the other parts of the weld, heat-affected zone, and unaffected stock.

To study this zone with respect to other parts of the weld joints, two "C" steel weldments were made like those studied at Case Institute. Special Kinzel-type specimens were prepared from each weldment, as shown in Figure 22, and tested to determine if fracture would initiate in the zone of low-notch ductility. The root of the notch in these specimens was located in the central plane between the top and bottom surfaces of the plate and was transverse to the weld joint, as shown in the enlarged sketch of a cross section of the joint in Figure 22. This made it possible to test all parts of the joint at the same time by bending the specimens.

The notch-root radii of these specimens were lapped to remove the work-hardened metal and eliminate its influence on crack initiation. To lap the notches, an 0.018-inch-diameter music wire was pressed into the notch roots and rotated at high speed, using 600-grit valve paste for cutting. This operation polished the root of the notch enough so that after etching (lightly with 2 per cent Nital) it was easy to observe the first cracks, and to determine in which zone of the specimen they were located.

The specimens were tested by alternately bending them a slight amount and then examining the root of the notch visually at 30X magnification. Two of the specimens were tested at 75 F, one was tested at -40 F, and three were tested at -80 F.

The test results for these six specimens are given in Table 3. In the specimens tested at 75 F, surface tears were observed in all zones. As the specimens were bent more, the first cracks of any size occurred in the heat-affected zone and weld metal. However, in the specimens tested at the low temperatures, although surface tears occured first in the heat-affected zone and zone of low-notch ductility, the first cracks occurred in the weld metal.

Two conclusions can be drawn from these tests. First, the milti-pass weld has better ductility at room temperature than the bead weld of the standard Kinzel-type specimen. Second, the zones of low notch ductility did not contribute materially to the failure of these special Kinzel-type specimens, even though surface tears initiated in these zones at low temperatures.

It is possible, however, that these surface tears could affect the behavior of small, notched specimens such as are used at Case Institute[10]. In a structural failure, it is possible that a crack progressing parallel with a welded joint might follow the zone of low-notch ductility, but it is believed doubtful whether this zone would act as a fracture initiator in the sense that weld metal does.

TABLE 3. RESULTS OF CRACK STUDIES OF "C" STEEL KINZEL-TYPE SPECIMENS MADE FROM DOUBLE-VEE BUTT-WELDED PLATE

		Origin of Surface Tears			Origin of Cracks		
Specimen Number	Test Temperature, F	Deflection, Inch(1)	Total Permanent Set, Inch	Zone	Deflection, Inch(1)	Total Permanent Set, Inch	Zone
AC-229-2	+75	0.050	-----	All zones	0.100	-----	Heat-affected
AC-229-3	+75	0.075	0.050	All zones	0.100	0.023	Weld and heat-affected
AC-232-1	-40	0.075	0.040	Heat-affected	0.075	0.040	Weld
AC-229-1	-80	0.100	0.079	Heat-affected, low-notch ductility	(Specimen fractured)		
AC-232-2	-80	0.050	0.019	Heat-affected, low-notch ductility	0.065	0.041	Weld
AC-232-3	-80	0.065	0.021	Heat-affected, low-notch ductility	0.100	0.081	Weld

(1) Deflection as measured from preceding permanent set. For this reason, total permanent set is given.
Total permanent set is cumulative from the successive bends.

USE OF CRACK DATA TO EXPLAIN BEHAVIOR OF KINZEL-TYPE SPECIMENS

The data presented here on the initiation and propagation of cracks can be applied to the interpretation of previous test data on welded and unwelded Kinzel-type specimens. Using this information, it is possible to explain, by differences in fracture behavior, the inferiority of welded specimens compared with unwelded specimens.

Observed Differences in Welded and Unwelded Kinzel-Type Specimens

In the past phases of this investigation, and in work conducted by other investigators, it has generally been noted that a series of welded specimens of a given steel, tested over a range of temperatures, usually has a higher transition range than similar unwelded specimens of the same steel. The welded specimens characteristically absorb less energy than unwelded ones at any specific temperature, and especially at lower temperatures. This fact is illustrated by the data listed in Tables 4 and 5, which were obtained from welded and unwelded Kinzel specimens of "B_r" and "C" steels. Curves of absorbed energy versus temperature are shown in Figure 23. These data were presented in a previous report on this project[12].

Energy data for the Kinzel-type specimens were originally obtained from the autographic load-deflection curves. The area under each load-deflection curve to the point of maximum load was measured by a planimeter, and this area was multiplied by the scale constant to obtain the energy in inch pounds.

TABLE 4. COMPARISON OF ENERGY ABSORBED BY UNWELDED AND WELDED KINZEL-TYPE SPECIMENS OF "B_r" STEEL TESTED AT VARIOUS TEMPERATURES

Test Temperature, F	Absorbed Energy to Maximum Load, In.-Lb.	
	Unwelded Specimen	Welded Specimen
80	19,000	15,000
40	20,000	11,000
20	18,000	5,000
0	17,000	4,000
-40	16,000	1,000

TABLE 5. COMPARISON OF ENERGY ABSORBED BY UNWELDED AND WELDED KINZEL-TYPE SPECIMENS OF "C" STEEL TESTED AT VARIOUS TEMPERATURES

Test Temperature, F	Absorbed Energy to Maximum Load, In.-Lb.	
	Unwelded Specimen	Welded Specimen
200	18,000	8,000
160	14,000	8,500
120	13,000	7,000
80	10,000	3,000
40	8,000	2,000
0	7,000	1,000
-40	7,000	---

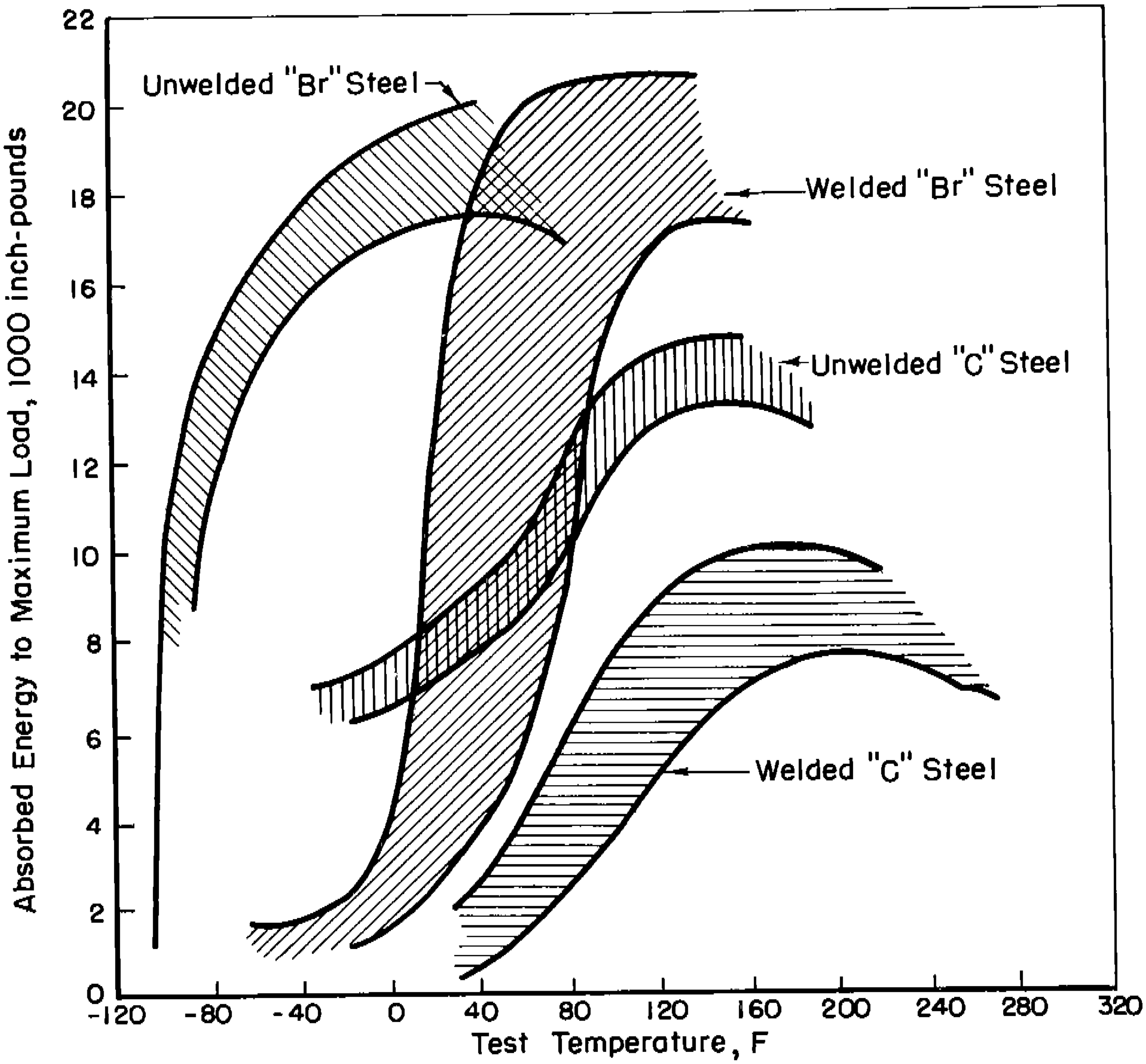

FIGURE 23. ABSORBED ENERGY DATA FOR WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEEL[12]

0-17078

Division of Absorbed Energy

It is known from work described in this report at what deflections cracks are initiated and begin to propagate in welded and unwelded Kinzel-type specimens of "B_r" and "C" steels. These data make possible the division of energy absorbed by the Kinzel-type specimen into two parts, (a) the energy absorbed to start cracking, and (b) the energy absorbed after cracking was started. In this way, a quantitative study can be made of the behavior of welded and unwelded test specimens.

By using the start of crack propagation to divide the energy absorbed by Kinzel-type specimens, the effect on specimen behavior of the weld area (weld metal and heat-affected zone) can be demonstrated. Figures 24 and 25 show average load-deflection curves for welded and unwelded "B_r" and "C" steel specimens at each of the test temperatures used in the crack study. The deflections at which cracks are formed and then propagate are indicated. The area under each curve to the point at which a crack 0.005 inch deep is formed represents the energy absorbed to the point of crack initiation. These energies have been determined and are plotted in Figure 26. Energy to maximum load was obtained from average data previously reported[9, 12].

In each case prior to cracking, the welded specimens absorbed much less energy than the unwelded specimens of the same steel. The welded specimens of "B_r" and "C" steel absorbed about the same amounts of energy to cracking, except for the welded "C" steel at 40 F. which absorbed less.

Figure 27 compares the energy after cracking in Kinzel-type specimens for the two steels at the various test temperatures. Welded and unwelded "C"

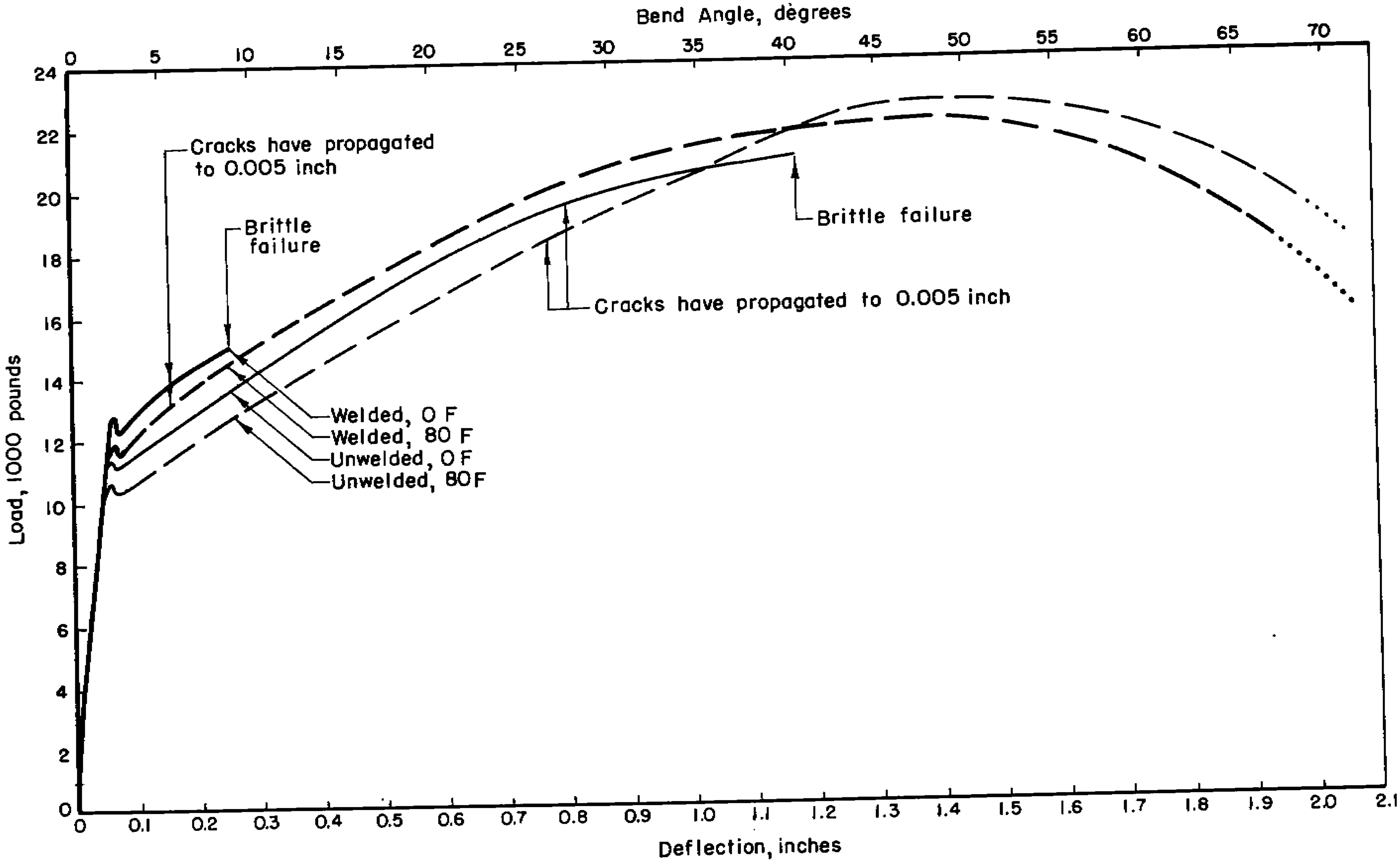

FIGURE 24. AVERAGE LOAD-DEFLECTION CURVES FOR WELDED AND UNWELDED "Br" STEEL KINZEL-TYPE SPECIMENS TESTED AT VARIOUS TEMPERATURES.

O-17079

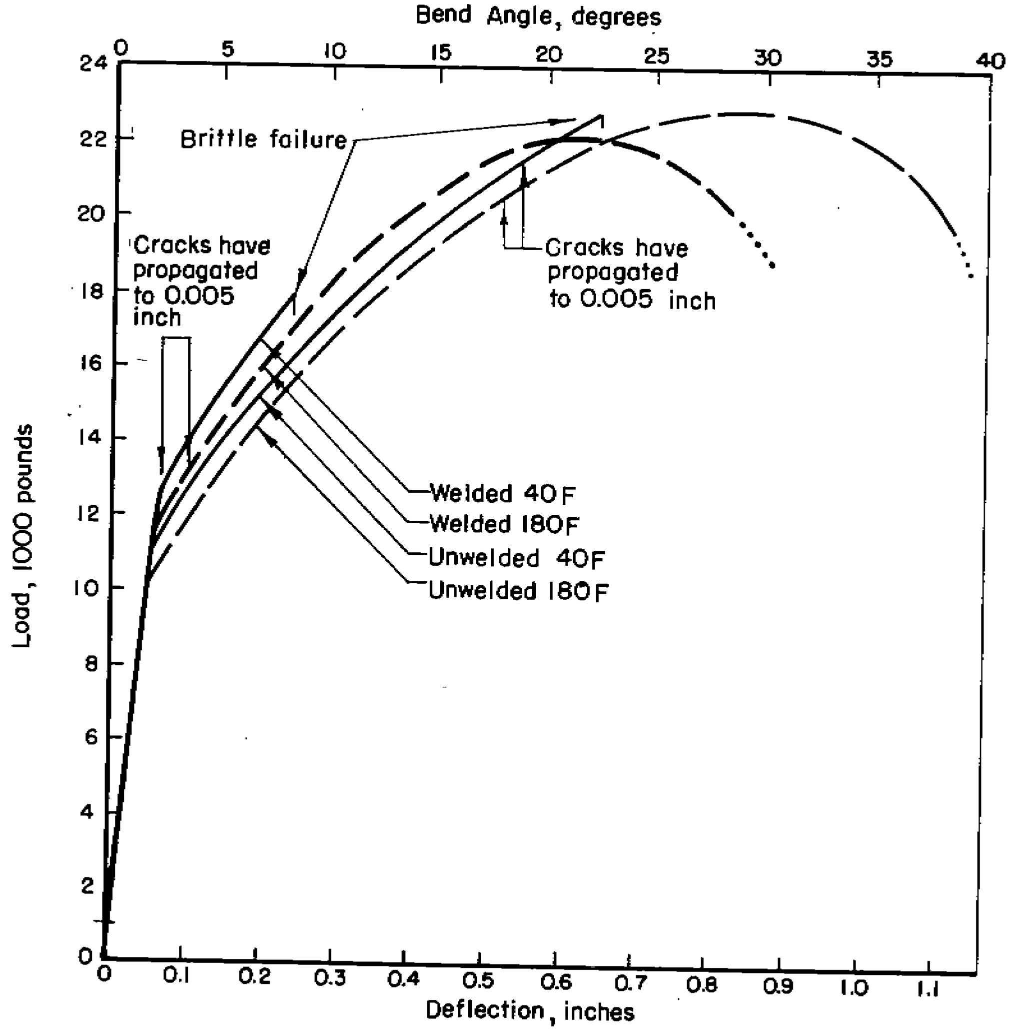

FIGURE 25. AVERAGE LOAD-DEFLECTION CURVES FOR WELDED AND UNWELDED "C" STEEL KINZEL-TYPE SPECIMENS TESTED AT 180F AND 40F.

