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TECHNICAL PROGRESS REPORT

ON

THE FUNDAMENTAL FACTORS INFLUENCING THE BEHAVIOR OF WELDED STRUCTURES UNDER CONDITIONS OF MULTI-AXIAL STRESS, AND VARIATIONS OF TEMPERATURE, STRESS CONCENTRATION, AND RATES OF STRAIN

BY

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and W. M. BALDWIN, JR.

Case Institute of Technology
Under Bureau of Ships Contract NObs-45470

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.
November 28, 1949

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2101 CONSTITUTION AVENUE, WASHINGTON 25, D. C.

COMMITTEE ON SHIP STEEL

November 28, 1949

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Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-34 entitled "The Fundamental Factors Influencing the Behavior of Welded Structures Under Conditions of Multiaxial Stress, and Variations of Temperature, Stress Concentration, and Rates of Strain." This report has been submitted by the contractor as a Technical Progress Report of the work done on Research Project SR-99 under Contract NObs-45470 between the Bureau of Ships, Navy Department and Case Institute of Technology.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Steel, Division of Engineering and Industrial Researh, 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,

Robert F. Mehl

RFM:mh

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 presents results of part of the research program conducted under the Ship Structure Committee's directive "to investigate the design and methods of construction of welded steel merchant vessels."

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THE FUNDAMENTAL FACTORS INFLUENCING THE BEHAVIOR OF WELDED STRUCTURES UNDER CONDITIONS OF MULTI-AXIAL STRESS, AND VARIATIONS OF TEMPERATURE, STRESS CONCENTRATION, AND RATES OF STRAIN

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In Cooperation With

Committee on Ship Steel
Division of Engineering and Industrial Research
National Research Council

Cleveland, Ohio

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ABSTRACT

An investigation was made to determine the dependence of zones of low ductility in weldments upon the steel and upon the welding conditions and heat treatment. The ductility was evaluated by means of eccentric notch-bar tension tests conducted at various low temperatures.

A zone of low ductility was found in two low carbon ship plate steels at a distance of 0.3 - 0.4" from the weld centerline when the weldments were made with 100°F preheat and interpass temperature.

A 400°F preheat and interpass temperature improved the ductility in the critical zone, lowering the transition temperature from -20°F to -45°F.

A 1100°F postheat practically eliminated the zone of lowered ductility, the transition temperature being lowered to -70°F.

Temperature measurements made during welding showed that the embrittled region was not heated above the lower critical temperature.

No change in microstructure could be noted between the critical zone and the unaffected base plate. Microhardness tests showed only slight hardening in the embrittled region.

The occurrence of the embrittled region is thought to be due to some subcritical temperature phenomena which may be the supersaturation and precipitation of carbon or carbides from the alpha phase.

INTRODUCTION

This report summarizes the work completed on a project sponsored by the Ship Structure Committee and conducted under U. S. Navy Contract NObs-45470 and covers the period from September 1, 1948 to July 1, 1949. An earlier report SSC-24, (1)* covered the period from July 1, 1947 to September 1, 1948.

Steel structures have been shown to fail in a brittle manner when subjected to certain service conditions. The conditions which may lead to brittle failure include multiaxial stresses, stress concentration, low temperature, section size, and rate of loading.

The ductility of a structure loaded under a combination of these embrittling factors may be reduced to a low value. Ductility then becomes a more important measure of the structure's resistance to failure than its strength, since it is known that a crack may propagate through a region of low ductility with the absorption of only a small amount of energy.

Since the incidence of brittle failures in ships had increased with the adoption of the welding process for fabrication, it was felt that the welding process must alter the properties of steel. Various investigations employing a number of different specimens have shown that the ductility of a weldment is lower than the ductility of the steel of which the weldment is made.

The general purpose of this investigation was to establish the existence of zones of low ductility in commercially welded ship plate by means of a test which would be sensitive to variations in material and welding conditions. If such zones could be isolated, investigation was to be made of their dependence upon material, variations in the welding process, and heat treatment.

The first report (1) showed that a zone of minimum ductility was located at a distance of 0.3 - 0.4 inch from the weld centerline for a weldment made from "C" steel with a 100°F preheat and interpass temperature. The transition

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* Numbers in parentheses refer to the bibliography at the end of the report.

temperature of this zone, as determined by the eccentric notch tensile test, was -20°F as compared with -65°F for the unaffected base plate.

The investigation was extended to cover "A" steel and the effects of preheating and post heating on "C" steel.

MATERIAL

The ship plates selected for this investigation were two of the so-called "project steels" which have been investigated by other groups under the sponsorship of the Ship Structure Committee. Steel "C" was selected because it has been shown to have a high transition temperature, and steel "A" was chosen because it has a lower transition temperature although it has the same approximate composition. Both were semi-killed steels and in the "as-rolled" condition.

The properties reported for these steels are as follows (2):

TABLE I

Properties of Steel Plate

Chemical Analysis

	Carbon	Manganese	Phosphorous	Sulfur	Silicon
C Steel	0.24%	0.48%	0.012%	0.026%	0.05%
A Steel	0.26%	0.50%	0.012%	0.039%	0.03%

	Aluminum	Nickel	Copper	Chromium	Molybdenum
C Steel	0.016%	0.02%	0.03%	0.03%	0.005%
A Steel	0.012%	0.02%	0.03%	0.03%	0.006%

	Tin	Nitrogen	Vanadium	Arsenic
C Steel	0.003%	0.009%	< 0.02%	< 0.01%
A Steel	0.003%	0.004%	< 0.02%	< 0.01%

Mechanical Properties

	Yield Point psi	Tensile Strength psi	Elongation Per Cent
C Steel	39,000	67,400	25.5(8"gage)
A Steel	37,950	59,910	33.5(2"gage)

PROCEDURE

Test Specimen

Many types of specimens have been used to evaluate the properties of steels and welded structures. In order to establish the existence of zones of lowered ductility, a specimen was needed which would test only a small volume of metal, since the ductility gradient would be expected to be quite steep in a critical region. Such a test must also include some of the previously mentioned embrittling factors which serve to lower the ductility of the whole plate to such a point that the minimum or critical region can be located. The eccentric notch bar tension test meets these requirements in that a very small volume of metal controls the reaction of the specimen, that is, the fiber at the notch bottom which is subjected to the maximum tension stress is the fiber in which fracture initiates (and propagates through the specimen.) The position of this fiber can be chosen at will. The embrittling factors of eccentric loading, multiaxial stress, and a stress raiser are present in the eccentric notch test and low temperature can be added.

The eccentric notch bar tension test has been used in a number of investigations to differentiate among steels (heat treated to the same strength levels) which are known to have different service properties (3)(4). In Fig. 1 the properties of four steels are compared, at room temperature, by means of concentric and eccentric notch tests (3). The data used to draw these comparison curves are shown in Fig. 2 where notch strength ratio* is plotted for both the concentric and the eccentric tests as a function of ductility. There appears to be a relation between the two types of notch strengths and the ductility as measured by the contraction in area for the concentric test. Up to two per cent ductility, the concentric notch strength seems to be dependent upon the ductility. Specimens which are strained over two per cent have lost their high initial stress concentration which was one of the embrittling agents and consequently the notch strength becomes independent of the ductility. The eccentric notch test, however, extends the dependence of the notch strength upon ductility up to approximately ten per cent by the addition of another embrittling factor, that of eccentric loading.

It can be seen from Fig. 1 that the eccentric notch test was able to detect differences in the four steels. The rating was in the same order as that shown by the concentric notch test, i.e., the two nickel steels gave higher values than the chromium steel, with the manganese steels showing the poorest performance. The ductility level of ship plate steel is too high to show up any regions of lowered ductility at room temperature but with the addition of the added embrittling agent of low temperature the eccentric notch bar tension test can be expected to detect differences in the various zones encountered in a weldment.

Welding Procedure

All of the weldments were made at Battelle Memorial Institute under closely controlled conditions. Details of the welding process are given in Figs. 3 and 4.

Each weldment was 18" x 24" x 3/4", constructed of two plates 9" x 24" x 3/4"

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* Notch strength ratio is defined as the ratio between the notch strength and the tensile or ultimate strength.

in dimensions. These plates were flame cut from the same large plates and 3/4 inch was machined from the edges to be welded in order to eliminate the heat effect of the flame cutting. The edges to be welded were then machined to a 30° bevel and 1/8 inch root face as shown in Fig. 3.

The plates were tack welded using one inch tacks at each end and at the center of the plate, leaving 3/16" clearance between the root faces. A copper back-up bar coated with a thin layer of wollastonite was used for the first weld pass.

No restraint other than the tack welds was used on the weldments and since two inches from each end of the plate were to be discarded, no runoff tabs were required. All welding was manual, using 3/16 inch diameter E6010 electrodes with DC reverse polarity. The welding data are given in Table II.

TABLE II

Welding Data

Harnischfeger - D. C. Welder

Electrode 3/16" E6010 Reversed Polarity

Current	150 amps	Pass 1
	165 amps	Passes 2-6
Voltage	25 volts	Passes 1-6
Welding Speed	3.6 in/min	Pass 1
	4.8 in/min	Passes 2-6
Electrode Burn Off Rate	8.5 in/min	Passes 1-6

The weldments were preheated prior to the first weld pass. After each pass the weld joint was cooled normally in still air until the desired interpass temperature was reached and then the next pass was made.

Weldments were made using 100°F preheat and interpass temperature and 400°F preheat and interpass temperature. A total of six weldments were made for this phase of the investigation.

After completion of welding, the welded joint was sand blasted and then radiographed for weld imperfections.

Temperature Measurements

Tempilaq was used on some of the weldments to determine the 600°F and 1300°F isotherms on the surface.

On two weldments temperature measurements were made at the midthickness of the plate during welding. These weldments were made with 100°F and 400°F preheat and interpass temperatures. Thermocouples were placed at varying distances from the weld centerline so that the range of temperature from 1300°F to 600°F could be covered. The thermocouple holes were 3/32" diameter drilled at 30° angle, parallel to the machined bevel surface. The holes were staggered so that the temperature distribution was not disturbed in front of each thermocouple. Fig. 5 shows one of the weldments with the thermocouples in place.

All temperature measurements were made at the midthickness of the plate, the same region that was tested in the eccentric notch tests. High speed recorders were used to record the temperatures from the start of each welding pass until some time after the pass was completed.

Specimen Preparation

Strips, 1/2 inch wide, were cut from the welded plates perpendicular to the weld. Each strip was etched so that the weld area was visible and the weld centerline could be located. The specimen locations were then laid out so that the notch bottom was the desired distance from the weld centerline and so that the fiber carrying the highest tension load was along the midthickness of the plate. The location of such a specimen (away from the weld) is shown in Fig. 6.

The notch test specimen is shown in Fig. 7. These specimens had a circumferential 60° V-notch removing 50 % of the cross sectional area, and a root radius less than 0.001 inch.

Testing Procedure

The test equipment and procedure were the same as those used in the first part of the investigation(1).

The specimens were placed in the fixtures, Fig. 8, so that the fiber from the center of the plate received the maximum tensile stress. The initial eccentricity was set at 1/4", that is the centerline of the specimen was displaced 1/4" from the line of pull of the tensile machine, as shown in Fig. 7.

The specimen was cooled to a temperature about 5°F below the desired testing temperature, allowed to warm up to the testing temperature and then tested. The tests were performed at constant temperature since the testing time was about 30 seconds whereas the warming-up rate was about 1°F/min. The specimens were cooled by means of isopentane, dry ice, and liquid nitrogen. Temperatures were measured by placing a pentane thermometer directly beside the specimens. All of the tests were carried out at a low strain rate, the crosshead speed of the tensile machine was approximately 0.1 inch per minute.

The property that was measured was the eccentric notch strength, maximum load divided by the original area at the notch bottom.

RESULTS

Steel Comparison

The ductility minimum which was observed for the "C" steel at a distance of 0.3 - 0.4 inch from the weld centerline (1) probably would occur in weldments made of other steels. In order to check this an investigation was made on "A" steel weldments. These weldments were welded using the same conditions as for the "C" steel (1).

The data for all of the eccentric notch tests appears in the appendix. The distribution of values for the unaffected base plate* tested at various temperatures, Fig. 9, was of the same type as that for the "C" steel, Fig. 10, except that the entire distribution was shifted to lower temperatures, the transition temperature** being about -80°F as compared with -65°F for the "C" steel. The range of values for a given testing temperature was also smaller, particularly at the higher temperatures, indicating that the "A" steel was slightly more uniform.

In order to compare results for the two steels and three welding conditions, average curves were drawn (dashed curves in the figures). These average curves were drawn midway between the upper and lower limits of the distributions. A comparison of the average curves for the "A" and "C" steel base plates, Fig. 11, shows the lowering of the transition temperature. The difference in values at the higher testing temperatures is due to the higher tensile strength of the "C" steel, (see Table I).

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* Unaffected base plate specimens were taken at distances of two inches or more from the weld centerline and thus were unaffected by the welding, since the maximum temperature reached in this zone was less than 600°F for all welding conditions.

** Transition temperature is here defined as the temperature at the midpoint of the average notch strength curve (dashed line in the figures), which gives about the same temperature as the knee in the upper distribution limit.

The distribution of notch properties, determined at -10°F, at various distances from the weld centerline is shown in Fig. 12. The eccentric notch strength was fairly uniform across the plate. However a slight minimum was observed at 0.3 - 0.4 inch from the weld centerline and the slight maximum at the weld junction 0.1 - 0.2 inch from the weld centerline.

The distribution determined at -70°F, Fig. 13, showed the presence of a definite minimum at the location 0.3 - 0.4 inch from the weld centerline. A maximum is also evident at the weld junction. The positions of the minimum and maximum are identical with those found for the "C" steel.

Tests on a number of specimens of "A" steel from the region of low ductility were made at various temperatures. From these tests, Fig. 14, it can be seen that the transition temperature is about -40°F. A comparison of the average curve for this position of minimum ductility with a similar curve for "C" steel, Fig. 15, shows that the curves are very similar, the curve for the "A" steel being about 20°F lower than that for the "C" steel.

Preheat and Postheat

In order to investigate the possible beneficial effects of preheating and postheating, weldments of "C" steel were made using a 400°F preheat and interpass temperature, and a postheat treatment was given to a "C" steel weldment which had been welded with a 100°F preheat. The post heat treatment consisted of holding the weldment at 1100°F for one hour, furnace cooling to 300°F, followed by air cooling to room temperature.

The sampling and testing techniques for this phase of the work were kept the same as previously. (1)

The results for the 400°F preheat are given in Figs. 16, 17 and 18. As was to be expected, the distribution of values for the unaffected base plate, Fig.

16, was practically identical to that for the 100°F preheat, Fig. 10. However the distribution of values across the weld determined at -80°F, Fig. 17, showed a definite improvement, over the 100°F preheat, in the region of low ductility. The variation of values in this region is greater and approaches that of the base plate.

This improvement can also be seen in Fig. 18, which shows the change of notch strength with temperature in the zone of low ductility. The transition temperature has been shifted to about -45°F as compared with -20°F for the 100°F preheat, (see Fig. 15.)

The results for the 1100°F postheat are given in Figs. 19, 20 and 21. The distribution of values for the unaffected base plate, Fig. 19, showed less variation than the weldments which were not postheated, Figs. 10 and 16. The variation of values was less at the higher temperatures and the transition temperature was shifted to a lower temperature, -75°F as compared with -65°F.

The distribution of notch strengths at -80°F, Fig. 20, shows that the minimum which was previously observed at 0.3 - 0.4 inch from the weld centerline has been practically eliminated, that is, the material in this zone shows the same range of values as the unaffected plate.

