AN INVESTIGATION OF THE RESISTANCE TO BRITTLE FRACTURE OF GENERAL PURPOSE STRUCTURAL STEEL CANADIAN STANDARDS ASSOCIATION SPECIFICATION G40.12-1964

A Thesis

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by

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SYNOPSIS

Canadian Standards Association (C.S.A.) G40.12 general purpose structural steel was subjected to tests in order to determine its resistance to brittle failures under operating conditions. The tests conducted were as follows:

1. Standard Tension tests

   To determine the yield point and the ultimate strength of the steel.

2. V-Notched Charpy Impact tests

   To determine the steel's transition temperature range.

3. Kinzel Notch Bend tests

   To determine the welding characteristics of the steel.

4. Notched Tension tests

   To determine the steel's behaviour under varing conditions of temperature, notch effect, prestraining and strain rate.

The following conclusions can be made from this investigation:

1. This steel had a ten foot-pound ductility temperature of $-40^{\circ}F$.
2. The notch toughness of this steel was good.
3. The presence of notches in this steel, prestraining by compression, tension, and welding with or without the presence of notches, did not produce brittle failure above $-30^{\circ}F$ in tension members.
4. Brittle failures did occur in this steel above the ductility temperature. These failures were caused by welding cracks and impact loading. The failures occurred after appreciable plastic flow at the base of the notch.
5. In the presence of prestraining, notches could produce brittle failures in this steel below its ductility temperature with a reduced amount of plastic flow at the base of a notch.

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CHAPTER I

INTRODUCTION

The problem of brittle failures is common to all steel plate structures, whether the structures are rivetted or welded. This problem has been in existance for over eighty years; but it has only been properly identified in the past twenty or twenty five years. This new awareness has brought on new steels and improved methods of fabrication.

Fundamentals of the Brittle Failure Phenomenon[1]

The Stress Strain Curve

The basis of all structural design is the stress strain curve. Such a curve is shown in Figure 1 for mild steel. This diagram can be divided into four basic parts.

These four basic parts are:

(a) The initial straight line portion where the stress is proportional to the strain and the material behaves elastically.

(b) The initiation of plastic behaviour, introducing the terms of proportional limit, elastic limit, proof stress, per cent yield stress, and yield point. The material is both stretching and getting narrower throughout its length with no significant increase in the load.

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[1] A.I.A. File No. 13-A A Primer on Brittle Fracture page 1.

(c) The load increases and the specimen stretches considerably and continues to get narrower. It is during this stage that elongation takes place and the material stretches beyond its original length (20 or 30 per cent in conventional structural steel). Also during this stage, because of the cold-working undergone in elongation, the maximum load is reached (the tensile strength).

(d) Finally, a reduction in area takes place, the load falls off, and the specimen fails.

Conventional Design Viewpoints

All these stages and physical changes are important. On the whole, the only ones playing a direct part in structural design are those measured in pounds per square inch (p.s.i.), yield strength and tensile strength. While the designer specifies minimum elongation and looks to this for added assurance, deformation is not a quantitative part of any design formula. This leaves a loophole in design if it is looked upon as predicting what may take place in service in the structure. The conventional design viewpoint presupposes that yielding will take place at areas which may be overstressed, such as at notches. This may be a questionable assumption.

During yielding or stretching, contracting or narrowing took place in the specimen. Suppose we could stop the piece from contracting laterally. The specimen, then, would automatically stop yielding, in which case there would be no elongation and no reduction in area. Even if the steel were loaded to its breaking point, it would break without yielding. The result would be a brittle fracture.

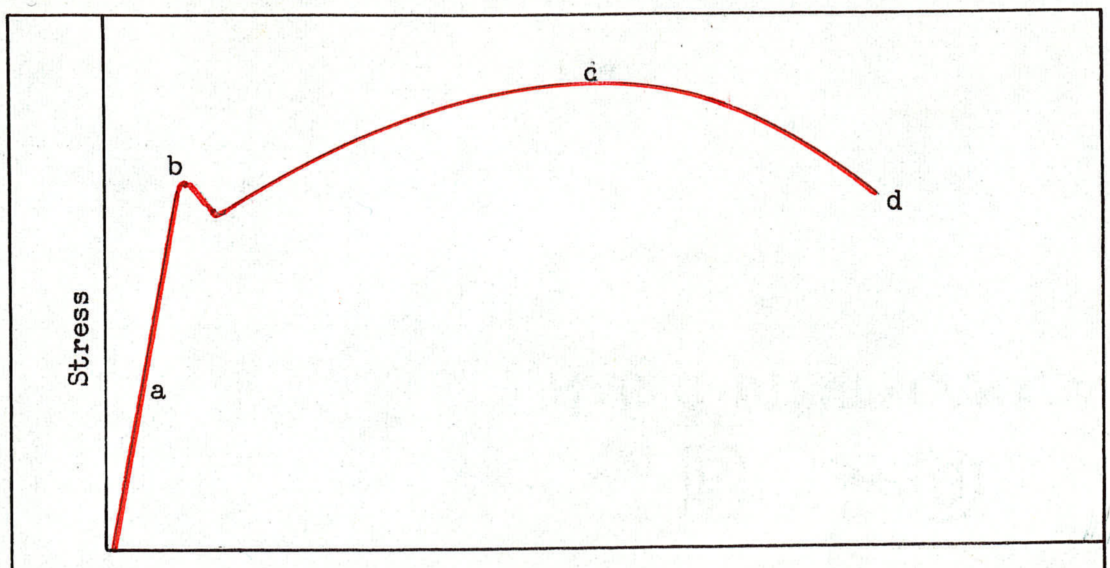
All the physical properties would be absent, including the yield strength which was used as a basis of design.