0-17080

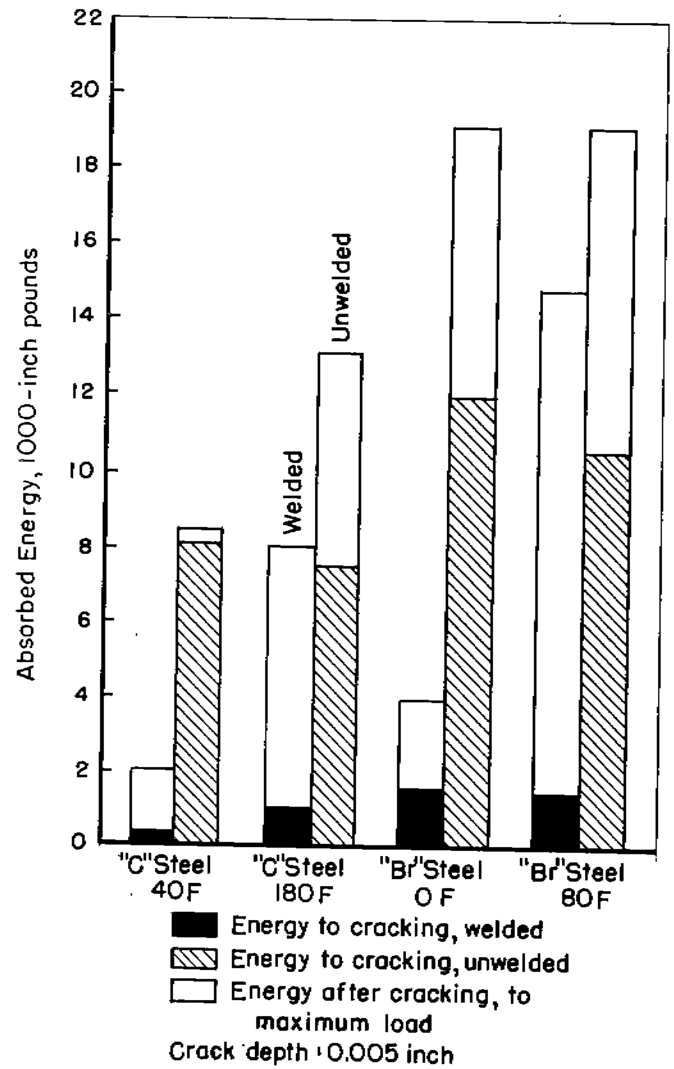

FIGURE 26. COMPARISON OF ENERGY TO CRACKING AND ENERGY AFTER CRACKING ABSORBED BY WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEELS.

0-17081

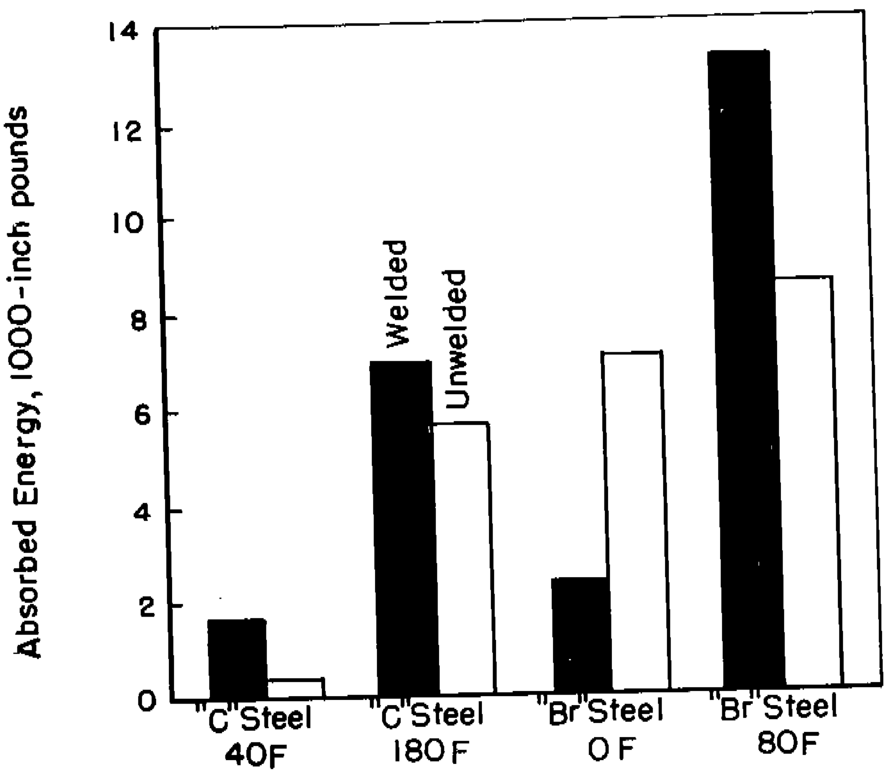

FIGURE 27. ENERGY AFTER CRACKING ABSORBED BY WELDED AND UNWELDED KINZEL-TYPE SPECIMENS OF "Br" AND "C" STEELS.

0-17082

steel at 40 F, and welded "Br" steel at 0 F, represent cleavage failures. These comparisons are made to demonstrate that relatively little of the difference in energy absorbed by welded and unwelded "B_r" and "C" steel Kinzel specimens was the difference in energy absorbed after the crack was started. In the over-all effect on Kinzel-type specimens, the difference in energy absorbed to start cracking between welded and unwelded specimens of the same steel was greater than the difference in energy absorbed after cracking started. In other words, it was the early fracture of the weld metal that contributed most to the poorer performance of the welded specimens as measured by the energy criterion. Therefore, the weld metal is a more dominant factor in controlling the performance of the specimens than the steel in the specimen.

Comparison With Results of Other Investigators

The results of this crack study have confirmed quantitatively what other investigators have observed qualitatively. The extreme sensitivity of columnar weld metal was observed in early work at Battelle(1) and has been reported by Professor Earl Parker in bend tests of welded tubes(5). Offenhauer and Koopman(6) observed that in bead-welded bend specimens, a crack was formed in the early stages of the test which was sharper than any notch which could be machined. Stout(7) has stated that welds may provide a ready origin of crack formation. Graf(4) has reported the crack origin in weld metal of weld bead bend specimens. He also shows a test girder in which transverse cracks were found in the heat-affected zone of web-to-flange welds on the tension flange after some deflection. Flanigan(2) and Offenhauer and Koopman(6) have observed that the start of fracture in welded bend specimens is independent of test temperature.

Flanigan[11] has already done considerable work in demonstrating that the improvement observed in welded bend specimens from preheat and postheat were due to better weld metal properties. He has attributed the gain in weld metal ductility to slower cooling rates, which in turn affect the quantity and distribution of hydrogen present in the weld area.

SUMMARY

1. In welded and unwelded Kinzel-type specimens of "B_r" and "C" steel, small, discontinuous surface tears were observed in the notch roots after the specimens were deflected 0.050 inch at midspan. These discontinuous tears were present across the entire width of the specimens, and were found in specimens tested above and below the transition range.

2. With an increase in deflection of the Kinzel-type specimens beyond 0.050 inch, one of the surface tears increased in depth or propagated. The deflections at which cracks began to propagate were measured. It was found that cracks started at different deflections, and that cracks propagated at different rates. Cracks started in the weld metal of welded specimens and began to propagate at very small deflections, while the cracks in unwelded specimens did not propagate until much larger deflections. Test temperature apparently had little effect on the deflection at which cracks started. Specimens of "C" steel, both welded and unwelded, cracked at lower deflections than "B_r" steel specimens.

3. In "B_r" steel specimens, laminations acted as crack arrestors. In welded "C" steel specimens, cracks tended to follow the grain boundaries of the coarse, heat-affected zone.

4. Cracks were found to originate in the heat-affected zone of Lehigh-type specimens.

5. Kinzel-type specimens prepared from a 0.33 per cent carbon and 0.88 per cent manganese steel cracked first in the heat-affected zone.

6. In Kinzel-type specimens of "C" steel taken from a weldment similar to those studied at Case Institute of Technology, surface tears originated in the heat-affected zone and zone of low-notch ductility in specimens tested at -40 F and -80 F. However, it was in weld metal that cracks propagated in these specimens.

7. The energy absorbed by welded and unwelded Kinzel-type specimens was divided in two parts: (1) energy absorbed by specimen prior to cracking, and (2) energy absorbed by specimen after cracking started. When these energies were compared, it was found that the difference between energies prior to cracking absorbed by welded and unwelded specimens was greater than the difference in energies absorbed after cracking. The early fracture of the weld area contributed most to the poorer performance or low-energy absorption of welded specimens.

CONCLUSIONS

Tests of ship steel with the Kinze-type specimen have demonstrated that the main reason for the poor performance of welded specimens, as compared with prime plate specimens, is the early propagation of a crack in the weld metal. This finding points to the structure and character of the weld metal as the critical feature of the test, in the same way that the notch is the critical feature of a notched bar test. After the start of the crack, the response of the test bar depends on the notch behavior of the material of which it is made. The better performance of the "B_r" steel in these tests reflects its superior notch toughness, as compared to the "C" steel.

This finding points to the possible use of the Kinzel test specimen for appraising weld metal and welding technique. Since, in ship plate of the grade which was used here, it is the weld metal that appears as the weak link, the performance of the specimen might be materially improved by improving the weld metal.

It should be recognized that even when using the same electrode, but on different steels, different results will be obtained in weld metal crack propagation, as a function of the different base metals. But the weakness of the weld metal overshadows effects of the base plate. With modification, that is by removing all the weld metal at the notch root, the specimen might be used to study the effects of the heat of welding on the steel.

FUTURE WORK

This report describes work recommended by the Project SR-100 Advisory Committee at its meeting of June 2, 1949.

The following program of future work at Battelle Memorial Institute was discussed and approved by the Project Advisory Committee meeting of March 9, 1950.

1. Influence of weld-metal properties on fracture initiation and propagation.

   a. The influence of normal mild-steel weld metals as normally used in making typical joints in welded ships will be studied. Samples of these welds will contain interdendritic fissures and low ductility, resulting from rapid cooling and procedure common to ship welding. Other samples will have the benefit of preheat, slow cooling, and postheat sometimes used in ship construction.

   b. The influence of weld metals having special properties will be studied. These weld metals may have exceptional ductility, or a combination of exceptional ductility and high strength (100,000-psi yield strength).

2. Influence of various regions in the heat-affected zone adjacent to bead, fillet, and groove welds on fracture behavior of specimens tested at various temperatures and in various directions (e.g., transverse, longitudinal, and "side bend").

3. Correlation of laboratory work with behavior in service.

   a. Fracture data from tests at National Bureau of Standards, and those obtained by personnel of the Bureau of Ships and Model Basin by tests and observations on ships will be consulted.

   b. Influence of artificial notches and structural notches will be studied.

   c. Samples from actual welded structures (both failures and satisfactory sections) will be studied in some detail and the findings correlated with and interpreted by the assistance of the laboratory findings.

Data given in this report are recorded in Battelle Laboratory Book No. 3240, pp. 94-97; Book No. 3856, pp. 42-52; and Book No. 4698, pp. 19-41, 46-51, 60-70, 89-97.

RGK:FRB:PJR:CBV/mt
December 20, 1950

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APPENDIX A

TABLE A-1. DEPTH OF LARGEST CRACKS IN UNWELDED "B_r" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 80 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack – Units at 400X (1 Unit = 0.000352 Inch)								
			Section					Average of Sections 2-3-4		Average of Sections 1-5	
			1	2	3	4	5	Units	Inch	Units	Inch
AC-189-10	0.050	9,800	1	0	1	0	2				
AC-220-1	0.050	10,000	0	0	0	0	0	0.11	0.0000387	0.50	0.000176
AC-220-2	0.050	9,500	0	0	0	0	0				
AC-220-3	0.075	10,500	0	1	1	0	1				
AC-220-4	0.075	10,450	0	0	0	0	0	0.22	0.0000775	0.33	0.000116
AC-220-5	0.075	10,600	0	0	0	0	1				
AC-189-7	0.125	10,800	3	1	1	2	3				
AC-189-8	0.125	11,000	1	2	20	2	2	3.44	0.00121	1.83	0.000645
AC-189-9	0.125	10,900	1	1	1	1	1				
AC-220-6	0.150	11,750	3	1	0	1	0				
AC-220-7	0.150	11,900	0	1	1	2	1	0.89	0.000313	1.16	0.000409
AC-220-8	0.150	11,400	1	0	1	1	2				
AC-189-4	0.250	12,900	1	2	0	1	1				
AC-189-5	0.250	12,650	2	5	1	6	1	3.22	0.00114	1.16	0.000409
AC-189-6	0.250	12,900	1	3	4	7	1				
AC-155-2	0.500	15,800	1	8	1	4	1				
AC-155-3	0.500	15,000	3	1	3	4	1	3.55	0.00125	1.83	0.000645
AC-155-4	0.500	15,800	3	4	3	4	2				
AC-189-1	0.700	17,100	4	10	9	5	17				
AC-189-2	0.700	17,100	8	8	4	3	4	5.78	0.00204	6.16	0.00217
AC-189-3	0.700	17,250	2	4	4	5	2				
AC-155-5	0.750	17,900	5	11	15	10	4				
AC-155-6	0.750	18,100	3	4	16	4	4	8.23	0.00290	4.17	0.00148
AC-155-7	0.750	17,950	4	4	6	4	5				
AC-155-14	0.800	18,300	11	20	8	15	10				
AC-155-15	0.800	18,450	17	20	18	22	10	18.11	0.00638	11.0	0.00388
AC-155-16	0.800	18,300	10	25	22	13	8				
AC-155-11	0.850	18,500	4	9	20	27	7				
AC-155-12	0.850	18,400	5	35	45	30	11	22.55	0.00793	7.33	0.00258
AC-155-13	0.850	18,400	7	12	20	5	10				
AC-155-8	0.900	19,050	18	42	38	33	28				
AC-155-9	0.900	18,600	13	18	28	42	18	35.88	0.0126	18.00	0.00633
AC-155-10	0.900	18,900	15	40	57	25	15				
AC-155-17	1.250	19,500	80	137	330	174	118	136.20	0.0479	52.66	0.0185
AC-155-18	1.250	19,200	57	156	217	212	61				

TABLE A-2. DEPTH OF LARGEST CRACKS IN UNWELDED "B_r" STEEL KINZEL SPECIMENS TESTED BELOW THE TRANSITION TEMPERATURE AT 0 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch) Section 1	Section 2	Section 3	Section 4	Section 5	Average of Sections 2-3-4 Units	Average of Sections 2-3-4 Inch	Average of Sections 1-5 Units	Average of Sections 1-5 Inch
AC-188-8	0.050	11,100	3	1	2	1	1				
AC-215-1	0.050	10,900	0	0	0	0	0	0.55	0.000194	0.67	0.000246
AC-215-2	0.050	11,200	0	1	0	0	0				
AC-215-3	0.075	11,250	1	1	0	1	1				
AC-215-4	0.075	11,450	0	0	0	0	0	0.44	0.000156	0.67	0.000246
AC-215-5	0.075	11,300	0	0	0	2	2				
AC-188-5	0.125	12,000	0	1	2	1	2				
AC-188-6	0.125	11,800	0	0	0	0	0	0.78	0.000274	1.00	0.000352
AC-188-7	0.125	12,000	2	1	1	1	2				
AC-215-6	0.150	12,600	2	1	0	2	0				
AC-215-7	0.150	12,650	0	2	1	2	2	1.20	0.000423	1.00	0.000352
AC-215-8	0.150	12,800	1	1	1	1	1				
AC-156-1	0.250	14,000	1	1	1	1	1				
AC-156-2	0.250	14,100	2	4	1	1	1	1.40	0.000493	1.20	0.000423
AC-156-3	0.250	14,300	1	2	1	1	1				
AC-156-4	0.350	15,300	2	1	1	1	1	1.00	0.000352	1.50	0.000528
AC-156-5	0.500	17,100	1	1	1	2	1				
AC-188-1	0.500	16,350	4	5	7	9	7				
AC-188-2	0.500	16,400	5	4	7	5	4	4.38	0.00154	3.70	0.00130
AC-188-3	0.500	16,600	3	3	3	4	4				
AC-188-4	0.500	16,250	4	6	L(1)	L(1)	4				
AC-156-12	0.650	18,350	2	8	4	7	2	6.20	0.00218	2.50	0.000880
AC-156-13	0.650	18,400	3	6	6	L(1)	3				
AC-156-6	0.700	20,000	3	8	4	8	7				
AC-156-7	0.700	18,800	8	7	25	5	3	8.66	0.00305	5.00	0.00176
AC-156-8	0.700	18,900	5	5	10	6	4				
AC-156-9	0.750	19,250	8	9	13	5	15				
AC-156-10	0.750	19,000	6	9	11	14	7	9.77	0.00344	6.66	0.00234
AC-156-11	0.750	18,900	9	9	11	8	7				
AC-156-14	0.900	20,150	9	18	25	40	8	26.66	0.00939	8.75	0.00308
AC-156-15	0.900	20,050	10	27	30	20	8				
AC-156-16	1.250	21,200	90	132	156	123	71	140.00	0.0493	94.75	0.0334
AC-156-17	1.250	21,250	80	132	132	165	118				

(1) L - Lamination.