The elimination of the minimum shows up as a lowering of the transition temperature for this region, Fig. 21. The transition temperature has been shifted to -70°F as compared to -20°F for the weldment which was not postheated.

A comparison can now be made on the effects of preheating and postheating.

The transition curves for the unaffected base plates of "C" steel, Fig. 22, show that:

1) Data for the 100°F and 400°F preheat fit on the same curve.

2) The postheated plate has less variation in values but almost the same transition temperature as the plates without postheat.

3) The notch strength at the higher testing temperature was lower for the postheated plate because of a slight softening of the material. This was shown also by the hardness tests described later.

A comparison of the distributions of notch strength across the welds determined at -80°F, Fig. 23, shows the improvement which has been made. The 400°F preheat shows a definite improvement and the postheat treatment virtually eliminates the region of low ductility.

This improvement is even more noticeable in a comparison of the transition curves for this region, Fig. 24. The transition temperature of -20°F for the 100°F preheat was shifted to -45°F by the 400°F preheat, and to -70°F by the postheat treatment.

Microstructure

An investigation was made on the microstructure in the critical zone (0.3" from the weld centerline) for all three welding conditions on "C" steel.

In Fig. 25, photomicrographs for the unaffected base plate and the 0.3" position at 100x and 2000x magnifications are shown for a "C" steel weldment with 100°F preheat and interpass temperature. There seems to be no difference in the structures of these two locations.

In Fig. 26, photomicrographs are shown for the 0.3" position for "C" steel weldments which were preheated at 400°F and postheated at 1100°F. These, also seem to have the same structure as the unaffected base plate.

Microhardness Tests

Microhardness tests were made on all of the weldments with a Tukon Hardness Tester using a 136° Diamond Pyramid Indentor and 1000 gram load. The indentations were about 0.004 inch (0.1 mm) long and were spaced at intervals of 0.01 inch (0.25 mm).

Microhardness surveys were made across representative sections of all the welds at the midthickness of the plates. These results are shown in Fig. 27. The greatest variation in hardness was shown by the "C" steel weldment with 100°F preheat. A number of hardness peaks were found, the highest one being at the weld junction. The other peaks were due to the composite heat affected zone caused by the six weld passes. To compare this scale with Rockwell hardness tests, the maximum hardness of 240 on the DPH scale corresponds to about Rockwell C20, and the minimum hardness of 150 on the DPH scale corresponds to about Rockwell B80.

The "C" steel weldment with 400°F preheat had almost a flat hardness distribution with no prominent peaks.

The hardness distribution curve for the weldment which was postheated was similar to that of the weldment without postheat except that the peaks were lowered from a maximum of DPH 240 to DPH 200. The overall level of the whole curve was also lowered indicating some softening of the whole plate.

The hardness curve for the "A" steel weldment was similar to that for the "C" steel weldment, but the peaks were lower and the overall curve was lower for the "A" steel.

A more detailed investigation was made of the "C" steel weldment with 100°F preheat. Surveys were made across the thickness of the plate at various distances from the weld centerline. From these surveys a model, Fig. 28, was constructed which shows the overall hardness picture and the complexity of the heat affected zone. The sketch in the figure shows the position of the weldment and the six weld passes. The effect of each weld pass can be seen as a peak in hardness, the zones from each peak blending together to give the overall picture. The zone of low ductility lies in the region behind the hardness peaks where the hardness distribution is relatively flat.

A few sections from the model at various distances from the weld centerline, Fig. 29, show the magnitude of the peaks especially at 0.08 and .12 inches from the weld centerline.

Temperature Measurements

The results of the temperature measurements made during the welding of the "C" steel, as illustrated in Fig. 5, are given in Figs. 30, 31 and 32. In Fig. 30, the maximum temperatures reached during the welding process are shown as a function of the distance from the weld centerline for the weldments with 100°F and 400°F preheats respectively. In the region of low ductility (0.3 - 0.4 inch from weld centerline) the temperature evidently never reached the lower-critical temperature for either weldment.

In Fig. 31, the complete heating and cooling history of the region of low ductility is given for both welding conditions. For each weldment the peak temperatures decrease for the last three weld passes. The 400°F preheat weldment showed a higher peak temperature for the first two passes than the 100°F preheat weldment.

A comparison of the heating and cooling cycles for the first pass for the two welding conditions, Fig. 32, shows that the 100°F preheat weldment has a faster cooling rate. This difference in cooling rate can be shown for all of the weld passes.

Specimen Size

The changes in notch strength and hardness were very rapid as the distance from the weld centerline was increased from zero to 0.5 inch. Consequently, a smaller specimen than the specimen which was used might be expected to show up greater differences in notch strengths.

A few specimens were made of "A" steel with 0.212" outside diameter and 0.150" notch diameter. The area of the notched section was thus one-half of that of the standard specimen. Tests were taken from the weld metal, base plate and the zones containing the maximum and the minimum eccentric notch strength. The specimens were tested at -70°F and the results are shown in Fig. 33 superimposed on the results of the standard specimens (taken from Fig. 13).

In the zone of minimum ductility the notch strengths of the smaller specimens fell in the range of values of the standard specimen. In the other positions the smaller specimens gave higher values. However, a higher notch strength would be expected in these regions because of the slightly smaller effective notch sharpness*, and the regular section size effect. The difference, however, was small. In the region of low ductility the fiber in maximum tension controls the reaction of the specimen so that the above-mentioned factors have a negligible effect.

This specimen then offers no advantages over the standard specimen when taken from the center of the plate.

<u>Subcritical Heating</u>

The temperature measurements that were made indicated that the embrittled zone for the 100°F preheat weldment was cooled from about 1000°F in the first three weld passes. An attempt was made to duplicate the embrittlement shown in the region of low ductility by means of heating and cooling of base plate. Blanks of "C" steel base plate were heated to 950°F held for 5 minutes and cooled to give three different cooling rates, air cool, oil quench, and water

* Notch sharpness is defined as the ratio of the radius of the cross section at the notch to the notch radius.

quench. Standard specimens were made and tested at -80°F. The notch strengths for all three rates of cooling were low, Fig. 34, and when compared to the spread of values for the base plate* at -80°F, it can be seen that the material was embrittled by this heating and cooling. The spread in values for base plate tested at -120°F will encompass all of the values so that in effect the transition temperature appears to have been raised approximately 40°F by these subcritical heating and cooling cycles. This is comparable to the change in transition temperature in the "C" steel weldment where the transition temperature of -65°F in the unaffected base plate, Fig. 10, was raised to -20°F in the critical region, Fig. 15, a change of about 45°F.

DISCUSSION OF RESULTS

The temperature measurements which were made during welding on both 100°F and 400°F preheat weldments showed that the zone of low ductility was not heated above the lower critical temperature. Also, no differences in microstructure could be distinguished in the structures in the critical zone and in the unaffected base plate.

The hardness tests cannot be correlated with the notch strength. The peak in hardness was associated with the maximum in notch strength, but the minimum in notch strength occurred in a region where the hardness variations were leveling off. Therefore, hardness cannot be used as a measure of ductility in these weldments.

An investigation on the annealing of low carbon steel (5) has shown that there are three factors which change the properties of a steel when it is cooled. The first of these is the gamma-alpha transformation which results in a reduced grain size and higher hardness. If the cooling is sufficiently fast a martensitic structure is formed which on tempering still remains relatively hard and

* Spread in values was obtained from Fig. 10.

has a ductility higher than that of pearlite. This may then account for the maximum in notch strength which was observed.

The remaining factors may account for the ductility minimum which was observed. The first, the solution effect, is essentially the formation of a supersaturated solid solution of carbon in ferrite which is harder than the equilibrium mixture. Associated with this is the other factor, aging. It results from precipitation of carbon or carbides from the supersaturated solution. The solid solution factor has its maximum effect upon fast quenching from the lower critical. However, the aging effect would be expected to have a maximum effect at some critical point of time and temperature, beyond which the effects would be decreased. These factors have been shown to produce an increase in hardness and an accompanying decrease in ductility in low carbon steel.

The solid solution and aging effects can occur simultaneously at the cooling rates found in the region of low ductility in the weldments. The heating and cooling curves showed that the temperature did not reach the lower critical and the cooling rates were not fast enough to obtain the maximum solid solution effect. However, the time-temperature relations which are encountered in the critical zone for a weldment with 100°F preheat may be those which would cause maximum embrittlement. The 400°F preheat weldment had a slower cooling rate which would permit less of the solid solution and aging effects and thus explain the improvement in the critical region. The almost complete elimination of the critical region by the postheat treatment would then be attributed to "overaging", that is the aging effect was carried past the critical point.* According to this hypothesis, varying combinations of preheat and postheat would be expected to give different degrees of improvement depending upon whether the solution and aging effects were carried to, or past, the critical point.

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* This effect of overaging was observed for the low carbon steel (5).

CONCLUSIONS

1. A zone of low ductility was detected in the welded plate, at a distance of 0.3 - 0.4" from the weld centerline for both "C" steel and "A" steel welded with 100°F preheat.
2. A 400°F preheat improved the ductility in the critical zone, lowering the transition temperature from -20°F to -45°F.
3. A 1100°F postheat practically eliminated the zone of low ductility, the transition being lowered to -70°F.
4. Temperature measurements showed that the occurrence of this region of low ductility is due to some subcritical temperature phenomena which may be the supersaturation and precipitation of carbon or carbides.

ACKNOWLEDGMENTS

Acknowledgment is given to the Battelle Memorial Institute for welding the plates and conducting the temperature measurements and particularly, to Messers. C. B. Voldrich, P. J. Rieppel, and M. Forman for their aid.

The authors are also indebted to Dr. S. I. Liu who made the micro-hardness tests.

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5. G. Sachs, L. J. Ebert, G. B. Kasik, and J. F. Nejedlik, "Fundamentals of Annealing Low Carbon Steel, Part I", Iron and Steel Engineer, (1946) November.

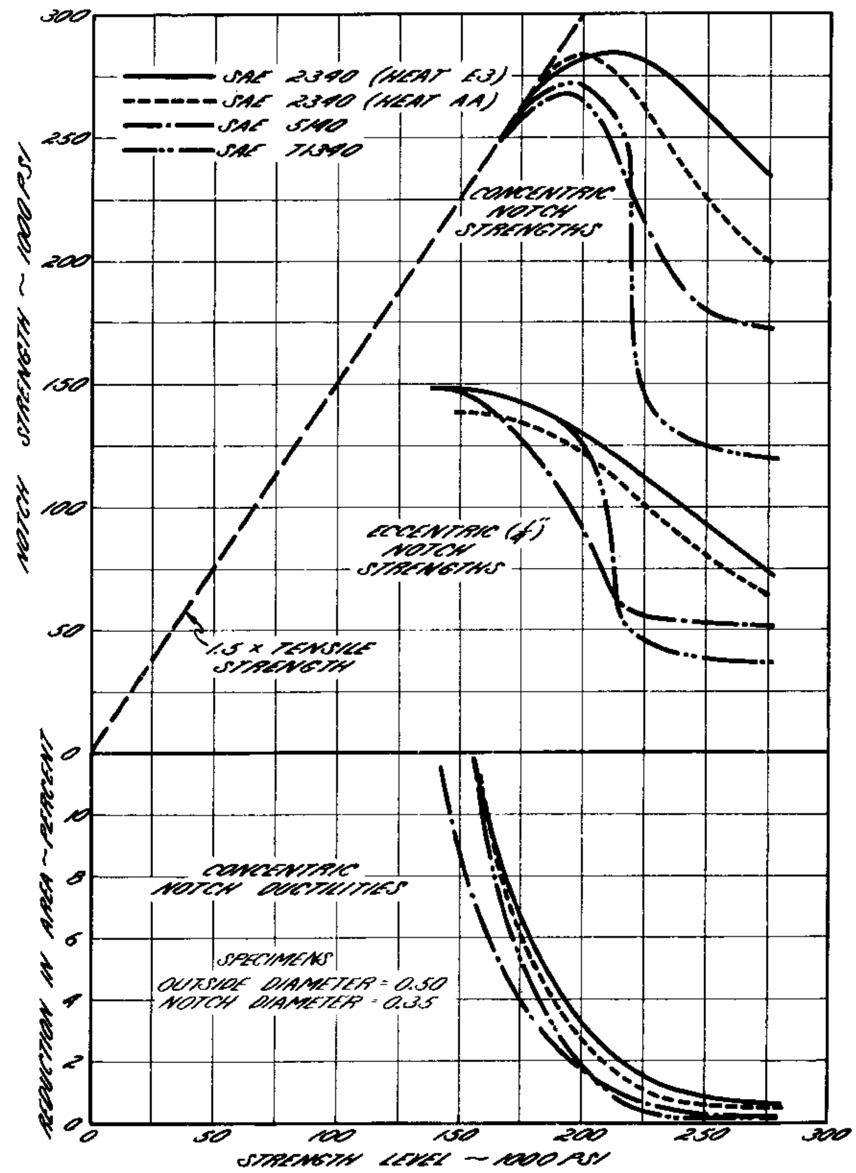


FIG. 1: NOTCH PROPERTIES AS FUNCTION OF STRENGTH LEVEL FOR VARIOUS STEELS (3).

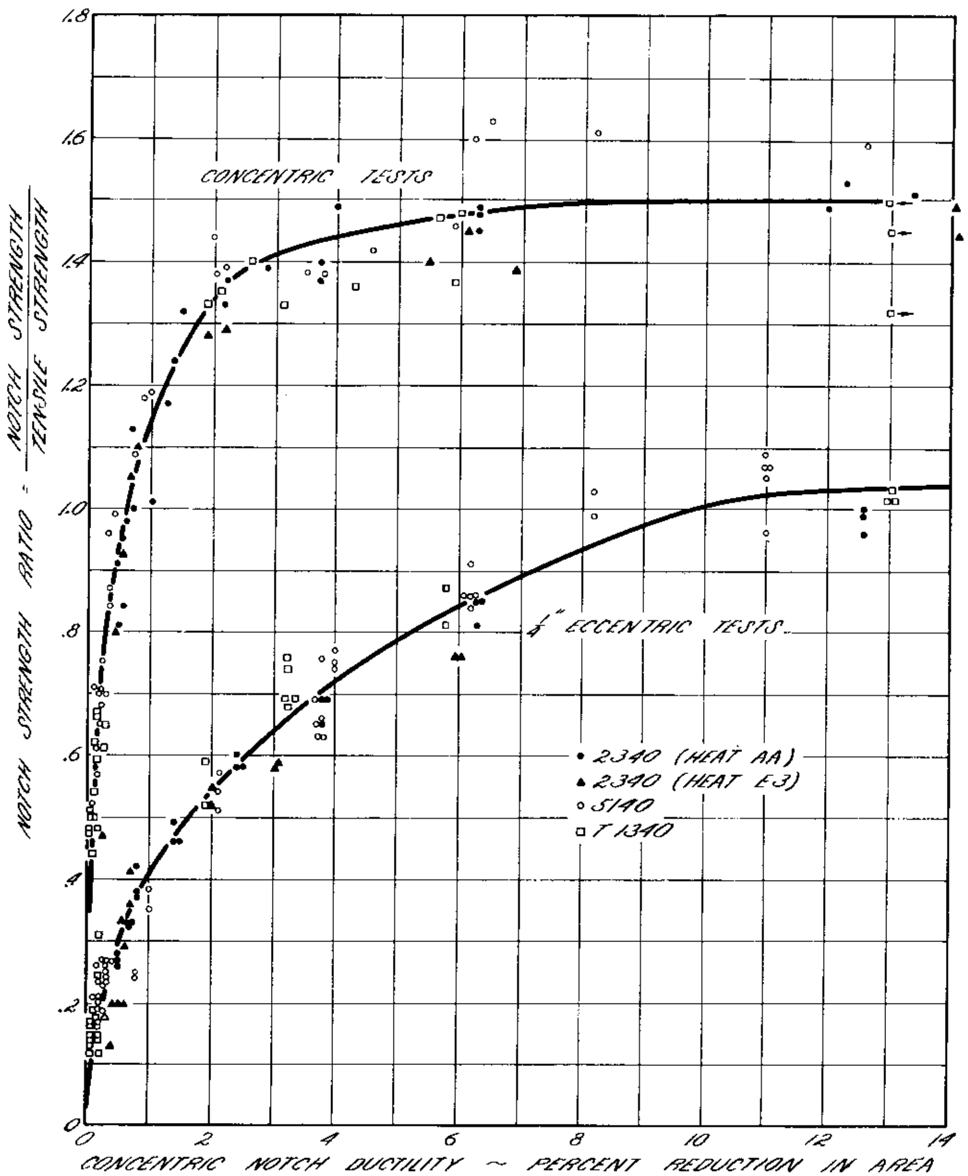


FIG. 2: RELATIONS BETWEEN CONCENTRIC AND ECCENTRIC NOTCH STRENGTH RATIOS AND NOTCH DUCTILITY.

