A STUDY OF BRITTLE FRACTURE INITIATION
IN PRESTRAINED NOTCHED STEEL
TENSION SPECIMENS

A Thesis

Presented to

the Faculty of Graduate Studies and Research

The University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

by

William Henry Butterfield

February 1963

ABSTRACT

In this investigation, standard notched specimen tests were conducted to determine the suitability of one grade of steel for varying service conditions. Typical service conditions, involving prestrain and residual stress in which the four factors: (a) low notch toughness, (b) notch effect, (c) temperature, and (d) high strain rate, were combined to cause brittle behaviour.

It is the author's opinion that the following conclusions can be made from this investigation:

1. The ten foot-pound ductility transition temperature for the V-notch Charpy impact test has good correlation with service tests.

2. The 2 per cent lateral contraction ductility transition temperature occurs within the brittle failure zone of this steel.

3. Pretensioning the steel 2 per cent in the absence of defects, increases its resistance to brittle fracture in the presence of defects.

4. Precompression to an average of 2 per cent in the presence of defects increases the susceptibility of this steel to brittle fracture.

5. The combination of low temperature with a sharp notch increases the susceptibility of steel to brittle fracture.

ACKNOWLEDGEMENTS

The author is deeply indebted to all who have contributed or assisted in carrying out this investigation. Special recognition is given to the following who played a major role in this research program:

(a) Assistant Professor R. Lazar, Department of Civil Engineering, The University of Manitoba, for his guidance throughout this program with technical advice and assistance.

(b) The National Research Council, who in the form of a grant, made financially possible, the purchase and construction of special equipment.

(c) Horton Steel Works Limited, who supplied all the steel used in this research program.

(d) Laboratory staff, Materials Testing Laboratory, Department of Civil Engineering, The University of Manitoba.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Every day more and more structures are being built which depend upon the strength of steel for their stability. In newer structures that are being built, steel is frequently subjected to more severe operating conditions. In most structures steel performs satisfactorily, because of its ductility, a property which allows steel to undergo considerable plastic deformation without reducing its load-carrying capacity. However, under special conditions of loading, geometry and temperature, this ductility is not developed and brittle behaviour results.

Causes of Brittle Behaviour

The phenomenon of brittle behaviour is not new and in every instance has caused some alarm. This is due mainly to its occurrence at low operating stresses, with the results generally catastrophic. Since the frequency of brittle fractures increased with the number of welded structures built, an extensive series of research programs has been set up to investigate this brittle behaviour of steel. From these research programs have come the following factors contributing to the brittle behaviour of steel.[1]

a) The structure must be composed of a material of low notch toughness.

b) The ductility of the steel has decreased with a lowering of the temperature.

c) A region of high strain rate exists somewhere in the structure.

d) The state of stress has been increased to yield proportions.

A combination of the above factors is necessary to cause the brittle behaviour of steel.

Limitations of Present Knowledge

The problem of brittle behaviour has received extensive investigation and at last the general pattern of behaviour seems to be resolved.[2] But, the engineer is still faced with the problem of what design criteria to use. Service correlations in the past have indicated that it must be some type of notched bar test to employ the factors responsible for brittle behaviour. The investigation presented here is

---

[1] M. E. Shank, Control of Steel Construction to Avoid Brittle Fracture (New York: Welding Research Council, 1957), p. 5.

[2] Earl R. Parker, Brittle Behaviour of Engineering Structures, (New York: John Wiley and Sons, Inc., 1957), p. 3.

based on the use of these notched bar tests.

This investigation was sponsored by a National Research Council grant and was performed at The University of Manitoba during the summer of 1962.

CHAPTER II

STATEMENT OF THE PROBLEM

The purpose of this investigation is to correlate the standard tension test, the Charpy impact test, and the Kinzel bend test with the notch effect in steel under different conditions of reduced ductility. The conditions of reduced ductility will be presented by means of large tension specimens.

From the standard tests the transition temperature above which brittle fracture does not occur will be determined. From the large tension tests the conditions aiding and preventing brittle fracture will be investigated.

Standard Tests

The standard tension test gives the modulus of elasticity, the yield point, and the ultimate strength for any type of steel at a given temperature. The per cent elongation over a given gauge length is a measure of the ductility of the steel. An investigation of the fracture surface will indicate either a cleavage or shear fracture or a combination of both.

A surface resulting from a cleavage failure is bright and granular and is an indication of brittle fracture. A surface resulting from a shear failure is gray and silky and is an indication of a ductile failure.[1]

The standard Charpy impact test measures the notch toughness of a material which is a measure of the energy required to cause failure.[2] The plot of energy versus temperature shows a decrease in energy absorption with a decrease in temperature. The transition from ductile to brittle behaviour is obtained from this plot and is referred to as the ductility transition temperature. Another criterion for transition temperature depends on the fracture surface and is referred to as the fracture appearance transition, which occurs at a higher temperature than the ductility transition temperature.

The notch bend test after Kinzel is one of the many tests used to determine the effect of welding on the notch toughness of steel.[3] It also evaluates the ductility of the heat-affected zone.

The criteria used to evaluate the transition temperature of the notch bend test consists of the per cent lateral contraction at the base of the notch and the angle of

---

[1]Earl R. Parker, Brittle Behaviour of Engineering Structures (New York: John Wiley and Sons, Inc., 1957), p. 6.

[2]Robert D. Stout and W. D'Orville Doty, Weldability of Steels (New York: Welding Research Council, 1953), p. 116.

[3]Ibid., p. 246.

bend at maximum load both compared at different temperatures.[4]

Large Tension Tests

The large tension specimens were used to reconstruct to a limited extent, conditions of operation that might be expected to result from service.

The conditions investigated involved compression with and without the presence of a notch, tension without the notch, and residual stresses due to welding, followed by tensile loading. The prestraining was done at room temperature and each series of specimens was tested over a given temperature range in order to determine the temperature effect.

Limitations of the Investigation

Steel reacts differently for variables consisting of changes in specimen geometry, temperature, loading conditions and metallurgical properties. As a result, it has been impossible to obtain an exact correlation between test results on different specimens.

This failure to obtain correlation between test results is in many cases the result of indiscriminate mixing of criteria used to judge performance.[5]

---

[4] S. A. Agnew, M. D. Mittelman and R. D. Stout, Some Observations on the Kinzel and Drop-Weight Tests, The Welding Journal 39 (5) Research Suppl., 205-s to 211-s, (1960).

[5] Parker, op. cit., p. 109.

In this investigation the variables of material, geometry and loading conditions have been eliminated in the large specimens which leaves the major variable being the method of prestrain which is being tested.

CHAPTER III

THEORETICAL CONSIDERATIONS

The fracture mode of steel can be either brittle or ductile depending on the conditions of loading. Ductile behaviour, characterized by shear-type fractures associated with plastic flow, depends on shear stresses. Brittle behaviour, characterized by cleavage-type fractures depends on tensile stresses. The transition from ductile to brittle behaviour depends on the ratio of maximum shear stress to maximum tensile stress. Low ratios are always associated with brittle behaviour.[1]

At regions of high stress concentration, for example the apex of a notch, ductile or brittle behaviour depends on the ability of the material to yield plastically. The stress has been raised to yield proportions because of the notch. When this plastic flow is prevented because of temperature or strain rate, the yield strength approaches the rupture strength and steel then becomes susceptible to brittle failure. In this way notch effect, strain rate and temperature combine to cause brittle behaviour in steel.

Notch Effect

The action of the notch is to decrease the ratio of

---

[1]Earl R. Parker, Brittle Behaviour of Engineering Structures (New York: John Wiley and Sons, Inc., 1957), p. 4.

maximum shear stress to maximum tensile stress by changing uniaxial tension to triaxial tension. This triaxial stress condition is the result of a combination of stresses in the longitudinal, thickness, and width directions.[2]

It is well known that the longitudinal stress at the apex of a notch increases to a value several times greater than the average stress depending on the acuity of the notch. Since this longitudinal stress is zero across the notch and abnormally high at the apex, different degrees of lateral contraction in the thickness direction are experienced in the regions adjacent to the notch. This results in tensile stresses of high magnitude at the notch apex and compressive stresses on the notch side of the apex as a result of the less rapid rate of contraction. Since the longitudinal tensile load tends to spread the notch, a tensile stress is produced on the face of the notch in the width direction with a maximum at the notch apex. As previously mentioned, the longitudinal stress is a maximum at the notch apex which results in the lateral contraction being greater at the base of the notch than in the regions above and below. This spreading of the notch and increased lateral contraction cause high tensile stresses to act in the width direction of the notch apex.

This triaxility of stress created by the notch lowers

---

[2] Ibid., p. 6.

the maximum shear stress to maximum tensile stress ratio, promoting brittle behaviour. The ratio is further reduced with an increase in plate thickness and an increase in notch acuity.

Strain Rate

Research has shown that the increase in strain rate increases both the yield strength and ultimate strength of structural carbon steel. This high sensitivity to strain rate is partly responsible for the brittle behaviour of steels.[3]

In notched specimens the strain rate is higher than in unnotched specimens because of the concentration of stress at the base of the notch. This strain rate is increased with the acuity of the notch. This increased strain rate has the effect of raising the transition temperature below which steel experiences brittle behaviour.

The strain rate in the structure may also be increased by increasing the rate at which the load is applied to the specimen. This means of increasing strain rate becomes quite effective when an impact rate of loading is used.

Temperature

The effect of temperature is most important in brittle behaviour of steel since structures of steel may operate

---

[3]*Ibid.*, pp. 39-41.

under conditions of large temperature variations.

There is an equivalence between strain rate and temperature, shown by the Charpy impact test.[4] From this test there is a temperature below which brittle behaviour occurs.

The ductility of steel to fracture also decreases with a lowering of temperature, demonstrated by a measure of lateral contraction and angle of bend at maximum load for each notch bend specimen.[5]

Limitations of Theoretical Considerations

No correlation between sensitivity to brittle fracture and principal stress has been developed as it is difficult to provide a means of controlling the ratio of maximum shear stress to maximum tensile stress. No standard test can fully relate strain rate to brittle behaviour since strain rate depends on loading conditions, temperature and specimen geometry.[6] Consequently, all that remains is the correlation of notch toughness and service performance by means of tests in which there is some control over the ductility of the steel.

---

[4] J. H. Gross, Comparison of Charpy V-Notch and Drop-Weight Tests for Structural Steels, Welding Journal, 39 (2), Research Suppl., 59-s to 66-s, 1960.

[5] Parker, Op. Cit., pp. 120-122.

[6] Ibid., p. 11.

CHAPTER IV

LABORATORY PROCEDURE

This investigation was performed in two sections. One section dealt with the performance of standard tests and the other section dealt with the performance of large tension tests.

All specimens were constructed from rolled bar 8 inches x 1/2 x 20 feet. The material in this bar conformed to specification ASTM A7-61T.[1] The bar was manufactured by the Algoma Steel Corporation, Limited, Sault Ste. Marie, Ontario, and had a heat number 32651. They were hot rolled mild steel bars of merchant quality.

I. STANDARD TESTS

Construction of Test Specimens

The Charpy impact specimens, shown in Figure 1, page 14, were manufactured according to ASTM E-60.[2] Twenty-seven specimens were cut parallel to the grain and the same number were cut perpendicular to the grain. The notch was machined in a direction perpendicular to the face of the bar. Special care was exercised in machining the specimens to the specified

---

[1] ASTM Standards 1961, Part 1, Ferrous Metals Specifications, A7-61T, p. 544.

[2] ASTM Standards 1961, Part 3, Metals Test Methods, E23-60, p. 79.

tolerances.

The tension specimens, shown in Figure 2, were manufactured according to ASTM E8-61T[3] except for a change from an 8 inch to a 2 inch gauge length. All specimens were cut parallel to the grain.

The notch bend specimen, shown in Figure 3 was constructed to conform to the Kinzel type.[4] Ten specimens were cut parallel to the grain and ten specimens were cut perpendicular to the grain. In each group of ten specimens five were welded and five were unwelded. The weld bead was placed with a 3/16 inch diameter E6010 electrode at a rate of 6 inches per minute, a current of 180 amperes and a voltage of 30 volts. A standard Charpy notch was placed transversely across the specimen and through the weld, having the standard notch depth in the base metal.

Test Equipment

The machine used for the Charpy impact test was the Olsen Impact Testing Machine shown in Figure 4, page 16. This machine has a Charpy test capacity of 264 foot pounds at a striking velocity of 16.5 feet per second. The coolant

---

[3]ASTM Standards 1961, Part 1, Ferrous Metals Specifications, E8-61T, p. 165.

[4]Robert D. Stout and W. D'Orville Doty, Weldability of Steels (New York: Welding Research Council, 1953), p. 247.

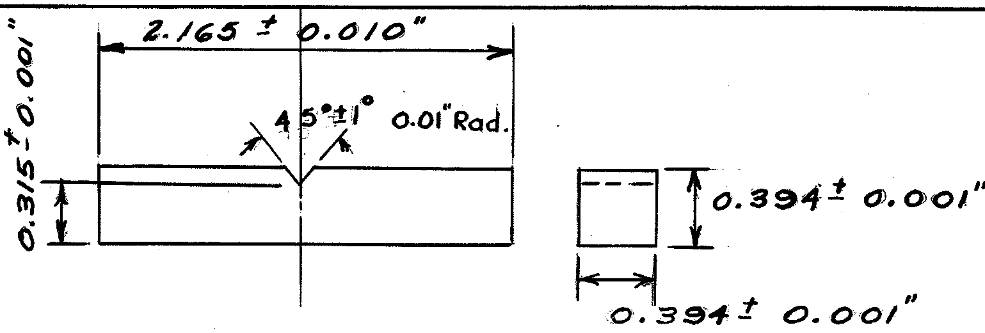


Figure 1. Details of a V-notched Charpy impact specimen.

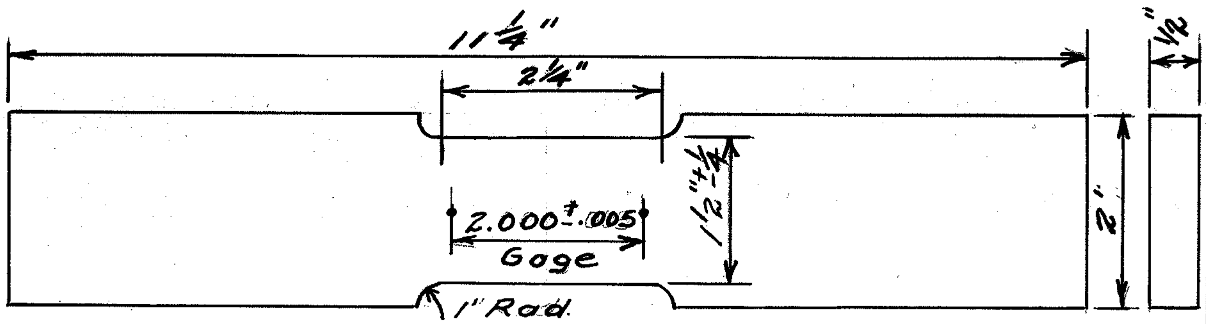


Figure 2. Details of a standard tension specimen.

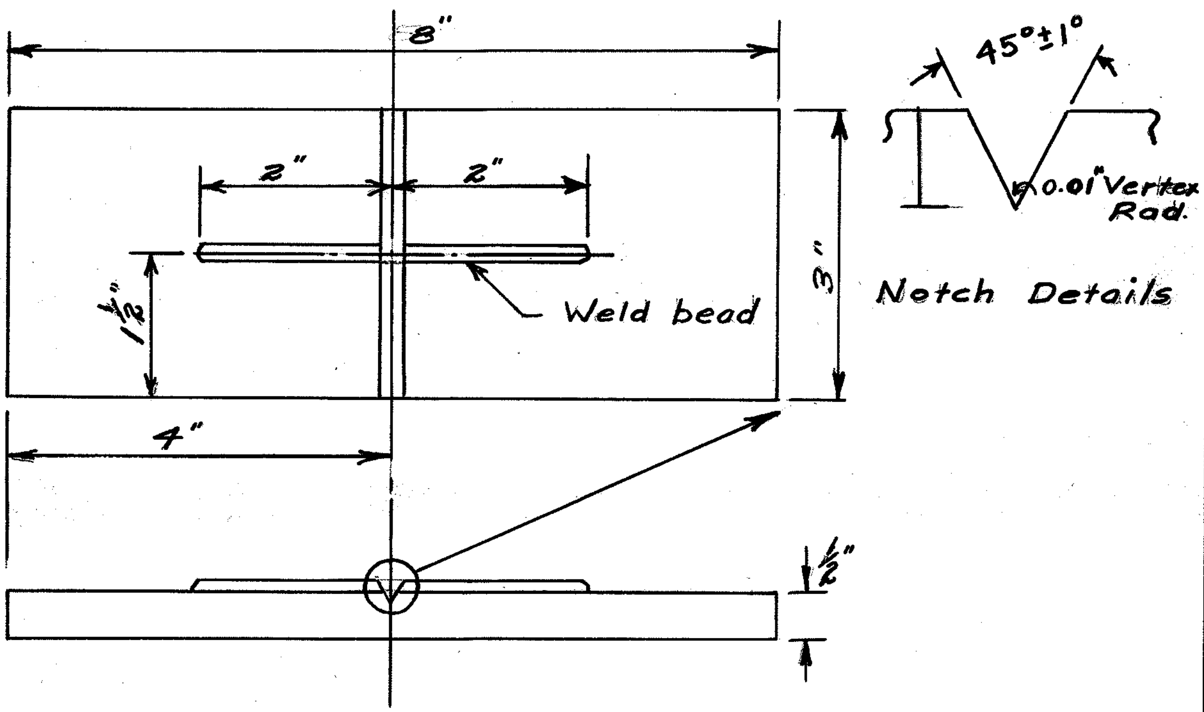


Figure 3. Details of a Kinzel notch bend specimen.

used was a mixture of acetone and solidified carbon dioxide. A Fahrenheit thermometer with a range of +60°F to -110°F was used for the temperature measurements.

The machine used for the standard tension test was the Riehle 60,000 Pound Precision Hydraulic Universal Testing Machine shown in Figure 5. On three specimens A, B, and D, SR-4 type A-4 strain gauges were used and one specimen C, the SR-4 type PA-3 post-yield strain gauge was used together with post-yield cement. Strain measurements were made using the SR-4 type N portable strain recorder.

The apparatus used to perform the standard notch bend test is shown in Figure 6, page 17. The machine used to supply the load was the Baldwin 30,000 Pound PTE Testing Machine. The coolant used was a mixture of acetone and solidified carbon dioxide. Temperature measurements were made using a Fahrenheit thermometer calibrated from +60° to -110°F.

Test Procedure

All the Charpy impact specimens were placed in the anvil shown in Figure 4, with the notch in tension. They were tested at temperatures ranging from +70° to -108°F. In all cases the testing procedure followed standard ASTM E23-60 procedure. Attempts were made to investigate the temperatures at the 10 foot pound and 15 foot pound energy values by decreasing the temperature increment in that region.

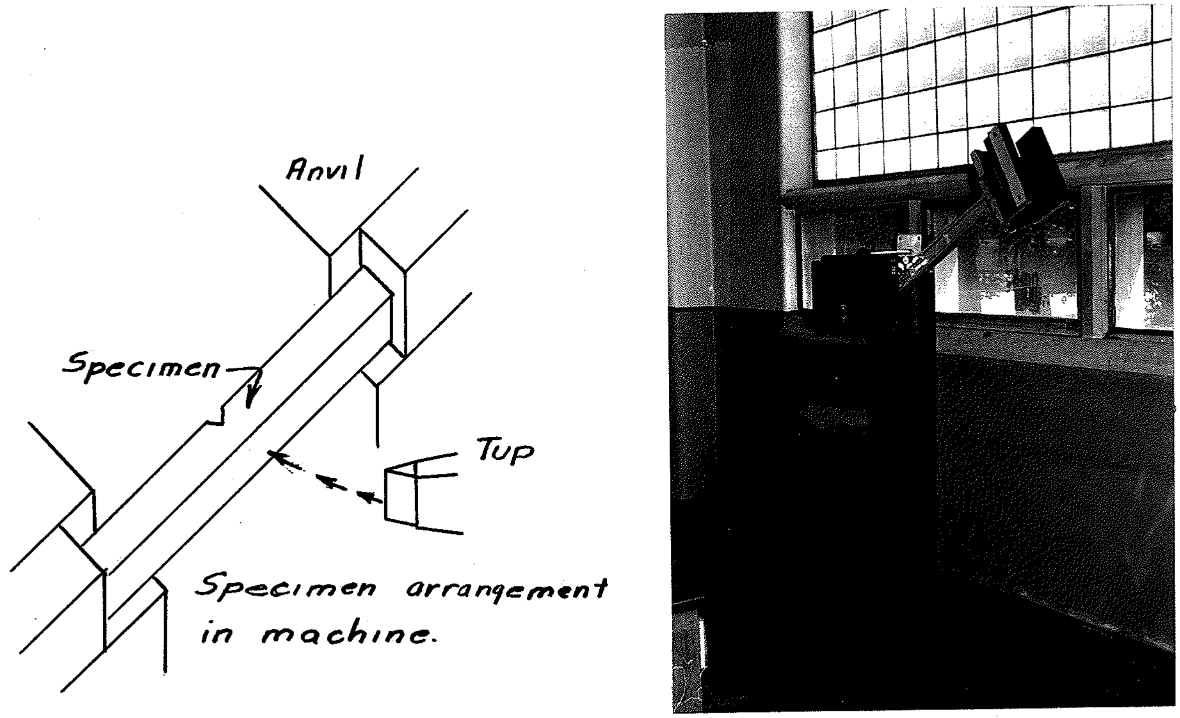


Figure 4. The Olsen Impact Testing Machine used for the Charpy impact test

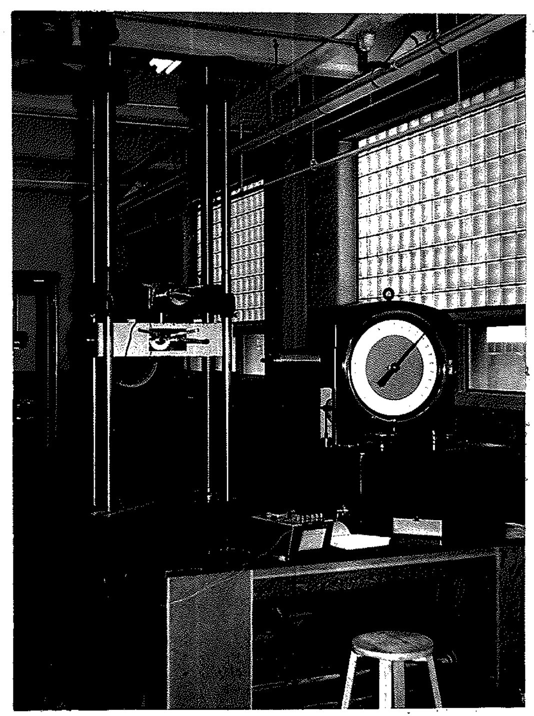
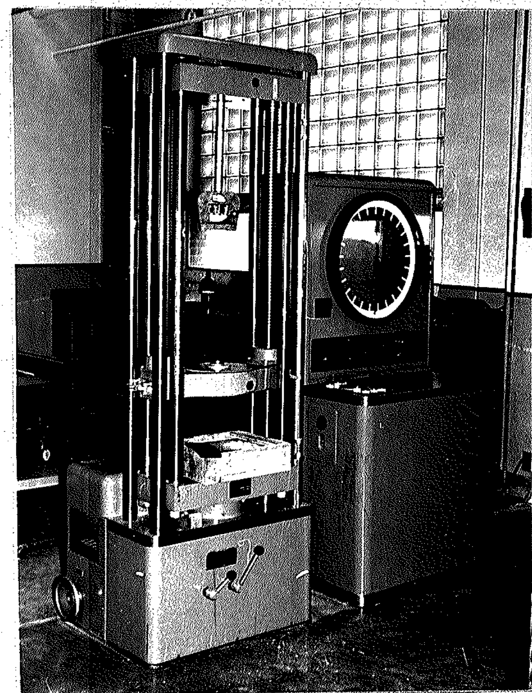
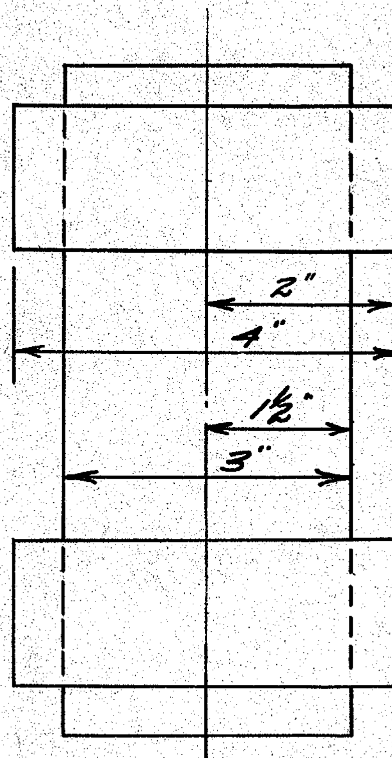


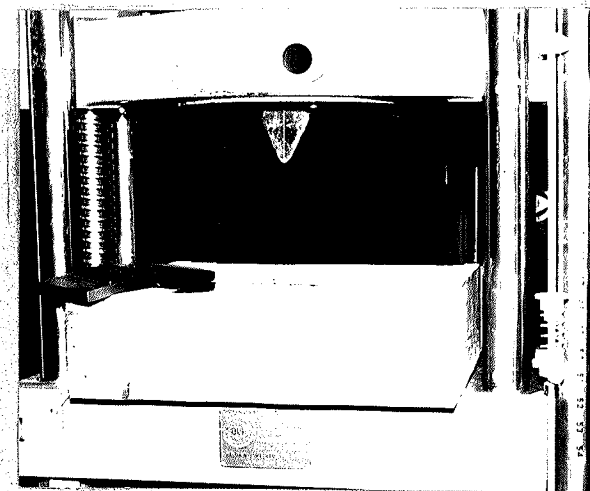
Figure 5. The Riehle 60,000 Pound Testing Machine used for the standard tension test.