TABLE A-3. DEPTH OF LARGEST CRACKS IN UNWELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 180 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch)								
			Section					Average of Sections 2-3-4		Average of Sections 1-5	
			1	2	3	4	5	Units	Inch	Units	Inch
AC-199-1	0.050	9,500	0	0	0	1	2	0.56	0.000197	0.50	0.000176
AC-199-2	0.050	10,000	0	0	1	0	1				
AC-199-3	0.050	9,500	0	1	0	2	0				
AC-216-4	0.075	10,500	1	1	1	1	1	1.00	0.000352	0.50	0.000176
AC-216-5	0.075	10,500	0	1	2	1	0				
AC-216-6	0.075	10,600	0	0	1	1	1				
AC-199-4	0.125	11,800	1	1	1	3	1	0.89	0.000333	0.83	0.000292
AC-199-5	0.125	12,300	1	0	1	0	1				
AC-199-6	0.125	11,700	0	1	1	0	1				
AC-216-1	0.150	12,800	1	1	7	2	0	1.89	0.000665	1.00	0.000352
AC-216-2	0.150	12,850	3	2	2	1	1				
AC-216-3	0.150	12,900	1	1	0	1	0				
AC-185-1	0.200	13,300	1	1	1	1	2	1.33	0.000468	1.33	0.000468
AC-185-2	0.200	15,000	1	1	2	2	1				
AC-185-3	0.200	14,800	2	2	1	1	1				
AC-216-7	0.250	15,650	2	3	5	3	3	2.66	0.000936	2.50	0.000880
AC-216-8	0.250	15,650	3	2	2	3	4				
AC-216-9	0.250	15,450	2	2	2	2	1				
AC-185-4	0.300	16,300	2	1	1	1	2	1.66	0.000584	2.16	0.000760
AC-185-5	0.300	16,100	3	1	3	2	1				
AC-185-6	0.300	17,200	1	2	2	2	4				
AC-185-7	0.400	18,650	2	4	4	2	2	2.79	0.000982	2.50	0.000880
AC-185-8	0.400	19,000	2	2	5	4	3				
AC-185-9	0.400	17,000	3	3	1	1	3				
AC-185-10	0.500	20,000	6	6	18	5	6	10.10	0.00356	4.50	0.00159
AC-185-11	0.500	19,600	4	2	20	14	4				
AC-185-15	0.500	18,600	3	5	7	14	4				
AC-185-12	0.600	21,000	75	112	115	72	46	85.80	0.0302	50.00	0.0176
AC-185-13	0.600	22,300	45	72	145	95	70				
AC-185-14	0.600	21,650	28	40	63	60	35				

TABLE A-4. DEPTH OF LARGEST CRACKS IN UNWELDED "C" STEEL KINZEL SPECIMENS
TESTED BELOW THE TRANSITION TEMPERATURE AT 40 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch)								
			Section					Average of Sections 2-3-4		Average of Sections 1-5	
			1	2	3	4	5	Units	Inch	Units	Inch
CU	0	0	0	0	0	0	0	0	0	0	0
AC-200-1	0.050	10,300	0	0	1	0	1				
AC-200-2	0.050	10,300	1	0	0	0	0	0.11	0.0000387	0.50	0.000176
AC-200-3	0.050	10,100	0	0	0	0	1				
AC-217-1	0.075	11,900	0	3	0	1	1				
AC-217-2	0.075	11,200	2	2	1	1	1	1.67	0.000588	1.16	0.000408
AC-217-3	0.075	11,200	2	3	3	1	1				
AC-200-4	0.125	12,000	2	1	1	1	1				
AC-200-5	0.125	12,800	2	1	1	1	1	1.00	0.000352	1.33	0.000468
AC-200-6	0.125	12,000	2	1	1	1	0				
AC-217-4	0.150	12,800	3	3	2	1	1				
AC-217-5	0.150	12,900	1	1	1	1	1	1.54	0.000542	1.83	0.000645
AC-217-6	0.150	12,500	4	1	2	2	1				
AC-184-1	0.200	14,300	1	1	1	2	1				
AC-184-2	0.200	15,800	1	1	1	1	1	1.33	0.000468	1.00	0.000352
AC-184-5	0.200	14,200	1	2	2	1	1				
AC-217-7	0.250	14,800	2	3	2	2	1				
AC-217-8	0.250	14,500	2	1	1	2	3	2.00	0.000704	1.56	0.000550
AC-217-9	0.250	14,800	4	3	2	2	2				
AC-184-3	0.300	16,300	3	2	1	1	4				
AC-184-4	0.300	18,100	1	1	1	2	1	2.11	0.000743	2.16	0.000760
AC-184-7	0.300	17,200	1	5	4	2	3				
AC-184-6	0.400	19,600	2	2	3	2	1				
AC-184-8	0.400	19,200	3	3	2	2	1	2.78	0.000980	1.83	0.000644
AC-184-9	0.400	19,200	2	4	4	3	2				
AC-184-10	0.500	19,800	11	13	11	9	4				
AC-184-11	0.500	19,500	4	8	3	30	3	9.42	0.00332	4.84	0.00170
AC-184-12	0.500	20,800	3	5	4	2	4				
AC-184-13	0.600	21,200	1	30	16	15	4				
AC-184-14	0.600	22,000	20	29	25	25	15	25.80	0.00909	11.16	0.00
AC-184-15	0.600	20,500	4	30	22	40	23				

TABLE A-5. DEPTH OF LARGEST CRACKS IN WELDED "B_r" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 80 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch) Section 1 Zone	Section 1 Depth	Section 2 Zone	Section 2 Depth	Section 3 Zone	Section 3 Depth	Section 4 Zone	Section 4 Depth	Section 5 Zone	Section 5 Depth	Section 6 Zone	Section 6 Depth	Section 7 Zone	Section 7 Depth	Section 8 Zone	Section 8 Depth	Section 9 Zone	Section 9 Depth	Section 10 Zone	Section 10 Depth	Average, Unaffected Base Metal Units	Average, Unaffected Base Metal Inch	Average, Heat-Affected Zone Units	Average, Heat-Affected Zone Inch	Average, Weld Metal Units	Average, Weld Metal Inch
AC-183-1	0.050	9,900	B	0	H	0	W	1	W	1	W	0	W	1	H	1	B	0	—	—	—	—						
AC-183-2	0.050	9,700	B	1	H	1	W	1	W	2	W	2	W	1	H	1	—	—	—	—	—	—	0.30	0.000106	0.90	0.000317	1.30	0.000457
AC-183-3	0.050	11,000	H	1	H	1	—	—	W	1	W	3	H	2	H	1	—	—	—	—	—	—						
AC-183-13	0.075	11,200	B	1	H	2	W	2	W	2	W	2	W	1	H	1	B	2	B	1	—	—	1.40	0.000493	2.20	0.000775	2.00	0.000704
AC-183-14	0.075	11,200	H	3	W	2	W	2	W	2	W	2	H	2	H	3	B	2	B	2	—	—						
AC-183-4	0.100	12,200	H	1	H	6	W	6	W	5	W	3	H	4	B	0	B	1	B	1	—	—						
AC-183-5	0.100	11,700	B	1	H	2	W	2	W	1	W	1	H	2	B	1	B	0	B	1	B	2	1.20	0.000423	2.70	0.000905	3.30	0.00116
AC-183-6	0.100	12,100	B	1	H	2	W	3	W	4	W	1	W	2	H	2	B	2	B	0	B	0						
AC-183-7	0.150	12,900	—	—	H	15	—	—	W	10	W	15	W	6	H	1	B	7	B	1	—	—						
AC-183-8	0.150	13,300	H	2	H	4	W	10	W	15	W	15	H	3	B	1	B	2	B	1	—	—	1.87	0.000658	3.88	0.00137	10.10	0.00356
AC-183-9	0.150	13,100	H	2	H	2	W	2	W	8	—	—	H	2	B	1	B	0	B	2	—	—						
AC-183-10	0.250	14,300	B	1	H	4	W	40	W	25	W	20	W	30	H	3	B	L(1)	B	3	B	2						
AC-183-11	0.250	14,900	H	5	W	40	W	40	W	40	W	50	H	4	B	2	B	2	B	2	—	—	3.11	0.00110	48.30	0.0170	72.46	0.0253
AC-183-12	0.250	14,400	H	43	H	142	W	228	W	142	W	142	H	142	B	9	B	5	B	2	—	—						

(1) L - Lamination

B = Base plate

H = Heat-affected zone

W = Weld metal

TABLE A-6. DEPTH OF LARGEST CRACKS IN WELDED "B_r" STEEL KINZEL SPECIMENS TESTED BELOW THE TRANSITION TEMPERATURE AT 0 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack – Units at 400X (1 Unit = 0.000352 Inch): Section 1		Section 2		Section 3		Section 4		Section 5		Section 6		Section 7		Section 8		Section 9		Section 10		Average, Unaffected Base Metal		Average, Heat-Affected Zone		Average, Weld Metal	
			Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Units	Inch	Units	Inch	Units	Inch
AC-153-13	0.050	11,500	H	1	H	1	W	2	W	0	W	3	W	2	H	0	H	2	—	—	—	—						
AC-153-14	0.050	11,500	H	0	H	1	W	0	W	1	W	1	W	1	H	3	B	0	—	—	—	—	0.00	0.00000	1.00	0.000352	1.10	0.000387
AC-153-15	0.050	11,400	H	1	H	1	W	1	W	1	W	0	W	0	H	1	H	0	—	—	—	—						
AC-153-1	0.075	12,300	H	2	W	3	W	6	W	5	H	3	H	2	B	1	—	—	—	—	—	—						
AC-153-2	0.075	12,500	H	0	H	0	W	1	W	1	W	1	H	2	B	1	B	1	—	—	—	—	1.00	0.000352	1.90	0.000670	3.60	0.001270
AC-153-3	0.075	12,100	H	2	H	2	W	4	W	7	W	4	H	2	H	4	B	1	—	—	—	—						
AC-153-4	0.100	11,900	H	1	H	1	W	1	W	1	W	2	H	1	B	1	B	1	—	—	—	—						
AC-153-5	0.100	12,900	H	1	H	7	W	8	W	8	W	7	H	2	B	1	B	2	—	—	—	—	1.20	0.000423	2.70	0.000905	3.30	0.001160
AC-153-6	0.100	12,750	—	—	H	1	W	3	W	2	W	3	W	2	H	3	B	2	B	1	B	1						
AC-153-7	0.150	13,900	B	3	H	3	W	14	W	20	W	8	H	2	B	1	B	0	—	—	—	—						
AC-153-8	0.150	13,100	B	0	—	—	W	9	W	4	H	17	H	0	B	4	B	0	—	—	—	—	1.11	0.000391	4.42	0.00156	10.00	0.003520
AC-153-9	0.150	14,100	B	0	H	3	W	10	W	5	H	5	H	1	B	1	B	1	—	—	—	—						
AC-153-10	0.250	15,000	B	2	H	71	W	118	W	189	W	61	H	2	B	15	B	8	—	—	—	—						
AC-153-11	0.250	15,450	B	10	H	47	W	142	W	71	W	66	H	4	B	3	B	2	—	—	—	—	6.42	0.002260	107.5	0.037800	171.4	0.060300
AC-153-12	0.250	15,100	B	5	H	228	W	427	W	356	W	284	H	284	H	117	—	—	—	—	—	—						

B = Base metal

H = Heat-affected zone

W - Weld metal

TABLE A-7. DEPTH OF LARGEST CRACKS IN WELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 180 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch)																									
			Section 1		Section 2		Section 3		Section 4		Section 5		Section 6		Section 7		Section 8		Section 9		Section 10		Average, Unaffected Base Metal		Average, Heat-Affected Zone		Average, Weld Metal	
			Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Units	Inch	Units	Inch	Units	Inch
AC-182-1	0.050	9,300	B	0	H	1	W	0	W	2	W	0	W	0	H	0	B	0	B	0	B	0						
AC-182-2	0.050	10,400	B	0	H	0	W	2	W	0	W	0	W	0	H	0	H	2	B	0	B	0	0.18	0.0000644	0.50	0.000176	0.64	0.000225
AC-182-12	0.050	9,700	B	0	H	0	W	1	W	0	W	2	H	0	H	1	B	0	B	1	B	1						
AC-218-1	0.075	11,300	B	2	B	1	H	2	H	15	W	5	W	7	W	15	H	6	B	1	B	1						
AC-218-2	0.075	11,700	B	1	H	3	H	1	W	10	W	14	W	6	H	8	B	3	B	3	B	1	1.33	0.000468	7.00	0.000246	13.6	0.004790
AC-218-3	0.075	11,750	B	2	B	1	H	13	W	13	W	18	W	35	H	16	H	0	B	0	B	0						
AC-182-4	0.100	11,800	B	1	H	2	W	0	W	3	W	10	W	2	H	2	B	1	—	—	—	—						
AC-182-5	0.100	13,750	B	1	H	1	W	1	W	40	W	22	W	5	H	1	B	4	—	—	—	—	1.50	0.000528	1.50	0.000528	11.30	0.003980
AC-182-6	0.100	13,400	B	0	H	1	W	3	W	25	W	20	W	5	H	2	B	2	—	—	—	—						
AC-182-7	0.150	14,100	B	2	H	1	W	10	W	40	W	7	W	40	H	3	B	2	—	—	—	—						
AC-182-8	0.150	14,400	B	2	H	5	W	20	W	22	W	33	H	33	B	5	—	—	—	—	—	—	2.83	0.000995	7.66	0.002700	23.70	0.008350
AC-182-9	0.150	14,400	B	2	H	2	W	12	W	32	W	35	W	10	H	2	B	4	—	—	—	—						
AC-182-10	0.200	16,400	B	5	H	51	W	142	W	132	W	145	H	80	H	10	B	4	B	1	—	—						
AC-182-11	0.200	16,400	B	5	H	12	W	107	W	120	W	125	W	80	H	4	B	2	—	—	—	—	3.71	0.001310	30.8	0.010850	117.4	0.041300
AC-182-13	0.200	16,900	B	3	—	—	W	105	W	128	W	90	H	28	B	6	—	—	—	—	—	—						
AC-182-14	0.250	16,100	B	1	H	50	W	150	W	155	W	135	H	70	B	25	B	1	B	0	—	—						
AC-182-15	0.250	16,700	B	10	H	55	W	140	W	215	W	200	H	17	B	44	B	8	B	15	—	—	16.9	0.00596	72.8	0.025700	182.0	0.064200
AC-182-16	0.250	18,900	B	44	H	110	W	200	W	230	W	213	H	134	B	53	B	7	B	6	B	6						

B = Base metal

H = Heat-affected zone

W - Weld metal

TABLE A-8. DEPTH OF LARGEST CRACKS IN WELDED "C" STEEL KINZEL SPECIMENS
TESTED BELOW THE TRANSITION TEMPERATURE AT 40 F

Specimen Number	Deflection, Inch	Maximum Load, Pounds	Depth of Crack - Units at 400X (1 Unit = 0.000352 Inch) Section 1		Section 2		Section 3		Section 4		Section 5		Section 6		Section 7		Section 8		Section 9		Section 10		Average, Unaffected Base Metal		Average, Heat-Affected Zone		Average, Weld Metal	
			Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Zone	Depth	Units	Inch	Units	Inch	Units	Inch
CW	0	0	B	0	H	0	W	0	W	0	W	0	H	0	B	0	—	—	—	—	—	—	0		0		0	
AC-181-1	0.050	10,500	B	0	H	1	W	3	W	1	W	0	W	0	H	0	B	0	—	—	—	—						
AC-181-3	0.050	10,000	B	1	H	0	W	1	W	2	W	2	H	2	H	0	B	1	—	—	—	—	0.25	0.000088	0.57	0.000201	1.09	0.000384
AC-181-6	0.050	10,300	B	0	H	0	W	0	W	2	W	0	W	1	H	1	B	0	—	—	—	—						
AC-219-1	0.075	11,750	B	2	H	1	H	23	W	3	W	3	W	5	H	2	H	1	B	0	B	1						
AC-219-2	0.075	12,400	B	1	H	1	H	1	W	4	W	3	W	2	H	1	B	2	B	2	B	1	0.90	0.000317	15.1	0.005320	58.4	0.020600
AC-219-3	0.075	12,000	B	1	H	2	H	45	W	150	W	195	W	160	H	105	H	0	B	0	B	0						
AC-181-2	0.100	12,500	B	1	H	2	W	1	W	1	W	2	H	1	B	1	B	1	—	—	—	—						
AC-181-4	0.100	13,400	B	1	H	1	W	1	—	—	W	1	H	1	B	1	B	1	—	—	—	—	1.00	0.000352	1.17	0.000412	1.11	0.000387
AC-181-7	0.100	14,400	B	1	H	1	W	1	W	1	W	1	W	1	H	1	B	1	—	—	—	—						
AC-181-5	0.150	14,000	B	1	H	2	W	2	W	4	W	2	H	4	B	0	B	1	—	—	—	—						
AC-181-10	0.150	16,300	B	1	H	85	W	195	W	220	W	200	H	240	B	3	B	0	—	—	—	—	22.90	0.008050	105.0	0.037000	130.0	0.045700
AC-181-11	0.150	16,500	B	1	H	7	W	4	W	15	W	12	W	4	H	2	B	1	—	—	—	—						
AC-181-13	0.150	16,900	B	1	H	140	W	265	W	240	W	295	W	355	H	360	B	220	—	—	—	—						
AC-181-8	0.200	15,900	B	1	H	2	W	15	W	5	W	45	H	10	B	4	B	1	B	1	B	1	1.00	0.000352	10.6	0.003730	41.66	0.014700
AC-181-12	0.200	16,500	B	0	H	1	H	20	W	40	W	75	W	70	H	20	B	0	B	1	B	0						