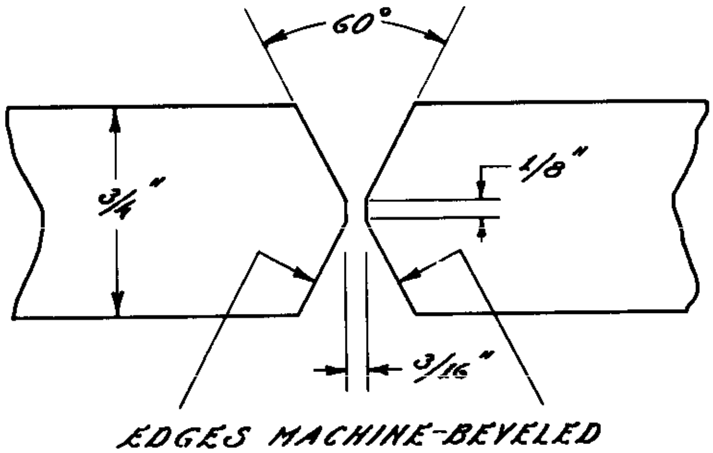
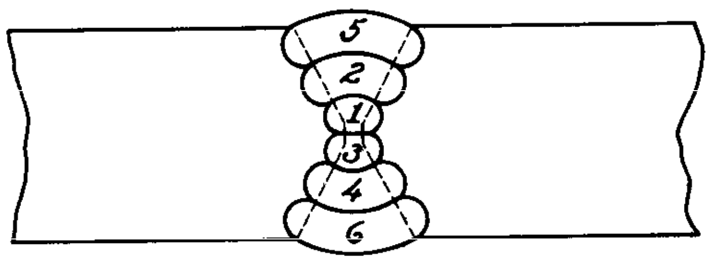


FIG. 3: PLATE PREPARATION



ELECTRODE ~ 3/16" E6010
PASSES 1, 3, 5, 6 : SAME DIRECTION
PASSES 2, 4 : OPPOSITE DIRECTION

FIG. 4: WELDING PROCEDURE

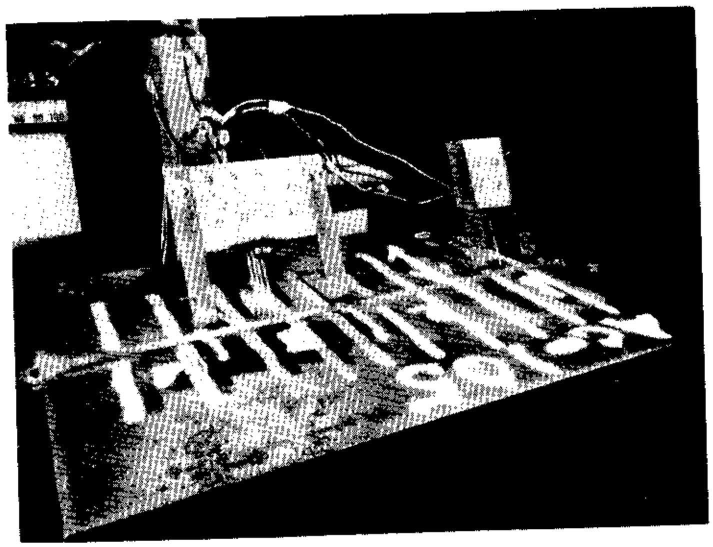


FIG. 5: SET UP FOR MEASURING
PLATE TEMPERATURES
DURING WELDING.

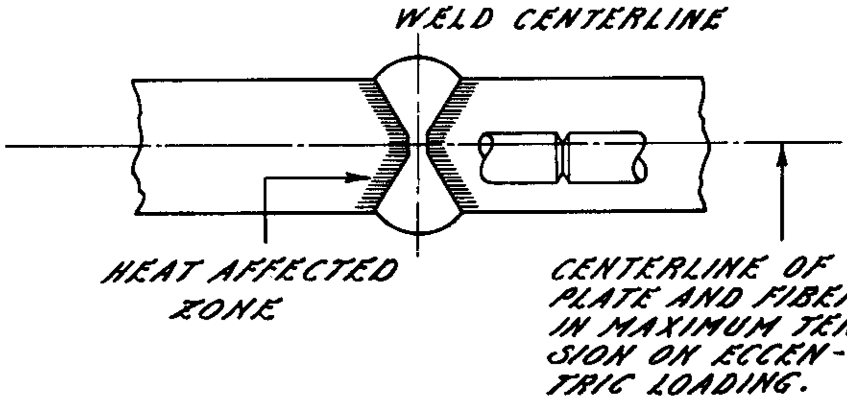


FIG. 6: LOCATION OF SPECIMEN IN THICKNESS DIMENSION OF WELDMENT.

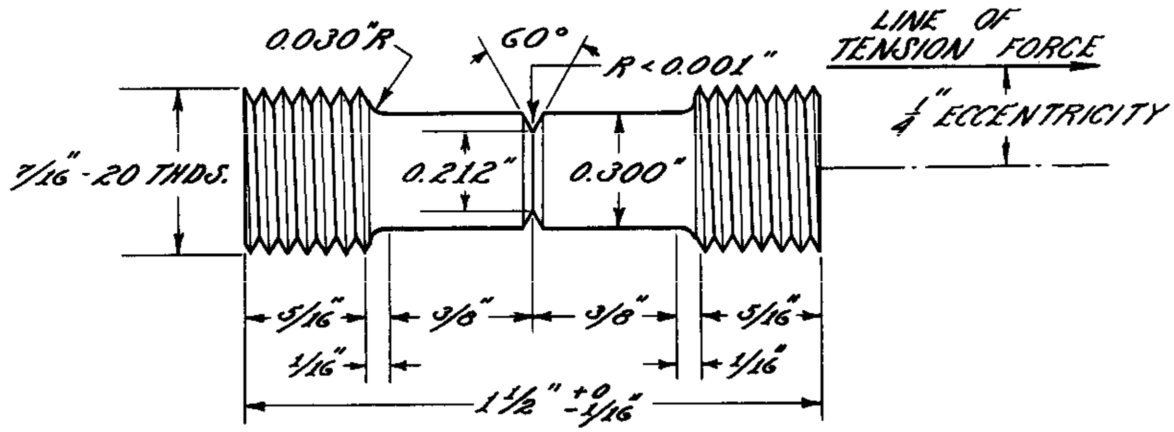


FIG. 7: SPECIMEN WITH 50 PERCENT SHARP NOTCH USED IN ECCENTRIC TESTING (50 PERCENT OF THE AREA REMOVED AT THE NOTCH BOTTOM).

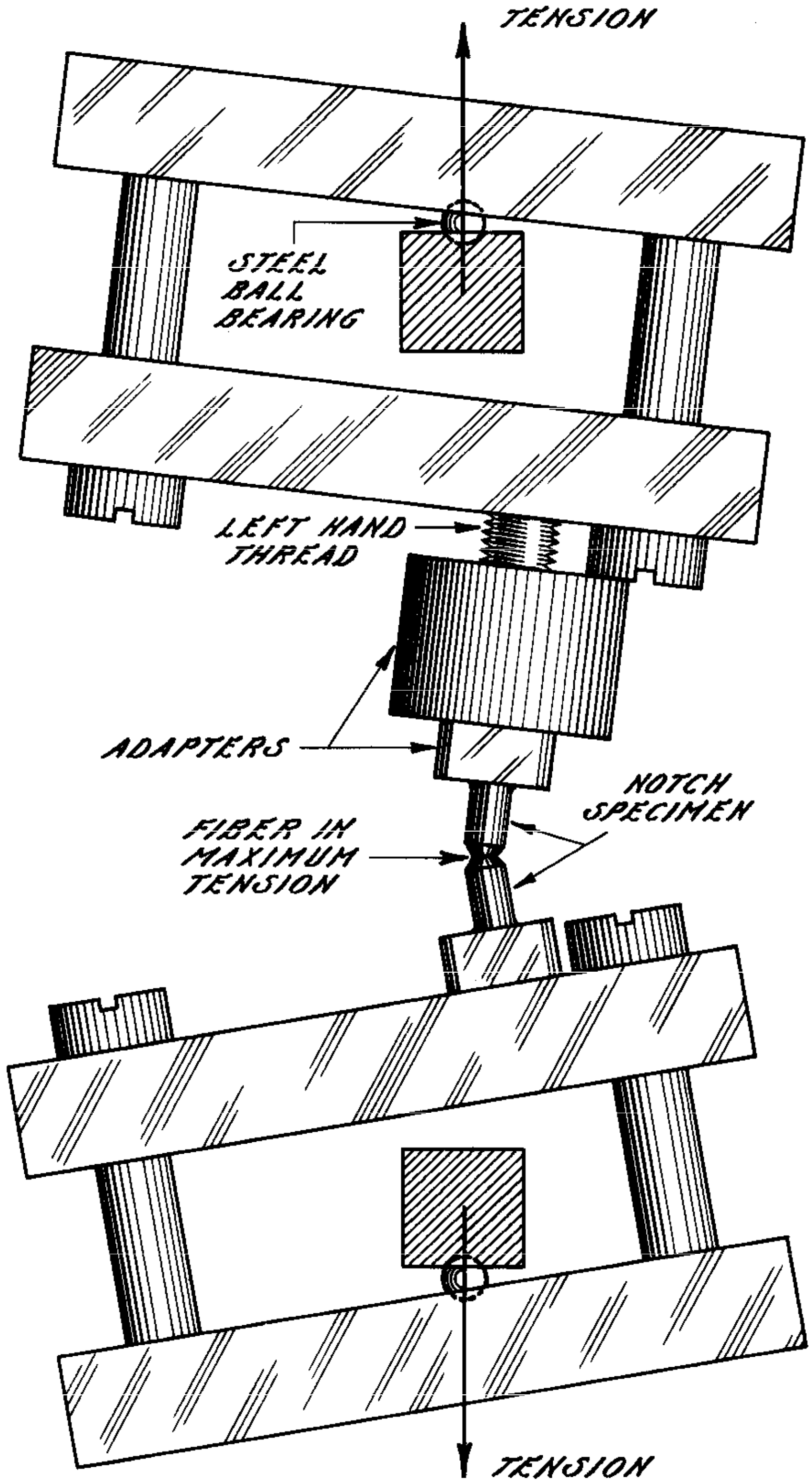


FIG. 8: METHOD OF LOADING TO OBTAIN 1/4 INCH ECCENTRICITY (ECCENTRICITY AND THE POSITION OF FIXTURES ARE EXAGGERATED).

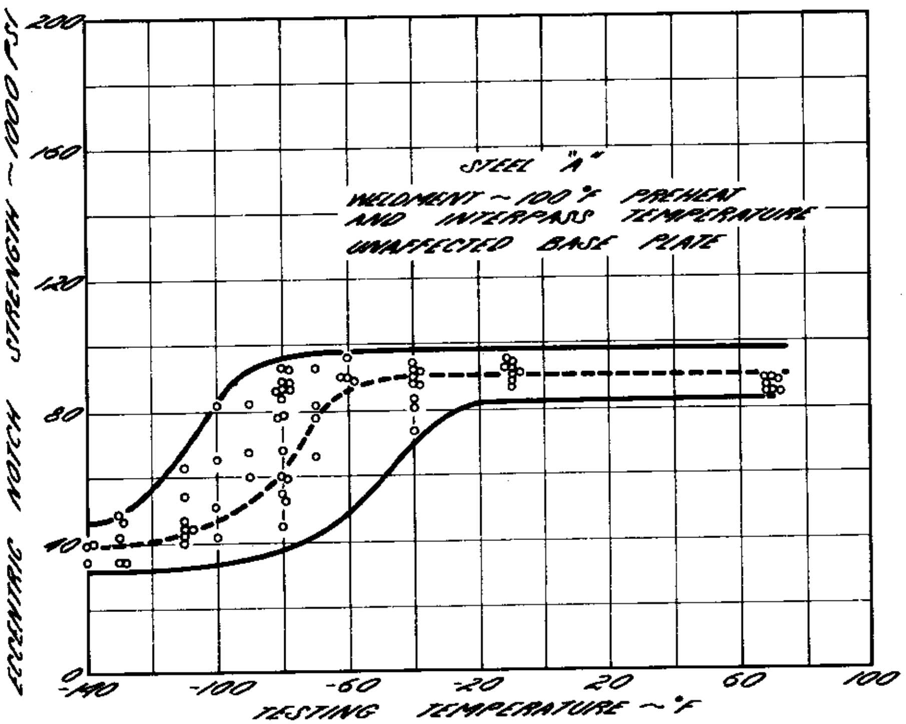


FIG 9: ECCENTRIC NOTCH STRENGTH OF THE UNAFFECTED BASE PLATE AS A FUNCTION OF TESTING TEMPERATURE.

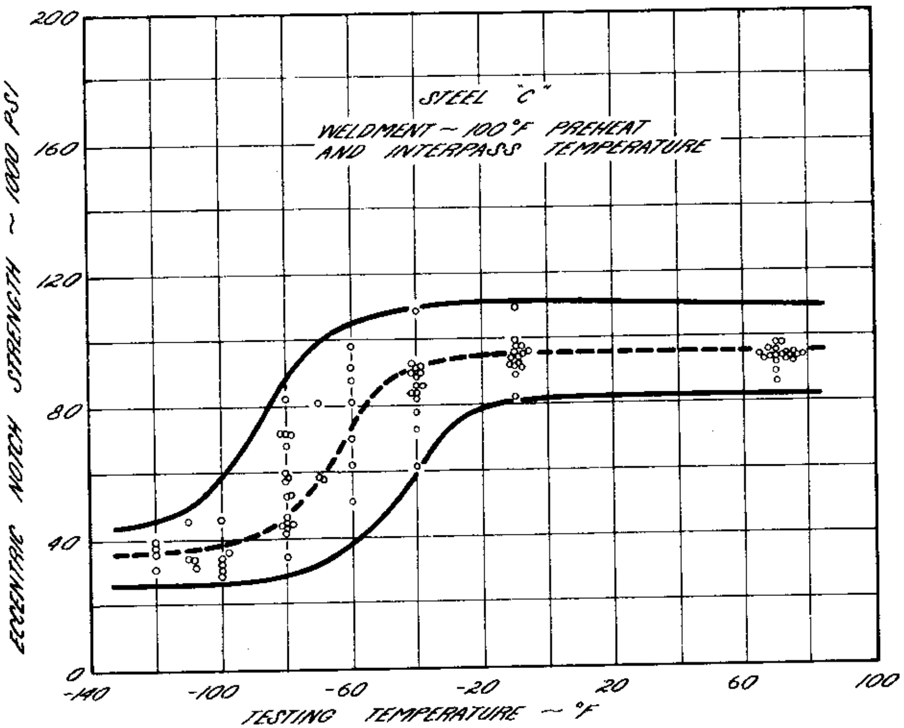


FIG. 10: ECCENTRIC NOTCH STRENGTH OF THE UNAFFECTED BASE PLATE AS A FUNCTION OF TESTING TEMPERATURE.