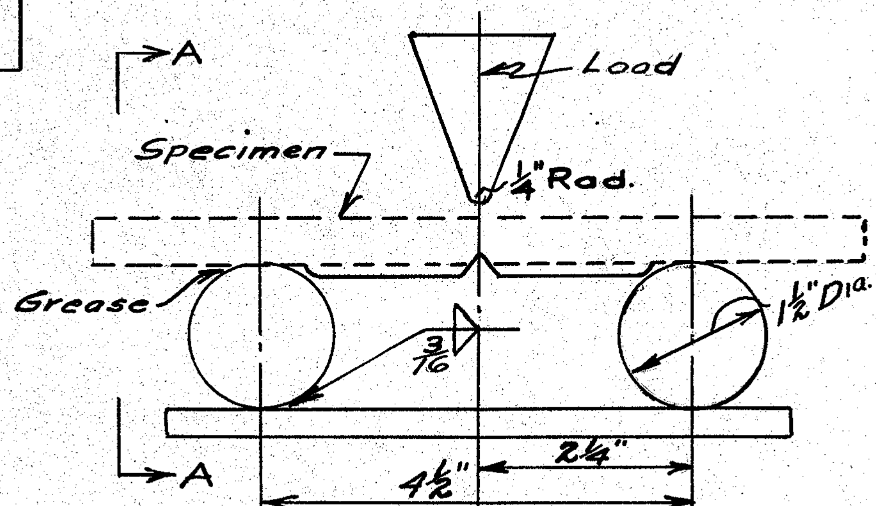
30,000 Pound Testing Machine



Section A-A



Apparatus with insulating box



Loading arrangement

Figure 6. Apparatus used to perform the Kinzel notch bend test.

The standard tension test was performed at room temperature of +70°F. Strain readings were performed at load increments of 1000 pounds. This rate of loading, to allow for the taking of strain readings, was approximately 4000 pounds per minute. The yield and ultimate strengths were recorded.

In the notch bend test the specimen was placed on the rollers, as shown in Figure 6, and the load was applied to the side opposite the weld so that the weld bead was in tension. The test was performed at temperatures of -80°F, -60°F, -30°F, 0°F, and +20°F. Each specimen was allowed to cool for 10 minutes before testing. The temperature was measured by holding the thermometer near the face of the specimen which contained the weld and which was submerged. The load was applied at a steady rate of approximately 40,000 pounds per minute and was rapidly released when ultimate load was reached.

From the standard tests performed, as described above, the temperature variation of notch toughness, ductility and weldability properties of steel, have been determined.

II. LARGE TENSION TESTS

Construction of Test Specimens

All specimens were 8 inches wide, 1/2 inch thick and 20 inches long with bars welded on the end to provide a grip to enable pulling in tension. The dimensions of these specimens were such that the width was sixteen times the thickness to ensure plate effect within the capacity of the machine. The length of the specimen was made two and one-half times the width to remove end effects from the notch.[5] The notch shown in Figure 7 was used in all the large tension specimens.

The type I series shown in Figure 8, contained no pre-strain and was tested after the notch was inserted.

The type II series was similar to the Type I series, except that approximately 2 per cent tensile prestrain was given to the specimen before the notch was inserted.

In the type III series shown in Figure 9, page 21, the notch was cut in a 5 inch strip removed centrally from the specimen. The length was made 5 inches so that the length-thickness ratio was 10 making it behave as a short column thus preventing buckling as it was compressed. The edges of this strip were bevelled with a double V bevel to make it easier to compress and to ensure a satisfactory weld. After the specimen was compressed in special apparatus shown in Figure 11, page 22, approximately 1.5 per cent, it was welded back into the specimen. The weld was made with a 3/16 inch diameter E6010 electrode at a current of 180 amperes and was

---

[5]ASTM Committee on Fracture Testing of High Strength Sheet Materials, <u>Fracture Testing of High-Strength Sheet Materials</u>, ASTM Bulletin, January 1960, No. 243, p. 29.

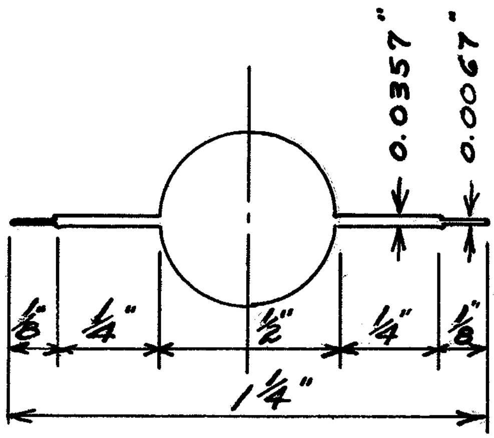
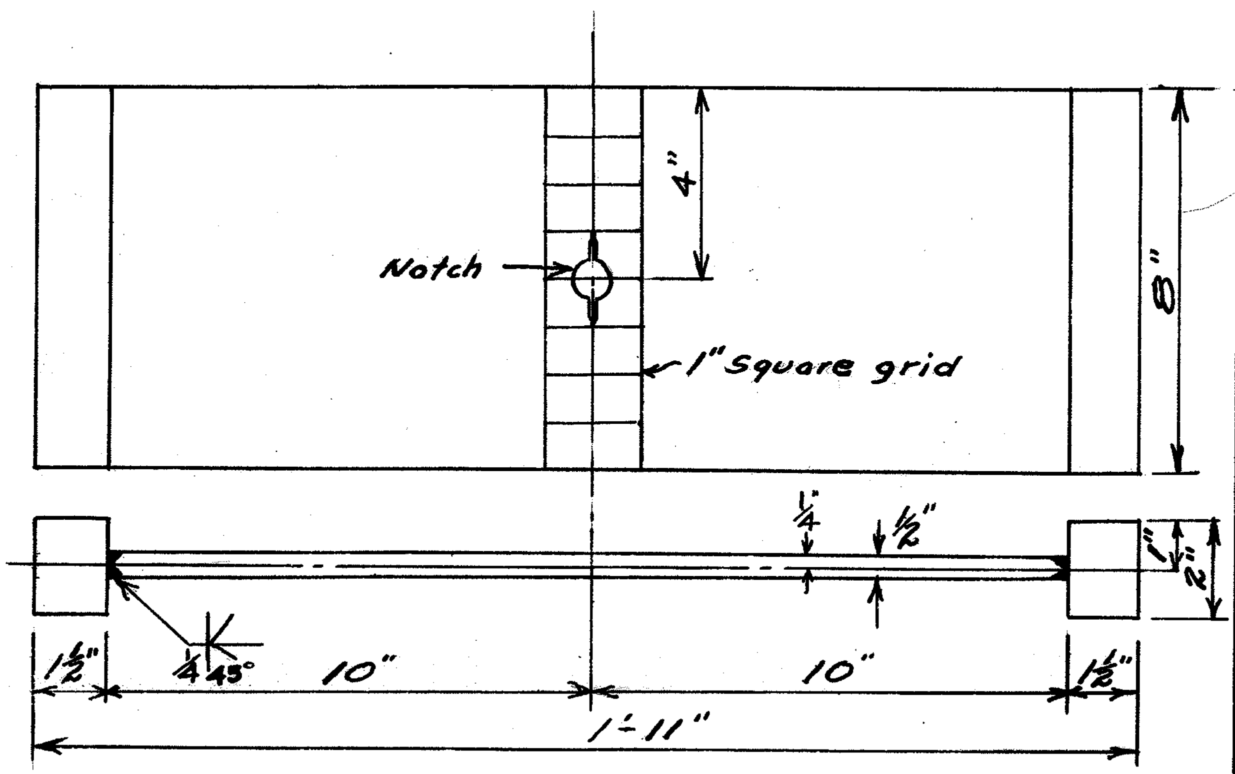
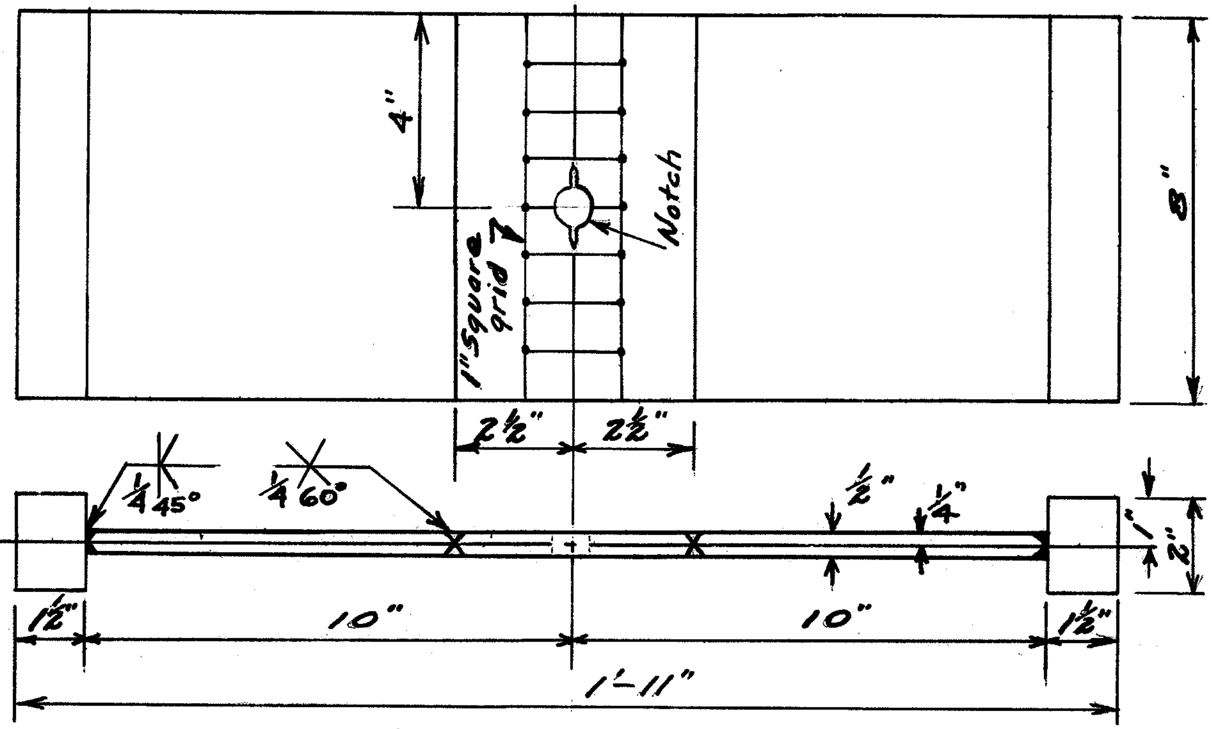


Figure 7. Standard notch details for large tension specimens



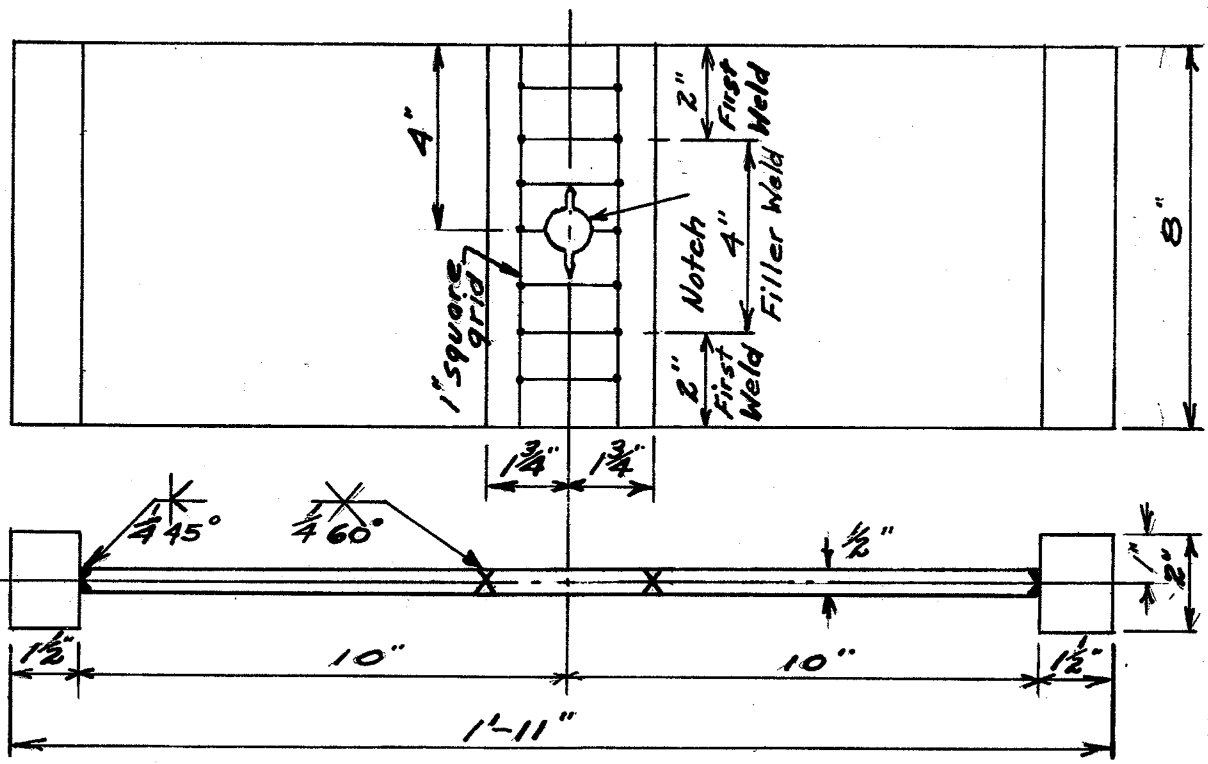
Type II specimen has notch inserted after prestraining

Figure 8. Details for types I and II tension specimens



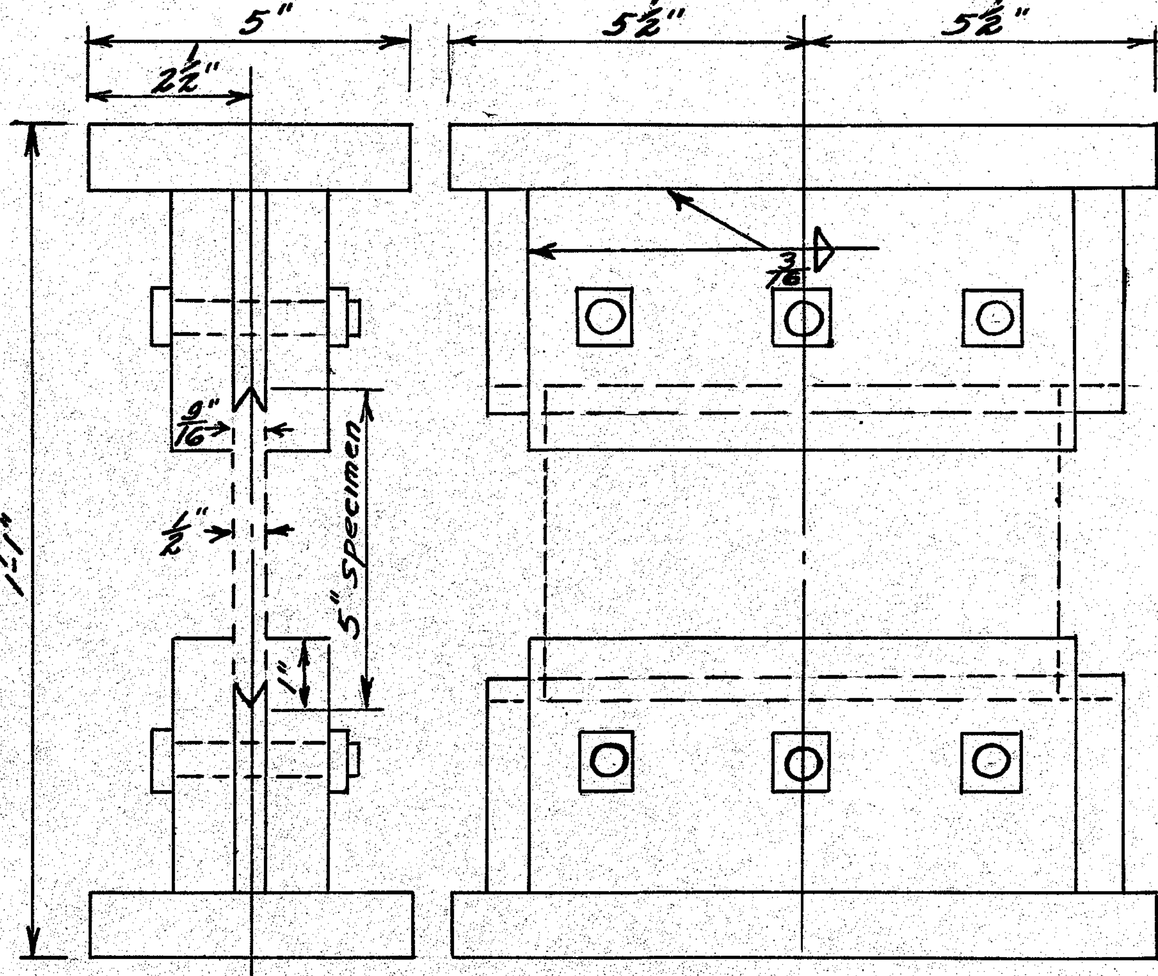
Type III specimen has notch inserted after plate was compressed

Figure 9. Details of types III and IV tension specimens.

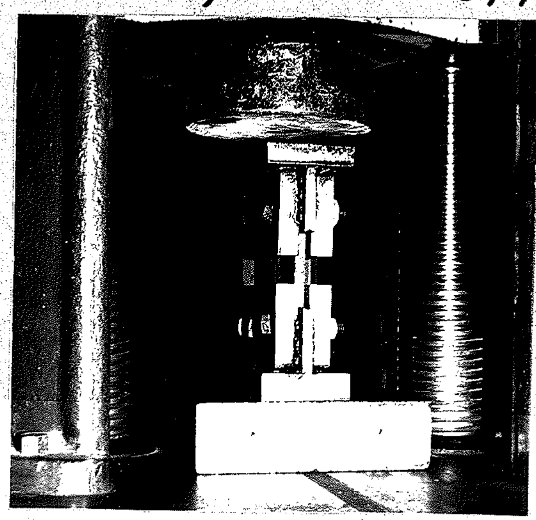


Special welding procedure showed by first and filler welds.

Figure 10. Details of type V tension specimens.



Test arrangement of apparatus



Apparatus in testing machine

Figure 11. Details of the compression apparatus for prestraining specimen types III and IV

laid by means of a single pass and a weave pass. Wet cloths were placed against the weld to protect the strain gauges from the heat generated during welding.

The construction of the type IV specimen was similar to that used for the type III specimen except that the notch was inserted in the central strip after it was compressed.

In the type V series a 3.5 inch strip was removed from the centre of the specimen and welded back, shown in Figure 10, page 21. The 3.5 inches was selected because research has shown that maximum residual stresses occur from 1 to 2 inches from the weld.[6] The 3.5 inches was also used because a preliminary test showed that this was the closest the weld could come to the strain gauges without harming them. During the welding procedure wet cloths were placed adjacent to the weld to protect the strain gauges. The welding procedure consisted of a light pass across the specimen followed by a 2 inch weave pass coming inward from each edge of the specimen. The specimen was cooled and then the remaining 4 inches was welded with the same type of weave pass. All welding was done with 3/16 inch diameter E6010 electrode at a current of 180 amperes.

Instrumentation

The instrumentation shown in Figure 12, remained

---

[6]N. R. Nagaraja Rao and Lambert Tall, Residual Stresses in Welded Plates, The Welding Journal, 40 (10) Research Supplement, 468-s to 480-s (1961).