B = Base metal

H = Heat-affected zone

W = Weld metal

TABLE A-9. SUMMARY OF AVERAGE CRACK DEPTH IN UNWELDED "B_r" STEEL KINZEL SPECIMENS TESTED ABOVE (80 F) AND BELOW (0 F) THE TRANSITION TEMPERATURE

Test Temperature, F	Deflection, Inch	Average Crack Depth: Sections 2-3-4- Units(1)	Sections 2-3-4- Inch	Sections 1-5 Units(1)	Sections 1-5 Inch
0	0.050	0.55	0.000194	0.67	0.000246
80	0.050	0.11	0.0000387	0.50	0.000176
0	0.075	0.44	0.000156	0.67	0.000246
80	0.075	0.22	0.0000775	0.33	0.000116
0	0.125	0.78	0.000274	1.00	0.000352
80	0.125	3.44	0.001210	1.83	0.000645
0	0.150	1.20	0.000423	1.00	0.000352
80	0.150	0.89	0.000313	1.16	0.000409
0	0.250	1.40	0.000493	1.20	0.000423
80	0.250	3.22	0.001140	1.16	0.000409
0	0.350	1.00	0.000352	1.50	0.000528
0	0.500	4.38	0.001540	3.70	0.001300
80	0.500	3.55	0.001250	1.83	0.000645
0	0.650	6.20	0.002180	2.50	0.000880
0	0.700	8.66	0.00305	5.00	0.00176
80	0.700	5.78	0.002040	6.16	0.002170
0	0.750	9.77	0.003440	6.66	0.00234
80	0.750	8.23	0.002900	4.17	0.001480
80	0.800	18.11	0.00638	11.00	0.00388
80	0.850	22.55	0.00793	7.33	0.00258
0	0.900	26.66	0.009390	8.75	0.003080
80	0.900	35.88	0.012600	18.00	0.006330
0	1.250	140.00	0.049300	94.75	0.033400
80	1.250	136.20	0.047900	52.66	0.018500

(1) Micrometer eyepiece units at 400X. 1 unit = 0.000352 inch.

TABLE A-10. SUMMARY OF AVERAGE CRACK DEPTH IN UNWELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE

Test Temperature, F	Deflection, Inch	Average Crack Depth Sections 2-3-4 Units(1)	Sections 2-3-4 Inch	Sections 1-5 Units(1)	Sections 1-5 Inch
40	0.050	0.11	0.0000387	0.50	0.000176
180	0.050	0.56	0.000197	0.50	0.000176
40	0.075	1.67	0.000588	1.16	0.000408
180	0.075	1.00	0.000352	0.50	0.000176
40	0.125	1.00	0.000352	1.33	0.000368
180	0.125	0.89	0.000333	0.83	0.000292
40	0.150	1.54	0.000542	1.83	0.000645
180	0.150	1.89	0.000665	1.00	0.000352
40	0.200	1.33	0.000468	1.00	0.000352
180	0.200	1.33	0.000468	1.33	0.000468
40	0.250	2.00	0.000704	1.56	0.000550
180	0.250	2.66	0.000936	2.50	0.000880
40	0.300	2.11	0.000743	2.16	0.000760
180	0.300	1.66	0.000584	2.16	0.000760
40	0.400	2.78	0.000980	1.83	0.000644
180	0.400	2.79	0.000982	2.50	0.000880
40	0.500	9.42	0.003320	4.84	0.001700
180	0.500	10.10	0.003560	4.50	0.001590
40	0.600	25.80	0.009090	11.16	0.000408
180	0.600	85.80	0.030200	50.00	0.017600

(1) Micrometer eyepiece units at 400X. 1 unit = 0.000352 inch.

TABLE A-11. SUMMARY OF AVERAGE CRACK DEPTH IN WELDED "Br" STEEL KINZEL SPECIMENS TESTED ABOVE (80 F) AND BELOW (0 F) THE TRANSITION TEMPERATURE

Test Temperature, F	Deflection, Inch	Average Crack Depth: Unaffected Base Metal, Units (1)	Unaffected Base Metal, Inch	Heat-Affected Zone, Units (1)	Heat-Affected Zone, Inch	Weld Metal, Units (1)	Weld Metal, Inch
0	0.050	0.00	0.000000	1.00	0.000352	1.10	0.000387
80	0.050	0.30	0.000106	0.90	0.000317	1.30	0.000457
0	0.075	1.00	0.000352	1.90	0.000670	3.60	0.001270
80	0.075	1.40	0.000493	2.20	0.000775	2.00	0.000704
0	0.100	1.20	0.000423	2.70	0.000905	3.30	0.001160
80	0.100	1.20	0.000423	2.70	0.000905	3.30	0.001160
0	0.150	1.11	0.000391	4.42	0.001560	10.00	0.003520
80	0.150	1.87	0.000658	3.88	0.001370	10.10	0.003560
0	0.250	6.42	0.002260	107.5	0.037800	171.4	0.060300
80	0.250	3.11	0.001100	48.30	0.017000	72.46	0.025300

(1) Micrometer eyepiece units at 400X. 1 unit = 0.000352 inch.

TABLE A-12. SUMMARY OF AVERAGE CRACK DEPTH IN WELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE

Test Temperature, F	Deflection, Inch	Average Crack Depth					
		Unaffected Base Metal		Heat-Affected Zone		Weld Metal	
		Units(1)	Inch	Units(1)	Inch	Units(1)	Inch
40	0.050	0.25	0.000088	0.57	0.000201	1.09	0.000384
180	0.050	0.18	0.0000644	0.50	0.000176	0.64	0.000225
40	0.075	0.90	0.0003170	15.10	0.005320	58.40	0.020600
180	0.075	1.33	0.000468	7.00	0.000246	13.60	0.004790
40	0.100	1.00	0.000352	1.17	0.000412	1.11	0.000387
180	0.100	1.50	0.000528	1.50	0.000528	11.30	0.003980
40	0.150	22.90	0.008050	105.00	0.037000	130.00	0.045700
180	0.150	2.83	0.000995	7.66	0.002700	23.70	0.008350
40	0.200	1.00	0.000352	10.60	0.003730	41.66	0.014700
180	0.200	3.71	0.001310	30.80	0.010850	117.40	0.041300
40	0.250	(Complete failure of specimens)					
180	0.250	16.90	0.00596	72.80	0.025700	182.00	0.064200

(1) Micrometer eyepiece units at 400X. 1 unit = 0.000352 inch.

APPENDIX B

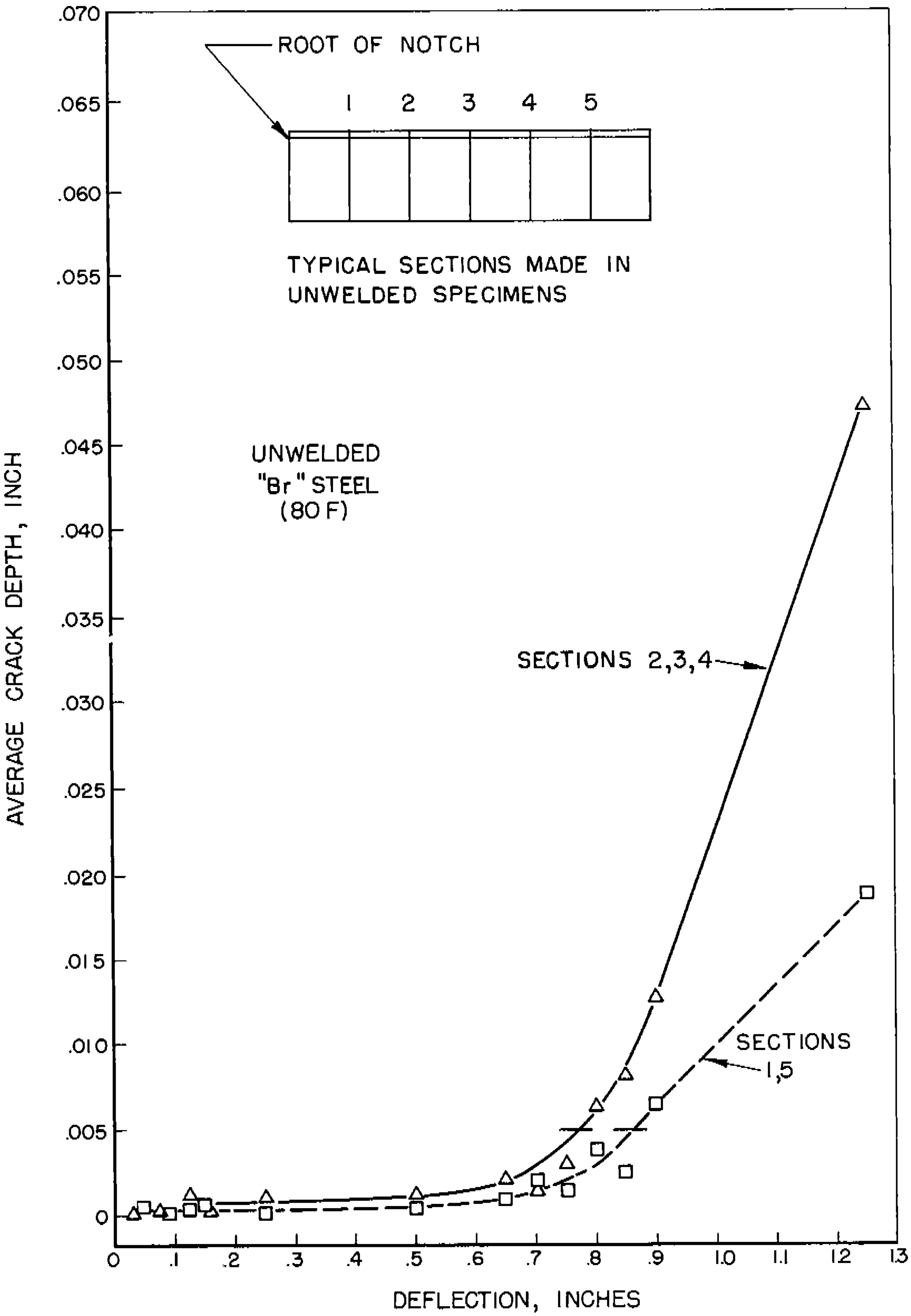

FIGURE B-1. COMPARISON OF AVERAGE CRACK DEPTH IN SECTIONS 2, 3, 4, AND SECTIONS 1, 5 OF UNWELDED "Br" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 80 F.

68406

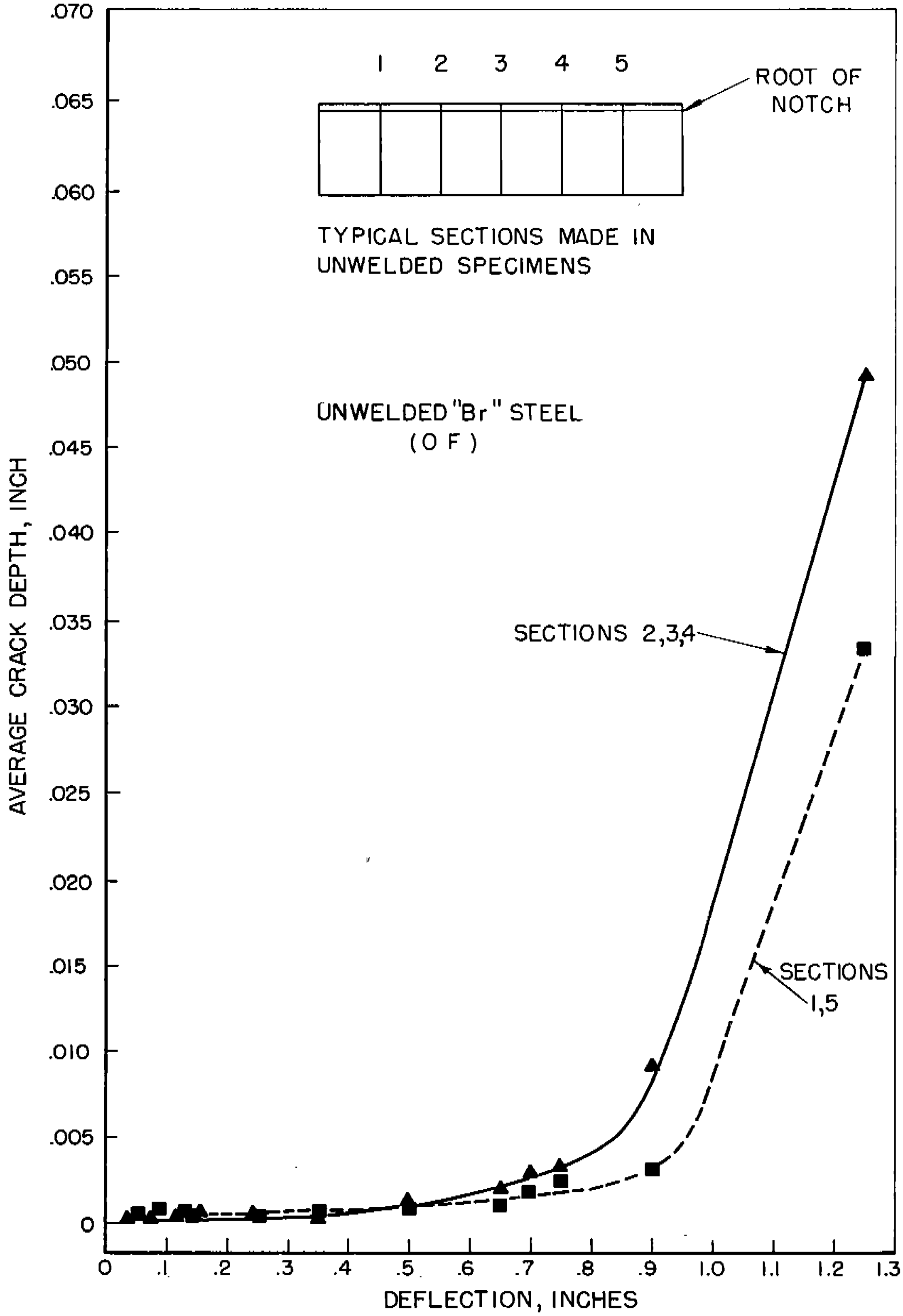

FIGURE B-2. COMPARISON OF AVERAGE CRACK DEPTH IN SECTIONS 2,3,4 AND SECTIONS 1,5 OF UNWELDED "Br" STEEL KINZEL SPECIMENS TESTED AT 0F.

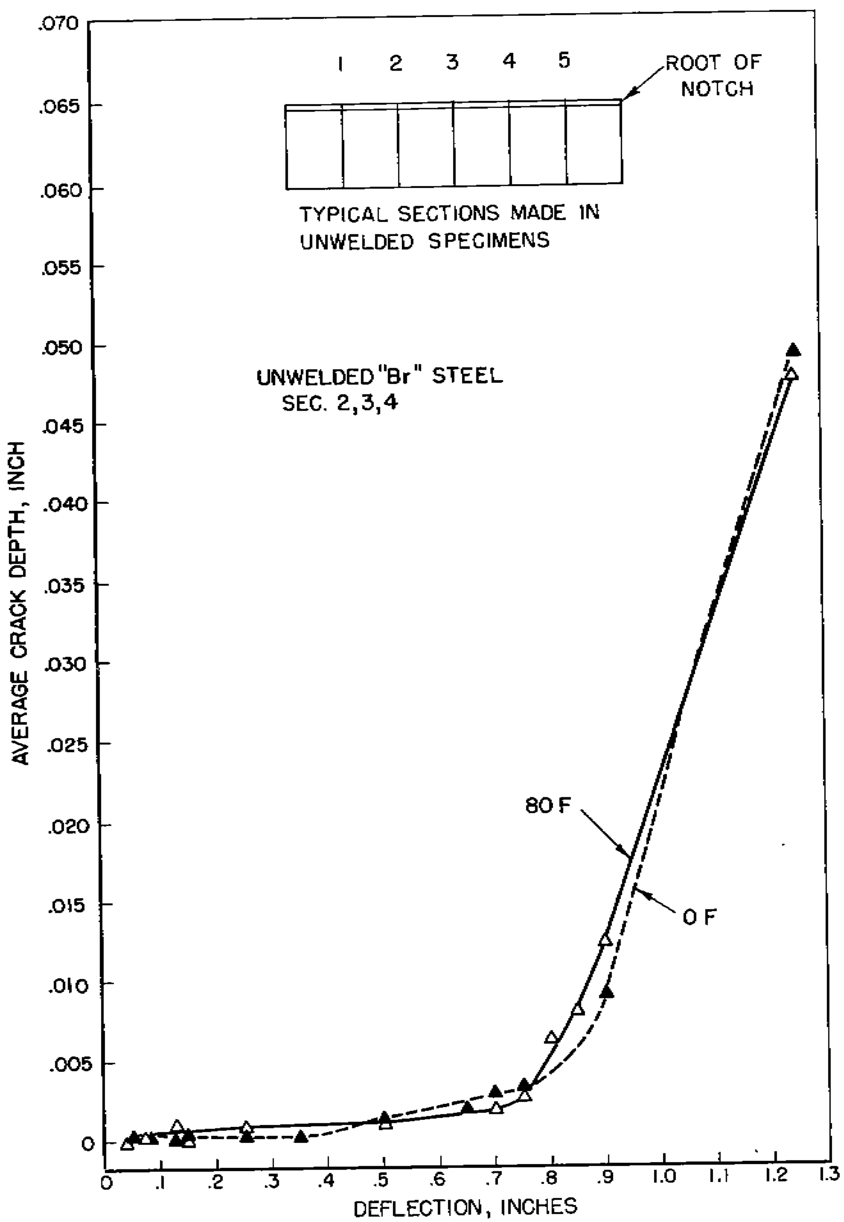

FIGURE B-3. COMPARISON OF AVERAGE CRACK DEPTH IN SECTIONS 2, 3, 4 OF UNWELDED "Br" STEEL KINZEL SPECIMENS TESTED AT 80F AND 0F.