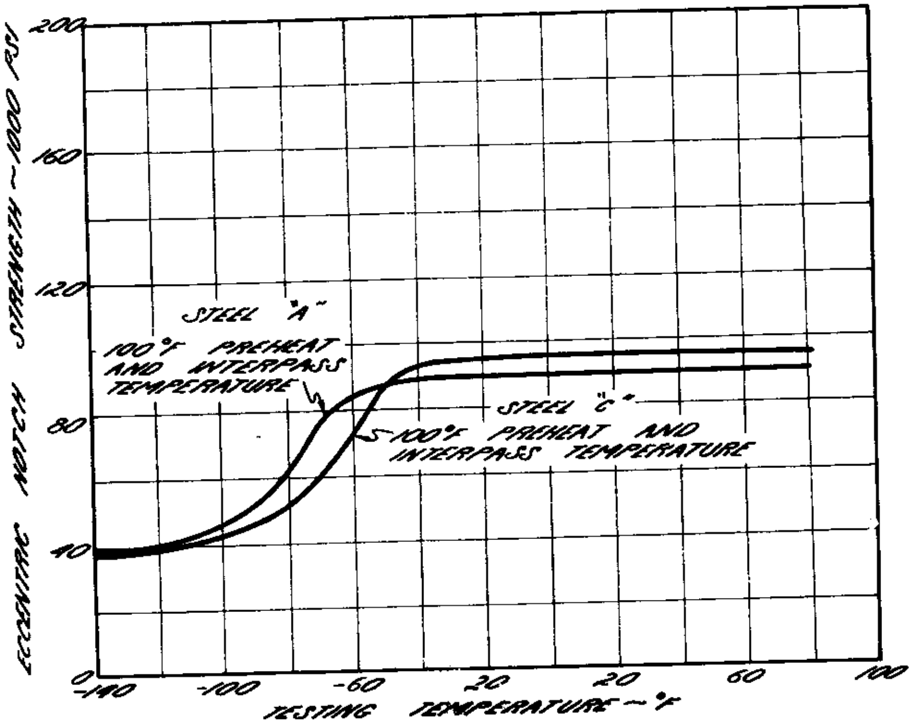


FIG. 11: TRANSITION CURVES OF THE UNAFFECTED BASE PLATE OF STEEL "A" AND "C".

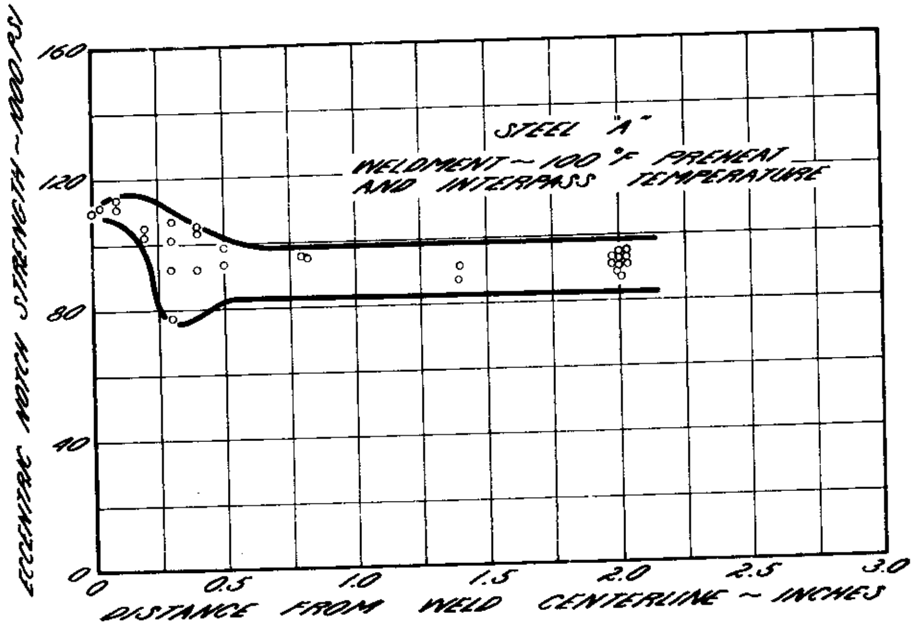


FIG. 12: DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH AT -10°F.

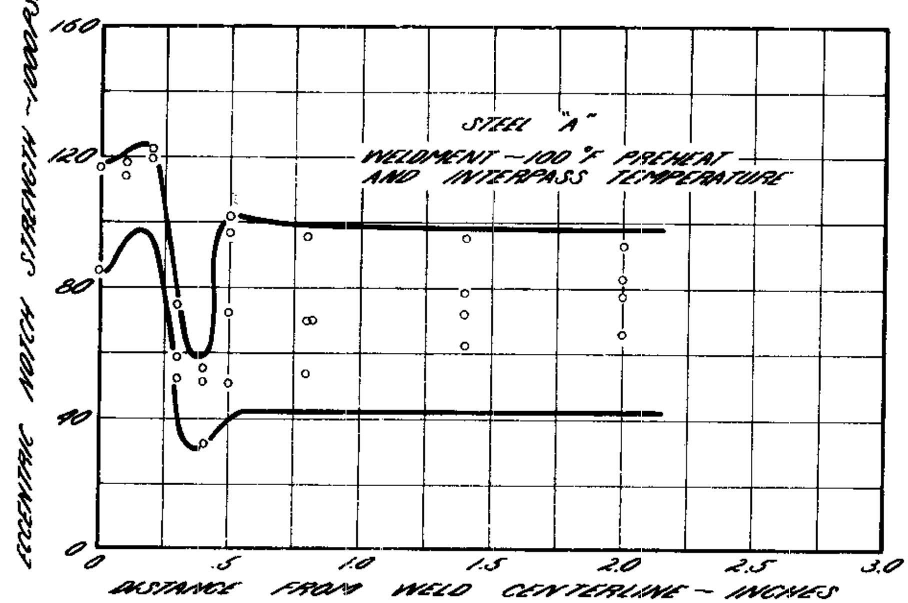


FIG. 13 : DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH AT -70 °F

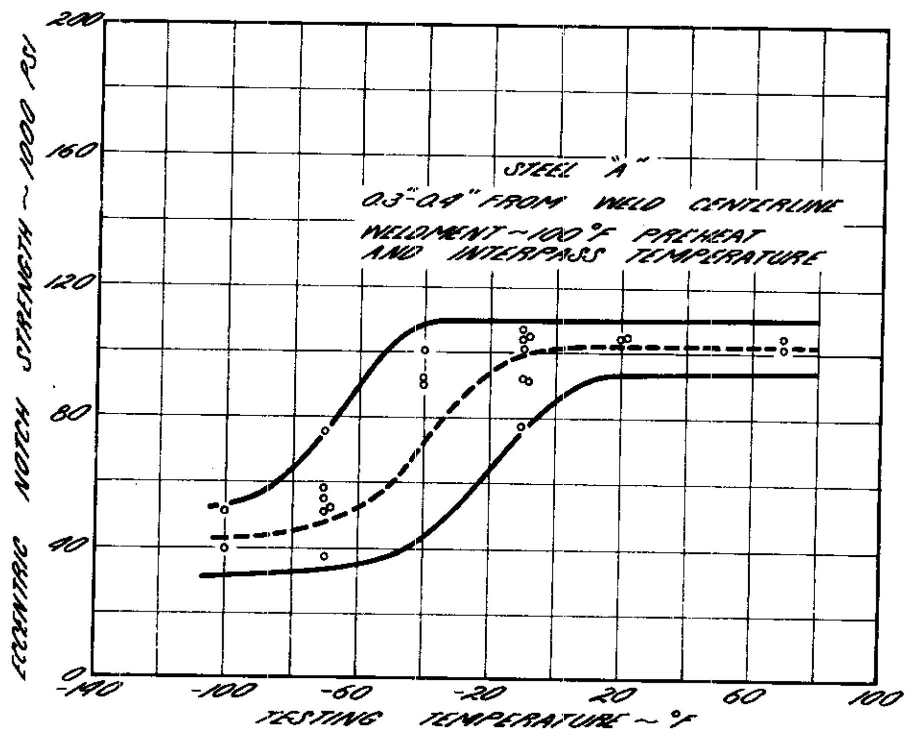


FIG. 14 : ECCENTRIC NOTCH STRENGTH OF THE REGION OF LOWEST DUCTILITY AS A FUNCTION OF TESTING TEMPERATURE.

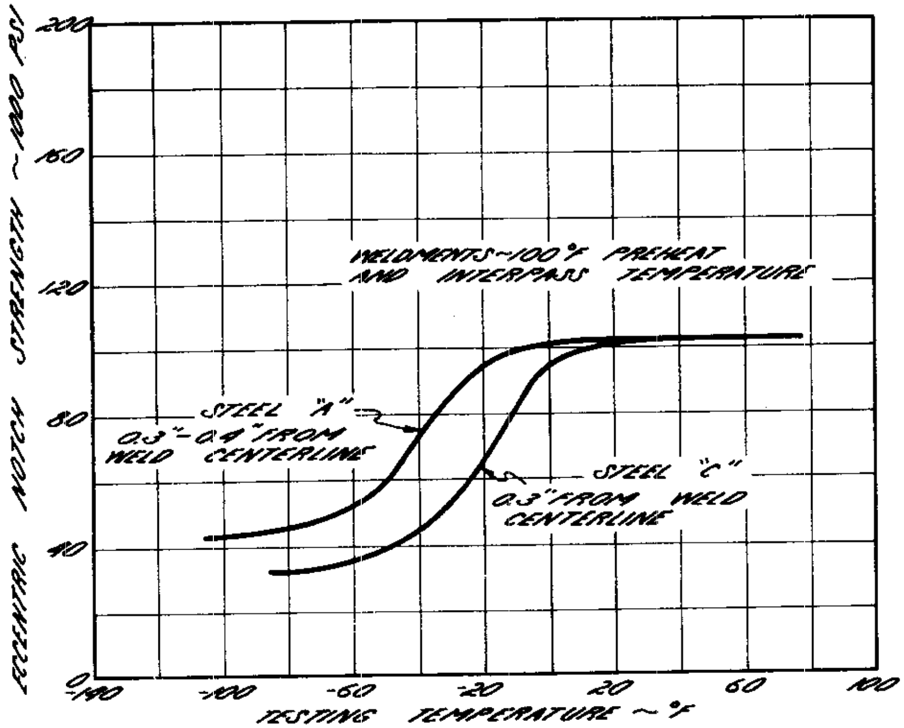


FIG. 15: TRANSITION CURVES OF THE REGION OF LOWEST DUCTILITY FOR STEELS "A" AND "C".

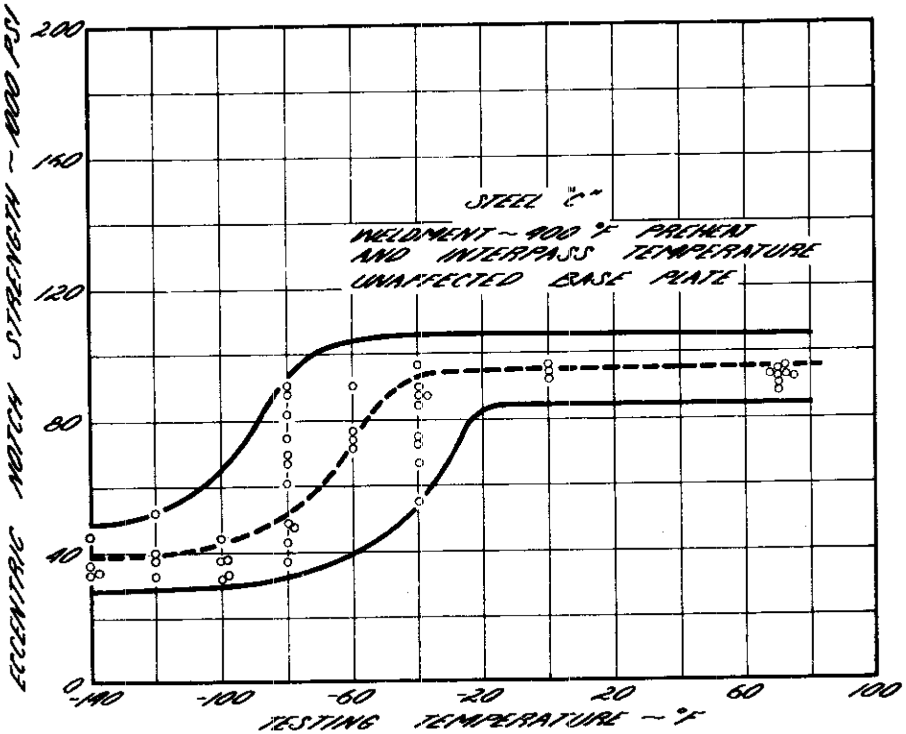


FIG. 16: ECCENTRIC NOTCH STRENGTH OF THE UNAFFECTED BASE PLATE AS A FUNCTION OF TESTING TEMPERATURE.

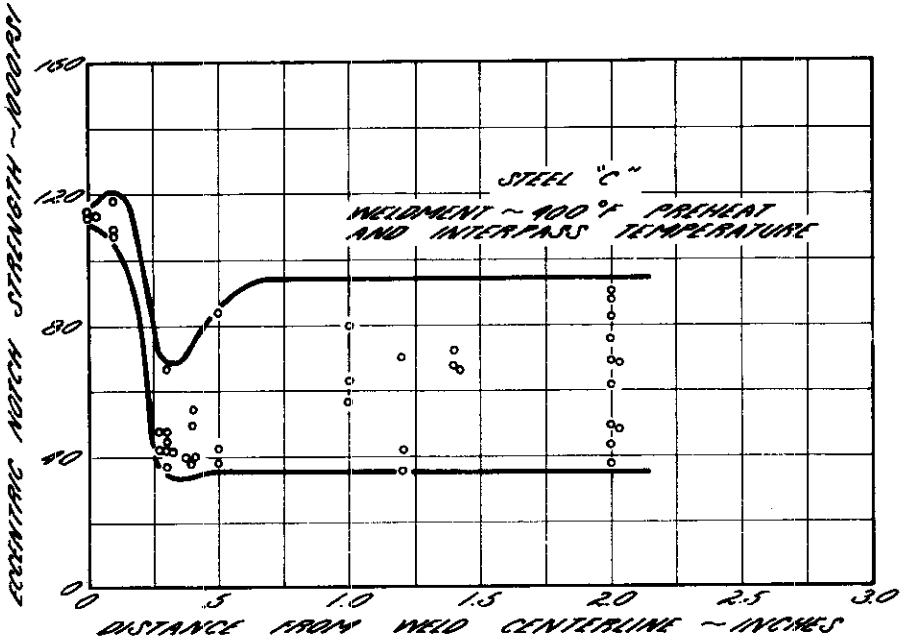


FIG.17: DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH AT -80 °F.