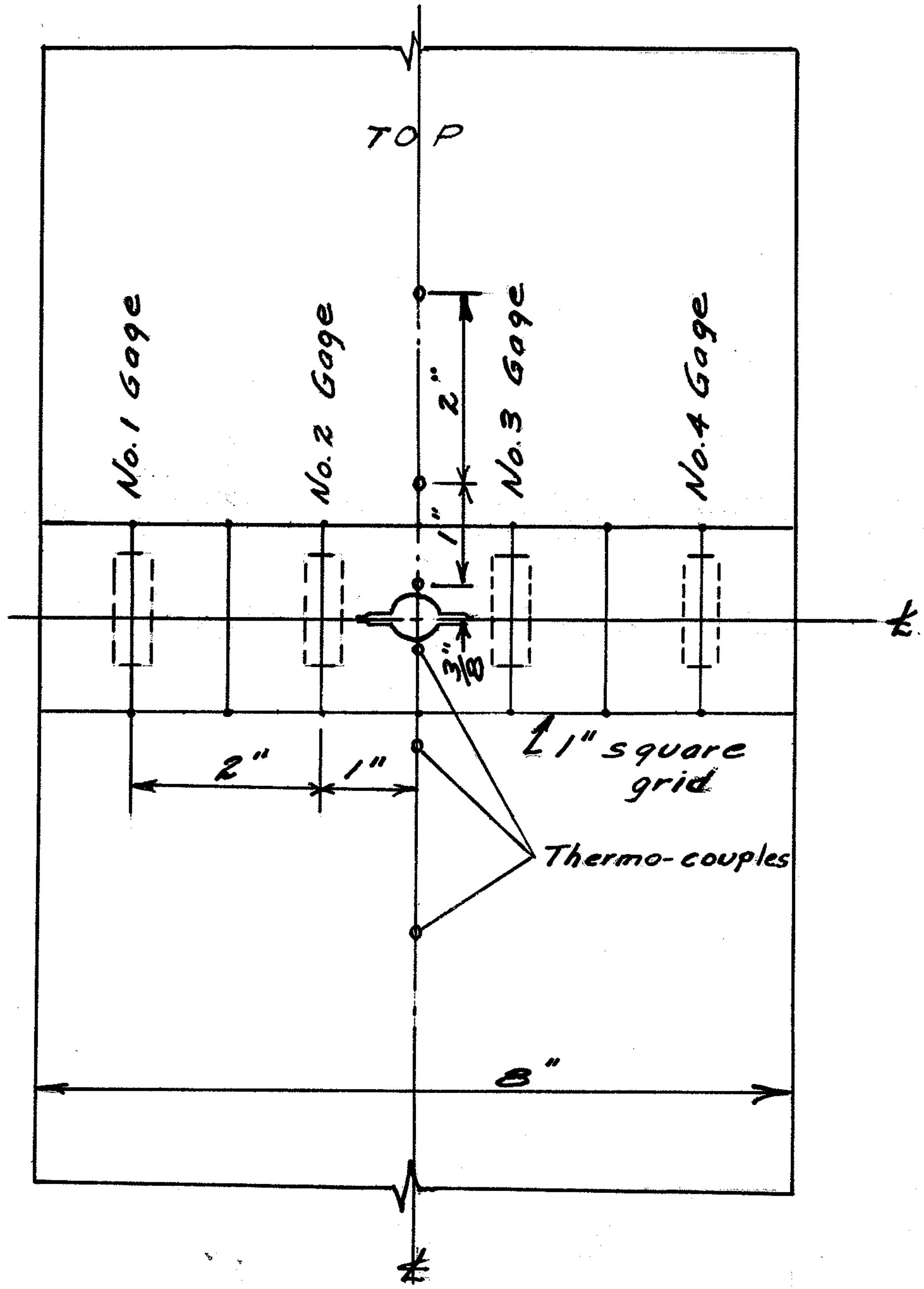


Figure 12. Diagram showing strain gage and thermo-couple layout for large tension specimens.

identical for each type series tested. The SR-4 type PA-3 post-yield strain gauges were attached to the specimen by means of post-yield cement. Short leads were soldered to each gauge and then a water-proofing compound consisting of Epoxylite 222 was placed over the gauge and leads. This water-proofing compound was cured by placing the specimen 18 inches below a bank of heat lamps. The dummy gauge was attached to the same material type as the specimen. All strain readings were recorded by means of the SR-4 type N portable strain recorder.

For measurement of residual strain due to welding in the type V series, SR-4 type A-7 strain gauges were attached to the specimens in the same manner used for the PA-3 type.

Thermo-couples, used for temperature measurement, were constructed from 24 gauge copper and constantan wire, and were oriented on the specimen as shown in Figure 12. A compound called Thermon, was used to set the thermo-couples into the specimen. This compound has the same thermal conductivity as steel. The temperature readings were recorded automatically by the Speedomax type 6 recording instrument. The reference temperature was $+32^{\circ}F$ provided by means of a mixture of ice and water.

Test Equipment

The Riehle 200,000 Pound Screw-Type Testing Machine was used for the large tension tests.

The grips, used to attach the specimens to the heads of the machine, were fabricated from A7 steel and were of welded construction throughout. Fabrication details are shown in Figure 13. Attention is drawn to the bearing surfaces at the pin connection which were machined to allow for swing in two directions to insure that no eccentricity would result in the loading.

The coolant used consisted of gasoline and solidified carbon dioxide for the $0^{o}F$ tests and acetone and solidified carbon dioxide for the $-30^{o}F$ tests. The cooling chamber was constructed of wood and is shown in Figure 14. Water, solidified due to the freezing action of the coolant, provided the sealant required.

Test Procedure

In each series of one type of specimen, one was tested at $+70^{o}F$, two at $0^{o}F$, and one at $-30^{o}F$. At $+70^{o}F$ the strain readings were recorded in load increments of 10,000 pounds. At $0^{o}F$ one specimen had strain recordings at 10,000 pound increments and one specimen at 50,000 pound increments. This was to study the effects of variation in strain rate at a constant temperature. The strain readings for the series at $-30^{o}F$ were taken in 20,000 pound increments. All specimens were loaded up to 150,000 pounds, and a comparison between each specimen was made. At loads causing yield of the

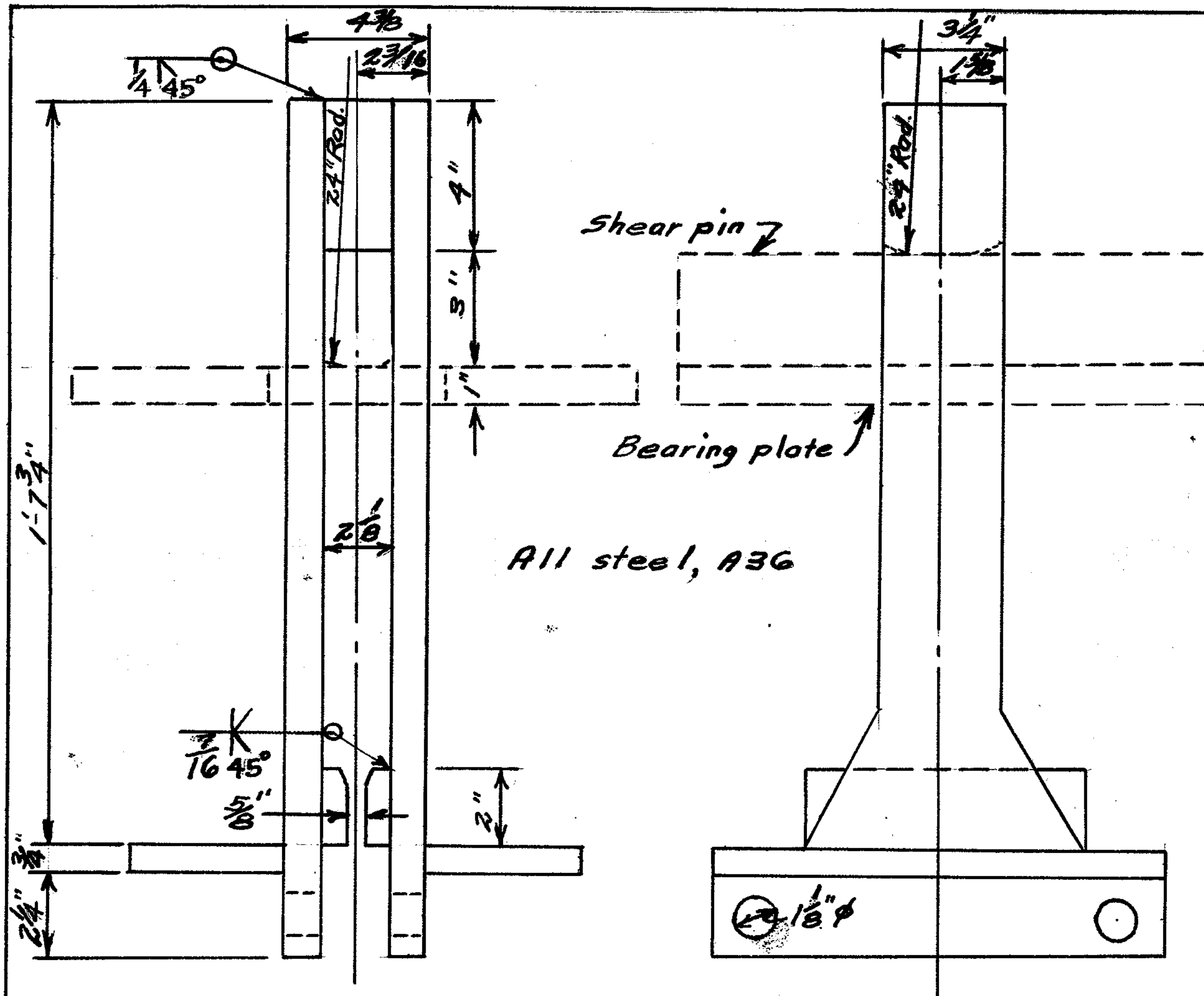
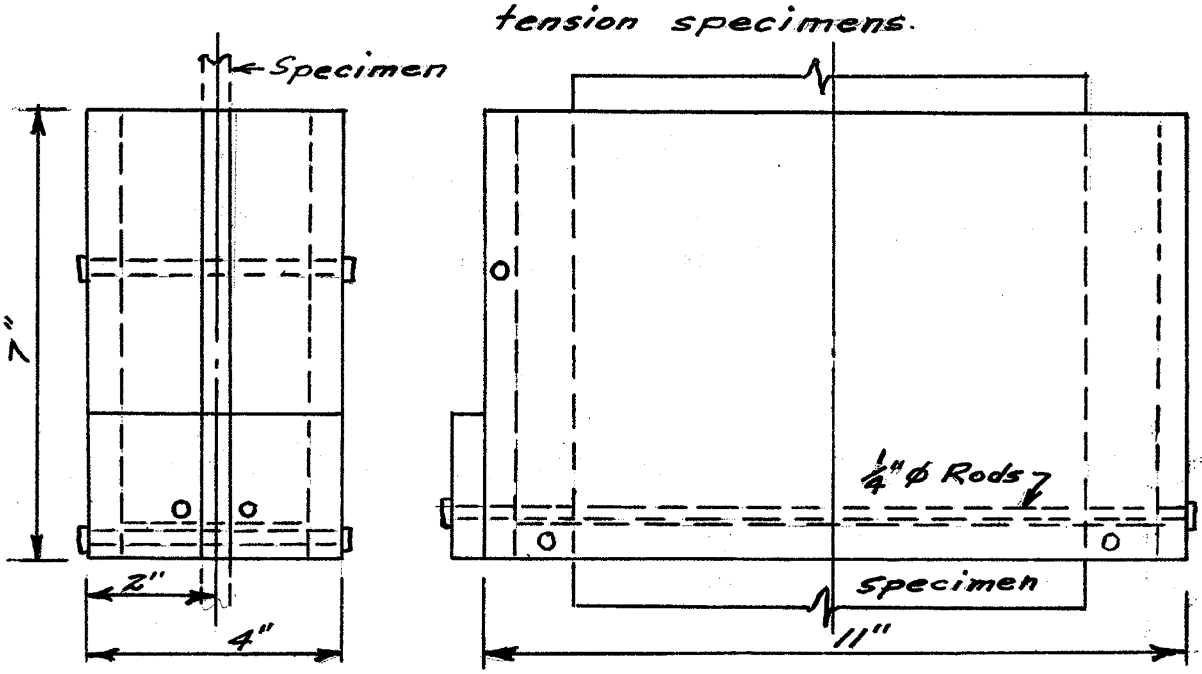


Figure 13. Details of grips used to pull large tension specimens.



All material ½" thick plywood

Figure 14. Details of cooling apparatus for cooling large tension specimens

specimen all strain readings were taken after the yield had ceased. An illustration of the testing procedure is given in Figure 15.

In specimen types III and IV the PA-3 strain gauges were used to measure compressive prestrain and were later used to measure strains due to the tensile loading of the specimen.

In specimen type V, the PA-3 strain gauges were attached to the specimen after the welding was completed. Residual stresses due to welding were recorded by the A-7 strain gauges.

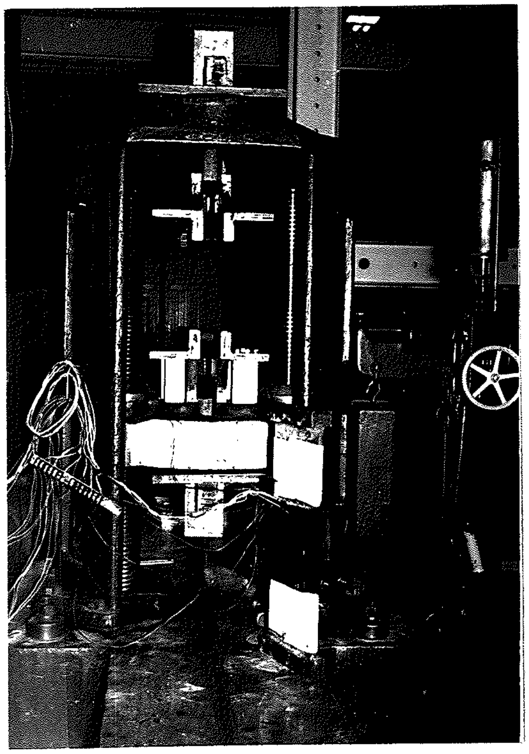
Any specimens not failing at 150,000 pounds were later loaded to the ultimate load at their respective temperatures with only the ultimate load recorded.

Suitability of Test Procedure

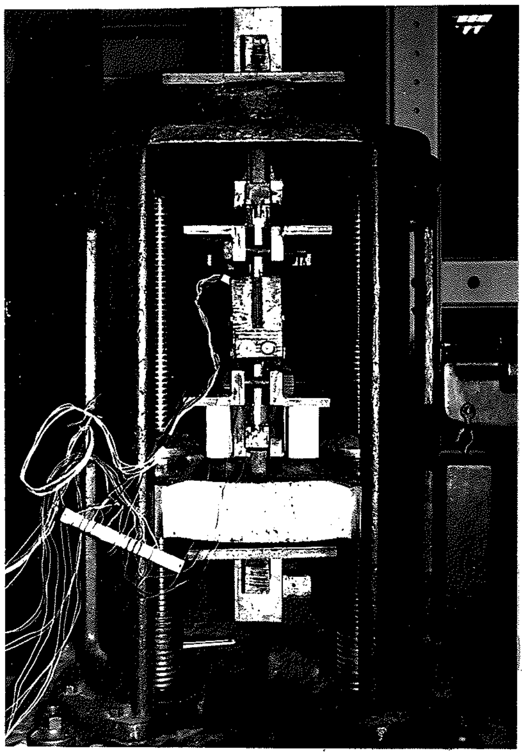
The purpose of this investigation was to achieve a comparison between a single notch effect and different methods of prestrain. Behaviour of the large tension specimens was to be predicted by standard tests. To achieve this goal the test procedures for both the standard and large tension tests were successful and the data recorded was useful.

However, some shortcomings in the apparatus used prevented more extensive data from being recorded.

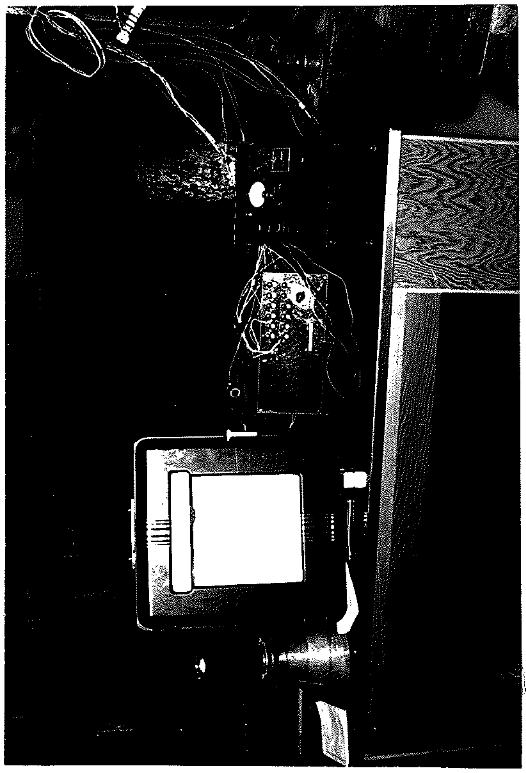
The size of the strain gauge prevented it from being placed closer than three-eighths of an inch from the notch



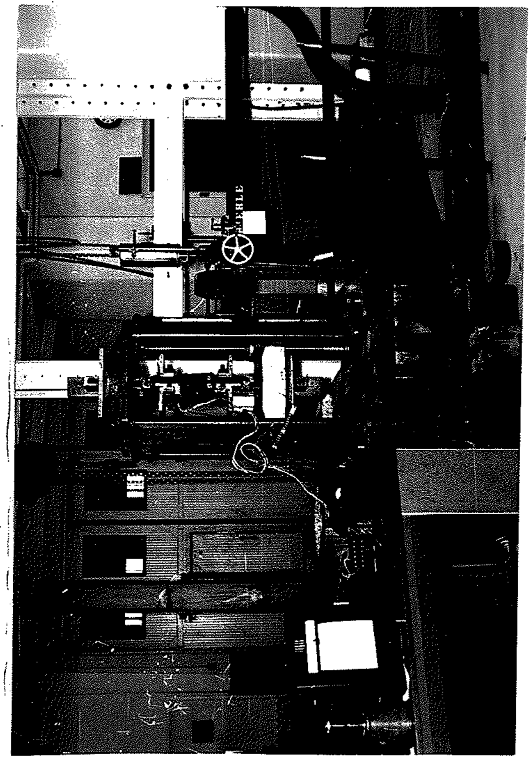
Cooling the specimen



Specimen in the testing machine



Instrumentation for test



Complete assembly for test

Figure 15. An illustration of the testing of a large tension specimen.

apex. This resulted in the failure to measure the high strains at the notch apex.

The water-proofing compound used at 0°F and -30°F did not yield with the gauge at the notch apex after excessive yield had taken place. This destroyed the gauge and also the readings that could have been taken into the plastic range of the steel.

CHAPTER V

RECORDED TEST DATA

Organization of Material

The test data recorded from this investigation consisted of strain gauge readings, impact values, per cent lateral contraction, angle of bend, and temperature readings.

The results from the standard tension tests are recorded in tabular form from which a graph was plotted. The Charpy impact test results and the Kinzel notch bend test are presented in their standard graphic form.

The results of the large scale tension tests are presented in tabular form to enable a comparison in ductility across the specimen to be made. The temperature readings are presented in graphic form to provide a clearer picture of the temperature gradient across the notch in the central portion of the specimen. Data for each series of one type are presented in a group in order that the temperature effect may be seen as the specimen is loaded. The photos taken of the notch area of each specimen were below or at 150,000 pounds depending whether brittle failure occurred below 150,000 pounds or whether the specimen remained intact at this load.

It is hoped that this method of material organization will give a clearer picture of the ductility transition in each series of tests.

Standard Tension Test

In Table I, A, B, and D represent the specimens tested with the SR-4 type A-7 strain gauges. Specimen C was tested with the SR-4 type PA-3 post-yield strain gauge together with its water-proof coating.

The load measurements were in pounds and the strain gauge readings in micro-inches per inches. The following terminology was used in Table I:

t = thickness of specimen in inches

w = width of specimen in inches

a = area of cross section of specimen in square inches

The stress strain curve, shown in Figure 16, page 34, was plotted to determine the modulus of elasticity of this type of steel.

Charpy Impact Test

The energy in foot pounds at each test temperature was recorded graphically in Figure 17, page 35, which is standard procedure for this test. From this graph the transition temperature for specimens cut parallel to the grain was compared to the transition temperature for specimens cut perpendicular to the grain.

TABLE I

STRAIN READINGS FOR STANDARD TENSION TESTS

Temperature +70°F

Specimen A, t = 0.4949 w = 1.4997 a = 0.742
Specimen B, t = 0.5020 w = 1.4955 a = 0.753
Specimen C, t = 0.4984 w = 1.4991 a = 0.748
Specimen D, t = 0.4944 w = 1.4954 a = 0.742

	Gauge Readings in Micro-Inches per Inch			
Load	A	B	C	D
1,000	0	0	0	0
2,000	55	50	50	50
3,000	105	100	90	100
4,000	150	150	130	150
5,000	190	200	175	200
6,000	235	250	210	250
7,000	275	295	255	300
8,000	315	335	300	345
9,000	360	385	340	390
10,000	405	435	390	440
11,000	450	480	430	490
12,000	495	520	480	540
13,000	545	570	520	580
14,000	595	615	570	630
15,000	640	660	620	670
16,000	690	710	660	720
17,000	730	755	710	770
18,000	775	795	760	815
19,000	820	845	800	860
20,000	865	890	860	905
21,000	910	940	920	950
22,000	925	985	980	1,000
23,000	970	1,040	1,030	1,055
24,000	1,015	1,090	1,080	1,110
25,000	1,060	1,135	1,140	1,150
26,000	1,095	1,165	1,180	1,205
27,000	1,125	1,200	1,230	1,250
27,700		Yield		
28,000				17,390
29,000				18,990
Ultimate Load	45,250	45,625	45,450	45,250

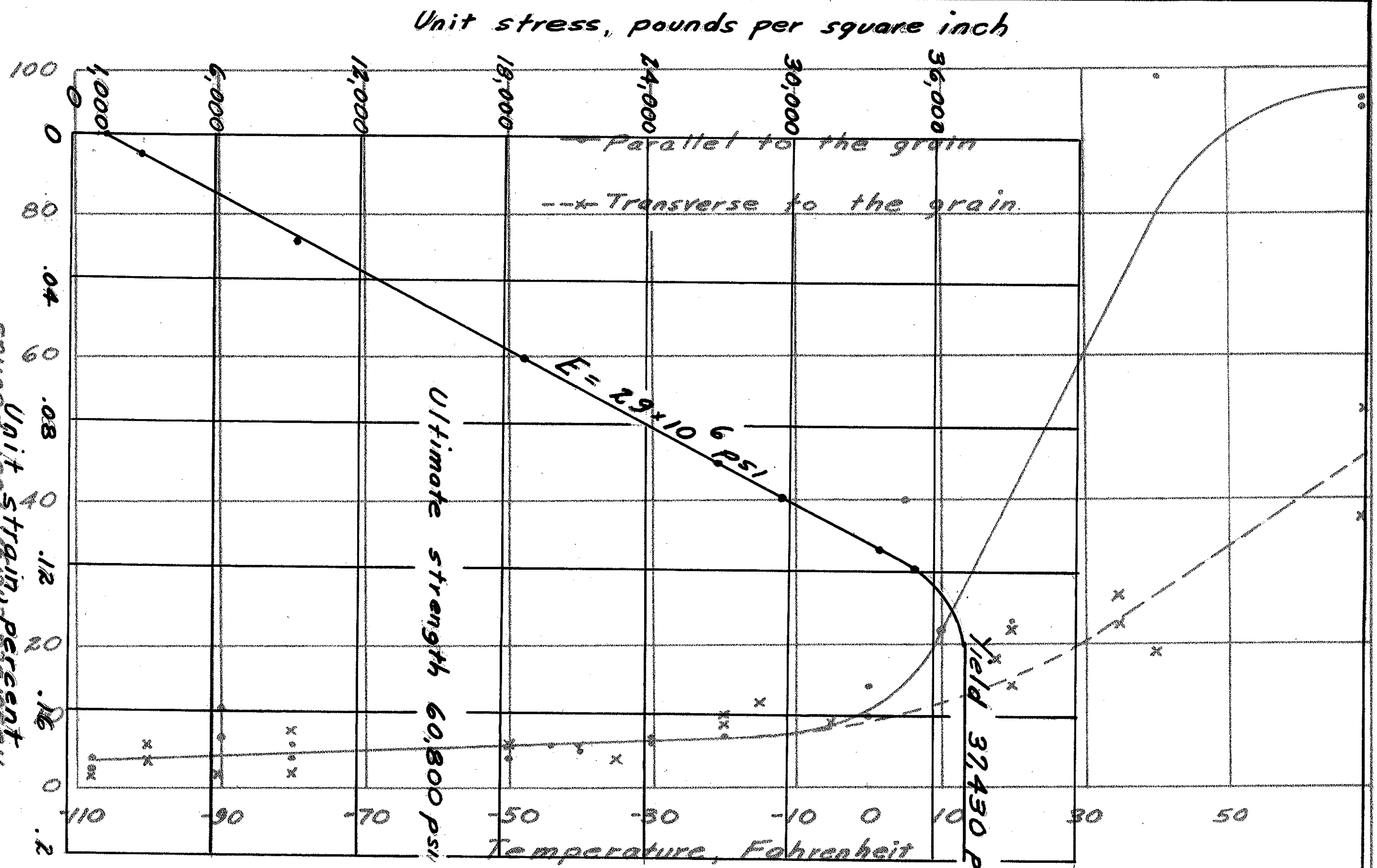


Figure 16. Stress-strain curve for A7 steel.