68404

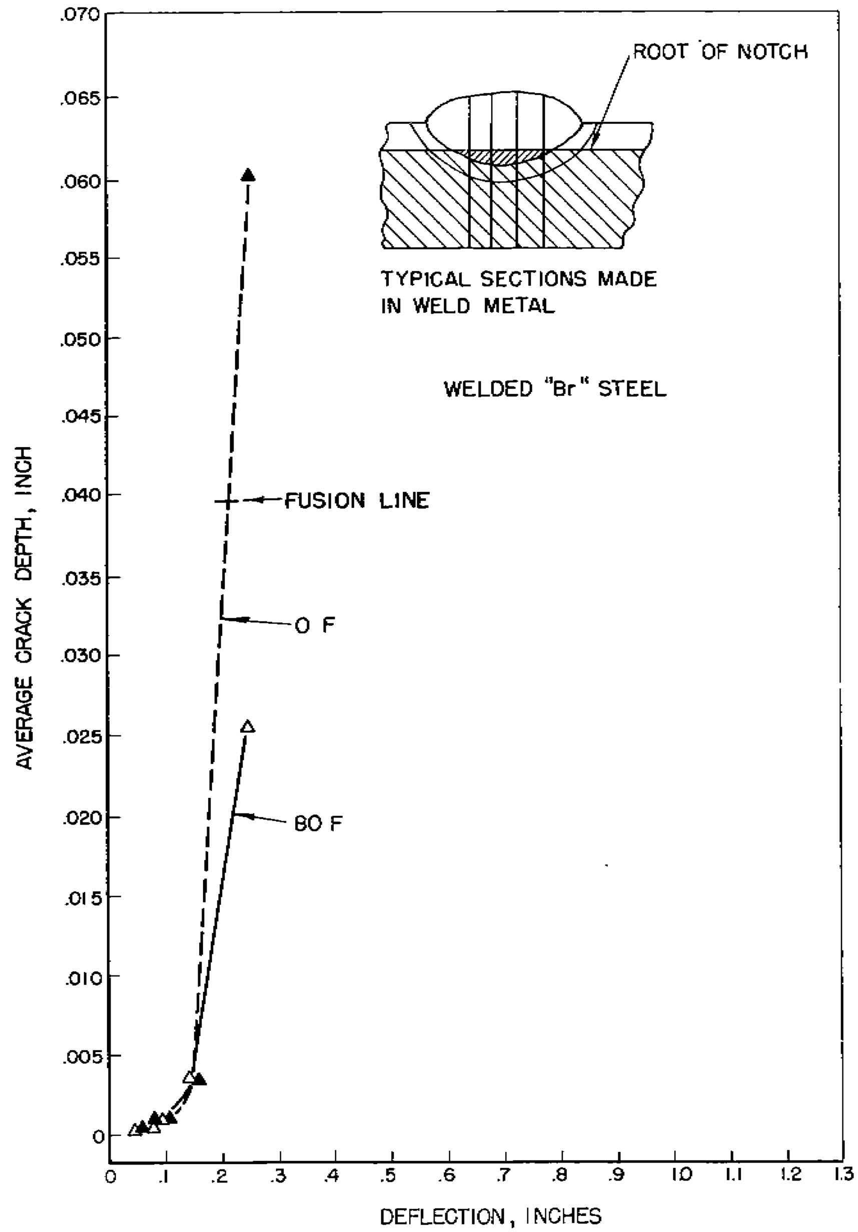

FIGURE B-4. COMPARISON OF AVERAGE CRACK DEPTH IN WELD-METAL ZONE OF WELDED "Br" STEEL KINZEL SPECIMENS TESTED ABOVE (80 F) AND BELOW (0 F) THE TRANSITION TEMPERATURE.

68423

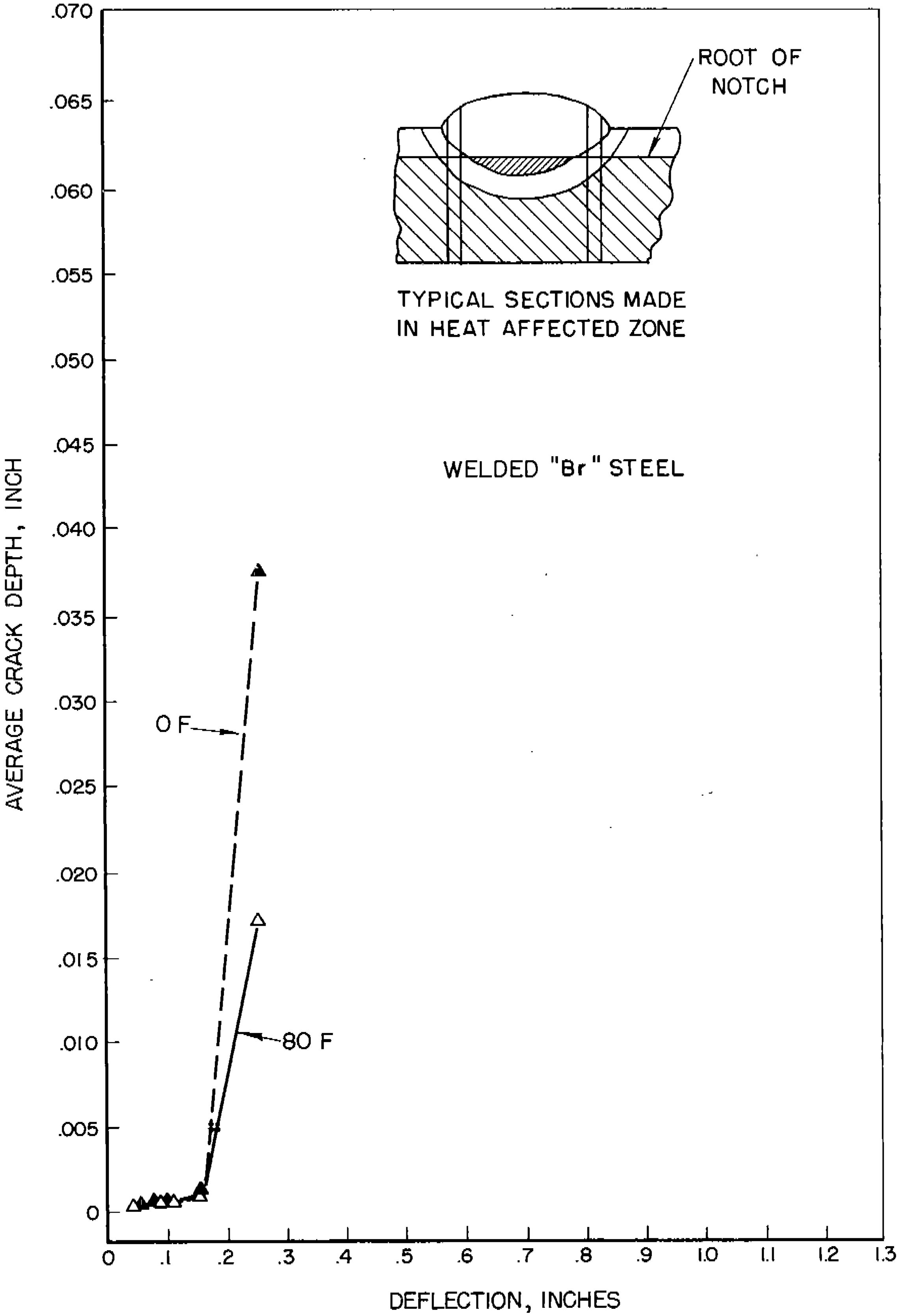

FIGURE B-5. COMPARISON OF AVERAGE CRACK DEPTH OF HEAT-AFFECTED ZONE OF WELDED "Br" STEEL KINZEL SPECIMENS TESTED ABOVE (80 F) AND BELOW (0 F) THE TRANSITION TEMPERATURE.

68419

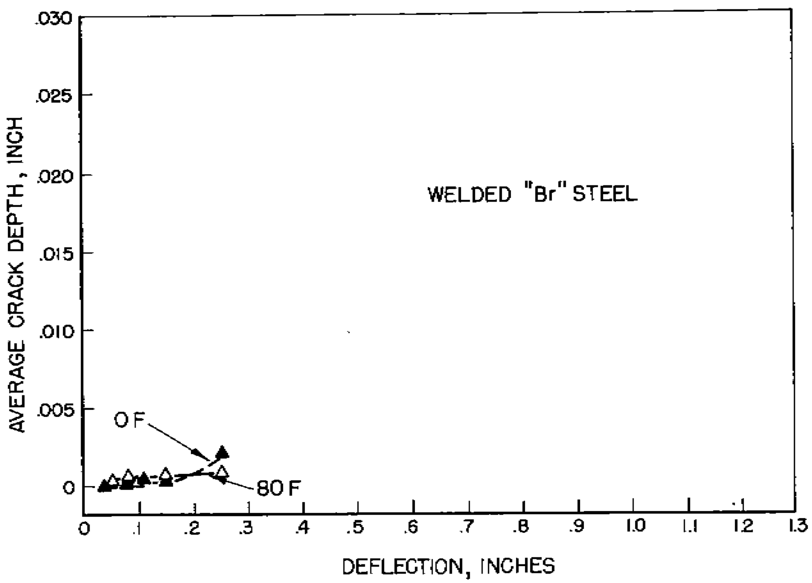

FIGURE B-6. COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE METAL OF WELDED "Br" STEEL KINZEL SPECIMENS TESTED ABOVE (80 F) AND BELOW (0 F) THE TRANSITION TEMPERATURE.

68420

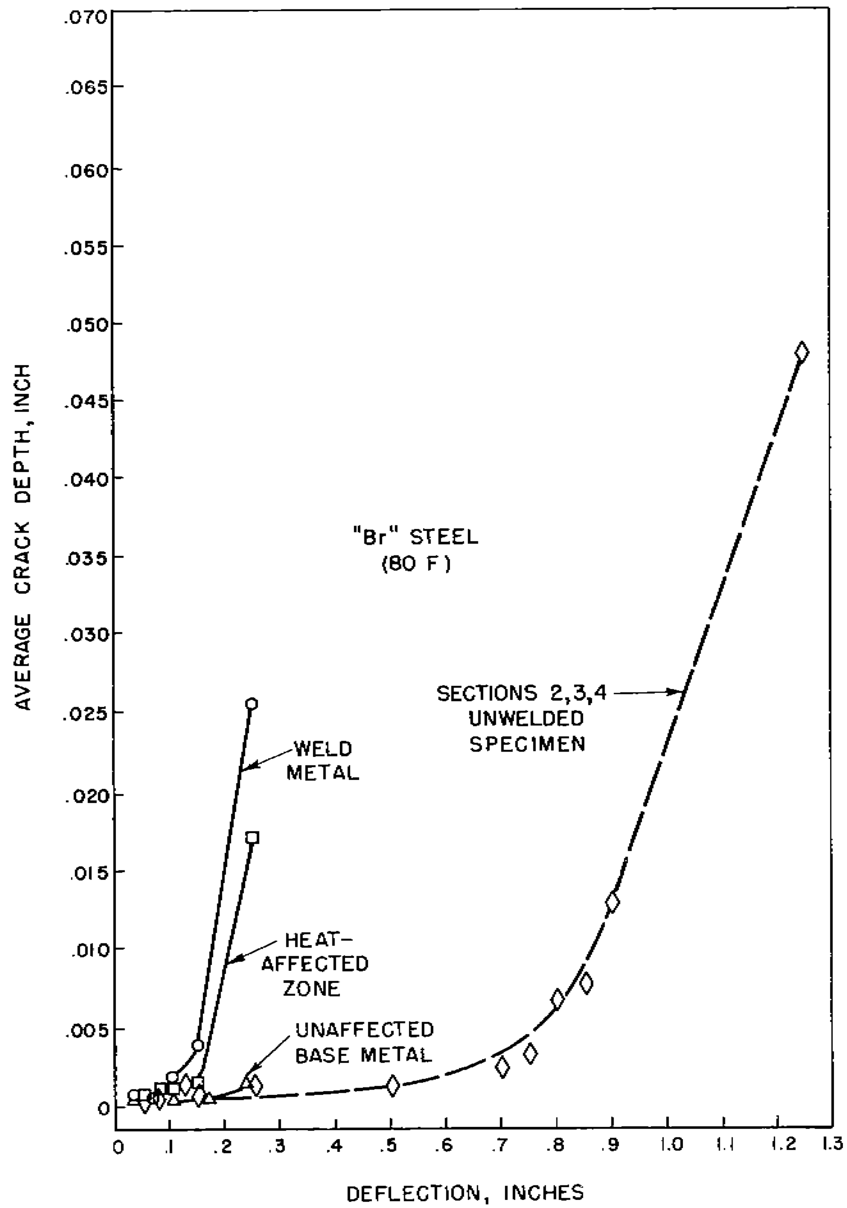

FIGURE B7. COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE METAL, HEAT-AFFECTED ZONE, AND WELD METAL OF WELDED "Br" STEEL KINZEL SPECIMENS, AND SECTIONS 2, 3, 4 OF UNWELDED "Br" STEEL KINZEL SPECIMENS, ALL TESTED ABOVE THE TRANSITION TEMPERATURE AT 80 F.

68412

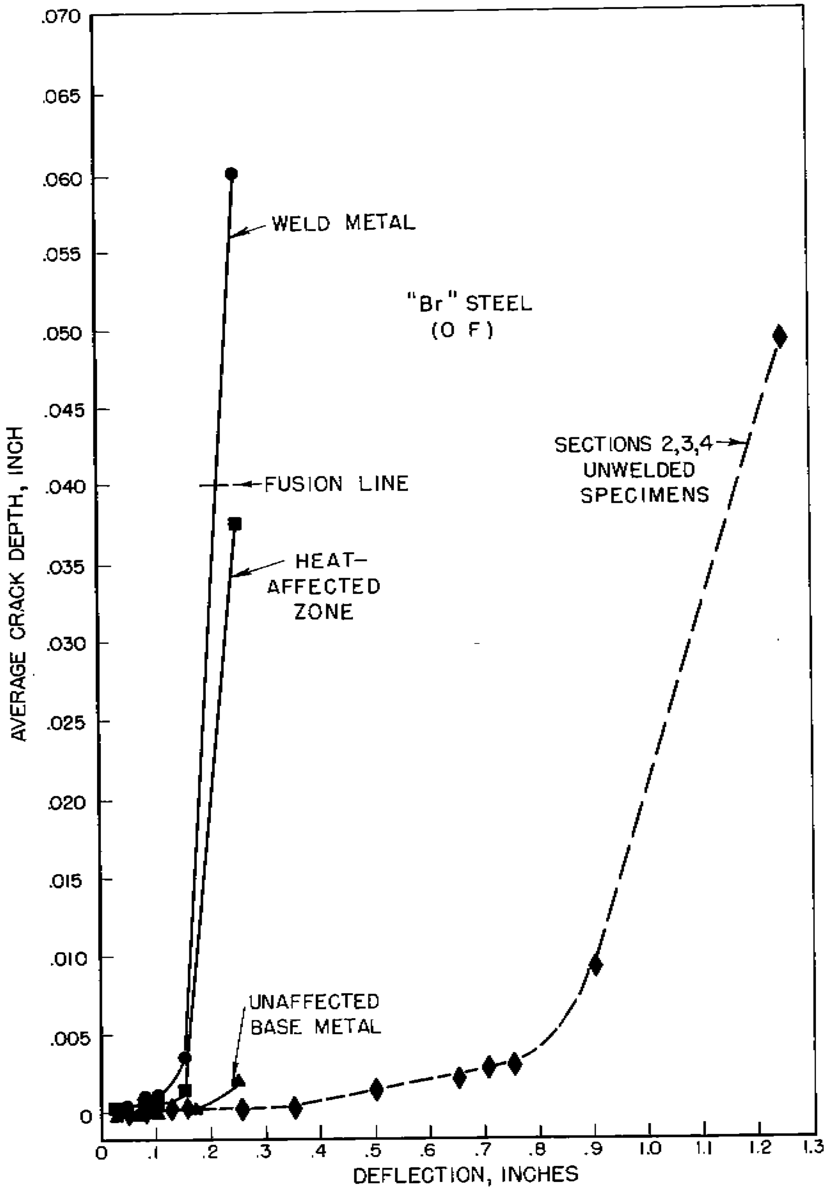

FIGURE B8. COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE METAL, HEAT-AFFECTED ZONE, AND WELD METAL OF WELDED "Br" STEEL KINZEL SPECIMENS, AND SECTIONS 2, 3,4 OF UNWELDED "Br" STEEL KINZEI SPECIMENS, ALL TESTED AT OF.