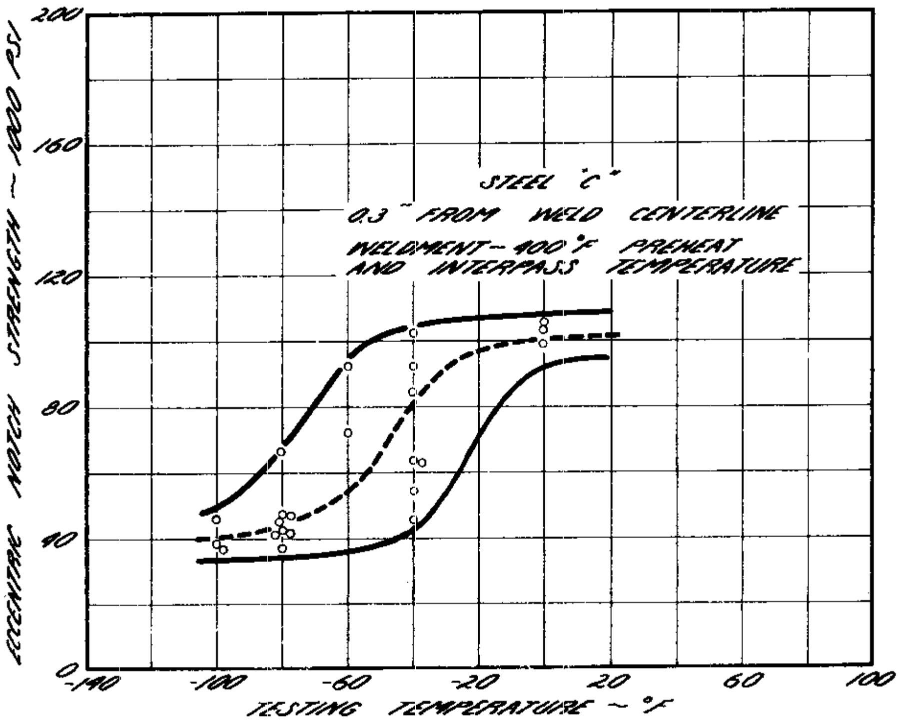


FIG.18: ECCENTRIC NOTCH STRENGTH OF THE REGION OF LOWEST DUCTILITY AS A FUNCTION OF TESTING TEMPERATURE.

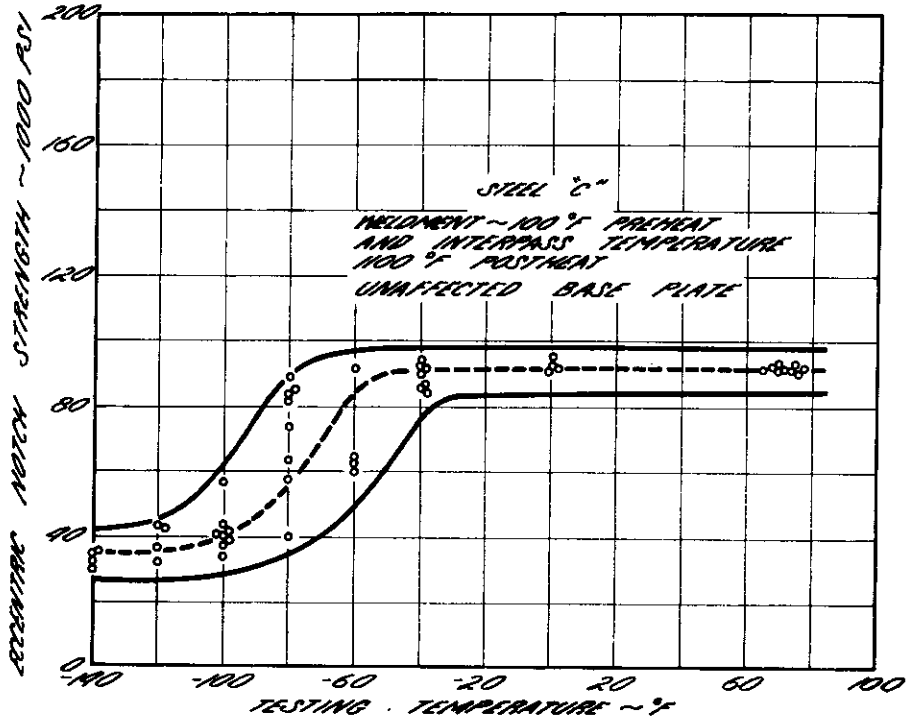


FIG.19: ECCENTRIC NOTCH STRENGTH OF THE UNAFFECTED BASE PLATE AS A FUNCTION OF TESTING TEMPERATURE.

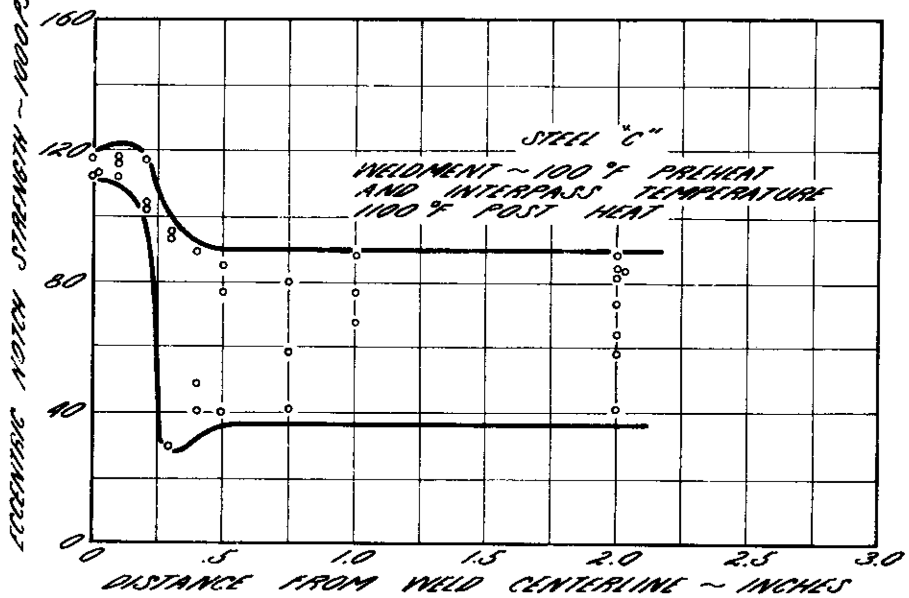


FIG.20: DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH AT -80 °F.

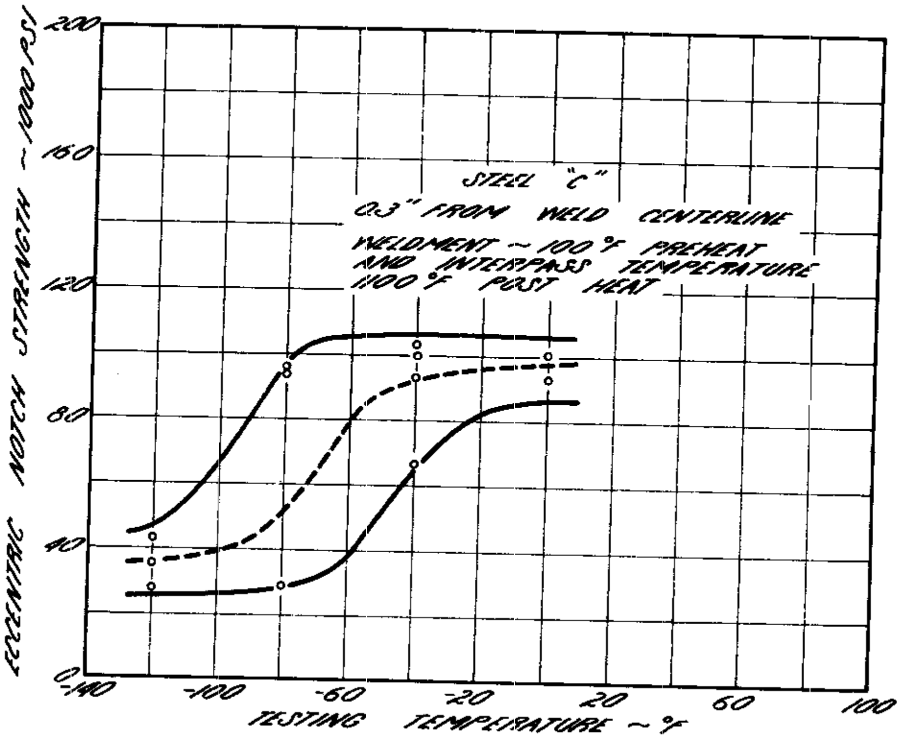


FIG. 21: ECCENTRIC NOTCH STRENGTH OF THE REGION OF LOWEST DUCTILITY AS A FUNCTION OF TESTING TEMPERATURE.

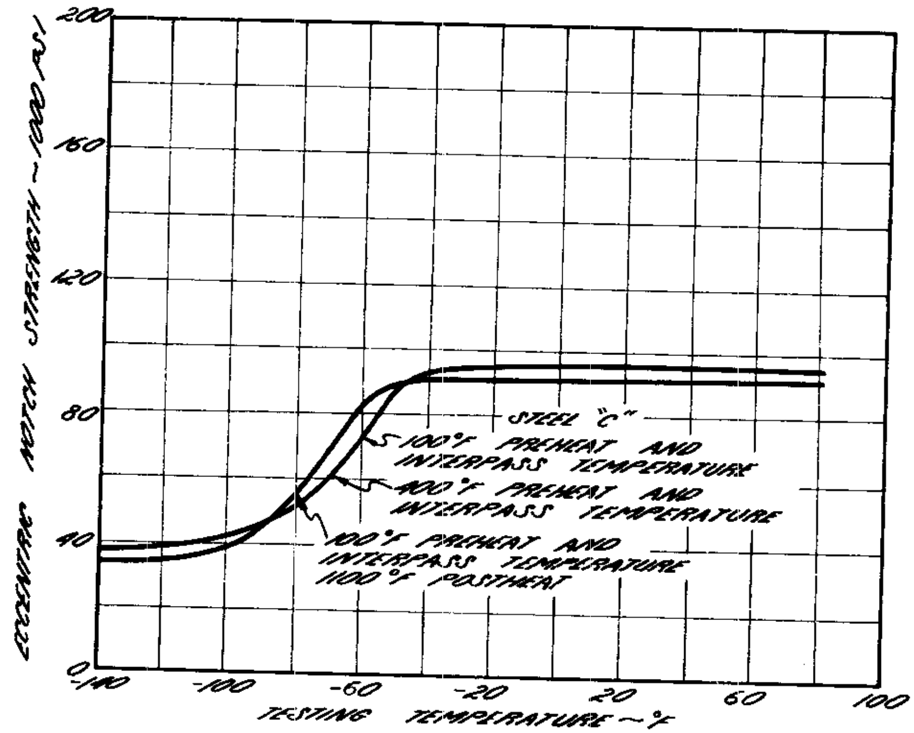


FIG. 22: TRANSITION CURVES OF THE UNAFFECTED BASE PLATE OF STEEL "C" FOR THREE WELDING CONDITIONS.

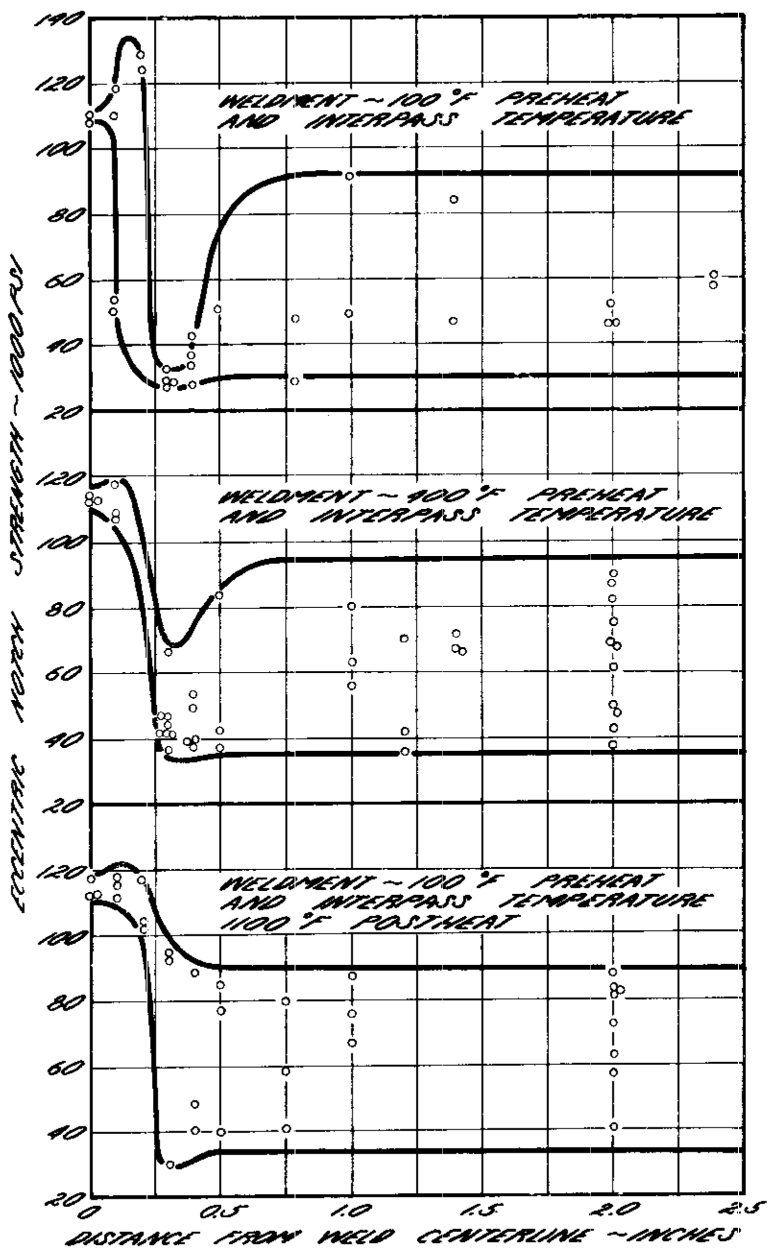


FIG. 23: DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH OF "C" STEEL AT -80°F FOR THREE WELDING CONDITIONS.