Figure 17. Standard V-notch Charpy impact data for A7 steel.

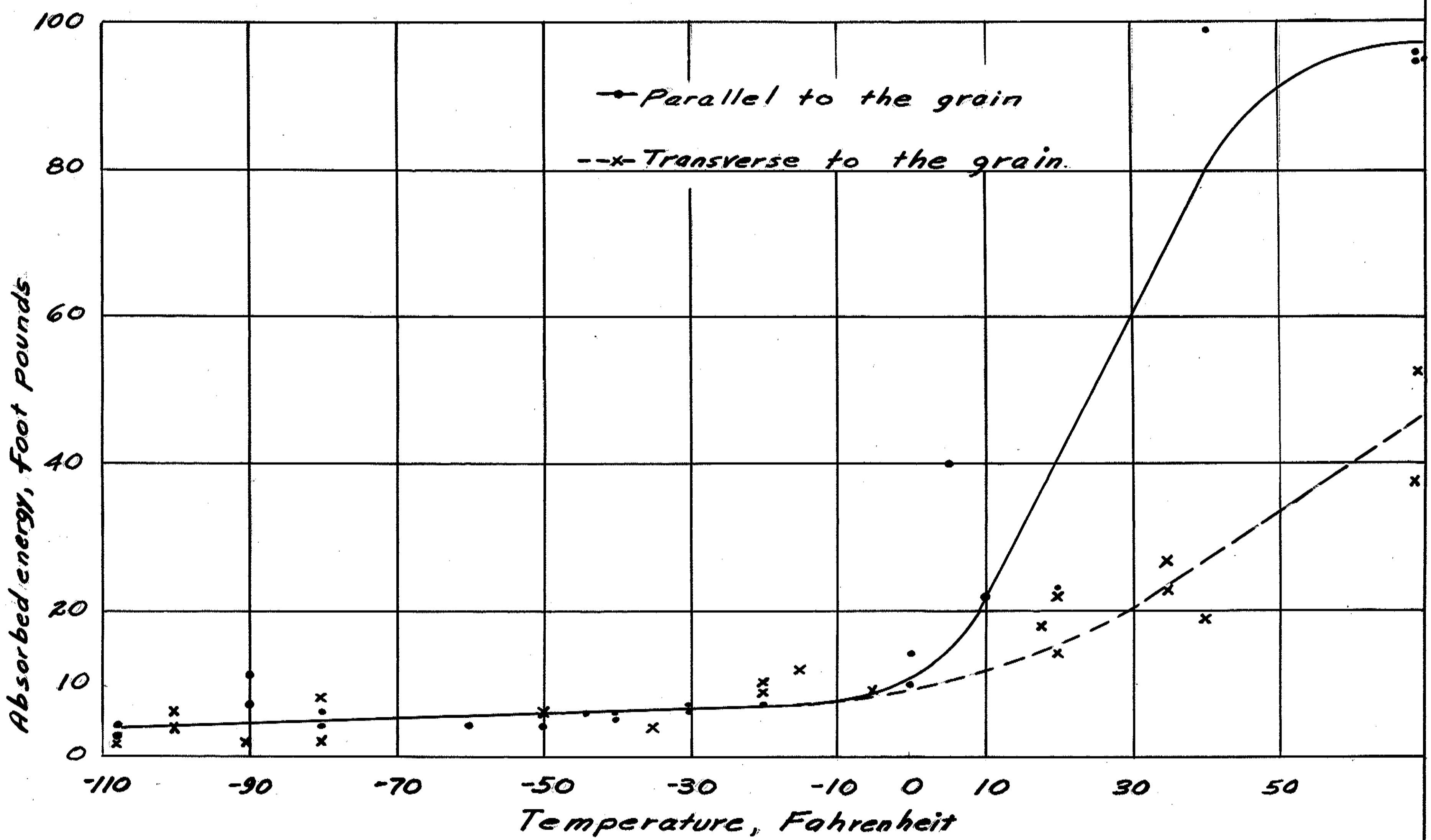


Figure 17. Standard V-notch Charpy impact data for A7 steel.

Kinzel Notch Bend Test

The test data for this test consisted of the per cent lateral contraction one thirty-second of an inch below the notch root and the angle of bend at maximum load. These were plotted against temperature in Figures 18 and 19. These graphs provided a comparison in transition temperature for welded and unwelded specimens cut parallel and perpendicular to the grain.

Change in Ductility with Temperature

In Figures 20 to 24 inclusive, pages 40, 45, 50, 55 and 60 respectively, the change in ductility with temperature is shown. All fractures shown occurred below the load of 150,000 pounds.

Gauge Readings

In Tables II to XXXVII inclusive, pages 41-44, 46-49, 51-54, 56-59, 61-64 respectively, for the large tension specimens, the load was measured in pounds and the gauge readings 1, 2, 3 and 4 were measured in micro-inches per inch. An initial load of 5000 pounds was used as zero gauge reading to insure that the loading apparatus was securely set in position. As yield of the specimen proceeded, the gauge readings were taken for a given load only when the yield had ceased. Some readings are marked "yield" as the strain readings were rapidly changing and could not be recorded.

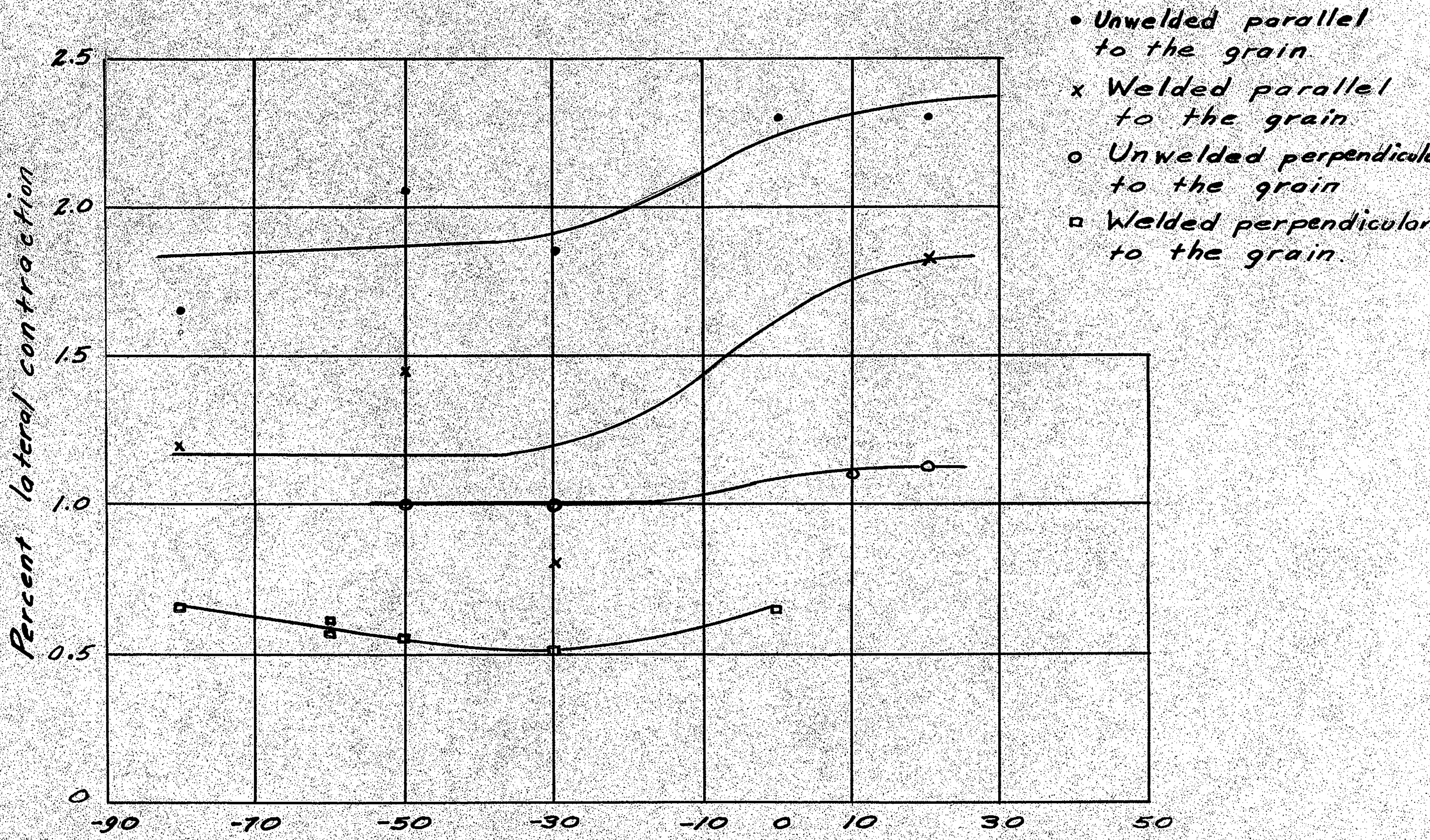


Figure 18. Kinzel notch bend test transition curves based on the lateral contraction at the root of the notch.

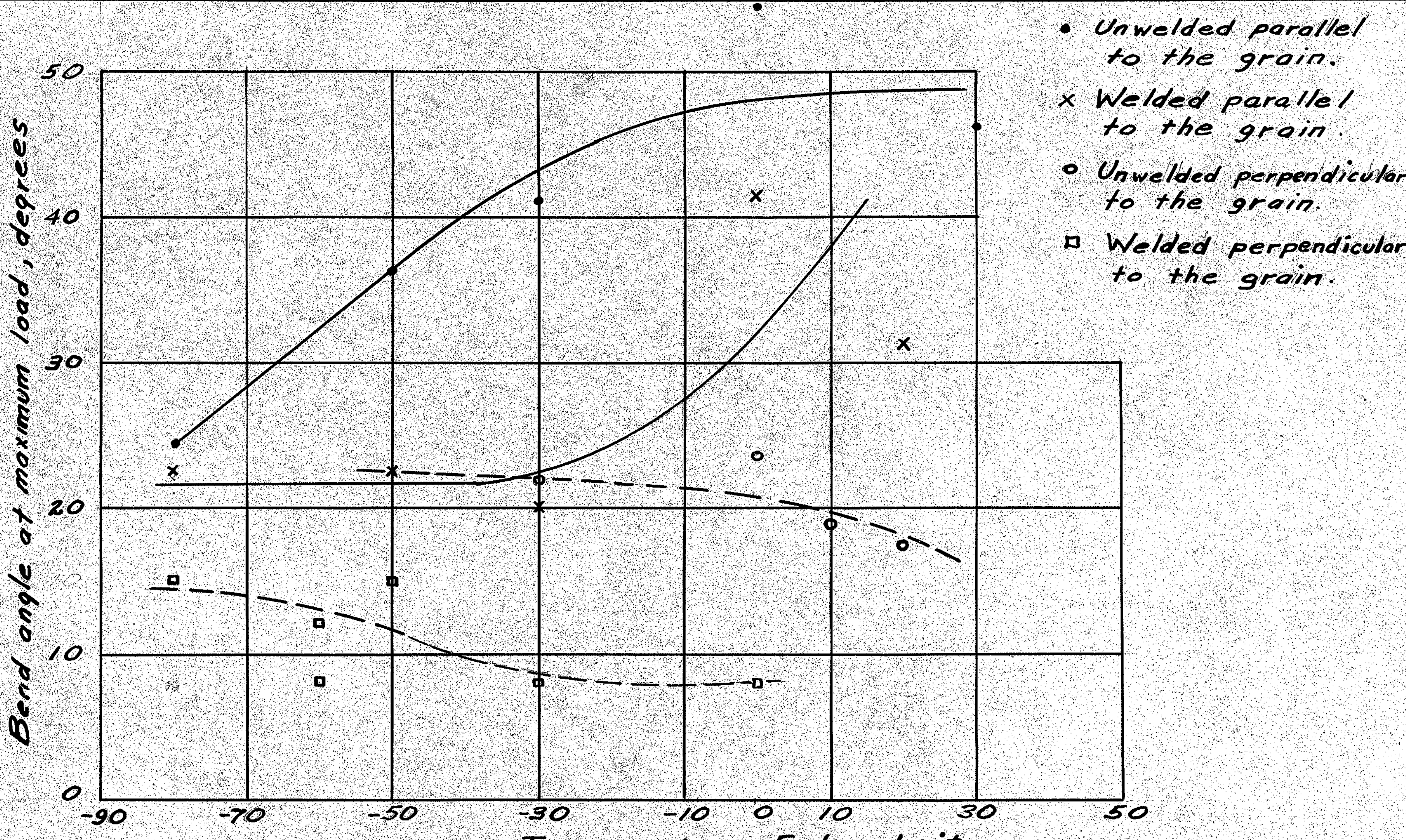


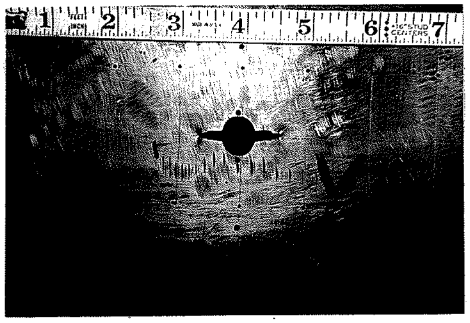
Figure 19. Kinzel notch bend test transition curves based on the angle of bend at maximum load.

The temperature indicated on the table was nominal as a slight temperature variation was experienced.

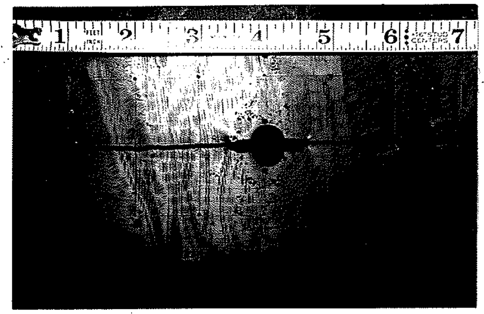
Temperature Readings

Temperature readings were recorded automatically in millivolts but are presented here in graphic form to show the temperature gradient experienced in the longitudinal direction from the notch. These graphs shown in Figure 25, page 65, show the type I specimens which are typical of the remaining types.

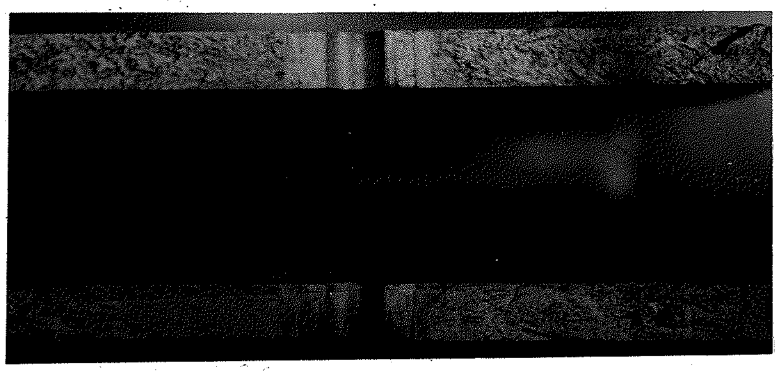
It is felt that this mode of presentation makes clearer the change in specimen ductility with temperature change and variation in type of prestrain.



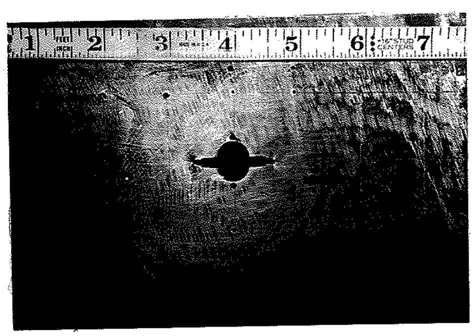
Specimen V_1 at +70°F



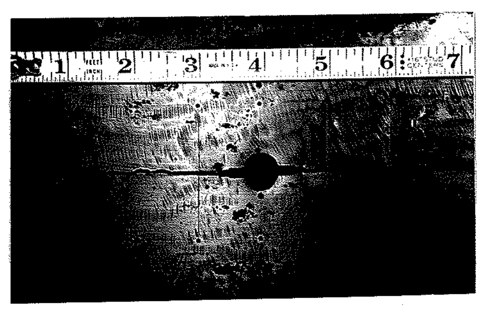
Specimen S_3 at 0°F



Typical cleavage pattern at 0°F and -30°F



Specimen T_5 at 0°F with increased strain rate.



Specimen U_3 at -30°F

Figure 20. An illustration of the change in ductility of a notched tension specimen with temperature changes, for the specimens with no prestrain loaded to 150,000 pounds.

TABLE II

STRAIN READINGS FOR TENSION TEST WITH NO PRESTRAIN

Specimen V | Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	10	20	20	30
20,000	30	60	60	90
30,000	80	160	160	190
40,000	160	270	290	300
50,000	250	405	390	415
60,000	340	540	470	530
70,000	450	600	670	660
80,000	560	760	870	790
90,000	695	1,005	1,135	940
100,000	835	1,250	1,400	1,090
110,000	970	1,710	2,270	1,300
120,000	2,700	10,130	11,000	8,390
130,000		Yield		
140,000	13,230	22,480	-	11,030
150,000	20,360	34,080	-	11,800

TABLE III

STRAIN READINGS FOR TENSION TEST WITH NO PRESTRAIN

Specimen S Temperature 0°F

	Gauge Readings in Micro-Inches per Inch			
Load	1	2	3	4
5,000	0	0	0	0
10,000	20	20	10	25
20,000	80	90	100	75
30,000	150	170	160	115
40,000	210	240	210	135
50,000	270	335	295	195
60,000	360	440	500	275
70,000	435	530	590	315
80,000	520	650	680	385
90,000	600	820	830	460
100,000	675	1,000	970	515
110,000	780	1,340	1,180	590
120,000	1,160	2,500	1,900	625
130,000	7,990	-	-	3,665
148,860	Specimen fractured			

TABLE IV

STRAIN READINGS FOR TENSION TEST WITH NO PRESTRAIN

Specimen T Temperature 0°F

Load	1	2	3	4
	Gauge Readings in Micro-Inches per Inch			
5,000	0	0	0	0
50,000	620	785	770	630
100,000	1,220	1,455	1,110	1,140
150,000		Yield		

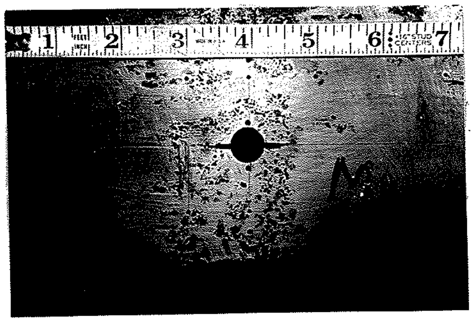
TABLE V

STRAIN READINGS FOR TENSION TEST WITH NO PRESTRAIN

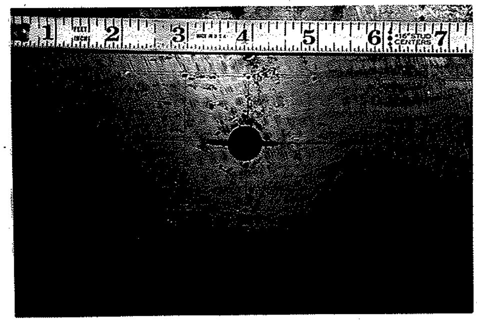
Specimen U Temperature $-30^{\circ}F$

Gauge Readings in Micro-Inches per Inch

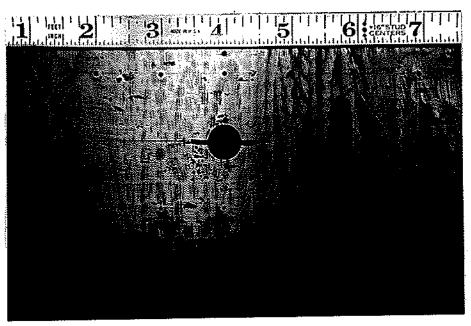
Load	1	2	3	4
5,000	0	0	0	0
20,000	15	30	30	30
40,000	65	170	130	190
60,000	225	380	260	340
80,000	445	680	520	550
100,000	655	1,080	860	830
120,000	965	1,860	1,420	1,070
140,000	4,925	Yield		
149,300		Specimen fractured		



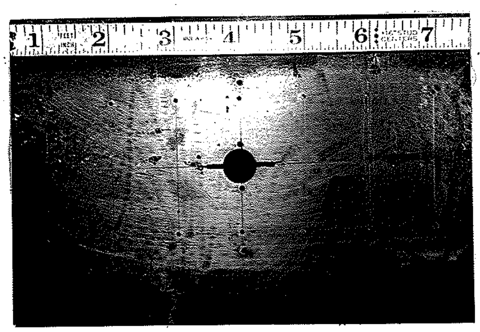
Specimen M, at +70°F



Specimen O, at 0°F



Specimen N, at 0°F with increased strain rate



Specimen E, at -30°F

Figure 21. An illustration of the change in ductility of a notched tension specimen with temperature changes, for the specimens with tensile prestrain loaded to 150,000 pounds.