68411

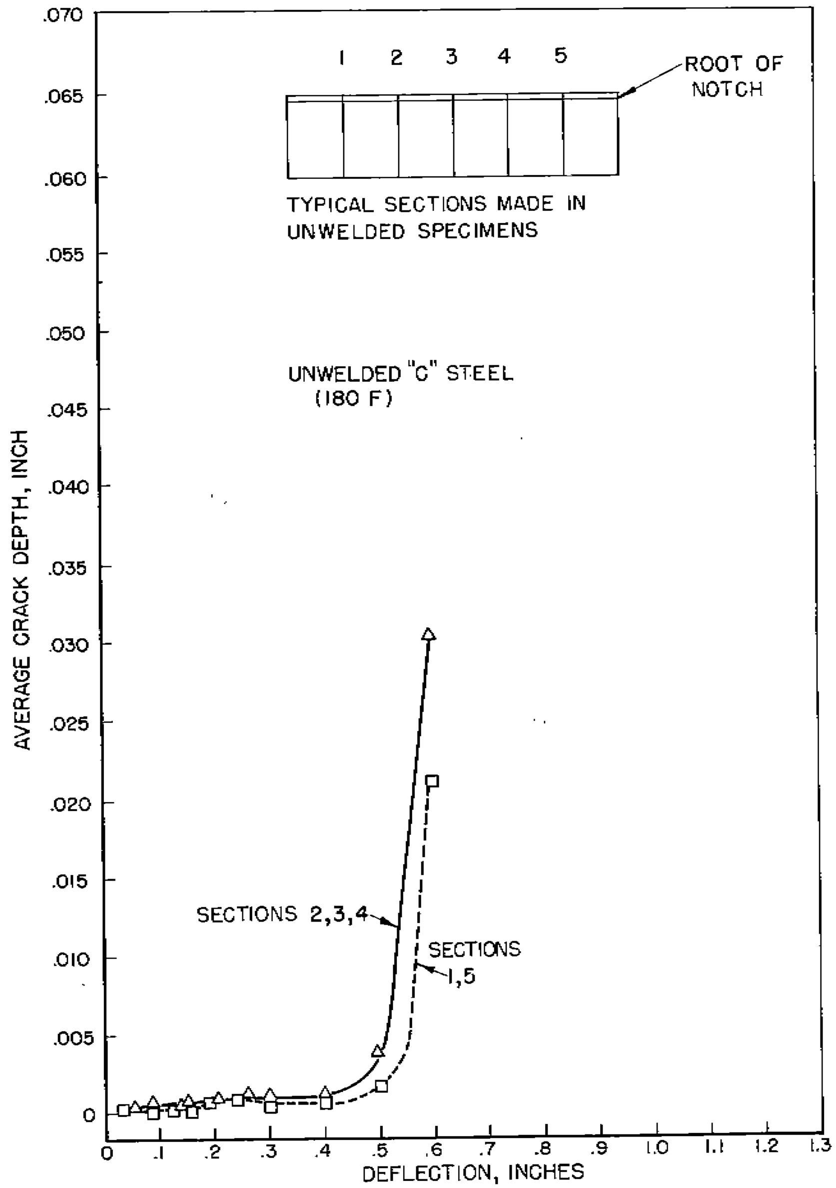

FIGURE B9. COMPARISON OF AVERAGE CRACK DEPTH OF SECTIONS 2,3,4 AND SECTIONS 1,5 OF UNWELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE AT 180 F.

68409

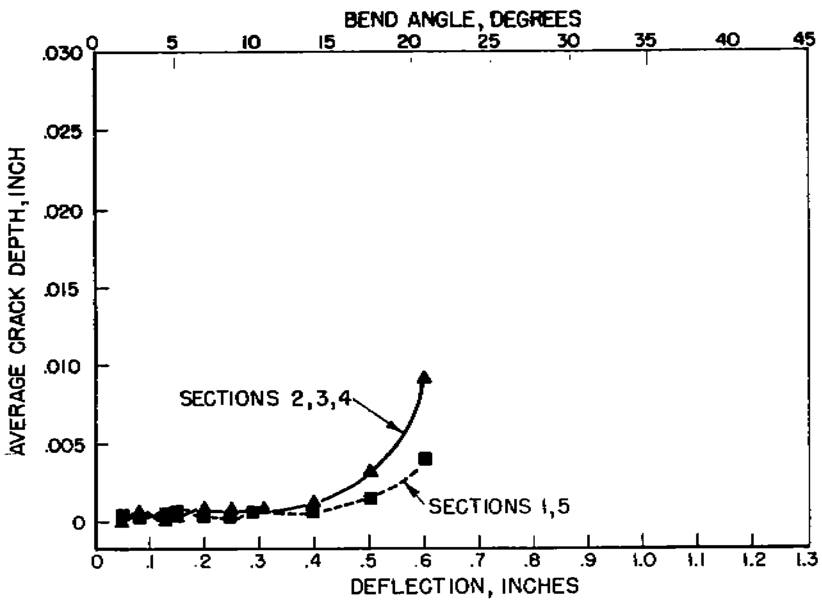

FIGURE B-10. COMPARISON OF AVERAGE CRACK DEPTH OF SECTIONS 2,3,4 AND SECTIONS 1,5 OF UNWELDED "C" STEEL KINZEL SPECIMENS TESTED BELOW THE TRANSITION TEMPERATURE AT 40F. 68408

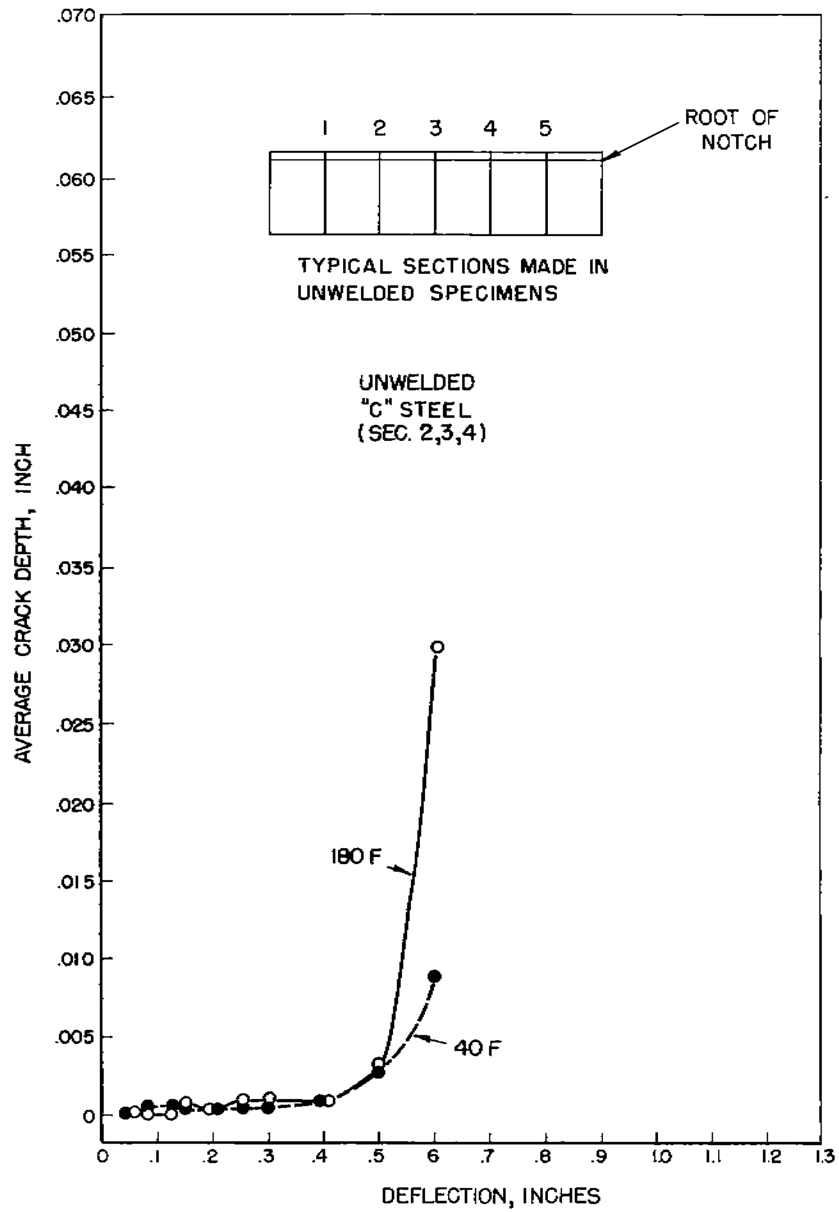

FIGURE B-11. COMPARISON OF AVERAGE CRACK DEPTH OF SECTIONS 2, 3, 4 OF UNWELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE. 68407

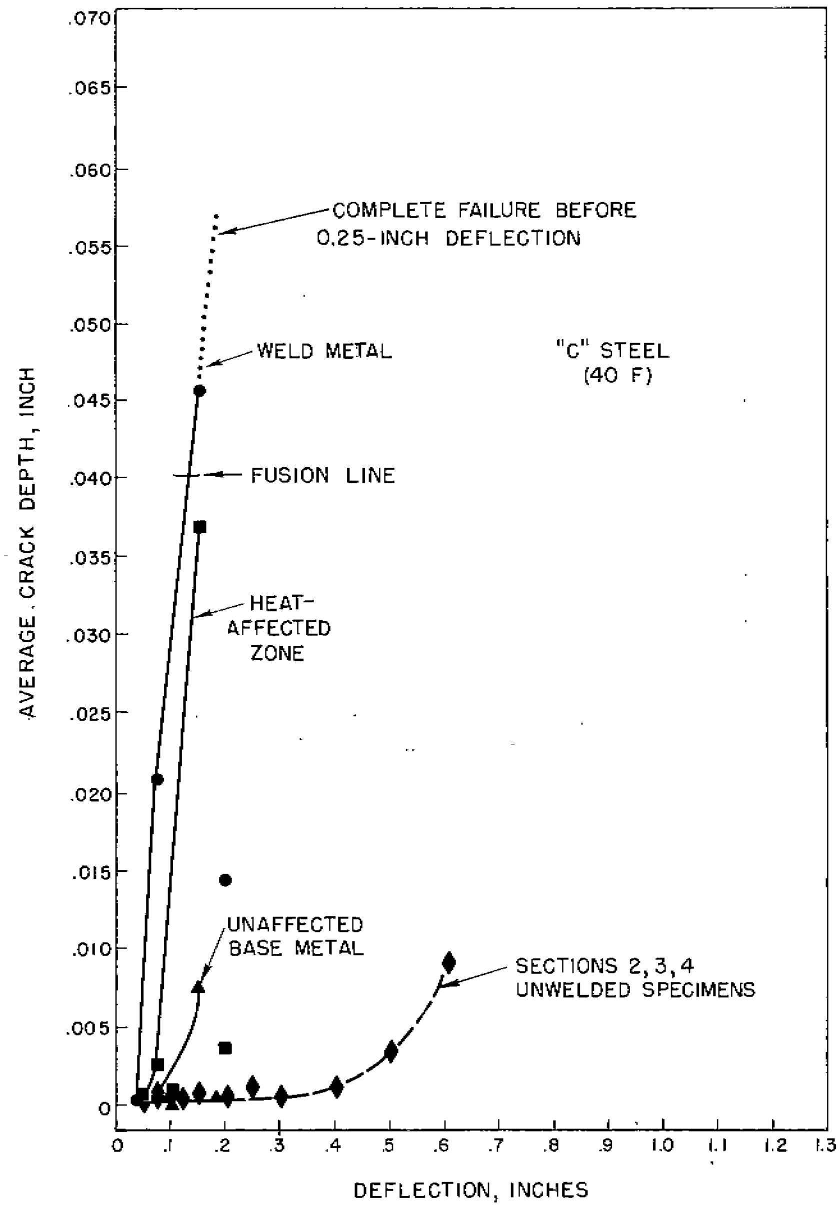

FIGURE B-12. COMPARISON OF AVERAGE CRACK DEPTH OF WELD METAL, HEAT-AFFECTED ZONE, AND UNAFFECTED BASE METAL OF WELDED "C" STEEL KINZEL SPECIMENS, AND SECTIONS 2,3, 4 OF UNWELDED "C" STEEL KINZEL SPECIMENS, ALL TESTED BELOW THE TRANSITION TEMPERATURE AT 40 F.

68409

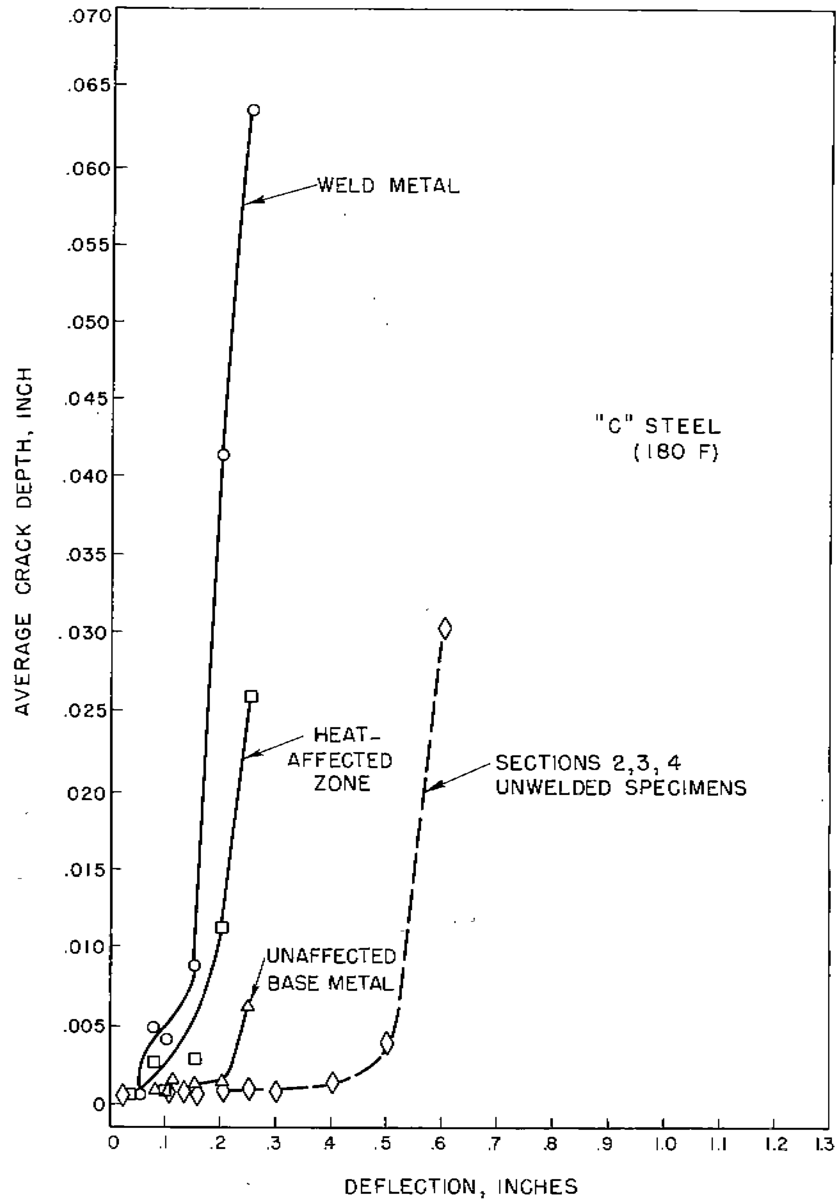

FIGURE B-13. COMPARISON OF AVERAGE CRACK DEPTH OF WELD METAL, HEAT-AFFECTED ZONE, AND UNAFFECTED BASE METAL OF WELDED "C" STEEL KINZEL SPECIMENS, AND SECTIONS 2,3,4 OF UNWELDED "C" STEEL KINZEL SPECIMENS, ALL TESTED ABOVE THE TRANSITION TEMPERATURE AT 180 F.