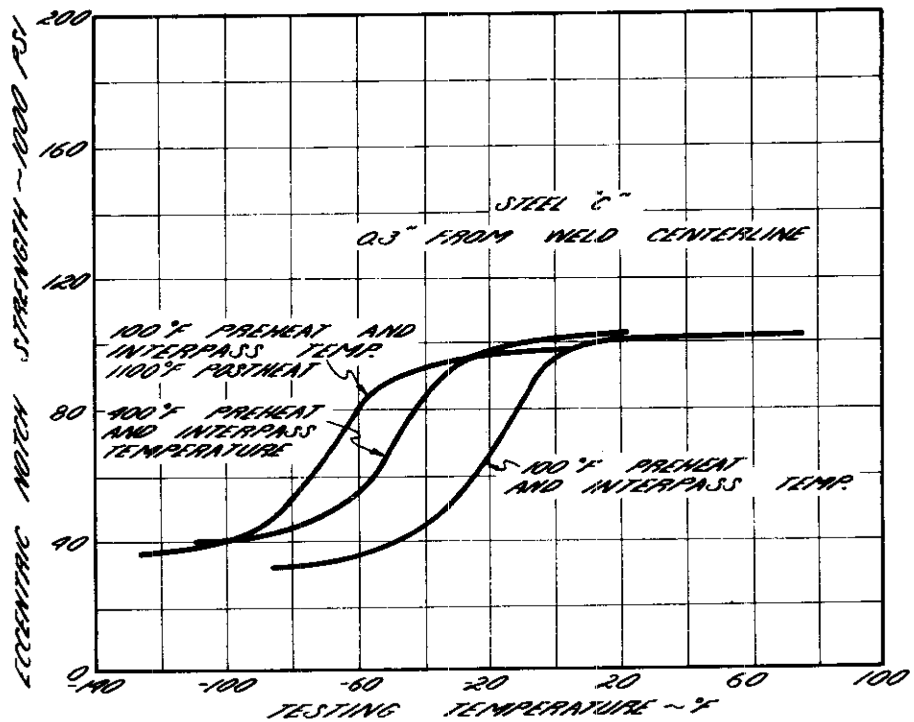
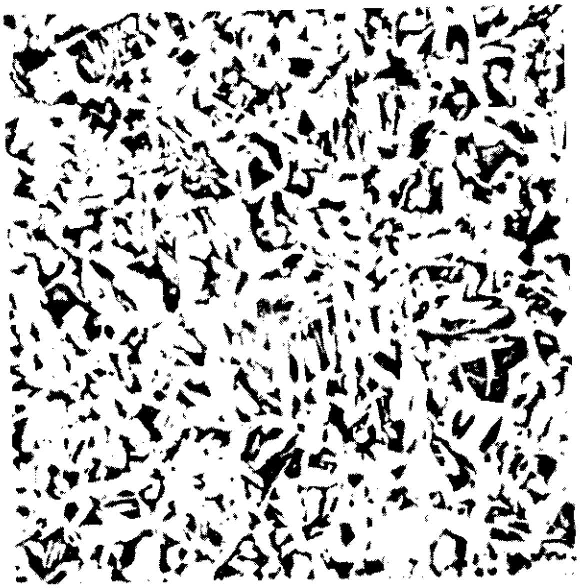
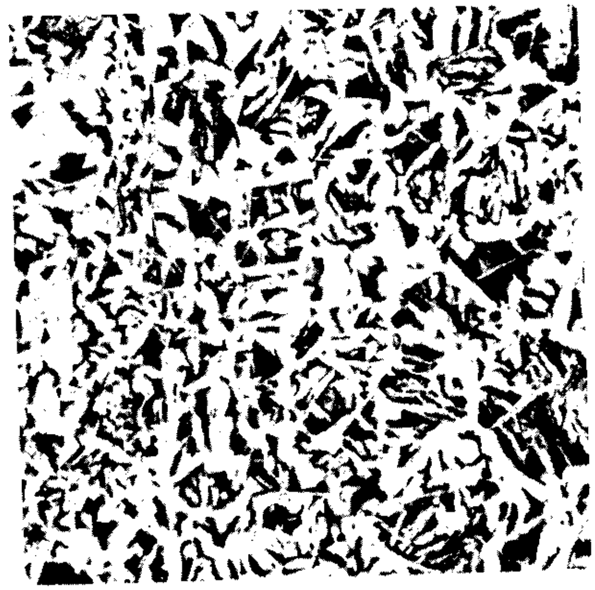


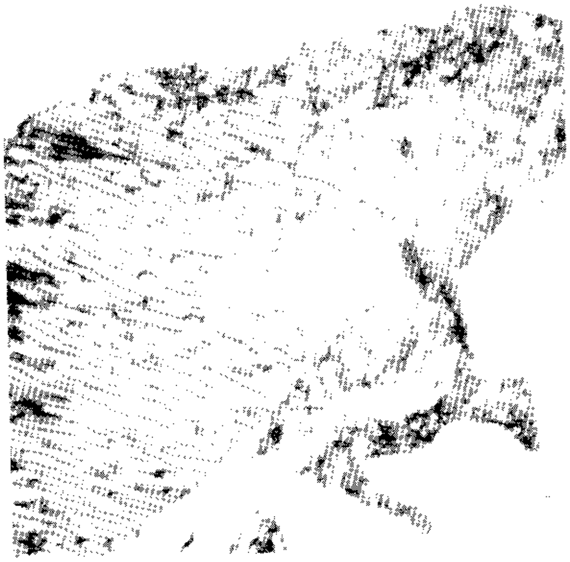
FIG. 24: TRANSITION CURVES OF THE REGION OF LOWEST DUCTILITY FOR THREE WELDING CONDITIONS.



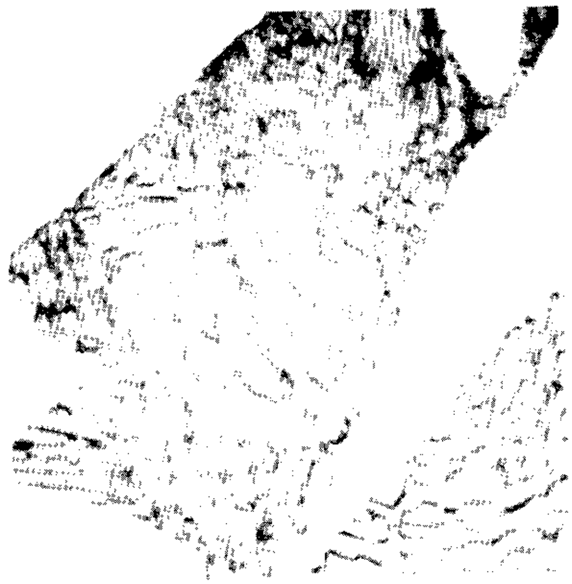
a. UNAFFECTED BASE PLATE
100X



c. 0.3 FROM WELD CENTERLINE
100X

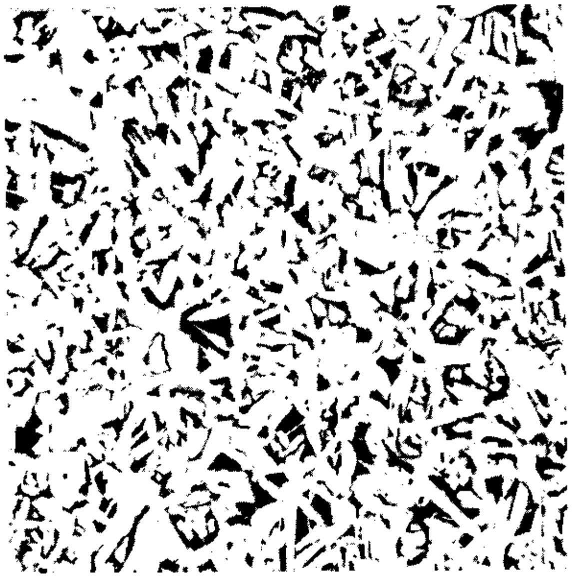


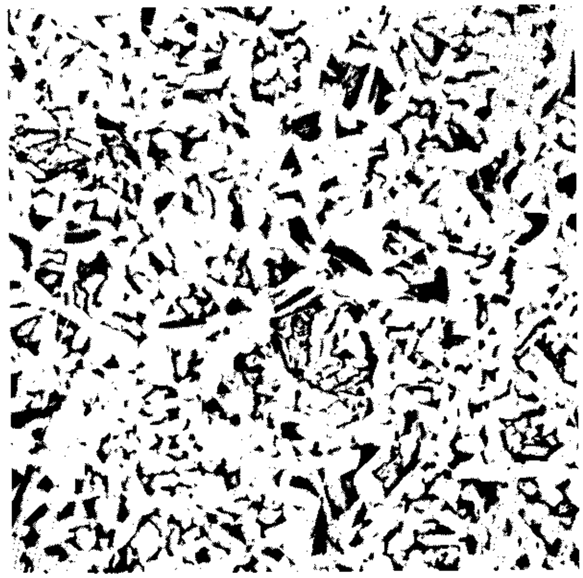
b. UNAFFECTED BASE PLATE
2000X



d. 0.3 FROM WELD CENTERLINE
2000X

FIG. 25: MICROSTRUCTURES OF UNAFFECTED BASE PLATE AND CRITICAL ZONE IN C STEEL WELDMENT MADE WITH 100°F PREHEAT AND INTERPASS TEMPERATURE (PICRAL ETCH)





a. 100X

c. 100X

b. 2000X

d. 2000X

a & b. 100°F PREHEAT AND INTERPASS TEMP.

c. & d. 100°F PREHEAT AND INTERPASS TEMP. 1100°F POSTHEAT

FIG. 26 : MICROSTRUCTURES OF CRITICAL ZONE (0.3 FROM WELD CENTERLINE) IN C STEEL WELDMENTS MADE WITH PREHEAT AND POSTHEAT RESPECTIVELY (PICRAL ETCH).

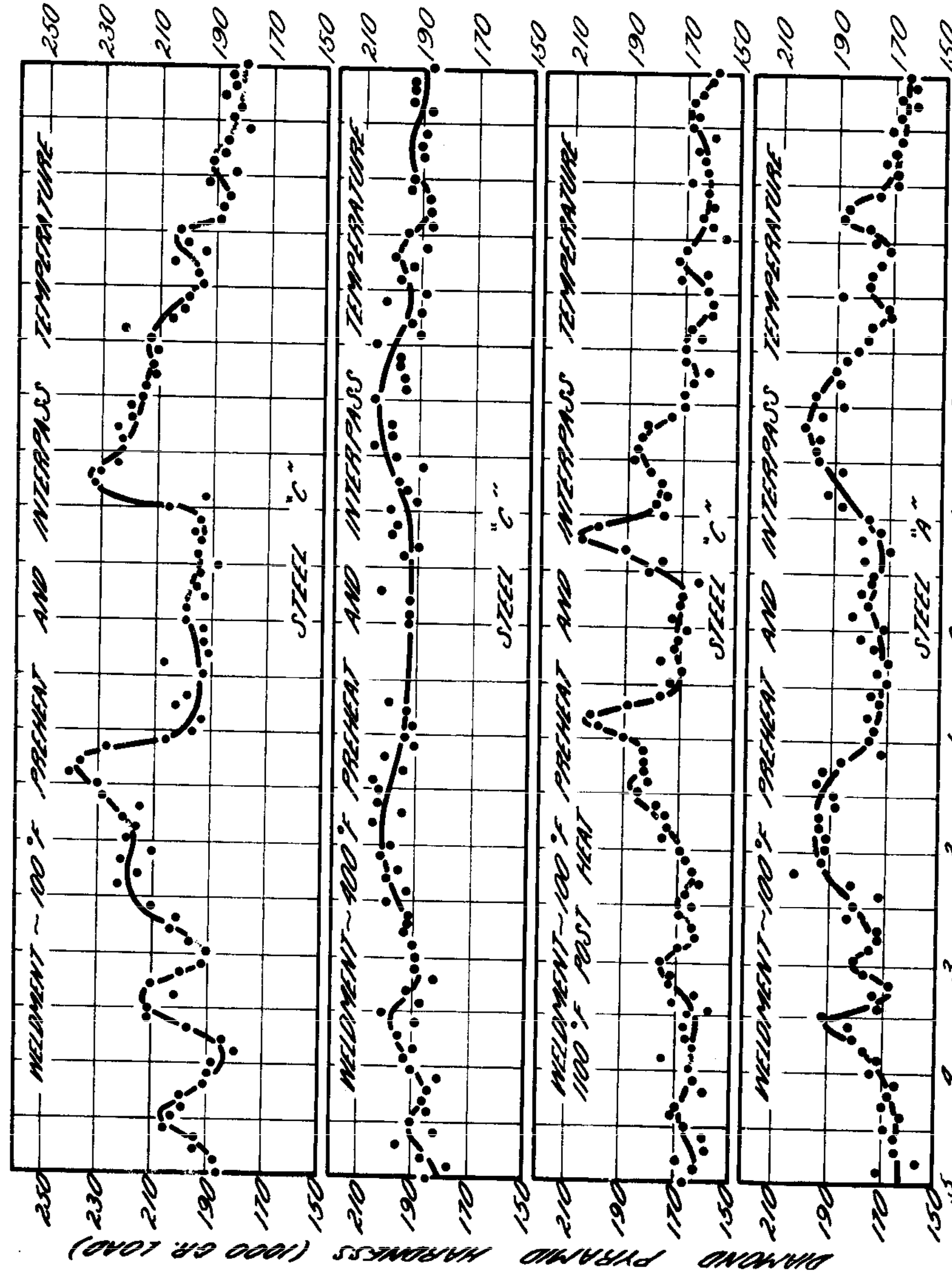


FIG.27. DISTRIBUTION OF MICROHARDNESS VALUES AT THE MIDTHICKNESS OF 3/4" PLATE WELDMENTS OF STEELS "C" AND "A".

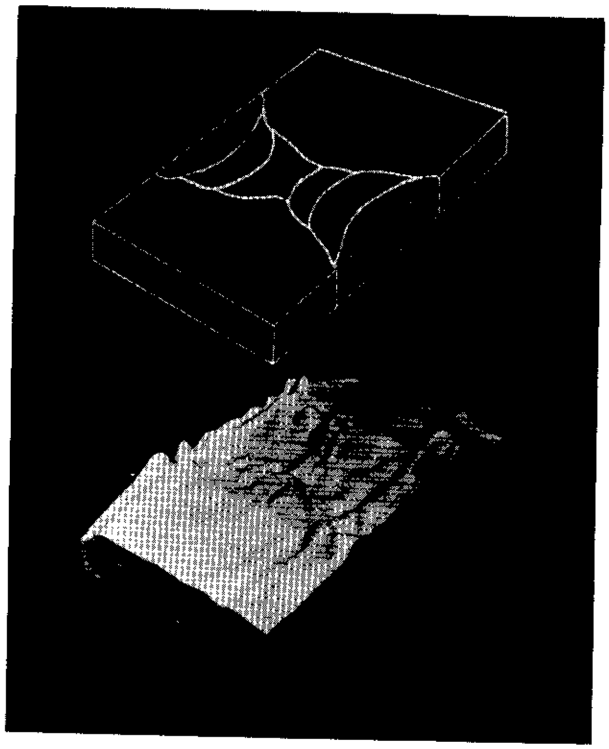


FIG.28: MICROHARDNESS SURVEY ON
A $\frac{3}{4}$" PLATE WELDMENT OF
STEEL C (100°F PREHEAT
AND INTERPASS TEMPERATURE)