TABLE VI

STRAIN READINGS FOR PRETENSION WITHOUT THE NOTCH PRESENT

Specimen M — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
20,000	75	75	75	90
40,000	175	170	175	210
60,000	380	375	405	440
80,000	640	615	625	690
100,000	930	885	915	990
120,000	1,240	1,165	1,155	1,280
140,000	1,520	1,460	1,510	1,510
145,000		Rapid yield		
Set	6,720	6,005	5,970	7,100

TABLE VII

STRAIN READINGS FOR TENSION TEST AFTER TENSILE PRESTRAIN

Specimen M — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	30	60	80	75
20,000	105	185	220	325
30,000	165	295	350	455
40,000	210	400	460	575
50,000	270	505	575	685
60,000	345	625	700	795
70,000	420	740	825	905
80,000	495	875	955	1,005
90,000	580	1,035	1,100	1,105
100,000	675	1,210	1,280	1,210
110,000	770	1,440	1,505	1,305
120,000	850	1,730	1,790	1,410
130,000	960	2,270	2,540	1,555
140,000	1,380	8,220	11,330	4,025
150,000		Yield		

TABLE VIII

STRAIN READINGS FOR PRETENSION WITHOUT THE NOTCH PRESENT

Specimen O — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
20,000	40	45	15	15
40,000	210	210	155	135
60,000	415	400	335	295
80,000	640	615	535	495
100,000	875	830	735	705
120,000	1,060	1,050	935	905
140,000	1,170	1,220	1,225	1,245
145,000		Yield		
Set	22,005	20,600	17,840	16,080

TABLE IX

STRAIN READINGS FOR TENSION TEST AFTER TENSILE PRESTRAIN

Specimen O — Temperature 0°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	110	130	145	125
20,000	240	290	325	280
30,000	305	395	460	305
40,000	385	475	570	405
50,000	455	570	685	500
60,000	535	630	800	590
70,000	605	735	925	690
80,000	680	840	1,070	790
90,000	765	940	1,210	860
100,000	840	1,060	1,425	950
110,000	925	1,200	1,665	1,020
120,000	1,050	1,405	1,970	1,180
130,000	1,145	1,690	2,525	1,235
140,000		Yield		
150,000		Yield		

TABLE X

STRAIN READINGS FOR PRETENSION WITHOUT THE NOTCH PRESENT

Specimen N — Temperature +70°F

Load	Gauge Readings in Micro-Inches per Inch 1	2	3	4
5,000	0	0	0	0
10,000	20	35	45	50
30,000	100	175	225	250
50,000	285	355	405	430
70,000	485	555	605	635
90,000	700	755	815	745
110,000	910	880	1,045	995
130,000	1,150	1,135	1,320	1,175
140,000	1,320	1,275	1,505	1,375
145,000		Yield		
Set	10,145	10,145	10,235	8,810

TABLE XI

STRAIN READINGS FOR TENSION TEST AFTER TENSILE PRESTRAIN

Specimen N — Temperature 0°F

Load	Gauge Readings in Micro-Inches per Inch 1	2	3	4
5,000	0	0	0	0
50,000	400	510	495	390
100,000	855	1,155	1,170	855
150,000	1,980	-	-	1,295

TABLE XII

STRAIN READINGS FOR PRETENSION WITHOUT THE NOTCH PRESENT

Specimen E Temperature +70°F

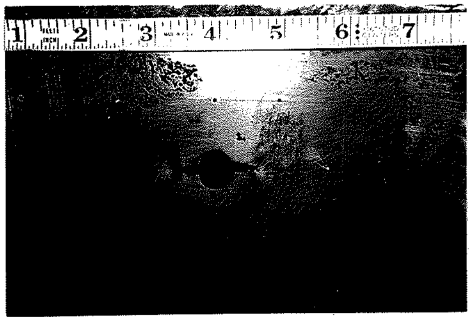
Load	Gauge Readings in Micro-Inches per Inch 1	2	3	4
5,000	0	0	-	0
10,000	105	90	-	80
30,000	425	375	-	290
50,000	675	590	-	450
70,000	975	850	-	620
90,000	1,205	1,060	-	845
110,000	1,375	1,240	-	1,055
130,000	1,395	1,360	-	1,250
140,000	1,495	1,520	-	1,450
145,000		Yield		
Set	18,090	15,120	-	15,090

TABLE XIII

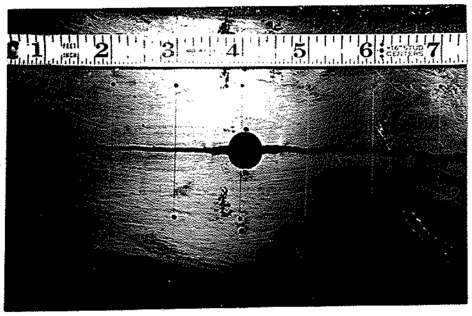
STRAIN READINGS FOR TENSION TEST AFTER TENSILE PRESTRAIN

Specimen E Temperature -30°F

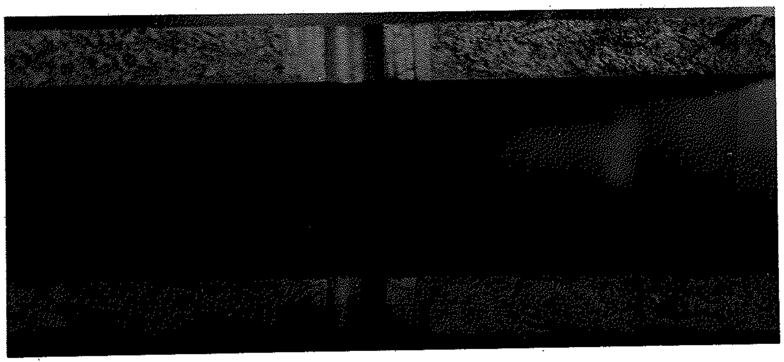
Load	Gauge Readings in Micro-Inches per Inch 1	2	3	4
5,000	0	0	-	0
20,000	180	265	-	315
40,000	290	460	-	520
60,000	415	670	-	680
80,000	530	880	-	880
100,000	665	1,180	-	1,045
120,000	830	1,650	-	1,150
140,000	1,010	2,600	-	1,390
150,000	1,450	3,230	-	1,960



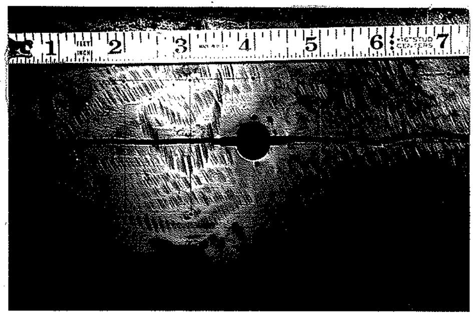
Specimen H, at +70°F



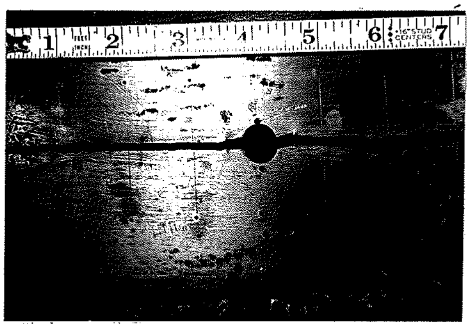
Specimen G, at 0°F



Typical cleavage fracture at 0°F and -30°F



Specimen R, at +0°F with increased strain rate.



Specimen F, at -30°F

Figure 22. An illustration of the change in ductility of a notched tension specimen with temperature changes, for the specimens pre-compressed with the notch present loaded to 150,000 pounds.

TABLE XIV

STRAIN READINGS FOR PRECOMPRESSION WITH THE NOTCH PRESENT

Specimen H | Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
20,000	150	95	114	180
40,000	310	225	284	365
60,000	460	395	454	545
80,000	600	605	664	705
100,000	740	1,055	1,224	865
120,000	955	5,640	5,609	1,230
140,000		Yield		
Set	9,555	15,770	18,030	7,700

TABLE XV

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen H | Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	30	15	15	25
20,000	90	90	100	100
30,000	155	195	200	175
40,000	235	340	335	255
50,000	330	565	560	370
60,000	440	855	910	550
70,000	640	1,335	1,410	730
80,000	820	1,895	2,040	955
90,000	1,020	2,635	2,810	1,195
100,000	1,240	3,525	3,950	1,535
110,000	1,600	4,985	5,430	1,865
120,000	2,080	7,805	8,230	2,445
130,000	4,110	14,665	14,480	3,705
140,000	8,900	21,095	19,610	8,755
150,000		Broke in weld		

TABLE XVI

STRAIN READINGS FOR PRECOMPRESSION WITH THE NOTCH PRESENT

Specimen G Temperature +70 °F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	80	15	20	135
30,000	305	65	130	405
50,000	470	270	310	585
70,000	600	510	530	695
90,000	710	795	805	795
110,000	815	1,485	1,540	865
140,000		Yield		
Set	6,060	13,700	11,175	4,340

TABLE XVII

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen G Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	15	5	15	10
20,000	50	10	50	40
30,000	145	150	125	70
40,000	240	290	200	100
50,000	420	510	380	160
60,000	600	830	560	220
70,000	940	945	840	330
80,000	1,480	1,060	1,120	440
90,000	1,950	2,005	1,280	685
100,000	2,420	2,950	2,440	930
110,000	2,980	4,460	3,550	1,540
120,000	4,210	6,760	5,100	2,150
130,000	6,510	-	-	3,000
140,810		Specimen fractured		

TABLE XVIII

STRAIN READINGS FOR PRECOMPRESSION WITH THE NOTCH PRESENT

Specimen R Temperature+70°F

Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	0
10,000	95	30	45	105
30,000	285	90	140	320
50,000	590	360	365	540
70,000	720	550	615	720
90,000	815	815	925	870
110,000	875	1,540	975	1,005
130,000	2,825	3,860	6,455	3,925
140,000		Yield		
Set	4,885	16,585	20,990	4,140

TABLE XIX

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen R Temperature 0°F

Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	0
50,000	770	975	885	610
100,000	1,050	3,640	3,225	2,300
145,360		Specimen broke		

TABLE XX

STRAIN READINGS FOR PRECOMPRESSION WITH THE NOTCH PRESENT

Specimen F Temperature +70 °F

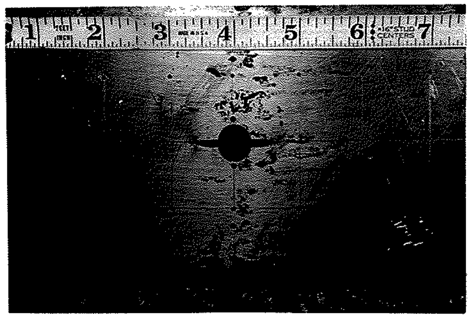
Load	Gauge Readings in Micro-Inches per Inch			
	1	2	3	4
5,000	0	0	0	0
10,000	100	25	25	115
30,000	300	75	80	350
50,000	450	225	245	495
70,000	585	455	485	600
90,000	695	725	790	705
110,000	790	1,425	1,885	780
130,000	3,270	-	-	1,750
145,000		Yield		
Set	7,380	20,775	22,775	6,050

TABLE XXI

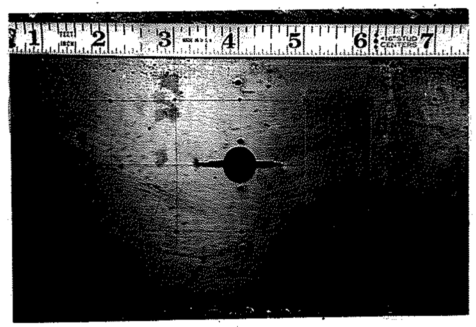
STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen F Temperature -30 °F

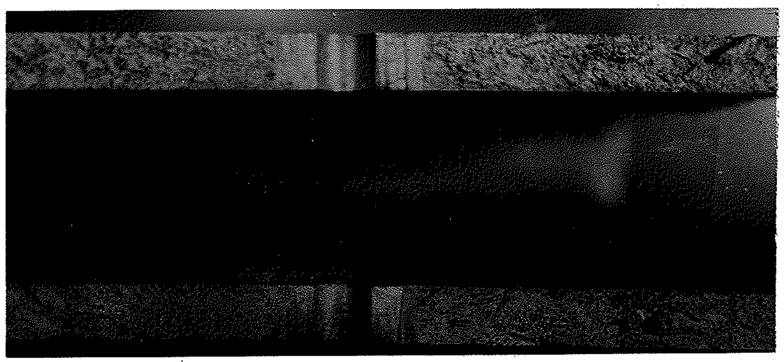
Load	Gauge Readings in Micro-Inches per Inch			
	1	2	3	4
5,000	0	0	0	0
20,000	10	30	80	70
40,000	50	90	200	170
60,000	60	220	370	190
80,000	140	490	820	320
100,000	170	1,120	3,300	1,310
120,000		Specimen fractured		



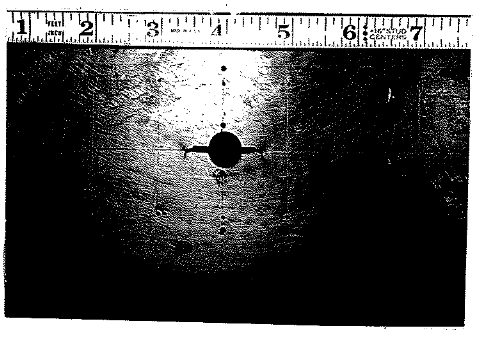
Specimen A, at +70°F



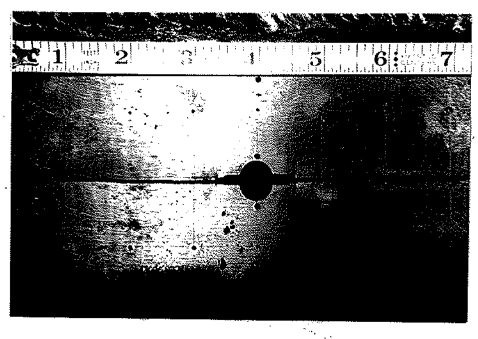
Specimen B, at 0°F



Typical cleavage fracture
at -30°F



Specimen D, at 0°F with
increased strain rate.



Specimen C, at -30°F

Figure 23. An illustration of the change in ductility of a notched tension specimen with temperature changes, for the specimens pre-compressed without the notch present loaded to 150,000 pounds.

TABLE XXII

STRAIN READINGS FOR PRECOMPRESSION WITHOUT THE NOTCH PRESENT

Specimen A — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	75	5	5	105
30,000	290	20	20	365
50,000	420	145	145	515
70,000	500	300	340	650
90,000	570	475	580	775
110,000	610	695	870	930
130,000	730	1,045	1,270	1,055
160,000		Yield		
Set	2,300	5,740	11,320	11,040

TABLE XXIII

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen A — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	10	40	20	30
20,000	70	100	110	100
30,000	145	210	235	190
40,000	235	380	380	280
50,000	335	625	550	390
60,000	475	1,000	850	590
70,000	675	1,560	1,310	920
80,000	840	2,270	2,050	1,475
90,000	1,030	3,290	2,990	2,120
100,000	1,220	5,520	4,310	3,040
110,000	1,460	6,480	6,270	4,190
120,000	1,690	9,470	9,040	5,590
130,000	2,660	18,940	14,500	7,260
140,000	10,550	26,870	22,150	8,490
150,000	16,140	35,700	30,600	10,790

TABLE XXIV

STRAIN READINGS FOR PRECOMPRESSION WITHOUT THE NOTCH PRESENT

Specimen B   Temperature +70°F

	Gauge Readings in Micro-Inches per Inch			
Load	1	2	3	4
5,000	0	0	0	0
10,000	70	10	10	90
30,000	320	60	60	410
50,000	450	180	180	565
70,000	550	325	330	650
90,000	660	500	540	670
110,000	780	725	775	780
130,000	950	980	1,060	920
140,000	1,060	1,160	1,220	1,000
160,000		Yield		
Set	7,105	12,970	10,685	9,880

TABLE XXV

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen B   Temperature 0°F

	Gauge Readings in Micro-Inches per Inch			
Load	1	2	3	4
5,000	0	0	0	0
10,000	25	20	35	15
20,000	100	110	100	45
30,000	195	225	215	120
40,000	320	375	340	305
50,000	450	570	520	415
60,000	635	930	810	550
70,000	1,065	1,800	3,255	755
80,000	1,675	4,870	3,895	945
90,000	2,155	6,020	4,895	1,355
100,000	2,815	7,740	6,265	1,885
110,000	3,545	10,040	7,985	2,585
120,000	4,525	-	10,265	3,255
130,000	5,785	-	13,365	4,255
140,000	Yield	-	-	Yield
150,000	10,635	-	-	8,605

TABLE XXVI

STRAIN READINGS FOR PRECOMPRESSION WITHOUT THE NOTCH PRESENT

Specimen D Temperature +70°F

Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	0
10,000	55	30	10	60
30,000	380	160	30	285
50,000	610	375	180	445
70,000	805	580	340	570
90,000	940	790	550	630
110,000	1,040	990	790	720
130,000		Yield		
150,000		Yield		
Set	8,255	9,075	7,050	2,915

TABLE XXVII

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen D Temperature 0°F

Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	0
50,000	320	570	750	600
100,000	1,310	3,800	4,000	1,270
150,000	10,870	-	-	7,160

TABLE XXVIII

STRAIN READINGS FOR PRECOMPRESSION WITHOUT THE NOTCH PRESENT

Specimen C — Temperature +70° F

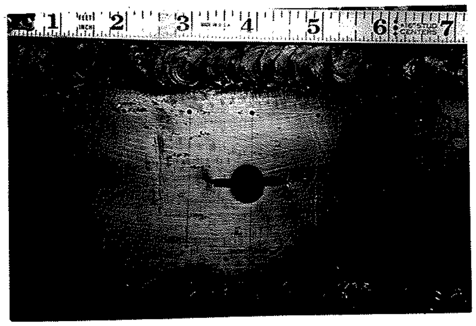
Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	0
10,000	30	15	15	35
30,000	155	65	65	130
50,000	230	135	140	205
70,000	390	310	330	405
90,000	545	485	510	560
110,000	670	660	670	620
130,000	710	785	720	625
145,000		Yield		
Set	5,225	4,340	5,005	4,735

TABLE XXIX

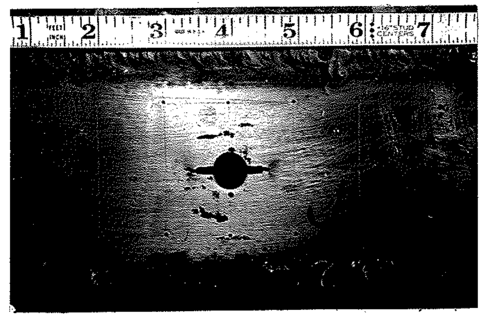
STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

Specimen C — Temperature -30° F

Gauge Readings in Micro-Inches per Inch				
Load	1	2	3	4
5,000	0	0	0	-
20,000	220	285	270	-
40,000	430	605	585	-
60,000	690	1,035	990	-
80,000	920	2,085	1,450	-
100,000	1,250	4,885	2,030	-
120,000	1,470	9,085	3,630	-
140,000		Yield		
150,000		Specimen fractured		

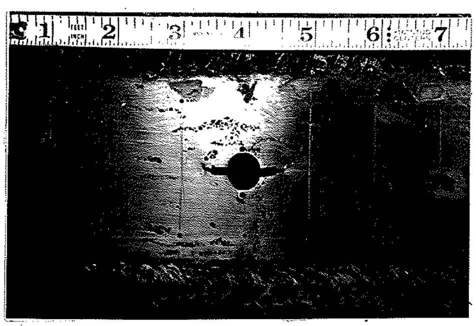


Specimen L, at +70°F

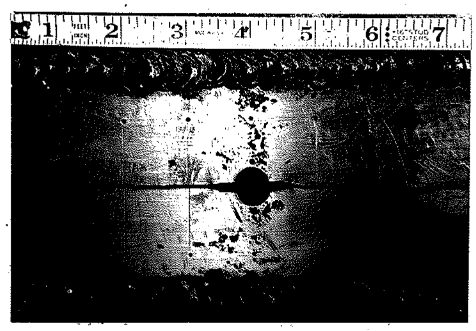


Specimen J, at 0°F

Typical cleavage fracture at -30°F.



Specimen K, at 0°F with increased strain rate.



Specimen P, at -30°F

Figure 24. An illustration of the change in ductility of a notched tension specimen with temperature changes, for the specimens with residual stresses due to welding loaded to 150,000 pounds.

TABLE XXX

STRAIN READINGS FOR RESIDUAL STRESSES DUE TO WELDING

Specimen L Temperature +70° F

Gauge Readings in Micro-Inches per Inch

	1	2	3	4
Initial Reading	10,265	7,105	7,325	10,075
Final Reading	4,485	2,110	1,700	4,660
Residual Strain	- 5,780	- 4,995	- 5,625	- 5,415

TABLE XXXI

STRAIN READINGS FOR TENSION TEST WITH RESIDUAL WELDING STRESSES PRESENT

Specimen L Temperature +70° F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	95	145	170	130
20,000	215	375	495	310
30,000	315	450	795	450
40,000	405	630	1,160	580
50,000	505	910	1,565	715
60,000	605	1,250	2,055	845
70,000	725	1,770	2,685	975
80,000	845	2,410	3,565	1,120
90,000	1,020	3,530	4,855	1,240
100,000	1,215	5,660	7,425	1,470
110,000	1,545	10,090	14,175	3,360
120,000	2,415	14,760	20,495	7,200
130,000	3,945	29,640	25,535	9,160
140,000	8,195	27,590	-	14,260
150,000		Yield		

TABLE XXXII

STRAIN READINGS FOR RESIDUAL STRESSES DUE TO WELDING

Specimen J — Temperature +70°F

Gauge Readings in Micro-Inches per Inch

	1	2	3	4
Initial Reading	2,690	3,040	3,850	1,885
Final Reading	230	4,015	2,110	960
Residual Strain	- 2,460	975	- 1,740	- 925

TABLE XXXIII

STRAIN READINGS FOR TENSION TEST WITH RESIDUAL WELDING STRESSES PRESENT

Specimen J — Temperature 0°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
10,000	27	10	30	25
20,000	79	80	95	75
30,000	155	235	265	125
40,000	225	400	365	115
50,000	320	680	550	185
60,000	435	1,000	830	320
70,000	605	1,450	1,265	455
80,000	765	1,940	1,765	625
90,000	1,040	2,550	2,335	805
100,000	1,380	3,590	3,385	1,040
110,000	2,115	5,800	5,315	1,465
120,000	3,025	9,800	8,845	1,985
130,000	4,965	-	-	2,975
140,000		Yield		
150,000		Yield		

TABLE XXXIV

STRAIN READINGS FOR RESIDUAL STRESSES DUE TO WELDING

Specimen K   Temperature +70°F

Gauge Readings in Micro-Inches per Inch

	1	2	3	4
Initial Reading	10,035	9,570	9,960	9,940
Final Reading	4,420	4,840	4,960	3,420
Residual Strain	- 5,615	- 4,730	- 5,000	- 6,520

TABLE XXXV

STRAIN READINGS FOR TENSION TEST WITH RESIDUAL WELDING STRESSES PRESENT

Specimen K   Temperature 0°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	0	0	0
50,000	835	1,250	1,040	565
100,000	1,535	5,340	4,280	1,395
150,000		Yield		

TABLE XXXVI

STRAIN READINGS FOR RESIDUAL STRESSES DUE TO WELDING

Specimen P Temperature +70°F

Gauge Readings in Micro-Inches per Inch

	1	2	3	4
Initial Reading	6,235	7,275	6,460	7,355
Final Reading	1,870	1,540	1,960	600
Residual Strain	- 4,365	- 5,735	- 4,500	- 6,755

TABLE XXXVII

STRAIN READINGS FOR TENSION TEST WITH RESIDUAL WELDING STRESSES PRESENT

Specimen P Temperature -30°F

Gauge Readings in Micro-Inches per Inch

Load	1	2	3	4
5,000	0	-	0	0
20,000	240	-	300	280
40,000	510	-	790	660
60,000	790	-	1,540	1,050
80,000	1,290	-	2,740	1,420
100,000	1,850	-	4,540	1,950
120,000	2,660	-	9,490	2,550
140,000	4,210	-	-	3,280
148,785		Specimen broke		

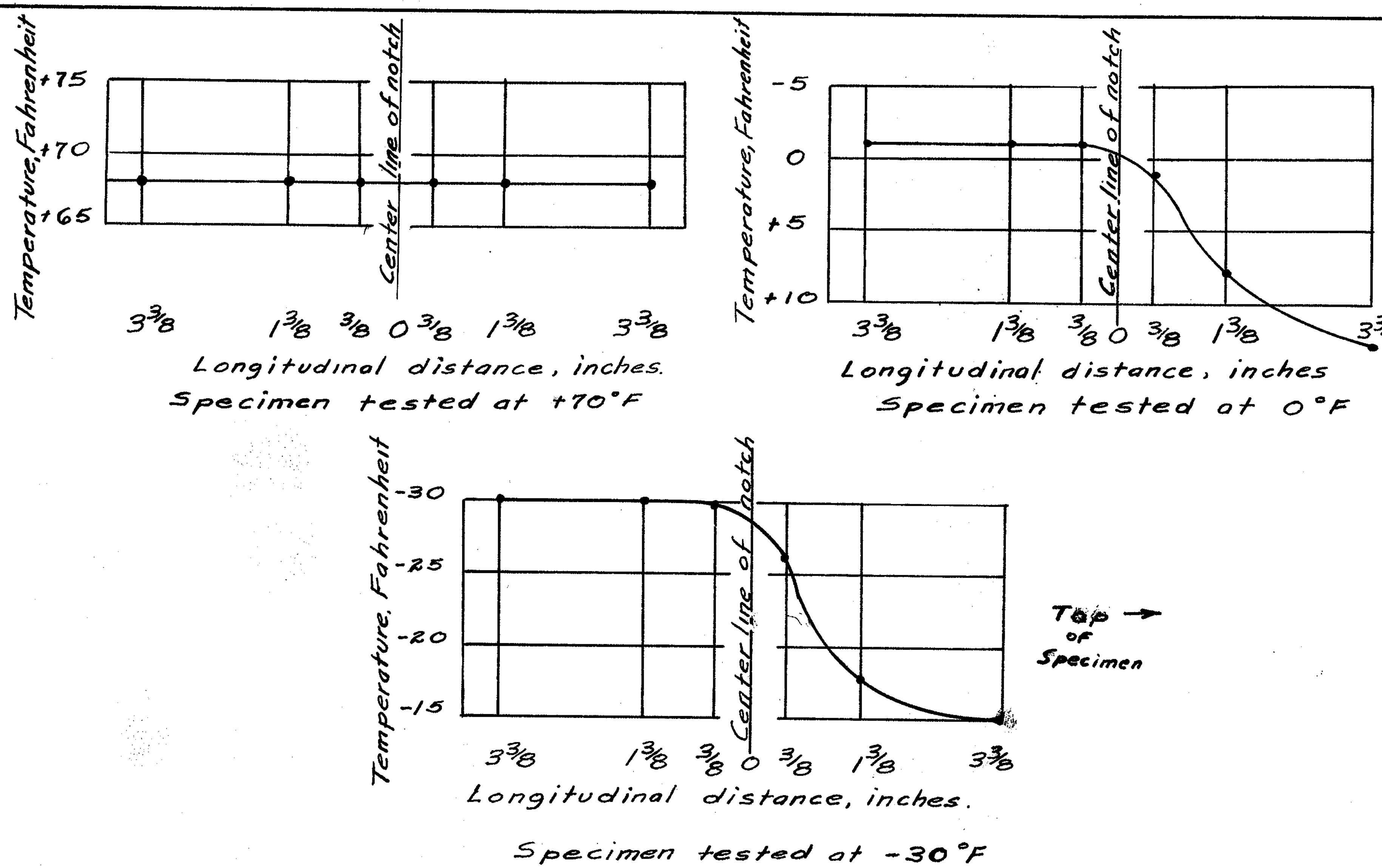


Figure 25. Typical temperature variation across notch in notched tension specimen.