68410

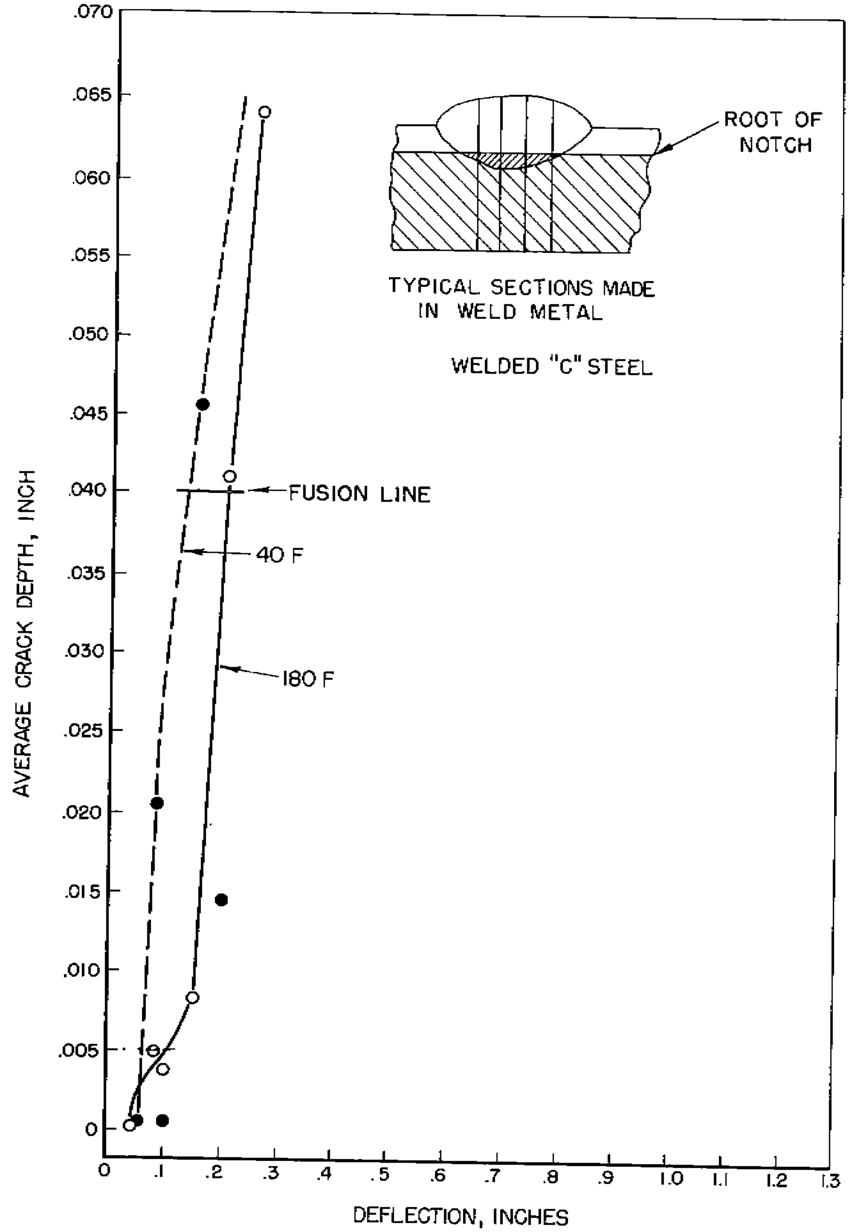

FIGURE B-14. COMPARISON OF AVERAGE CRACK DEPTH IN WELD-METAL ZONE OF WELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE.

68424

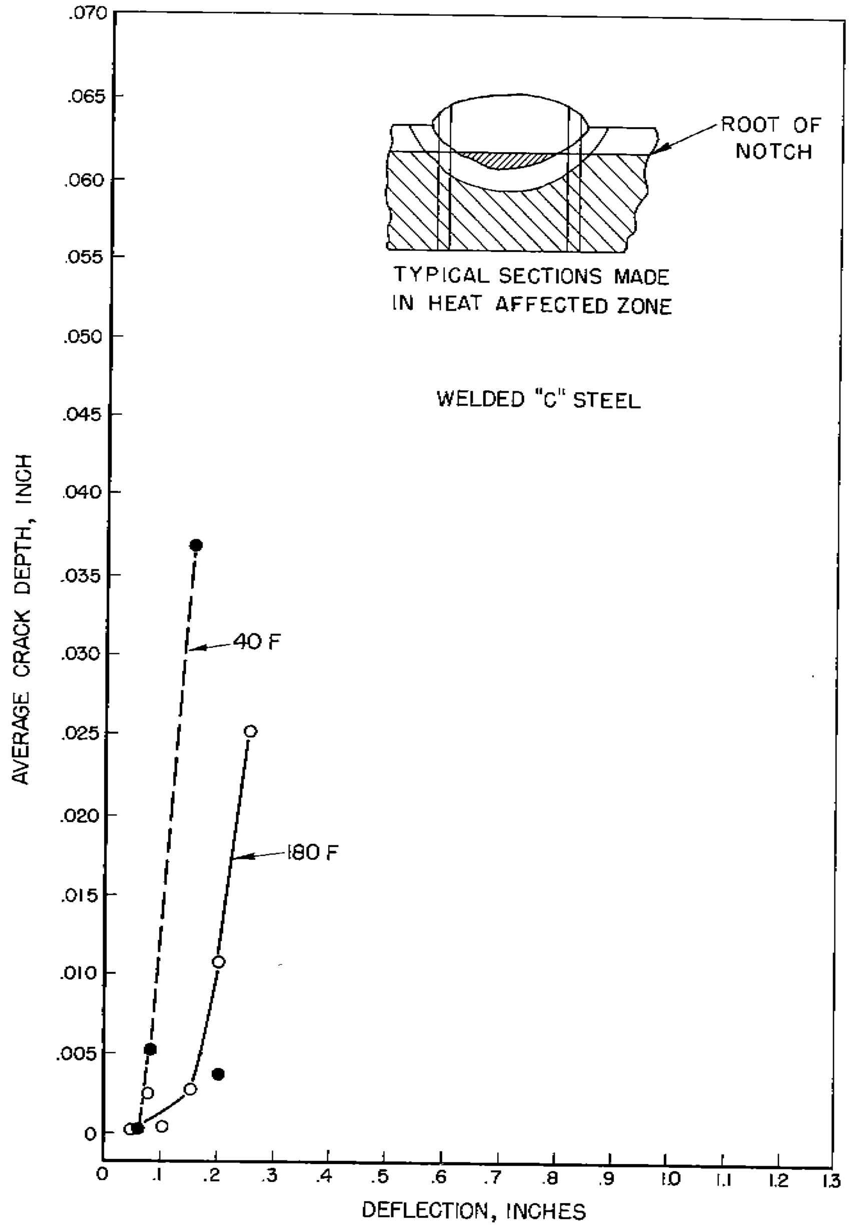

FIGURE B-15. COMPARISON OF AVERAGE CRACK DEPTH IN HEAT-AFFECTED ZONE OF WELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE.

68421

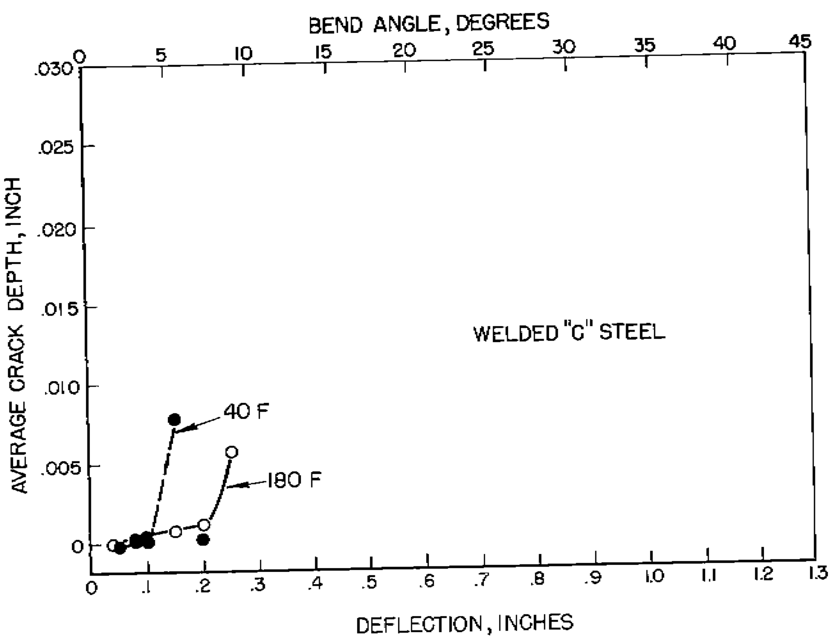

FIGURE B-16. COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE-METAL ZONE OF WELDED "C" STEEL KINZEL SPECIMENS TESTED ABOVE (180 F) AND BELOW (40 F) THE TRANSITION TEMPERATURE. 68422

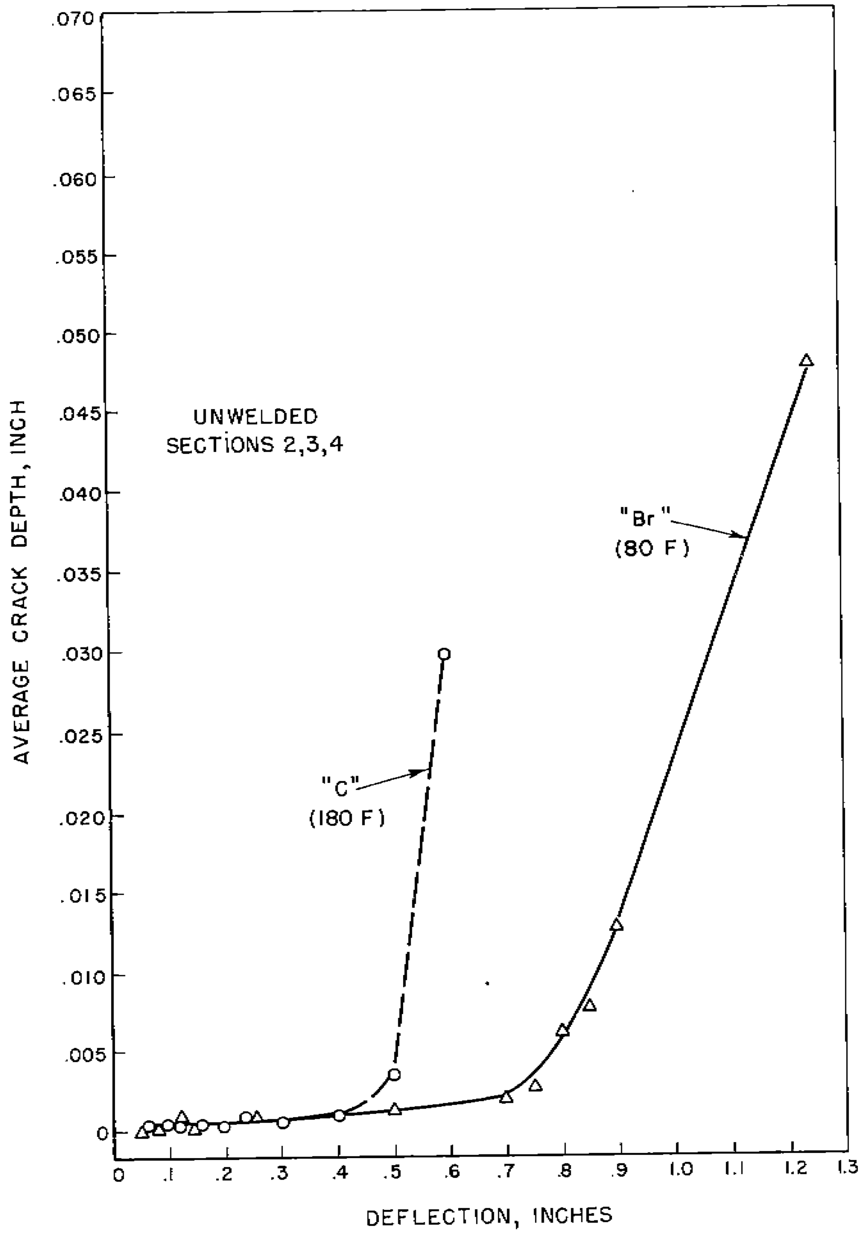

FIGURE B17. COMPARISON OF AVERAGE CRACK DEPTH IN SECTIONS 2,3,4 OF UNWELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED ABOVE THEIR TRANSITION TEMPERATURES.

68402

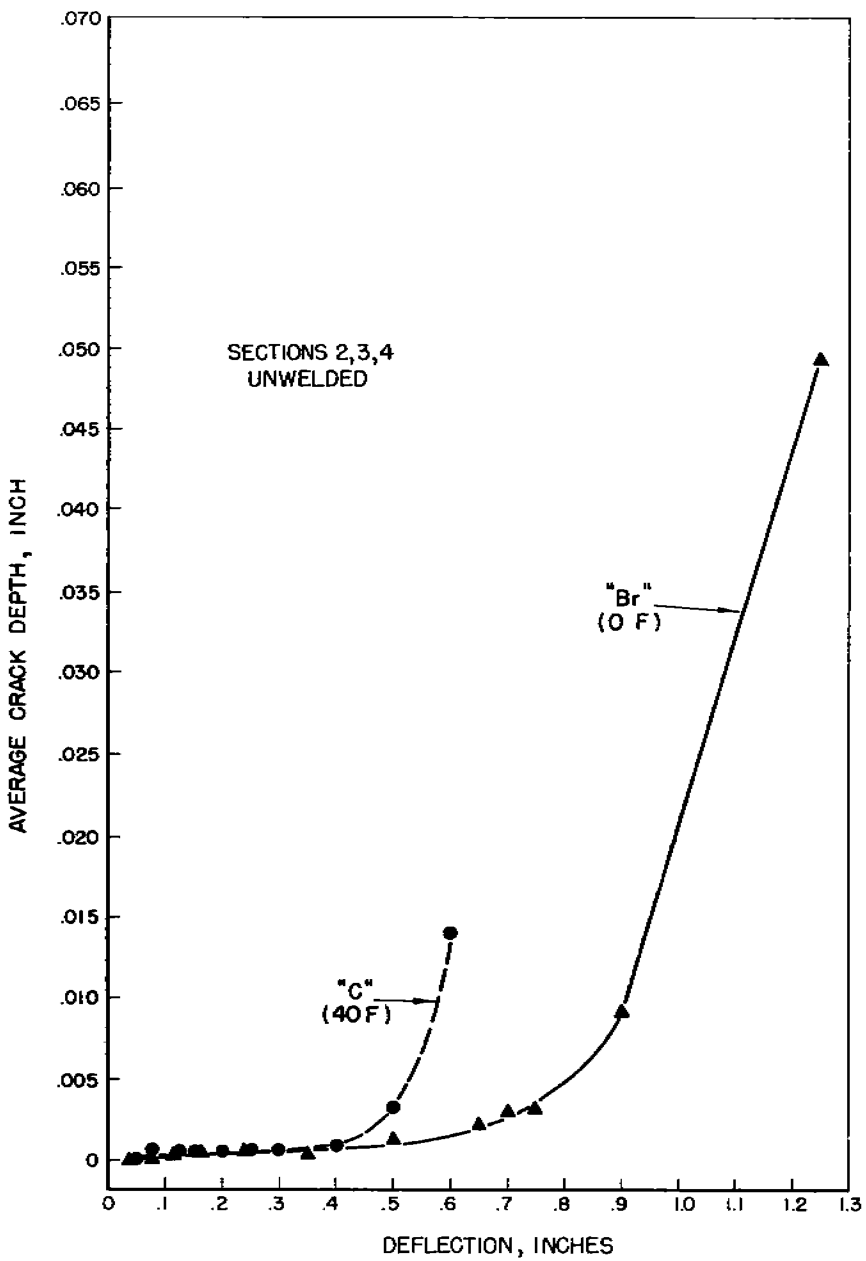

FIGURE B18. COMPARISON OF AVERAGE CRACK DEPTH IN SECTIONS 2,3,4 OF UNWELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED BELOW THEIR TRANSITION TEMPERATURES.

68403

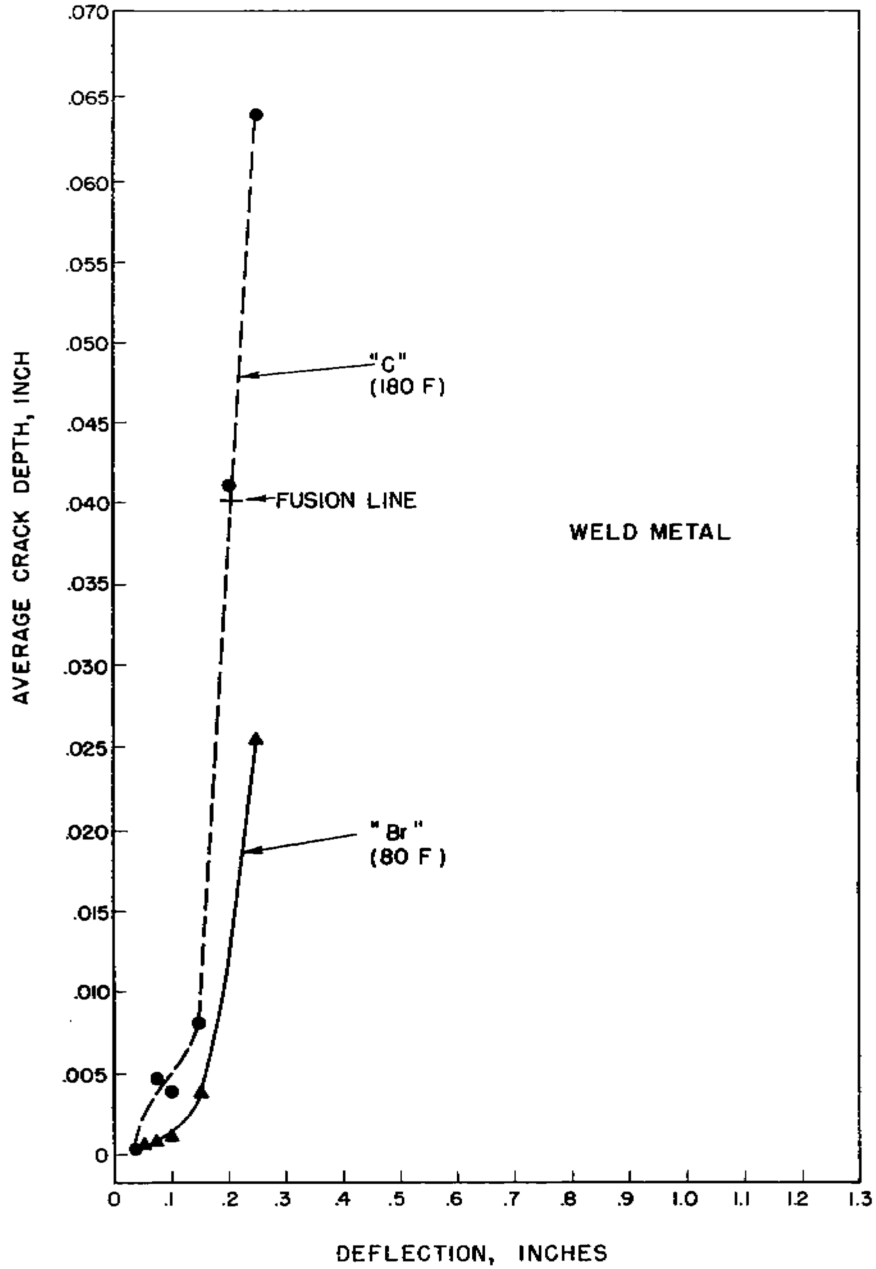

FIGURE B-19. COMPARISON OF AVERAGE CRACK DEPTH IN WELD METAL OF WELDED "Br" AND "C" STEEL SPECIMENS TESTED ABOVE THEIR TRANSITIONS TEMPERATURES.