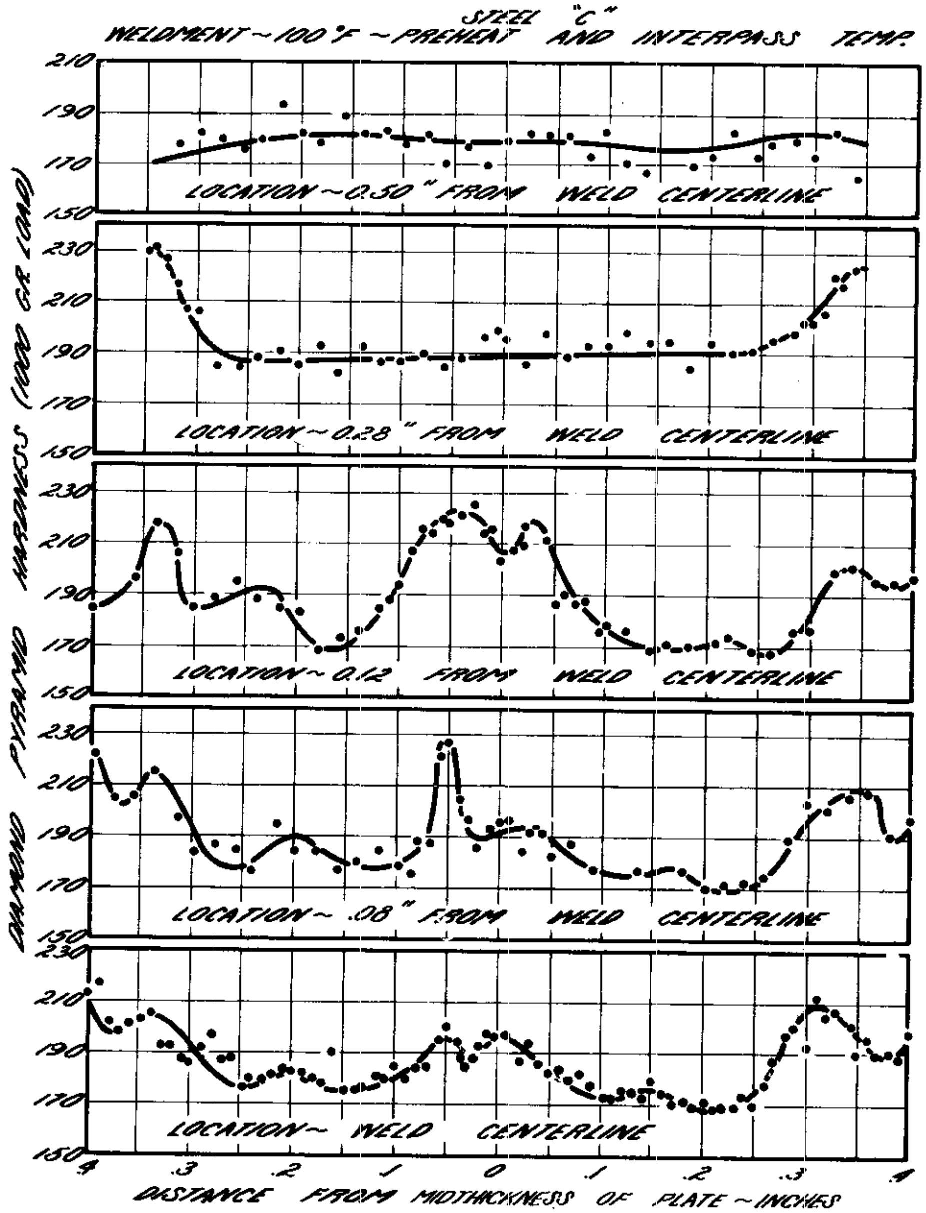


FIG.29: DISTRIBUTION OF MICROHARDNESS VALUES AT VARIOUS DISTANCES FROM THE WELD CENTERLINE.

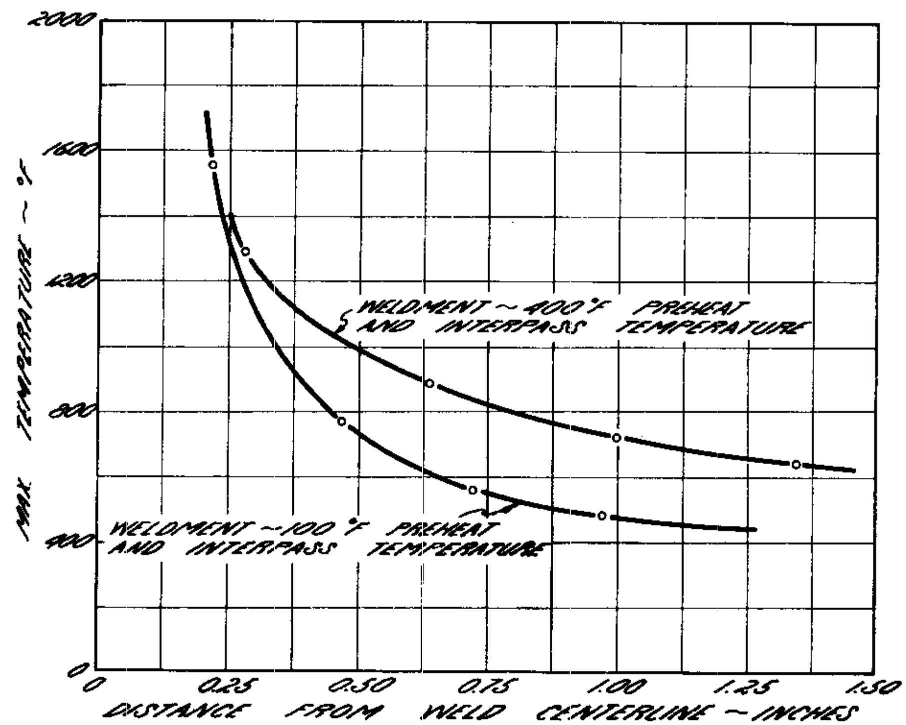


FIG.30: MAXIMUM TEMPERATURES REACHED DURING WELDING FOR TWO WELDING CONDITIONS.

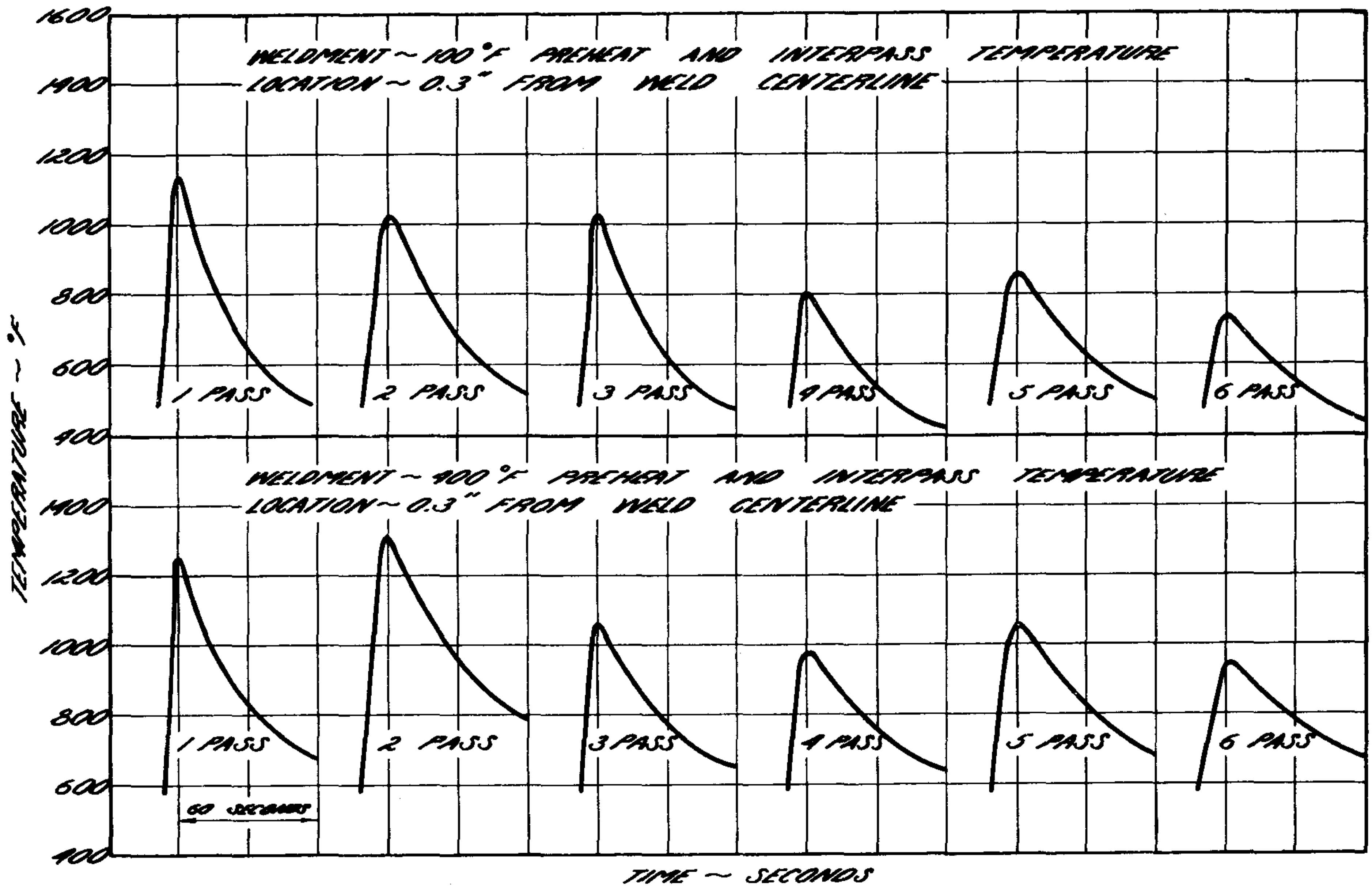


FIG. 31 : HEATING AND COOLING CURVES IN THE REGION OF LOWEST DUCTILITY FOR TWO 6 PASS WELDMENTS.

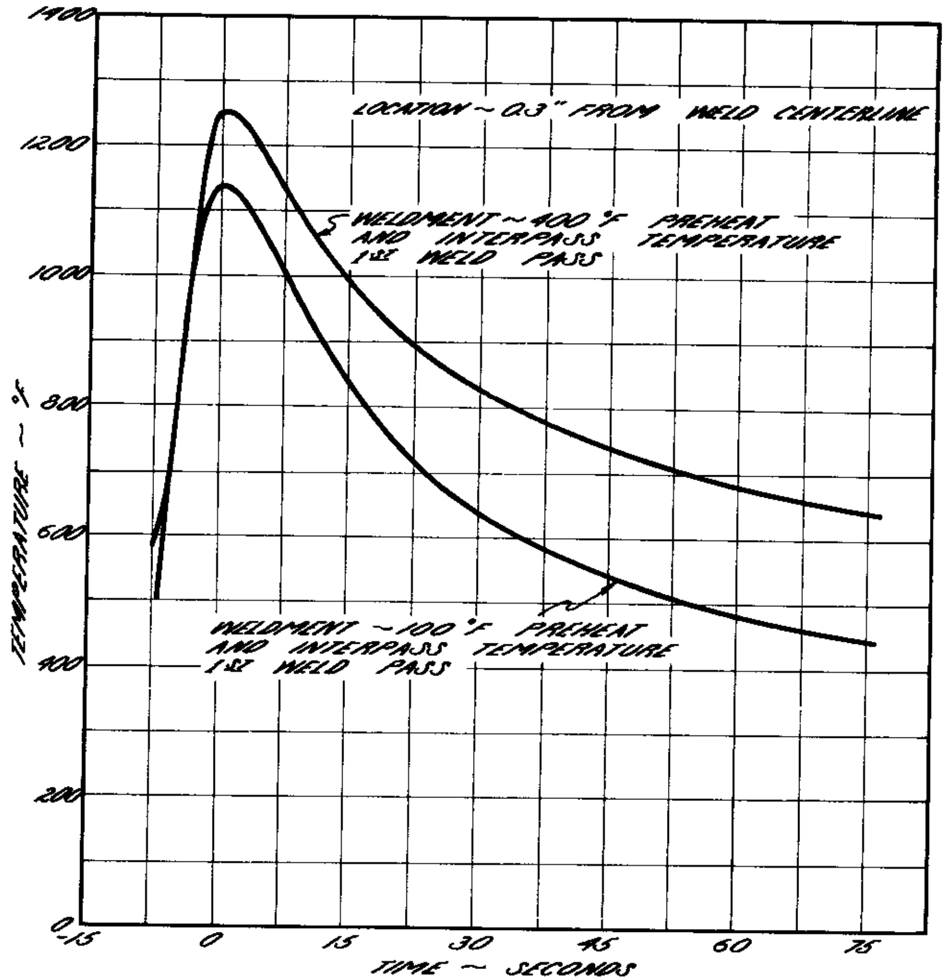


FIG.32: HEATING AND COOLING CURVES IN THE REGION OF LOWEST DUCTILITY FOR TWO WELDING CONDITIONS.

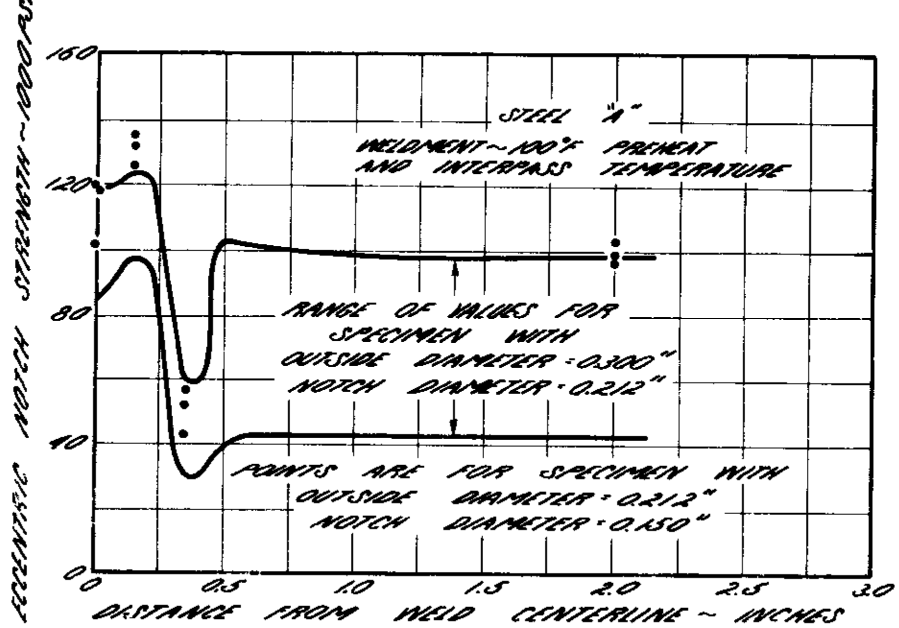


FIG.33: EFFECT OF SPECIMEN SECTION SIZE ON THE DISTRIBUTION OF ECCENTRIC NOTCH STRENGTH AT -70 °F.

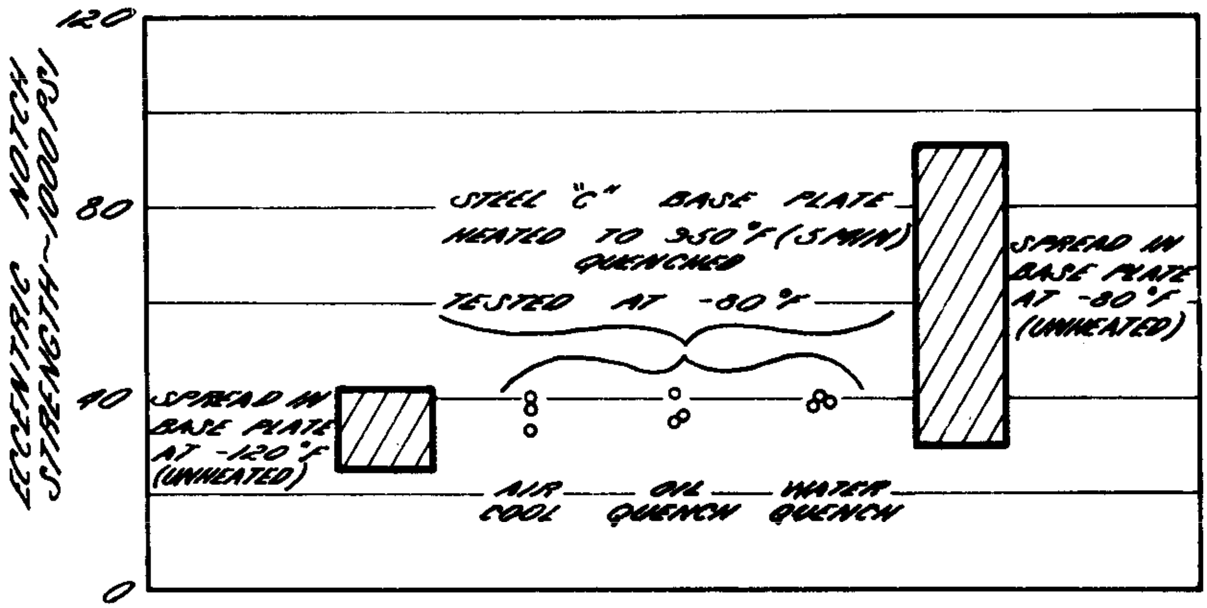


FIG. 34: EFFECT OF SUBCRITICAL HEATING AND COOLING ON THE ECCENTRIC NOTCH STRENGTH OF UNAFFECTED BASE PLATE.