CHAPTER VI

PRESENTATION AND DISCUSSION

I. PRESENTATION

The presentation of results is divided into two sections; standard test results and large tension test results. A better understanding of each is hoped to be achieved by this mode of presentation.

Standard Tests

The standard method for presenting data obtained from these tests will be used as a presentation of results. Therefore, the standard tension test results are shown in Table I, page 33, and Figure 16, page 34, the Charpy impact results are shown in Figure 17, page 35, and the Kinzel notch bend results are shown in Figures 18 and 19, pages 37 and 38. The temperature comparisons for all three tests are shown in Figures 26, 27, and Figure 28, page 69.

Large Tension Tests

The mode of presentation used for these test results has three purposes:

(a) To show the notch effect under different conditions of reduced ductility

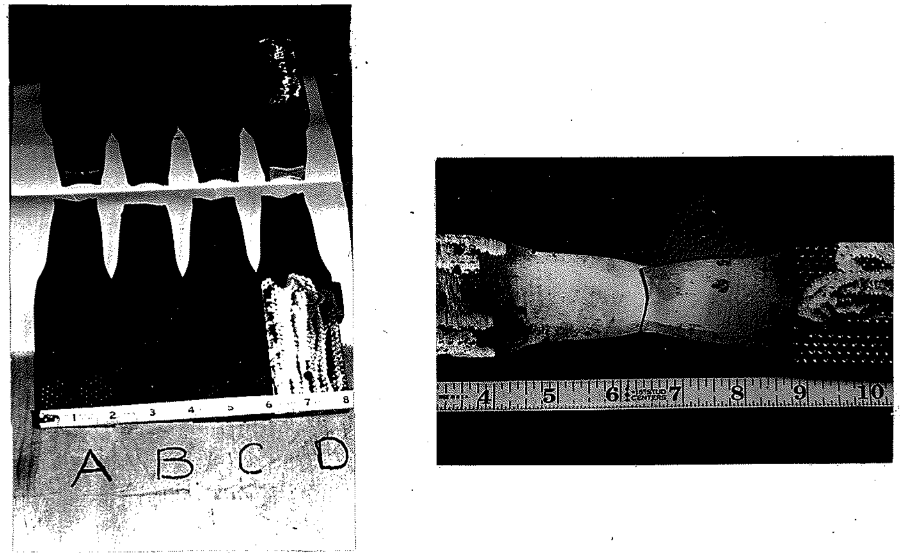


Figure 26. Standard tension specimens after fracture

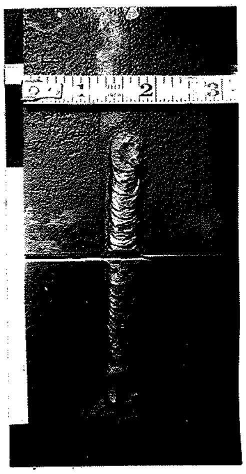
Figure 27. Charpy V-notch specimens after fracture.

(b) To show the notch effect under tension at different testing temperatures.

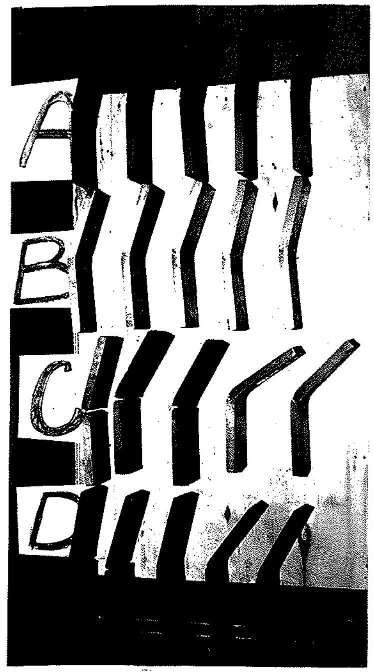
(c) To show the notch effect under tension at different strain rates.

As an overall picture of the large tension tests in Figure 29, there is illustrated the effect of loading to the ultimate load.

A comparison of notched tension specimen results is shown in Table XXXVIII, pages 70 to 72 inclusive. The gross average stress is based on the area of the total cross section and the net average stress is based on the area of the net section; the net section area is the result of subtracting the area occupied by the notch from the total cross section. The average stress is in kips per square inch, ksi. For per cent reduction in area the changes in width and thickness, measured at the level of the notch, are based on the change in total cross section and show the difference between ultimate conditions and the end of prestraining. The contraction at the base of the notch was measured one-sixteenth of an inch from the extreme end of the jeweller's saw cut and shows the difference between ultimate conditions and the end of prestraining. The percentages are calculated to ± 0.1 per cent. The per cent elongation in two inches for the outside is measured one inch in from the outside edge of the specimen, and for the centre is measured directly on the centreline of



Specimen welded perpendicular to the grain, tested at -30°F.



A. Welded parallel to the grain.

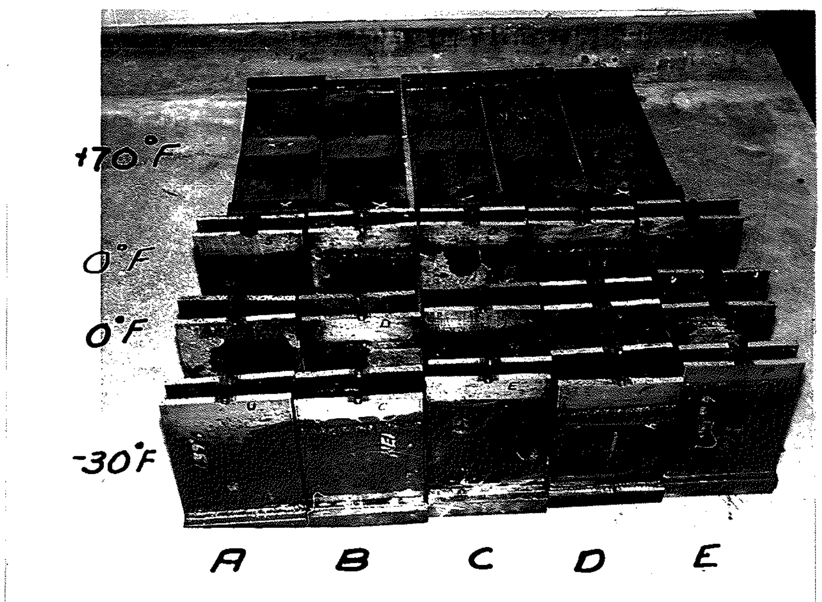
B. Unwelded parallel to the grain.

C. Unwelded perpendicular to the grain.

D. Welded perpendicular to the grain.

-80 -60 -30 0 +20 °F

Figure 28. Tested Kinzel notch bend specimens.



A. Specimens with no prestrain.
B. Specimens compressed without notch present.
C. Specimens with tensile prestrain.
D. Specimens compressed with notch present.
E. Specimens with residual stresses due to welding.

Figure 29. Large tension specimens at ultimate load.

TABLE XXXVIII
COMPARISON OF TEST RESULTS ON LARGE TENSION SPECIMENS.

Specimen Mark	Dimensions Width, Thickness. Inches	Ultimate Load Kips	Gross Average Stress ksi	Net Average Stress ksi	Percent Reduction In Area	Percent Elongation In 2 Inches: Outside	Percent Elongation In 2 Inches: Center	Percent Contraction At Notch Root	Temperature Fahrenheit	Fracture Surface
	Type I specimens, no prestrain.									
V	0.490 7.89	183.21	47.30	56.30	7.0	7.5	15.5	—	+70	Loaded to ultimate load.
S	0.497 7.89	148.86	37.90	45.05	3.3	2.0	4.0	5.7	0	Cleavage chevron pattern
T	0.493 7.89	173.96	44.70	53.25	3.1	3.0	7.0	7.1	0	Cleavage chevron pattern.
U	0.497 7.90	149.30	38.00	45.15	2.7	1.5	4.0	3.6	-30	Cleavage chevron pattern
	Type II specimens, tensile prestrain.									
M	0.499 7.89	187.48	47.50	56.40	4.5	1.5	1.5	—	+70	Loaded to ultimate load
O	0.496 7.89	175.58	44.80	53.30	2.0	2.1	3.0	4.4	0	Cleavage chevron pattern
N	0.501 7.90	170.82	43.10	51.25	2.8	3.0	4.0	5.0	0	Cleavage chevron pattern
E	0.497 7.89	154.77	39.40	46.90	2.3	2.0	2.0	1.7	-30	Cleavage chevron pattern

TABLE XXXVIII Continued

Specimen Mark	Dimensions Width, Thickness Inches	Ultimate Load Kips	Gross Average Stress Ksi	Net Average Stress Ksi	Percent Reduction In Area	Percent Elongation In 2 Inches		Percent Contraction At Notch Root	Temperature Fahrenheit	Fracture Surface
						Outside	Inside			
	Type III specimens, pre compression with notch.									
H	0.503 7.92	150.00	37.70	44.70	3.5	2.0	3.5	–	+70	Broke in weld
G	0.502 7.91	140.81	35.45	42.15	1.5	2.0	2.0	0.4	0	Clearage 10% shear
R	0.495 7.90	145.36	37.15	44.25	0.5	2.0	2.0	0.5	0	Cleavage 10% shear
F	0.500 7.92	120.00	30.30	36.00	0.5	1.0	1.0	0.2	-30	clearage chevron pattern
	Type IV specimens, precompression without notch.									
A	0.499 7.91	185.52	46.80	55.75	3.3	3.0	5.0	–	+70	Ultimate load only
B	0.496 7.93	173.36	44.10	52.25	1.8	1.0	1.0	4.7	0	Clearage 20% shear
D	0.501 7.90	171.73	43.30	51.60	3.0	2.0	3.0	6.8	0	Clearage 20% shear
C	0.500 7.90	150.00	38.00	45.10	1.2	1.0	2.5	4.0	-30	Clearage chevron pattern

TABLE XXXVIII Continued.

Specimen Mark	Dimensions, Width, Thickness, Inches	Ultimate Load, Kips	Gross Average Stress, Ksi	Net Average Stress, Ksi	Percent Reduction In Area	Percent Elongation In 2 Inches Outside	Percent Elongation In 2 Inches Center	Percent Contraction At Notch Root	Temperature Fahrenheit	Fracture Surface
	Type V specimens, residual welding stresses.									
L	0.495 7.90	173.20	44.25	52.60	3.1	2.0	4.0	–	+70	Ultimate load only
J	0.499 7.90	171.52	43.45	51.60	3.0	2.0	3.0	4.7	0	Cleavage chevron pattern
K	0.501 7.90	170.60	43.10	51.25	3.5	3.0	3.0	4.5	0	Cleavage chevron pattern
P	0.500 7.80	148.79	38.15	45.40	1.5	2.0	3.0	3.2	-30	Cleavage chevron pattern

the notch. The values are measured within ± 0.5 per cent and show the result only of the tensile load after prestrain. The contraction at the notch root for the specimens tested at $+70^{\circ}$F was not shown because it was impossible to take this measurement accurately, as the notch root was so badly deformed.

Figure 30 shows the effect of the notch in the specimen as the specimen was compressed.

Figures 32, 34, 36, 38 and 40, pages 76, 78, 80, 82 and 84 respectively, show the temperature effect on the change in strain rate with load for temperatures at $+70^{\circ}$F and -30°F. To show the notch effect on ductility, the load strain curve at $+70^{\circ}$F for the pretensioning of the type II series is shown.

The rate of strain increase from 10,000 pound increments to 50,000 pound increments has an effect on the load-strain curve as shown by Figures 31, 33, 35, 37 and 39, pages 75, 77, 79, 81 and 83 respectively. The load-strain curve for the unnotched specimen, mentioned previously, also is shown.

II. DISCUSSION OF RESULTS

The steel used in this investigation was A7 structural rolled-bar of merchant quality. The per cent chemical analysis of this steel type is as follows: Carbon 0.240, Manganese 0.530, Silicon 0.094, Sulphur 0.040, and

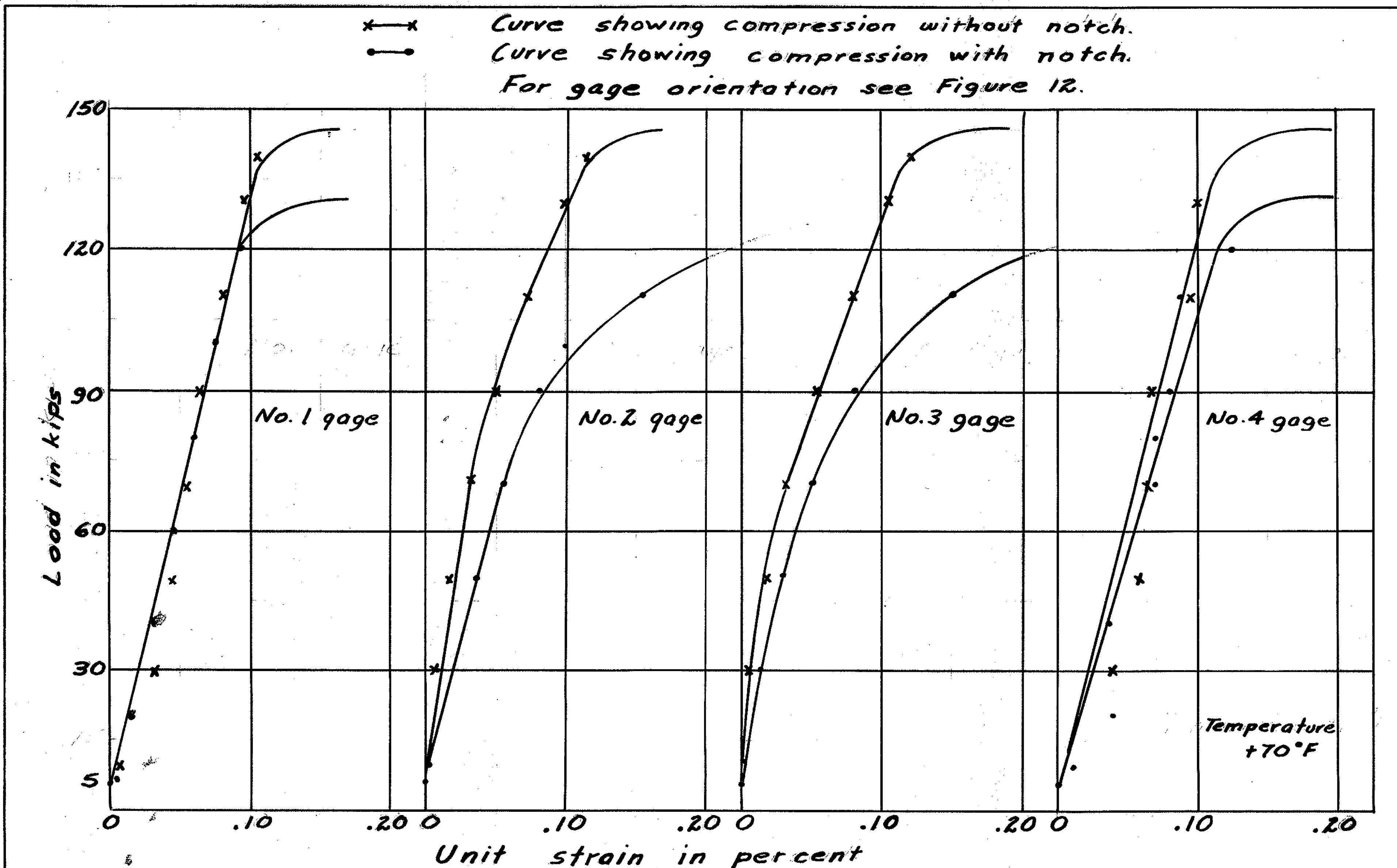


Figure 30. A comparison across the specimen, of the notch effect during compression.

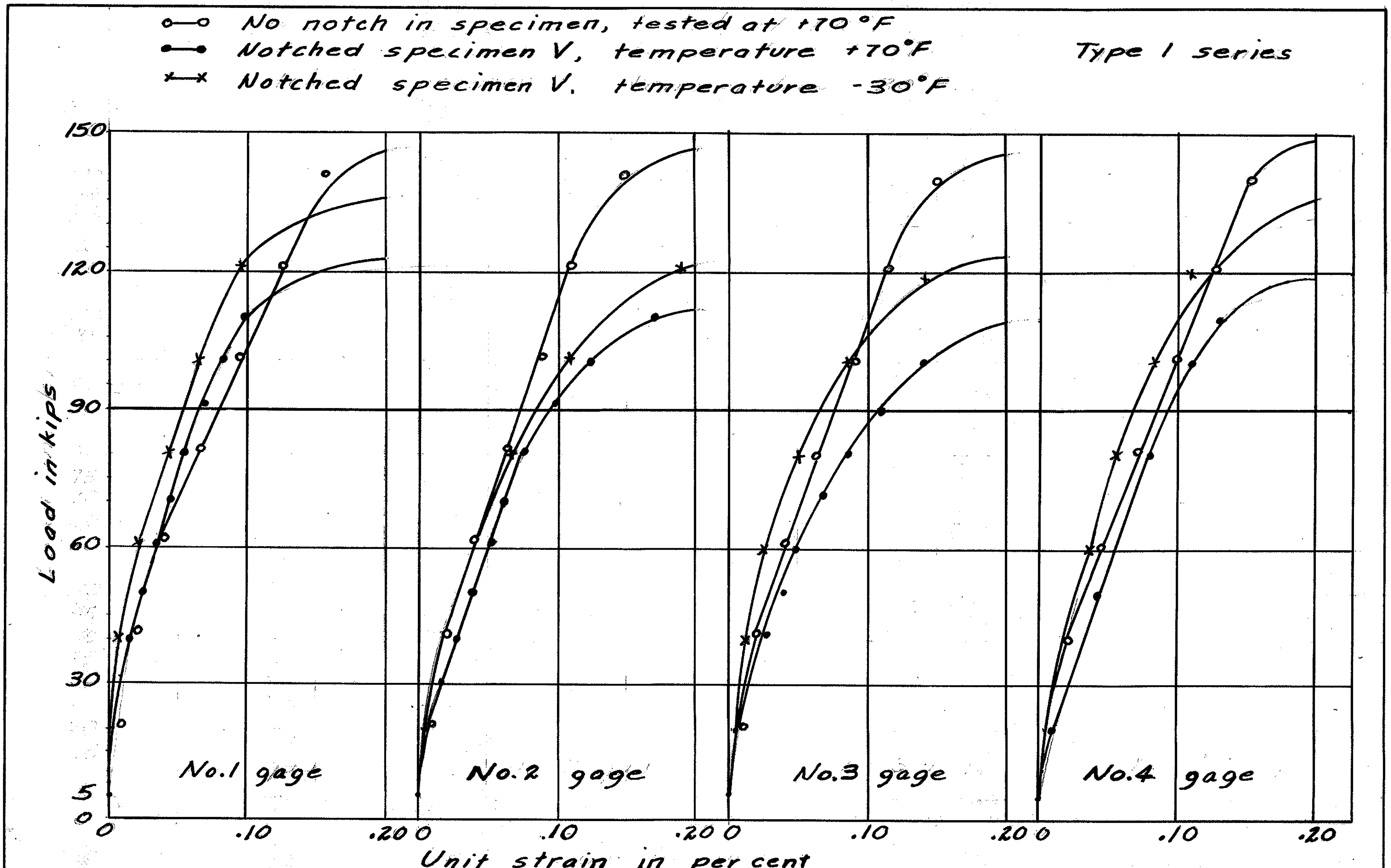


Figure 31. Comparison of temperature effects across notched tension specimens

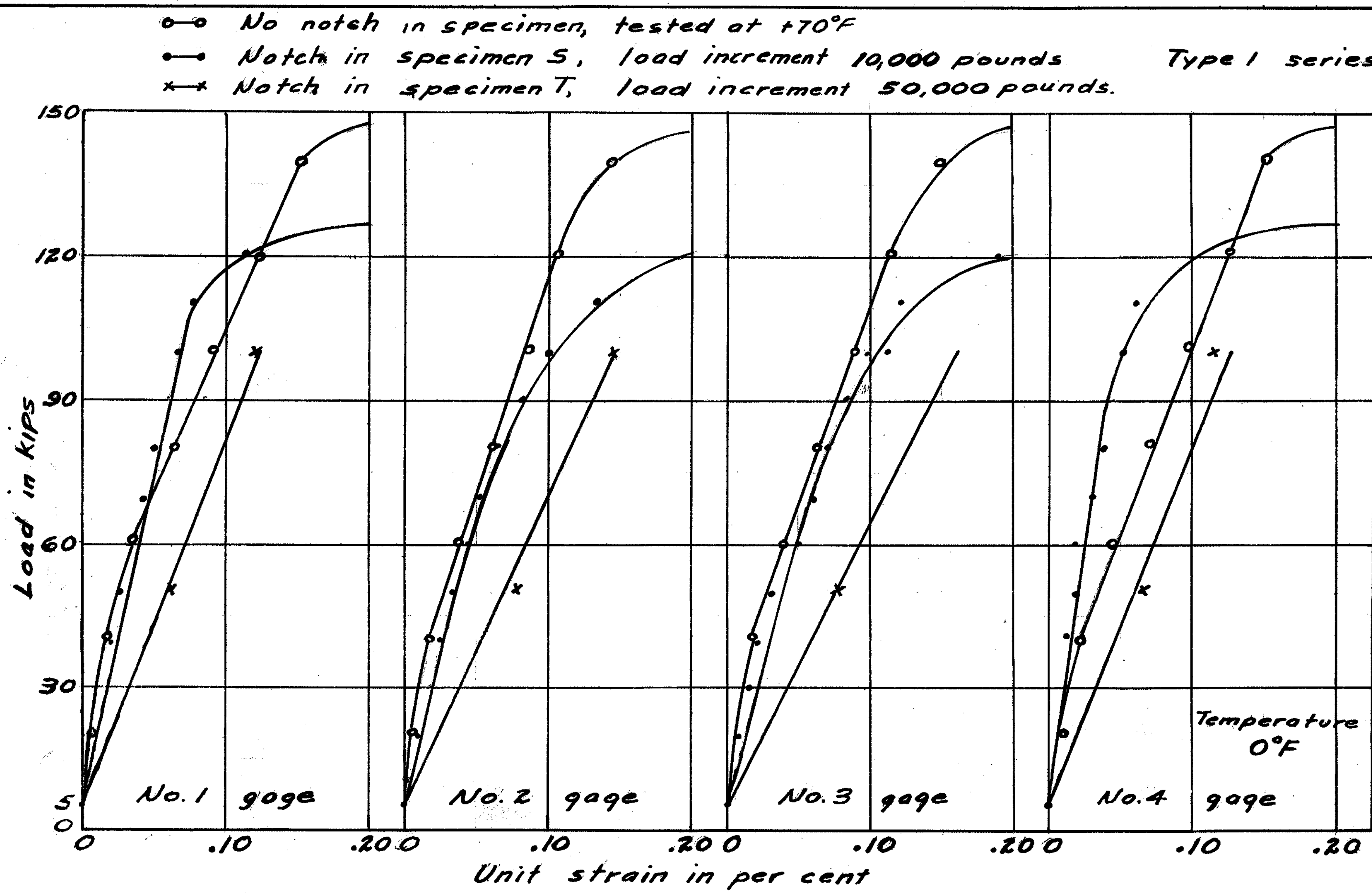


Figure 32. Comparison of strain rates across notched tension specimens.