68417

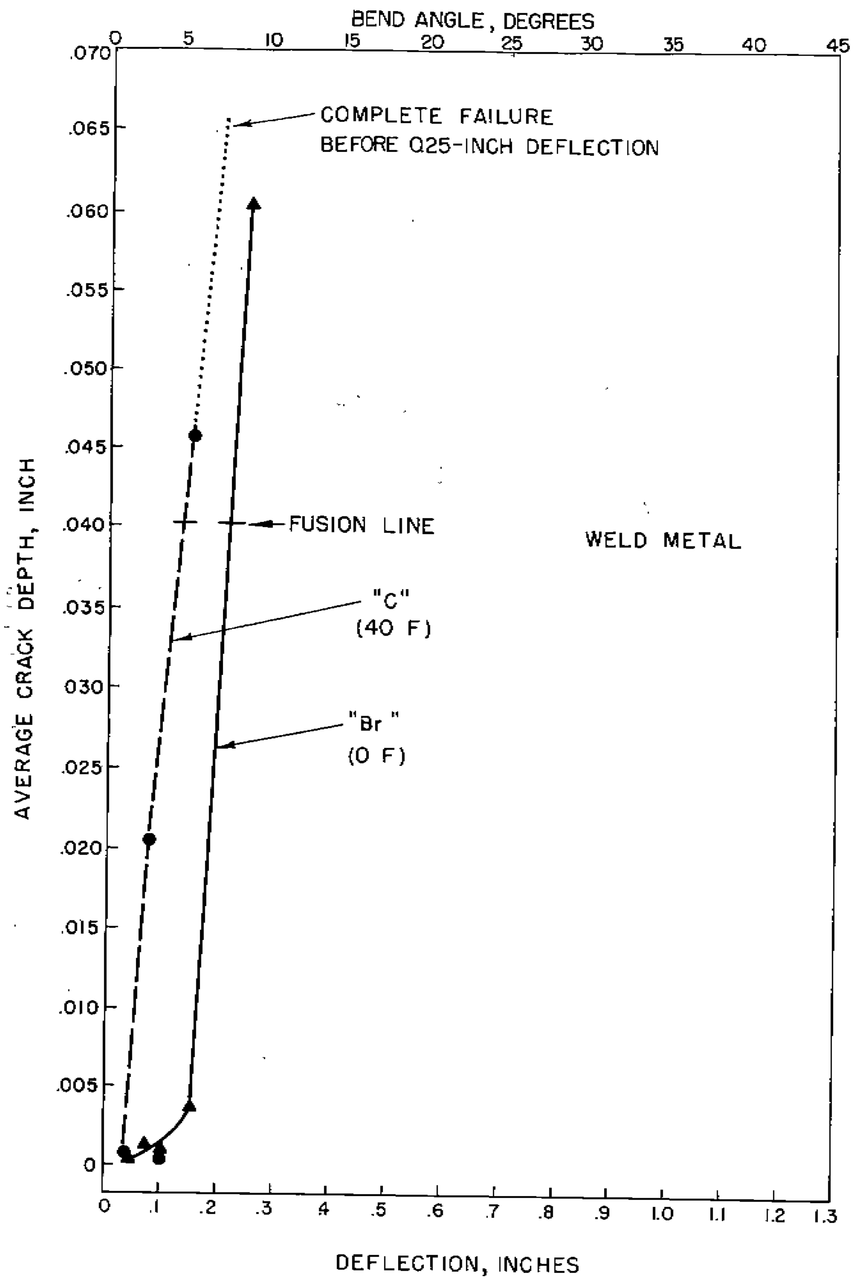

FIGURE B-20. COMPARISON OF AVERAGE CRACK DEPTH IN WELD METAL OF WELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED BELOW THEIR TRANSITION TEMPERATURES.

68418

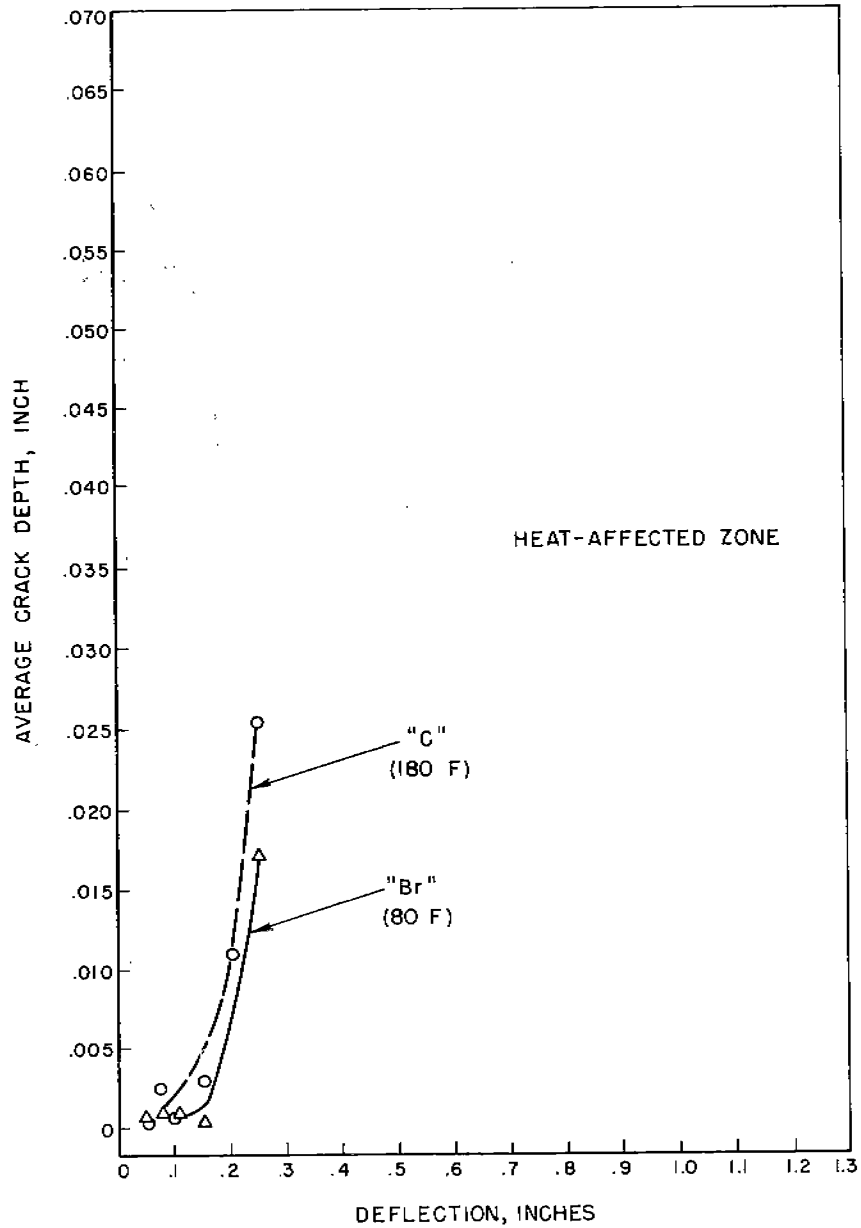

FIGURE B-21. COMPARISON OF AVERAGE CRACK DEPTH IN HEAT-AFFECTED ZONE OF WELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED ABOVE THE TRANSITION TEMPERATURE.

68415

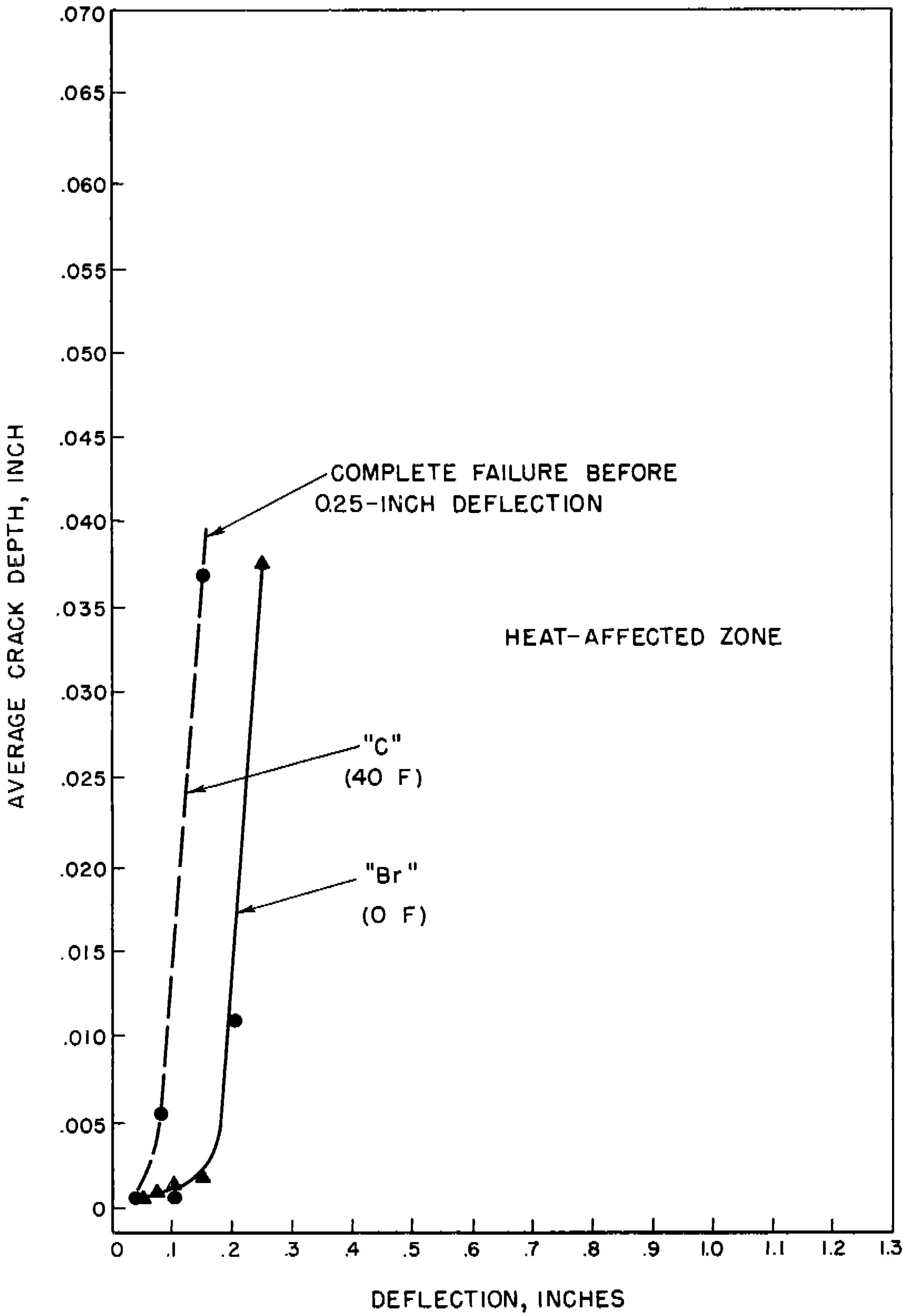

FIGURE B-22. COMPARISON OF AVERAGE CRACK DEPTH IN HEAT-AFFECTED ZONE OF WELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED BELOW THE TRANSITION TEMPERATURE.

68416

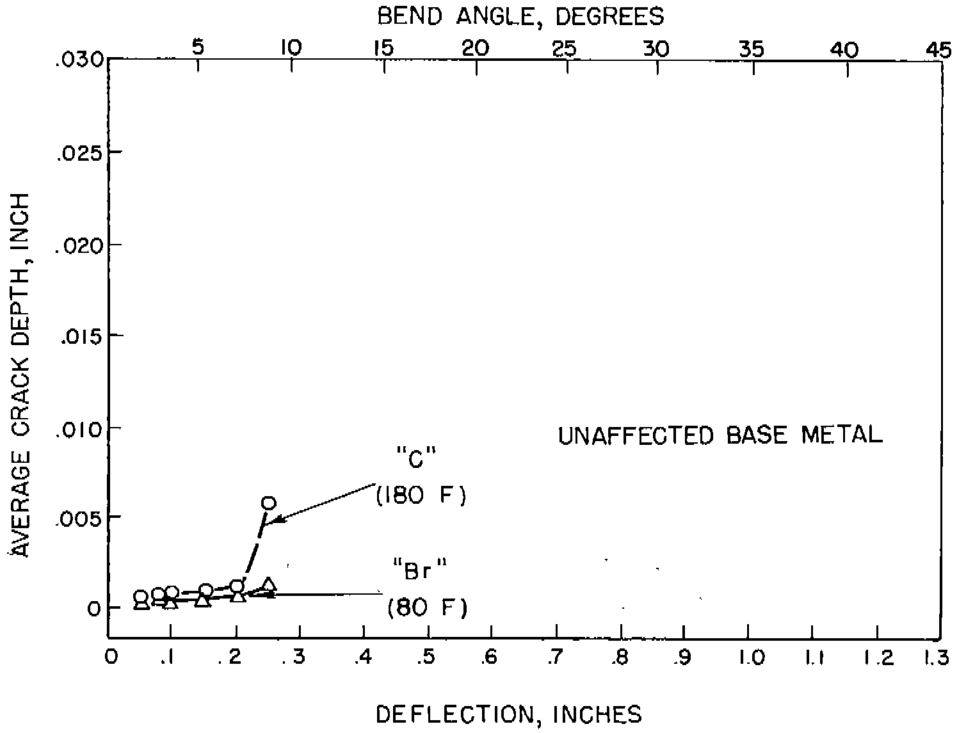

FIGURE B-23 COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE METAL OF WELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED ABOVE THEIR TRANSITION TEMPERATURES.

68413

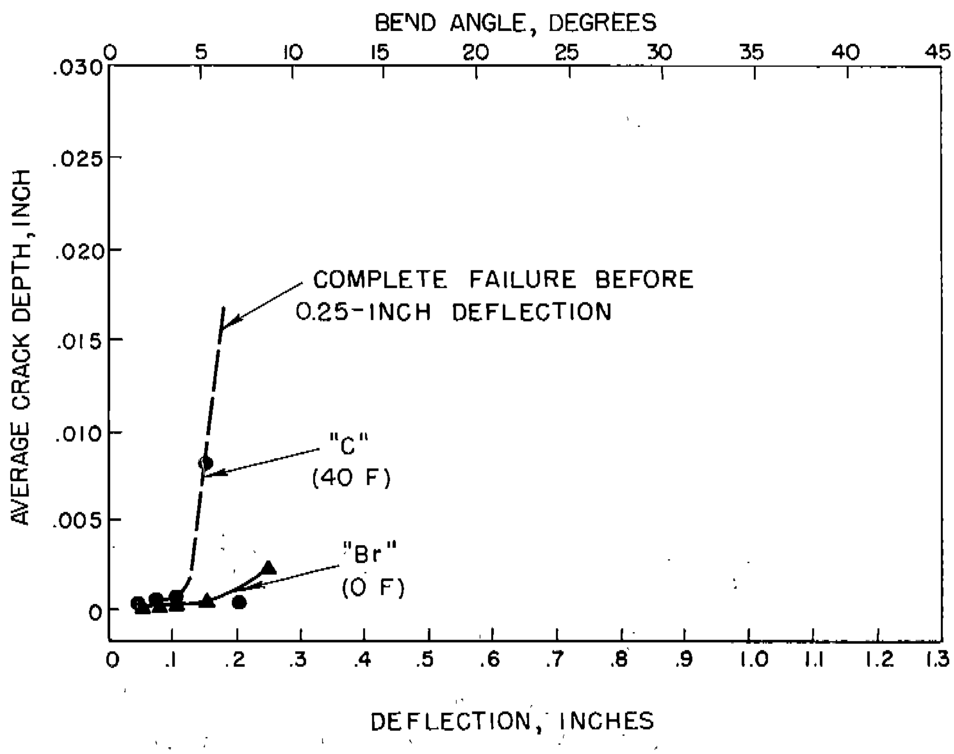

FIGURE B-24. COMPARISON OF AVERAGE CRACK DEPTH IN UNAFFECTED BASE METAL OF WELDED "Br" AND "C" STEEL KINZEL SPECIMENS TESTED BELOW THEIR TRANSITION TEMPERATURES.

68414