APPENDIX

TABLE I

Data C Steel Weldments 100°F Preheat

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi	Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0.0	RT	93.5	0.3	RT	96.2
0.0	RT	98.6	0.3	RT	108.5
0.0	-10	105.8	0.3	-10	94.5
0.0	-10	108.0	0.3	-10	68.8
0.0	-40	113.0	0.3	-10	109.0
0.0	-40	111.5	0.3	-10	63.5
0.0	-60	89.2	0.3	-40	69.3
0.0	-60	109.0	0.3	-40	46.7
0.0	-80	110.0	0.3	-40	31.4
0.0	-80	109.5	0.3	-40	42.4
			0.3	-60	53.2
0.1	RT	109.0	0.3	-60	33.0
0.1	RT	101.5	0.3	-60	35.2
0.1	-10	127.5	0.3	-60	30.8
0.1	-10	113.0	0.3	-60	38.1
0.1	-40	122.6	0.3	-80	28.7
0.1	-40	109.7	0.3	-80	29.7
0.1	-60	113.8	0.3	-80	29.5
0.1	-60	123.0	0.3	-80	32.5
0.1	-80	54.4			
0.1	-80	110.0	0.4	RT	103.5
0.1	-80	51.1	0.4	RT	104.0
0.1	-80	118.5	0.4	RT	102.5
			0.4	-10	65.0
0.2	RT	95.8	0.4	-10	86.0
0.2	RT	107.0	0.4	-10	100.0
0.2	-10	121.8	0.4	-40	89.7
0.2	-10	120.0	0.4	-40	75.7
0.2	-40	124.2	0.4	-40	34.2
0.2	-40	86.5	0.4	-40	59.2
0.2	-60	118.8	0.4	-60	42.7
0.2	-60	109.0	0.4	-60	43.5
0.2	-80	124.5	0.4	-60	62.3
0.2	-80	129.0	0.4	-80	37.2
			0.4	-80	42.5
			0.4	-80	34.9
			0.4	-80	27.9

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0.5	RT	99.0
0.5	RT	104.0
0.5	-10	78.8
0.5	-10	97.3
0.5	-10	63.4
0.5	-40	83.8
0.5	-40	62.3
0.5	-60	56.9
0.5	-60	98.8
0.5	-80	50.8
0.6	-40	59.6
0.6	-40	95.5
0.6	-60	60.6
0.6	-60	55.5
0.7	-40	69.3
0.7	-40	64.5
0.7	-60	50.4
0.7	-60	90.7
0.8	RT	96.0
0.8	RT	97.5
0.8	-10	76.4
0.8	-10	84.3
0.8	-40	55.7
0.8	-40	60.1
0.8	-60	59.8
0.8	-60	73.0
0.8	-80	46.8
0.8	-80	28.8
0.9	-40	89.2
0.9	-40	86.6
0.9	-60	71.5
0.9	-60	55.4

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
1.0	RT	95.8
1.0	RT	94.0
1.0	-10	103.0
1.0	-10	108.5
1.0	-40	91.0
1.0	-40	82.1
1.0	-60	86.1
1.0	-60	74.3
1.0	-80	49.5
1.0	-80	91.8
1.1	-60	71.7
1.1	-60	98.5
1.2	-60	70.8
1.2	-60	85.0
1.3	-60	40.8
1.3	-60	86.2
1.4	RT	95.0
1.4	RT	108.5
1.4	-10	92.4
1.4	-10	91.0
1.4	-40	86.0
1.4	-40	79.0
1.4	-60	87.0
1.4	-60	89.0
1.4	-80	47.2
1.4	-80	84.0
1.5	-60	54.4
1.5	-60	76.0
1.6	-60	50.4
1.6	-60	89.5
1.7	-60	85.0
1.7	-60	87.3
1.8	-40	61.5
1.8	-40	86.0
1.8	-60	85.7
1.8	-60	92.5

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
1.9	-60	79.5
1.9	-60	93.8
2.0	RT	94.2
2.0	RT	95.4
2.0	-10	89.3
2.0	-10	110.2
2.0	-60	61.8
2.0	-60	51.5
2.0	-60	98.2
2.0	-60	92.1
2.0	-80	46.3
2.0	-80	52.4
2.2	-40	91.4
2.2	-40	61.7
2.4	RT	98.5
2.4	RT	94.0
2.4	-10	96.5
2.4	-10	95.0
2.4	-80	60.0
2.4	-80	59.1
4.0	RT	98.0
4.0	RT	96.5
4.0	RT	92.3
4.0	RT	93.5
4.0	RT	89.5
4.0	RT	94.5
4.0	RT	92.8
4.0	RT	93.3
4.0	RT	92.5
4.0	RT	93.8
4.0	RT	94.5
4.0	RT	86.5
4.0	RT	94.3
4.0	-10	91.5
4.0	-10	82.3
4.0	-10	96.0
4.0	-10	92.5
4.0	-10	91.5
4.0	-10	96.5
4.0	-10	97.5
4.0	-10	93.3
4.0	-10	99.0
4.0	-40	109.0
4.0	-40	83.5
4.0	-40	78.3
4.0	-40	92.0
4.0	-40	92.3
4.0	-40	86.3
4.0	-40	73.3
4.0	-40	90.3
4.0	-40	82.2
4.0	-40	86.7
4.0	-40	64.4
4.0	-80	72.3
4.0	-80	45.0
4.0	-80	68.3
4.0	-80	43.8
4.0	-80	44.4
4.0	-80	43.4
4.0	-80	71.7
4.0	-80	53.5
4.0	-80	82.5
4.0	-80	57.8
4.0	-80	42.2
4.0	-80	72.1
4.0	-100	32.4
4.0	-100	34.3
4.0	-110	30.3
4.0	-110	46.3
4.0	-110	29.2
5.5	RT	95.5
5.5	RT	95.1
5.5	-10	98.0
5.5	-10	94.3
5.5	-40	88.8
5.5	-40	90.6
5.5	-50	87.1
5.5	-60	81.5
5.5	-60	70.5
5.5	-60	88.2
5.5	-70	80.9
5.5	-70	58.8
5.5	-70	58.3
5.5	-80	34.8
5.5	-98	36.0

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
6.0	-108	31.7
6.0	-110	45.2
6.0	-110	34.3
6.0	-110	34.0
6.0	-120	31.2
6.0	-120	35.5
6.0	-120	39.2
6.0	-120	37.5

TABLE II

Data A Steel Weldments 100°F Preheat

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0.0	-10	111.2
0.0	-10	110.0
0.0	-70	116.5
0.0	-70	85.0
0.1	-10	113.5
0.1	-10	110.7
0.1	-70	119.0
0.1	-70	114.0
0.2	-10	102.0
0.2	-10	105.3
0.2	-70	119.5
0.2	-70	122.0
0.3	-10	92.0
0.3	-10	77.6
0.3	-10	101.2
0.3	-10	106.9
0.3	-70	51.7
0.3	-70	58.3
0.3	-70	75.5
0.35	RT	101.3
0.35	RT	104.0
0.35	+20	104.2
0.35	+20	104.9
0.35	-40	89.8
0.35	-40	100.2
0.35	-40	90.7
0.35	-100	39.7
0.35	-100	51.3
0.4	-10	103.5
0.4	-10	91.5
0.4	-10	105.2
0.4	-70	55.0
0.4	-70	37.7
0.4	-70	51.1
0.5	-10	93.1
0.5	-10	98.3
0.5	-70	72.4
0.5	-70	50.5
0.5	-70	101.8
0.5	-70	97.1

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0.8	-10	95.8
0.8	-10	95.5
0.8	-70	52.8
0.8	-70	69.6
0.8	-70	95.5
0.8	-70	70.0
1.4	-10	87.3
1.4	-10	91.3
1.4	-70	71.6
1.4	-70	78.3
1.4	-70	62.3
1.4	-70	95.1
2.0	RT	87.5
2.0	RT	87.9
2.0	RT	88.1
2.0	RT	87.4
2.0	-10	88.2
2.0	-10	92.5
2.0	-10	87.0
2.0	-10	90.0
2.0	-10	94.2
2.0	-10	90.7
2.0	-10	92.5
2.0	-10	90.5
2.0	-10	94.8
2.0	-10	93.5
2.0	-40	93.4
2.0	-40	92.5
2.0	-40	91.4
2.0	-40	73.7
2.0	-40	88.7
2.0	-40	81.3
2.0	-40	90.7
2.0	-40	92.7
2.0	-40	92.5
2.0	-70	66.0
2.0	-70	81.3
2.0	-70	93.2
2.0	-70	77.6
2.0	-80	85.4
2.0	-80	53.8
2.0	-80	54.3

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
2.0	-80	78.7
2.0	-80	93.2
2.0	-80	88.7
2.0	-80	86.7
2.0	-80	93.3
2.0	-80	78.0
2.0	-80	60.0
2.0	-80	85.1
2.0	-80	59.0
2.0	-80	85.7
2.0	-110	40.1
2.0	-110	44.3
2.0	-110	42.4
2.0	-110	43.8
2.0	-130	48.3
2.0	-130	34.6
2.0	-130	47.0
2.0	-130	42.2
2.0	-140	34.8
2.0	-140	39.2
4.0	RT	84.8
4.0	RT	84.3
4.0	RT	84.8
4.0	-60	90.0
4.0	-60	89.0
4.0	-60	95.5
4.0	-60	90.0
4.0	-80	68.0
4.0	-80	83.5
4.0	-80	45.0
4.0	-90	82.8
4.0	-90	67.0
4.0	-90	59.8
4.0	-100	51.0
4.0	-100	81.8
4.0	-100	65.2
4.0	-100	41.6
4.0	-110	54.0
4.0	-110	62.8
4.0	-110	46.4
4.0	-130	34.0
4.0	-140	39.6

TABLE III

Data C Steel Weldments 400°F Preheat

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi	Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0.0	-80	114.1	1.2	-80	41.8
0.0	-80	112.5	1.2	-80	35.8
0.0	-80	113.0	1.2	-80	70.5
0.1	-80	118.0	1.4	-80	67.3
0.1	-80	107.1	1.4	-80	67.0
0.1	-80	109.7	1.4	-80	71.8
0.3	0	99.3	2.0	RT	92.4
0.3	0	104.0	2.0	RT	93.8
0.3	0	105.0	2.0	RT	93.2
0.3	-40	45.4	2.0	RT	93.0
0.3	-40	63.2	2.0	RT	95.3
0.3	-40	102.3	2.0	RT	90.0
0.3	-40	54.6	2.0	RT	88.0
0.3	-40	62.5	2.0	RT	92.2
0.3	-40	92.0	2.0	0	94.7
0.3	-40	84.5	2.0	0	93.4
0.3	-60	72.0	2.0	0	96.3
0.3	-60	92.2	2.0	-40	85.5
0.3	-80	42.2	2.0	-40	87.5
0.3	-80	41.4	2.0	-40	66.9
0.3	-80	47.2	2.0	-40	90.6
0.3	-80	37.2	2.0	-40	87.5
0.3	-80	41.6	2.0	-40	97.1
0.3	-80	66.7	2.0	-40	72.7
0.3	-80	46.9	2.0	-40	54.4
0.3	-80	44.7	2.0	-40	74.3
0.3	-100	46.0	2.0	-60	72.2
0.3	-100	37.0	2.0	-60	90.3
0.3	-100	38.4	2.0	-60	76.3
			2.0	-60	73.6
0.4	-80	38.3	2.0	-80	42.8
0.4	-80	49.2	2.0	-80	48.7
0.4	-80	39.1	2.0	-80	68.9
0.4	-80	53.8	2.0	-80	67.9
0.4	-80	39.2	2.0	-80	88.2
			2.0	-80	74.8
0.5	-80	37.6	2.0	-80	89.7
0.5	-80	84.2	2.0	-80	81.9
0.5	-80	42.0	2.0	-80	47.6
			2.0	-80	61.2
1.0	-80	56.2	2.0	-80	36.8
1.0	-80	80.2	2.0	-100	31.8
1.0	-80	63.2	2.0	-100	37.2

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
2.0	-100	44.1
2.0	-100	32.2
2.0	-100	37.6
2.0	-120	51.7
2.0	-120	40.2
2.0	-120	38.0
2.0	-120	33.2
2.0	-140	36.6
2.0	-140	45.1
2.0	-140	33.0
2.0	-140	34.4

TABLE IV

Data C Steel Weldments 100°F Preheat, 1100°F Postheat

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi	Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
0	-80	112.2	2.0	RT	93.0
0	-80	117.5	2.0	RT	92.1
0	-80	112.7	2.0	RT	91.1
			2.0	RT	91.2
0.1	-80	112.0	2.0	RT	92.2
0.1	-80	115.7	2.0	RT	92.7
0.1	-80	117.8	2.0	RT	91.8
			2.0	RT	90.1
0.2	-80	117.1	2.0	RT	92.1
0.2	-80	102.7	2.0	0	93.1
0.2	-80	103.9	2.0	0	92.2
			2.0	0	91.7
0.3	0	92.6	2.0	0	94.8
0.3	0	100.2	2.0	-40	85.8
0.3	-40	67.3	2.0	-40	94.7
0.3	-40	99.5	2.0	-40	85.4
0.3	-40	92.8	2.0	-40	86.7
0.3	-40	102.9	2.0	-40	90.0
0.3	-80	95.4	2.0	-40	92.2
0.3	-80	29.4	2.0	-40	91.4
0.3	-80	92.9	2.0	-60	62.6
0.3	-120	35.4	2.0	-60	64.3
0.3	-120	43.0	2.0	-60	60.7
0.3	-120	27.6	2.0	-60	91.5
			2.0	-80	81.5
0.4	-80	40.7	2.0	-80	88.6
0.4	-80	89.4	2.0	-80	73.4
0.4	-80	48.3	2.0	-80	83.9
			2.0	-80	84.1
0.5	-80	40.1	2.0	-80	63.8
0.5	-80	77.3	2.0	-80	40.7
0.5	-80	85.0	2.0	-80	58.0
			2.0	-100	43.4
0.75	-80	79.6	2.0	-100	34.1
0.75	-80	58.6	2.0	-100	40.3
0.75	-80	40.9	2.0	-100	40.6
			2.0	-100	38.8
1.0	-80	76.8	2.0	-100	57.2
1.0	-80	88.6	2.0	-100	38.4
1.0	-80	67.7	2.0	-100	40.7
			2.0	-120	43.4
			2.0	-120	32.8
			2.0	-120	42.7
			2.0	-120	36.9

Distance from Weld Centerline Inches	Testing Temperature °F	Eccentric Notch Strength 1000 psi
2.0	-140	29.4
2.0	-140	33.1
2.0	-140	34.6
2.0	-140	35.4