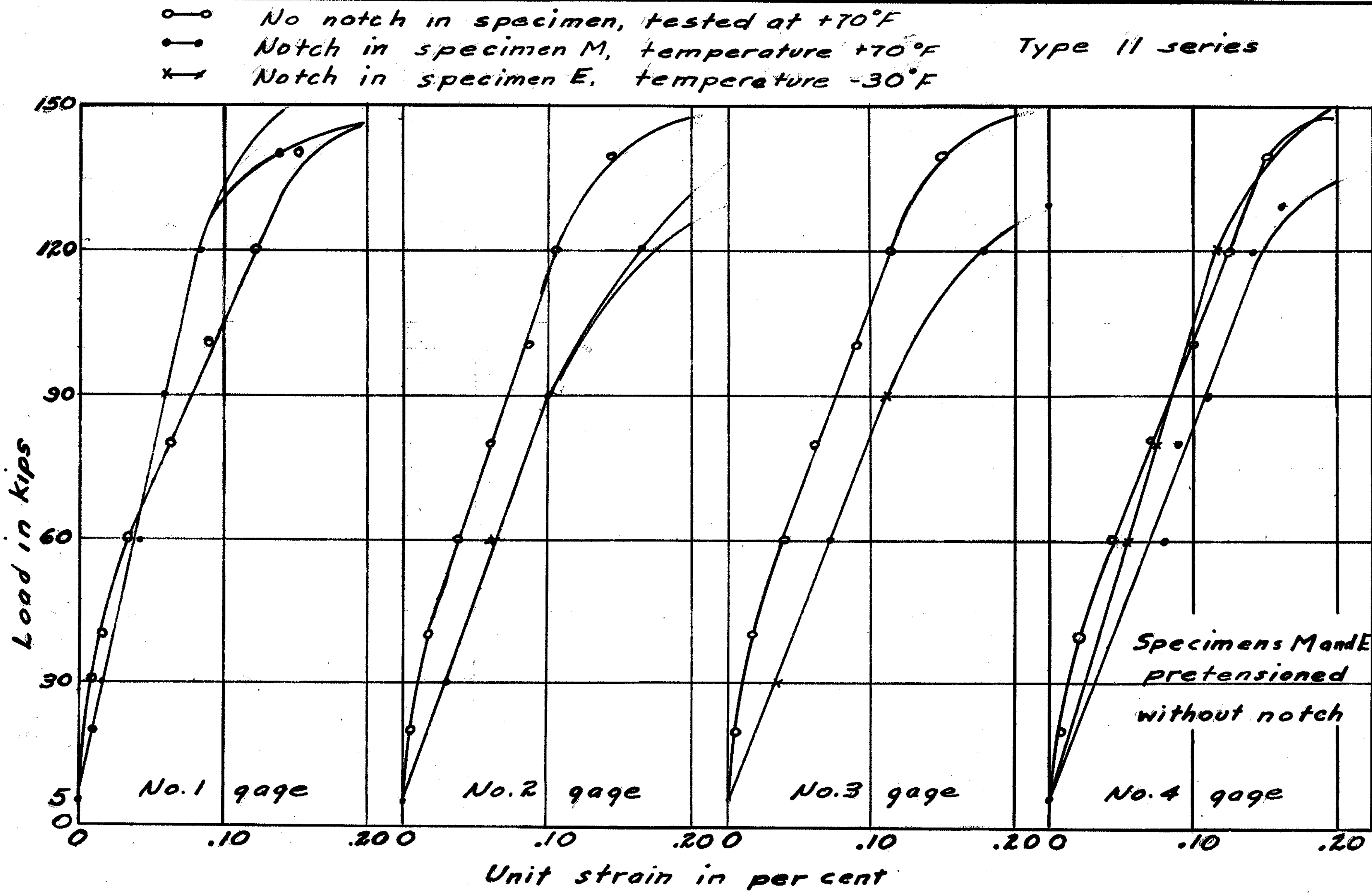


Figure 33. Comparison of temperature effects across notched tension specimens.

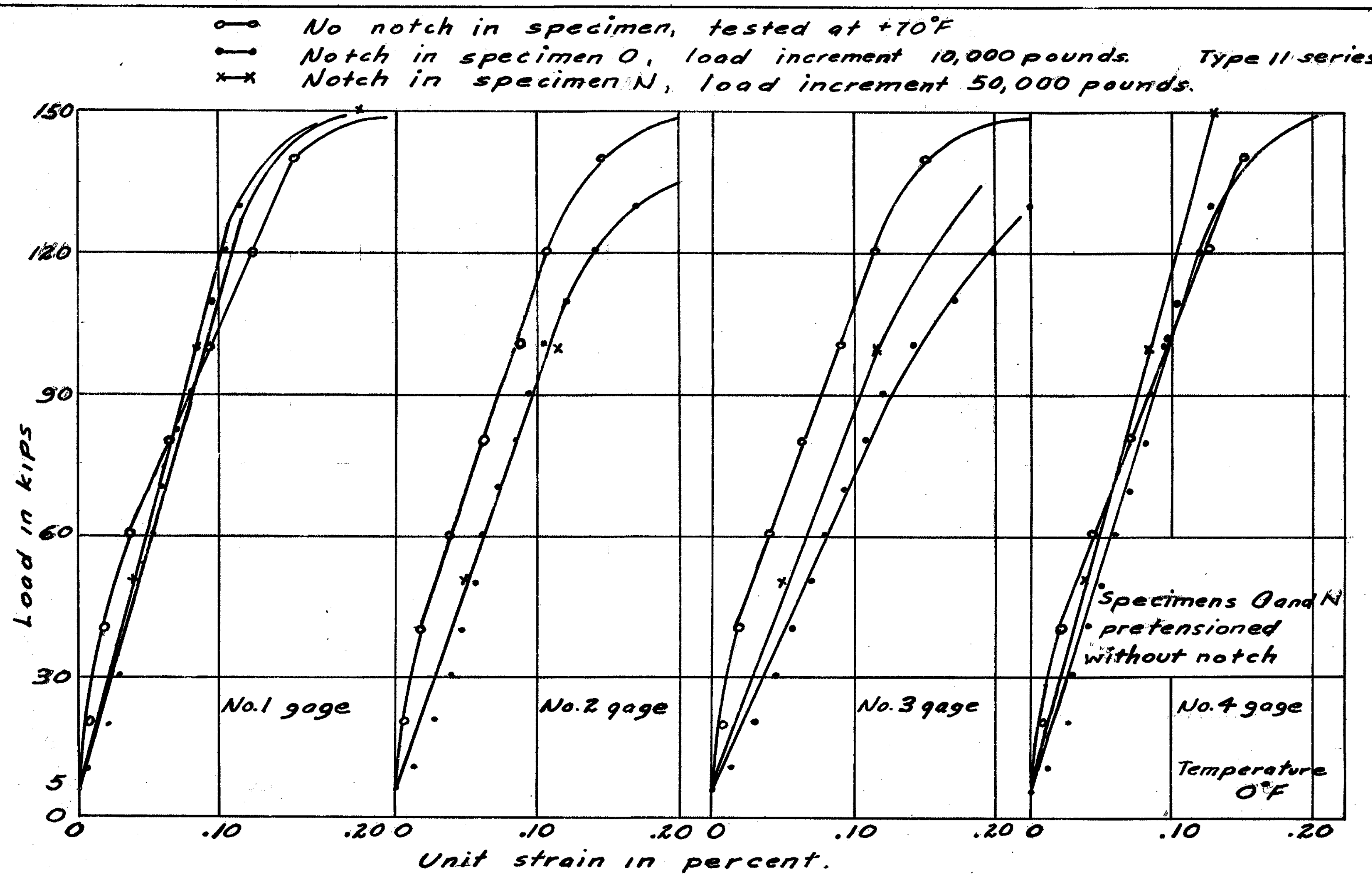


Figure 34. Comparison of strain rates across notched tension specimens.

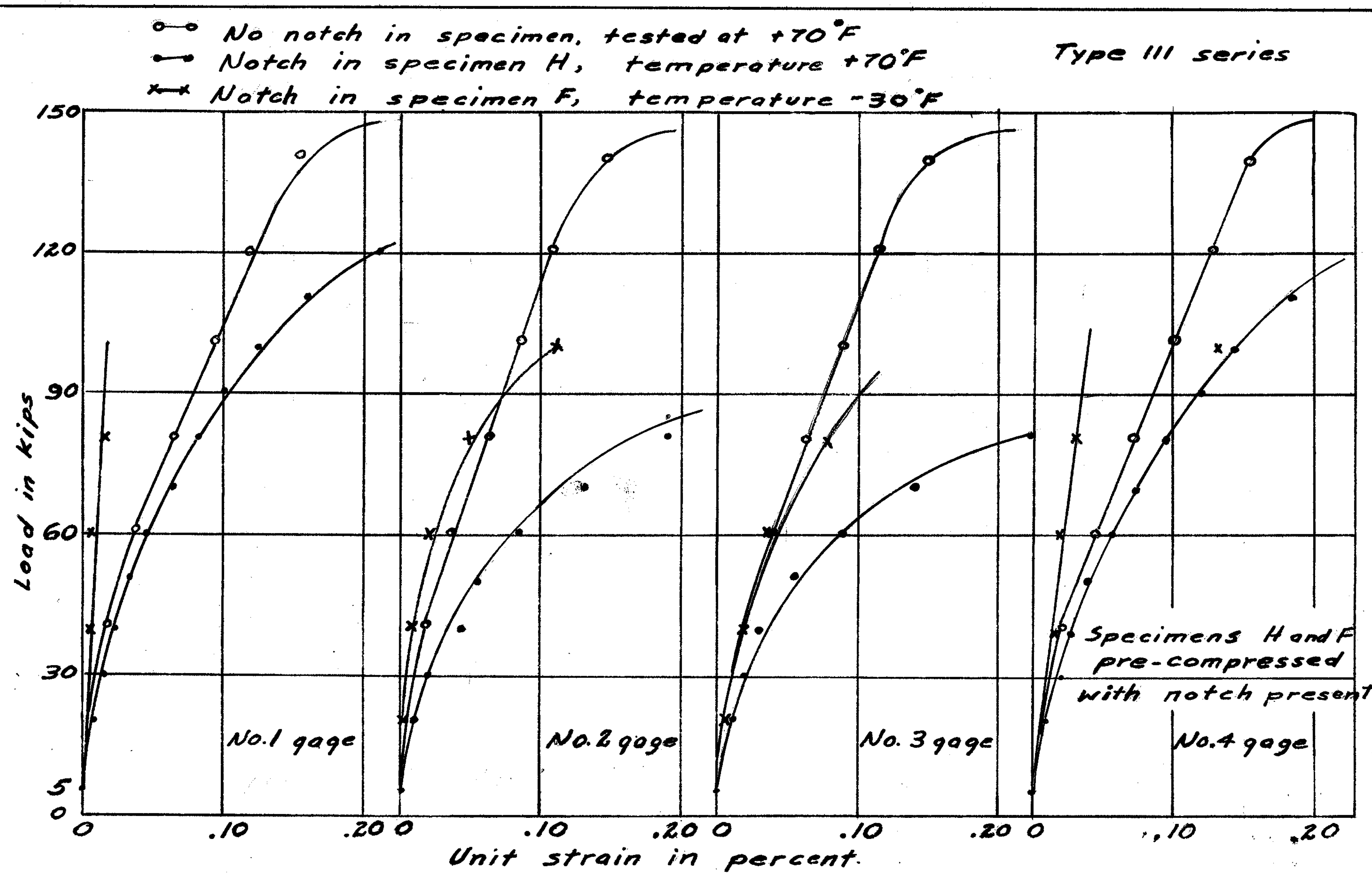


Figure 35. Comparison of temperature effect across notched tension specimens

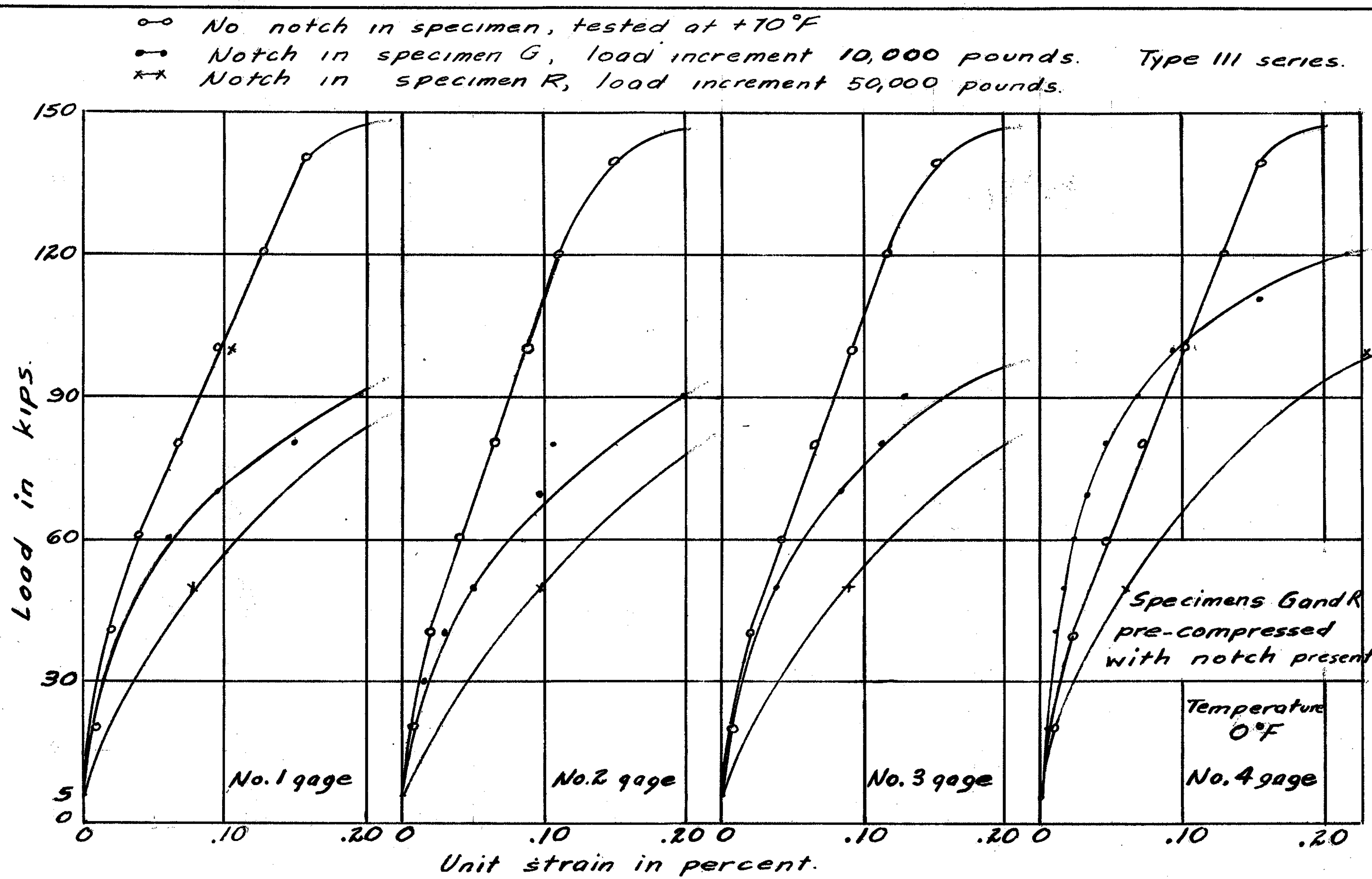


Figure 36. Comparison of strain rates across notched tension specimens.

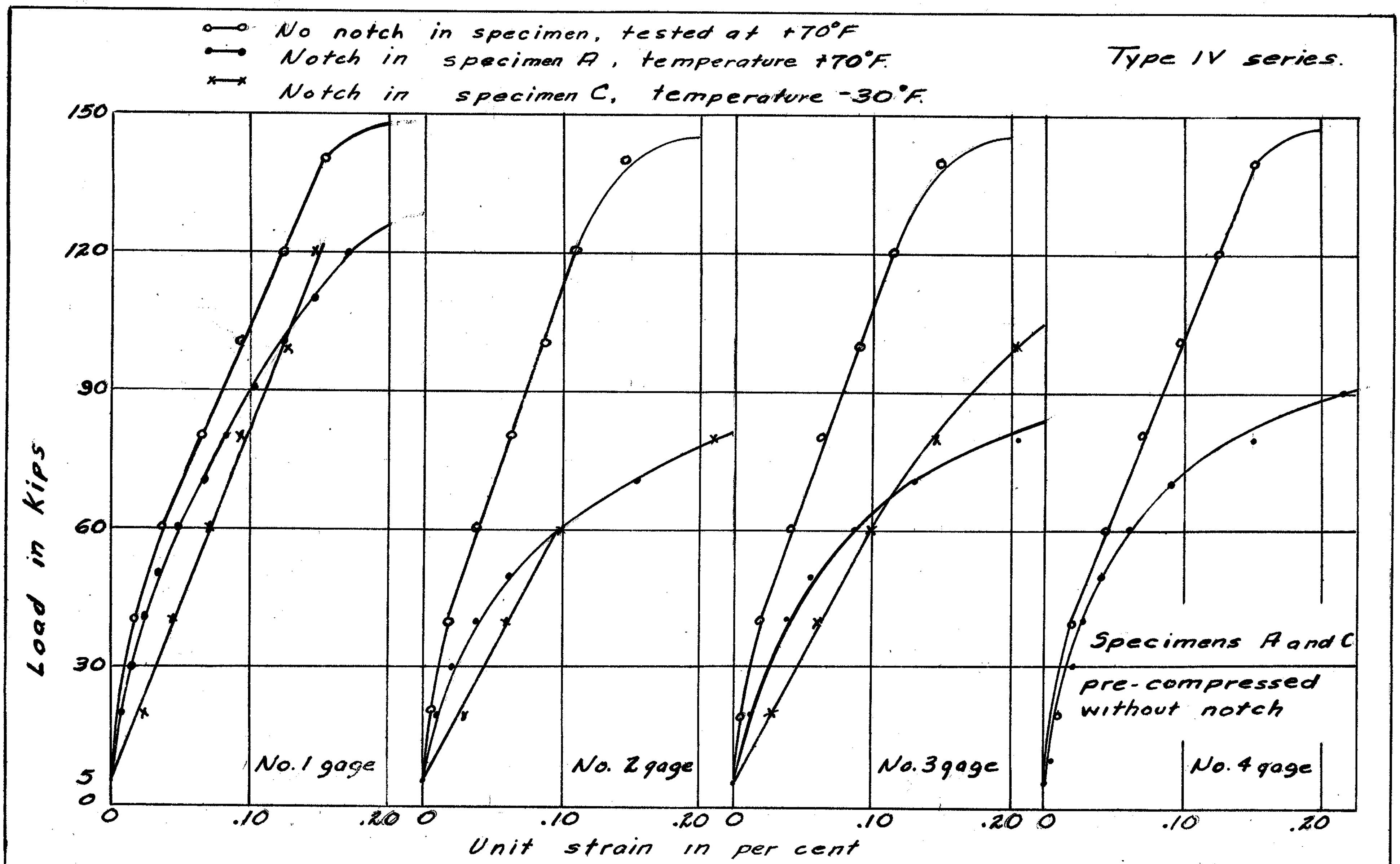


Figure 37. Comparison of temperature effect across notched tension specimens

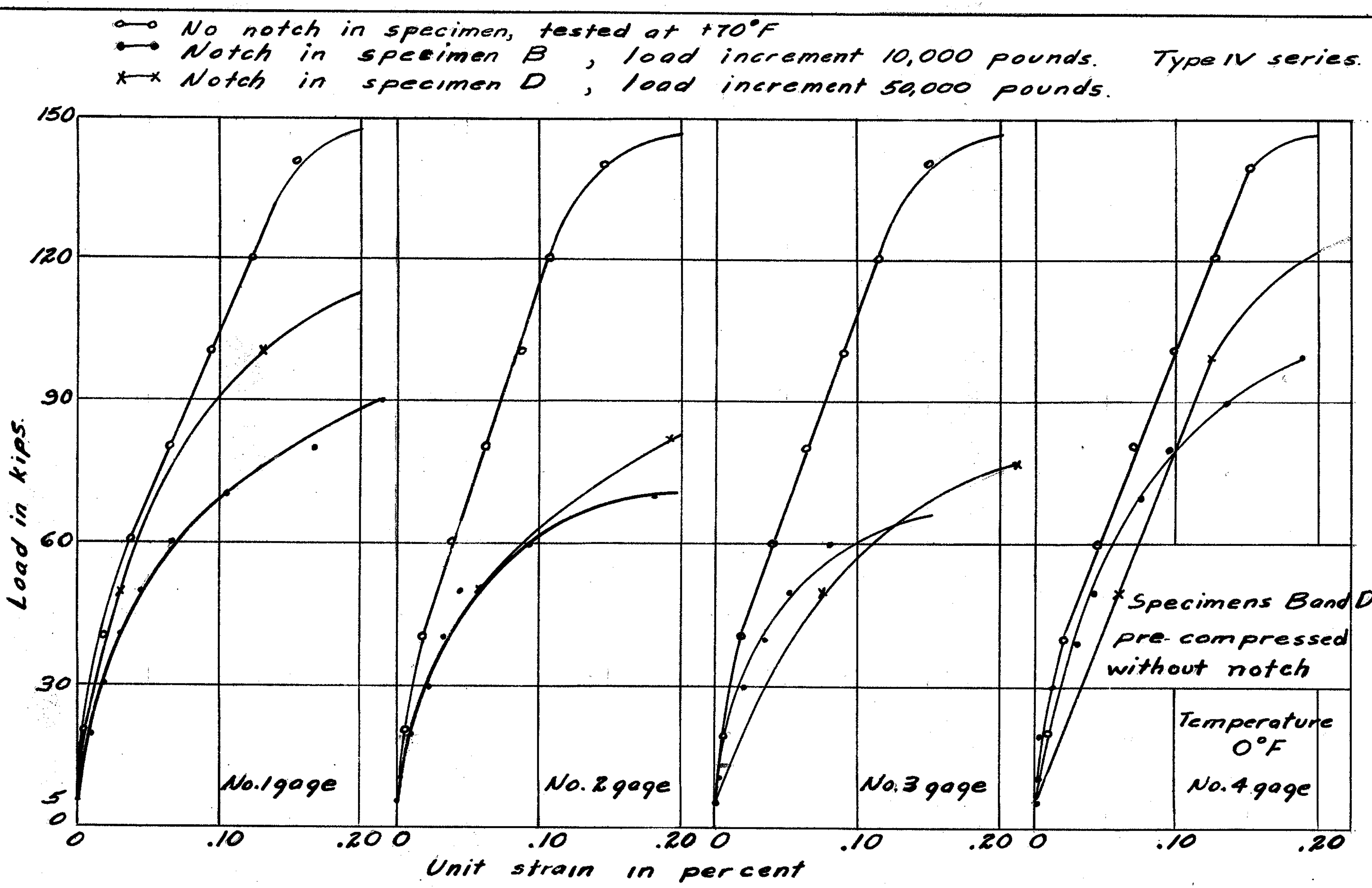


Figure 38. Comparison of strain rates across notched tension specimens.

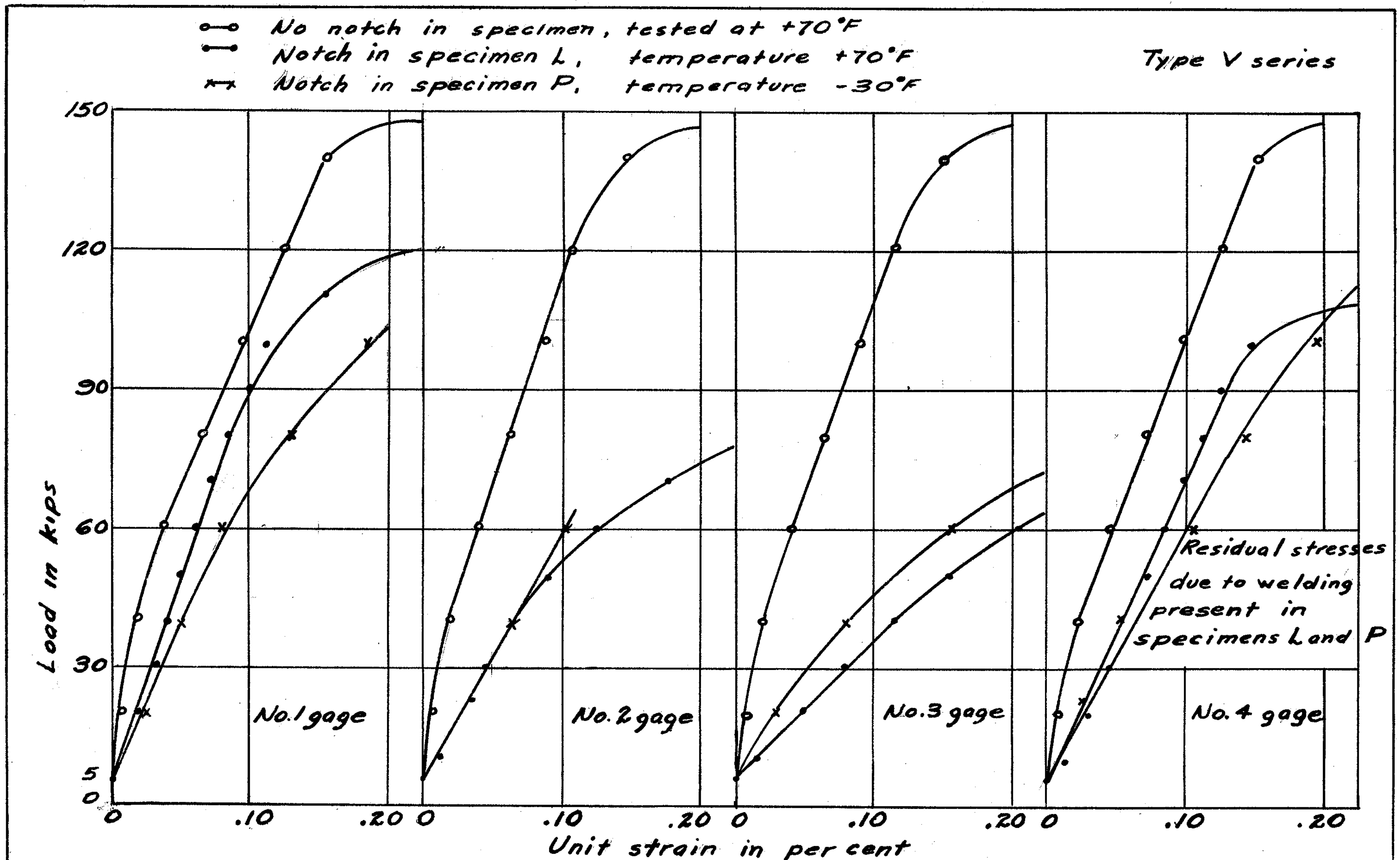


Figure 39. Comparison of temperature effects across notched tension specimens

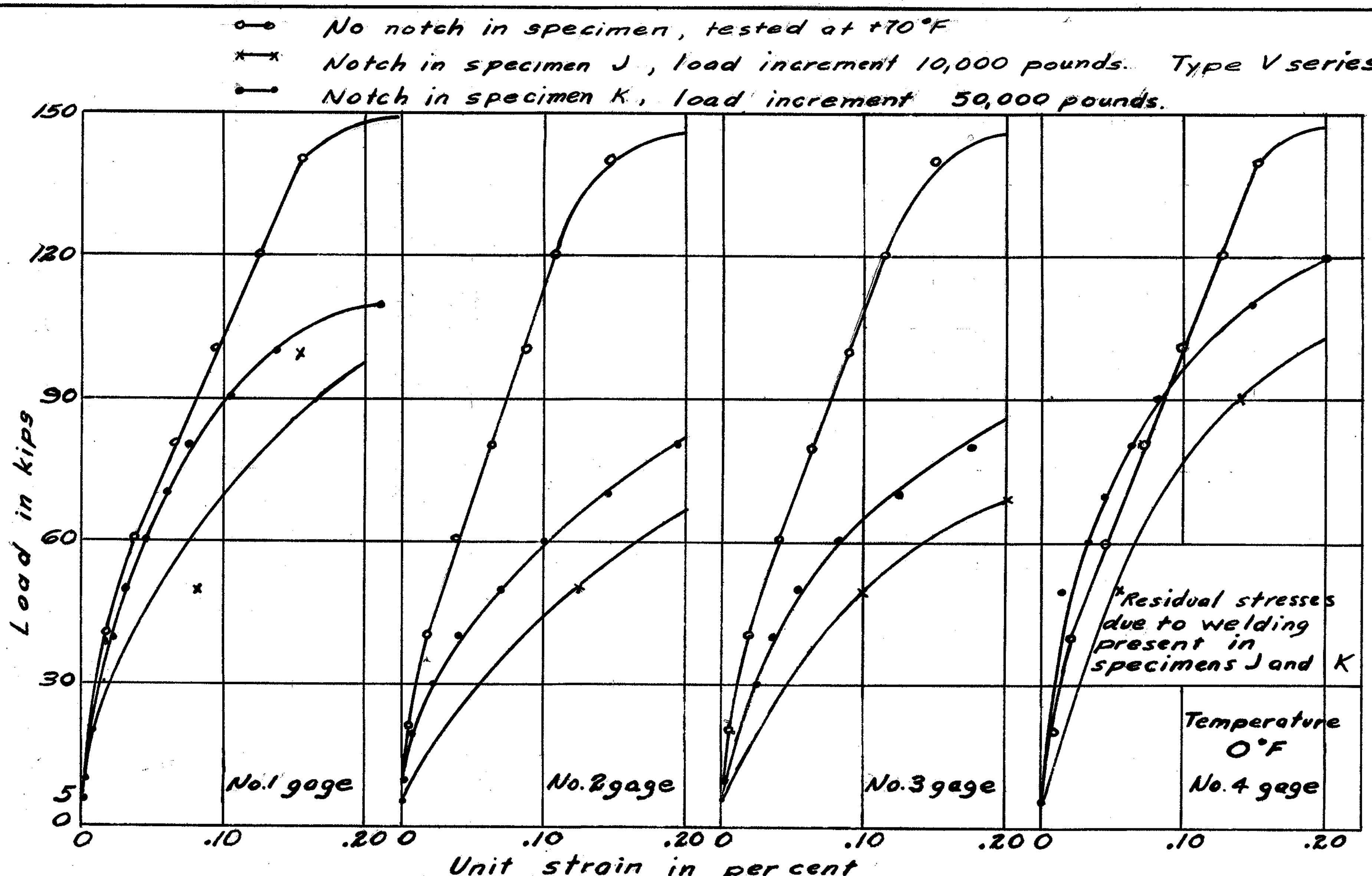


Figure 40. Comparison of strain rates across notched tension specimens.

Phosphorous 0.010. The 0.240 per cent carbon was made up of 0.180 per cent combined carbon FeC_3, and 0.060 per cent graphitic carbon. Comparing this steel to low carbon steels, 0.15 per cent carbon, and high carbon steels, 0.30 per cent carbon, this steel can be classed as a mild carbon steel.[1]

The following discussion includes a reference to the standard and large tension tests, a correlation between these tests, and the conclusions arrived at. From this investigation some recommendations for future research have been presented.

Interpretation of Standard Test Results

Results from the standard tension test, shown in Figure 16, page 34, indicate a modulus of elasticity of 29×10^3 kips per square inch, the yield strength was 37.43 kips per square inch, and the ultimate strength was 60.80 kips per square inch. An elongation of 48 per cent in a gauge length of two inches, after fracture, showed that this steel was quite ductile. From the above results and the chemical analysis this steel could conform to ASTM A36-61T.[2]

The fracture surface of the tension specimens was of

---

[1]Robert D. Stout and W. D'Orville Doty, Weldability of Steels (New York: Welding Research Council, 1953), p. 3.

[2]ASTM Standards 1961, Part 1, Ferrous Metals Specifications, A36-61T, p. 551.

a cup-cone gray and silky nature, indicating a shear type fracture. After the ultimate load was reached there was a sizeable reduction in load prior to failure, an indication of the inherent ductility of this steel type.

The correlation between strain gauge increments, shown in Table I, page 33, for the A-7 and PA-3 strain gauges was almost identical indicating that the reinforcing effect of the water-proofing compound had no effect on the strain measurement. The water-proofing compound, however, was not satisfactory in regions of high yield as it came off the specimen. It had not the ultimate yield capacity of the PA-3 strain gauges.

The Charpy impact test results are shown in Figure 17, page 35, and the specimens parallel to the grain show a sharp increase in energy absorption after $0^{o}F$ indicating a ductility transition point. The specimens cut transverse to the grain show a reduced ability to absorb energy and thus would be more susceptible to brittle behaviour. Therefore, in fabrication of structures, the strength of the steel lies with the direction of rolling. From this test the ductility transition temperature could be taken as $0^{o}F$ at an energy value of 10 foot-pounds. However, it is impossible to select one temperature and a range of 10 degrees on either side of this temperature might be more applicable.

The difficulty in using the Kinzel notch bend test as a service test is in the selection of the criteria used to estimate the ductility transition temperature. In Figure 18, page 37, the per cent lateral contraction one thirty-second of an inch below the notch root has been selected as a measurement of ductility. From a plot of these results with temperature four different curves are shown. The results show that brittle behaviour, signified by a decrease in lateral contraction, is aided by welding and cutting the specimens perpendicular to the grain. From this group of curves the 2 per cent lateral contraction for specimens unwelded parallel to the grain occurs at -20°F which corresponds with the 1.3 per cent lateral contraction for specimens welded parallel to the grain. The one per cent lateral contraction set down by some investigators has no meaning in this investigation except for the specimens cut transverse to the grain.[3]

The criterion of bend angle at maximum load shown in Figure 19, page 38, shows the increased brittle behaviour with welding and the increase in ductility with a rise in temperature. As a weldability test the ductility transition for a 25 degree bend would occur at approximately -20°F, the same as the 1.3 per cent lateral contraction transition.

In all the specimens that failed in a brittle manner,

---

[3] S. A. Agnew, M. D. Mittelman and R. D. Stout, Some Observations on the Kinzel and Drop-Weight Tests. The Welding Journal, 39 (5), 1960, Research Supplement 205-s to 211-s.

the fractures appeared to start at the weld shown in Figure 28, page 69, which is an indication that the heat affected zone adjacent to the weld is most susceptible to brittle failure. This zone may initiate the fracture and if conditions are favourable to crack propagation the fracture will continue.

In the specimens welded and unwelded transverse to the grain the crack perpendicular to the face of the specimen tended to propagate along the mid thickness line in the form of a shear crack. This is a definite indication of the lack of ductility of the steel in the direction transverse to the grain.

The change in ductility for these tests with temperature is illustrated in Figures 26, 27 and 28, pages 67 and 69.

Interpretation of Large Tension Test Results

In performing the large tension tests the condition of static loading only was investigated since the rate of loading of the screw-type machine could not be considered to be of impact magnitude. An increase in loading rate at constant temperature by increasing the load increment did produce some favourable results.

The large tension specimens were tested such that the ductility at 150,000 pounds of the specimens could be compared. The specimens were then further loaded to their ultimate. An illustration of the specimens at ultimate load is shown in Figure 29, page 69.

The specimen dimensions were selected to insure plate effect of the notch and to eliminate the effects of end restraint on the stress pattern surrounding the notch. Previous researchers have used notch widths of 0.2 to 0.3 of the specimen width.[4] In this investigation the notch width was made 0.16 of the specimen width to increase the plate effect around the notch. The jeweller's saw cut was used to provide the fracture initiation.

The specimens, compressed without the notch, showed a constant strain increase up to the yield point. By inserting the notch and then compressing the specimen the strain rate increased in the region surrounding the notch. Thus, the increased strain rate indicated that the plasticity at the apex of the notch was rapidly exhausted. As the strain gauges nearest the notch were three-eighths of an inch from the apex a considerably higher rate of strain could be expected at the notch apex. As the yield point in compression was reached the strain gauge readings became somewhat erratic. This possibly could have been the result of the lateral restraint, offered by the heads in contact with the specimen,

---

[4] ASTM Committee on Fracture Testing of High-Strength Sheet Materials, Fracture Testing of High-Strength Sheet Materials, ASTM Bulletin, 243 (1), 1960, p. 31.

which caused twisting which resulted in buckling of the specimen. This tendency to buckle governed the maximum load that was placed on the specimen. A graphic illustration of the notch effect on a compression specimen is shown in Figure 30, page 74.

In the task involving pretensioning of the specimens, the load was held above the yield point for a short period of time. As the rate of strain at yield was rapid and soon was off the range of the recorder the amount of yield could not be governed too closely. However, reasonable agreement was obtained between most of these specimens in terms of magnitude of pretensioning.

In the tests involving residual stresses the welding procedure used was intended to give tensile stresses at the notch root. As a result of the cooling process used to protect the strain gauges from the heat generated during welding only compressive prestrain occurred across the specimen. The heat effect on the strain gauges was not considered critical as the temperature in the region of the strain gauges was well below their safe operating temperature. This temperature was recorded by placing thermo-couples at varying distances from the edge of the weld.

During the testing of the specimens with welded inserts, some of the strain gauge readings appeared erratic at the lower loads. This was due to a slight misalignment of the insert with the remainder of the specimen, caused by welding distortion. This effect had no significant bearing on the test results.

The method of cooling used in this investigation produced a temperature gradient longitudinally over the notch as shown in Figure 25, page 65. This method of cooling provided the required temperature of the notch and since the crack propagated outward from the notch roots no ill effects of this gradient were found.

The notch effect on the specimens under various conditions of prestrain, were compared at temperatures of +70°F and -30°F as shown in Figure 31, 33, 35, 37 and 39, pages 75, 77, 79, 81 and 83 respectively. The specimens with no prestrain had an increased strain rate in the regions of the notch, indicating that the notch increased the rate of ductility reduction in a specimen. Pretensioning 2 per cent above the yield point reduced this rate considerably and pre-compression to the same magnitude with the notch present increased this rate. The welded inserts with residual welding stresses present gave results similar to those of pre-compression. The reduction in temperature from +70°F to -30°F had a reduction in strain rate indicating a reduction in ductility.

Figures 32, 34, 36, 38 and 40, pages 76, 78, 80, 82 and 84 respectively, show the effect on the strain rate of changing the load increment from 10,000 pounds to 50,000 pounds. For tensile prestrain and compressive prestrain without the notch present there was no change in strain rate. However, for precompression of the specimens with the notch present and the existence of residual welding stresses, there was a large increase in strain rate indicating that these two methods are susceptible to variations in strain rate.

In Table XXXVIII, page 70, the results of the large tension tests are given in comparative form. From the +70°F tests the specimen containing residual welding stresses had the lowest load and the specimen precompressed with the notch present had the lowest measure of ductility.

A reduction in temperature to 0°F caused a reduction in the load-carrying capacity and brittle fracture resulted at average stresses well above the yield point. All fractures contained the chevron pattern which pointed to the notch apex as the brittle fracture initiator. For the specimens precompressed there was some shear failure evident. All specimens failed suddenly with no yielding after the ultimate load was attained. The slight change in strain rate did not alter the load carrying capacity of the specimens.

At -30°F all the specimens failed in brittle fracture with the specimen having tensile prestrain reaching the highest load and the specimen having precompression with the notch present having the lowest load. The stresses were somewhat lower than at $0^{o}F$ but were still of yield proportions.

An investigation of the fracture surface showed that hair line cracks had developed at mid thickness across the notch in all specimens except those that were in the virgin state. A reasonable explanation might be that high tensile stresses were released at fracture and only those specimens with undamaged ductility could sustain these without splitting.

Therefore, the ultimate load has been reduced by the presence of the notch, the presence of temperature reduction, and the variation in strain rate within the specimen.

Correlation of Standard Test Results and Large Tension Test Results

One of the purposes of this investigation was to associate the results from standard tests with the results from large tension tests which could be representative of service conditions.

Through testing various modes of prestrain the most critical situation involved precompression with the notch present. With this procedure brittle fractures were obtained at $0^{o}F$ with average stresses slightly above the yield strength. By investigation of the Charpy impact test results the ten foot pound energy value occurred at $0^{o}F$. Therefore, a brittle fracture may be initiated by static loading and a jeweller's saw cut at the 10 foot pound energy temperature. These conditions could easily be provided by a weld defect under ordinary operating or erection conditions.

The Kinzel notch bend test showed a ductility transition temperature well within the danger zone and an empirical relationship would be needed to predict service applicability. This test does show what increase in the ductility transition temperature may be expected as a result of weld embrittlement.

The standard tension test does not provide information useable in predicting brittle behaviour of steel but does supply the designer with valuable limiting values on the use of the steel.

Recommendations for Future Work

This investigation was concerned primarily to determine the notch effect under various conditions of reduced ductility to see which conditions would promote brittle behaviour. This condition has been illustrated quite well and now the other variables could be investigated.

By changing the notch geometry and specimen thickness and using this same mode of precompression with the notch present possibly, a new ductility transition temperature could be obtained.

The amount of precompression might be increased with the above recommended changes in specimen geometry to determine what effect subsequent tensile loading would have on the ductility transition temperature.

Conclusions

At the beginning of this investigation the four factors involved in brittle fracture were considered to be notch toughness, notch effect, temperature and strain rate. The results of this investigation have shown how these four factors were successfully combined to produce brittle fracture. It was also found that by varying one of these factors the susceptibility of steel to brittle fracture could be increased.

The effect of the notch, because of its reduced cross section, its stress concentration abilities, and its ability to change uniaxial tension to triaxial tension, has a pronounced effect on brittle fracture initiation.

The difference in specimen behaviour showed that temperature plays a prominent role in brittle behaviour of steel. The specimens were able to undergo severe plastic deformation as long as the temperature was above the ductility transition temperature. Below the ductility transition temperature the specimen could not deform plastically as required and brittle behaviour occurred.

The physical strain rate increase as a result of a variation in loading had only an effect on the specimens whose ductility at the notch apex had already been exhausted by prestrain. However, this increase in strain rate in the region of a notch is very important because if ductility is prevented by conditions of temperature, brittle behaviour will result.

By prestraining the specimen in tension 2 per cent followed by a notch insertion and then by tensile loading, the susceptibility to brittle behaviour is greatly reduced. This applies also as the temperature is reduced.

By precompressing the plate 2 per cent with a notch present, a brittle fracture initiation region is produced at the notch apex which promotes brittle behaviour at low loads.

With static loading in the presence of a notch and a material of reduced ductility by precompression, there is good agreement between the ductility transition temperature so found and that obtained by using the standard Charpy impact test. The Kinzel notch bend test predicts brittle behaviour but is well within the danger zone and must be treated by an empirical relationship.

It is hoped that this investigation will be an advancement in the present research into this phenomenon of brittle fracture.

BIBLIOGRAPHY

BIBLIOGRAPHY

Agnew, S. A., M. D. Mittelman and R. D. Stout. Some Observations on the Kinzel and Drop-Weight Tests, The Welding Journal, 39 (5) Research Suppl., 205-s to 211-3, (1960).

ASTM Committee on Fracture Testing of High-Strength Sheet Materials, Fracture Testing of High-Strength Sheet Materials. ASTM Bulletin, No. 243 (1), 1960.

_______. ASTM Bulletin, No. 244 (2), 1960.

ASTM Standards 1961, Part 1, Ferrous Metals Specifications.

_______. Part 3, Metals Test Methods.

Gross, J. H. Comparison of Charpy V-Notch and Drop-Weight Tests for Structural Steels, The Welding Journal, 39 (2) Research Suppl., 59-s to 66-s,(1960).

Nagaraja Rao, N. R., and Lambert Tall. Residual Stresses in Welded Plates. The Welding Journal, 40 (10) Research Suppl., 468-s to 480-s, (1961).

Parker, Earl R. Brittle Behaviour of Engineering Structures. New York: John Wiley and Sons, Inc., 1957.

Shank, M. E. Control of Steel Construction to Avoid Brittle Failure. New York: Welding Research Council, 1957.

Stout, Robert D., and W. D'Orville Doty. Weldability of Steels. New York: Welding Research Council, 1953.