To understand brittle fracture hazards in design, the conditions which tend to restrain yielding in the component parts must be understood. These can be divided into four basic categories: Mechanical, Temperature, Velocity, and Materials.

Mechanical

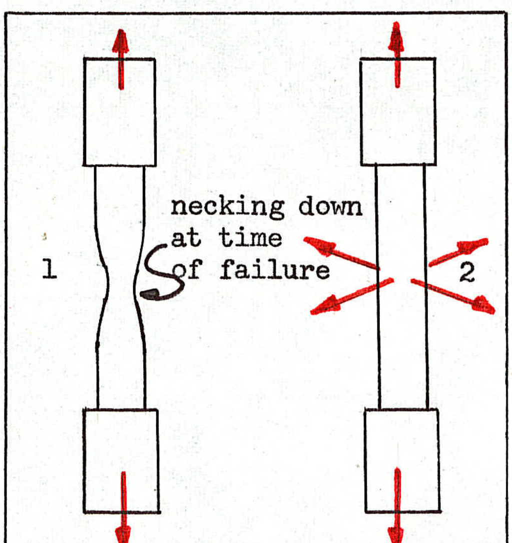
This category is directly tied in with design because it depends on how the structure to be loaded in service is to be designed.

Two test bars are shown in Figure 2. The test bar at the left is uniaxially loaded and is necking down as it approaches fracture. This is the manner of loading when the steel is tested for specification acceptance, and evaluating the minimum properties for design purposes. If the sample were made to A7 Specifications, it would yield at, say, thirty three thousand p.s.i., stretch thirty per cent, and fracture at about sixty thousand p.s.i. However, if the reduced diameter at the break were to be used, it would be found that this "fracture stress" would be about one hundred twenty thousand p.s.i. Now, if the same A7 test bar is loaded laterally as well as axially (as at the right in Figure 2), and if these lateral loads are high enough, plastic behaviour can be suppressed to the point where the bar would break in a brittle manner with no elongation stress of about one hundred twenty thousand p.s.i. rather than at sixty thousand p.s.i. This illustrates that the mechanical properties developed by the steel in a structure depend on how the steel is loaded.



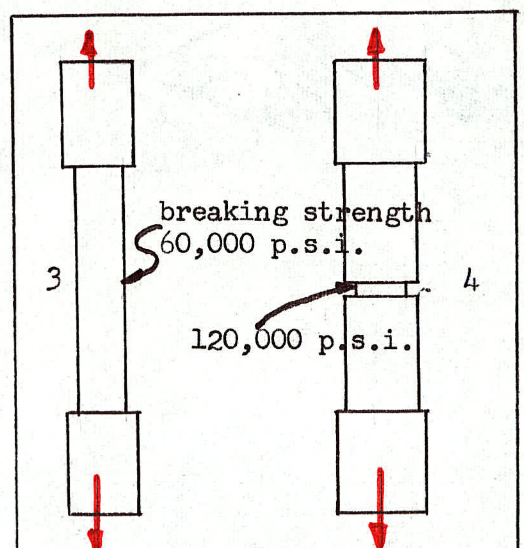
Stress-Strain Curve...Mild Steel

Fig. 1



Test Bar-Axially and Triaxially Loaded

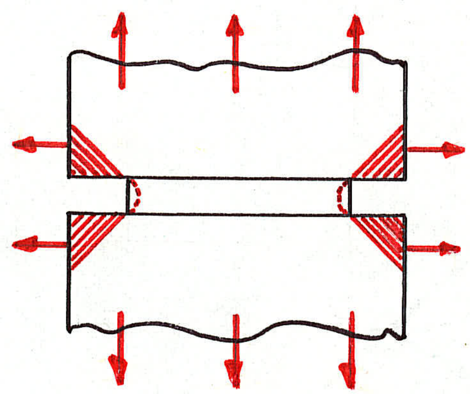
Fig. 2



Test Bar-Smooth and notched

Bar 3 has the same cross sectional area as the bar on the left (3)

Fig. 3



Close up of notched bar.

The reduced section is trying to get narrower as indicated by dotted lines (arrows),but shaded shoulders prevent this narrowing. This is equivalent to applying a lateral load.

Fig. 4

In Figure 3 we have two test bars with the same cross-sectional area. Assuming the bars are of the same material, the one at the right would take about twice the load to break it. The reason is that the material just above and below the notch restrains the section from contracting. This, in effect, is the same as applying a load normal to the axial load as indicated by the arrows in Figure 4.

Temperature

Specification tensile tests are made at room temperature, but lowering the test temperature provides the same effects of brittleness. This is shown in Figure 5 for a typical carbon steel.

Strain Rate

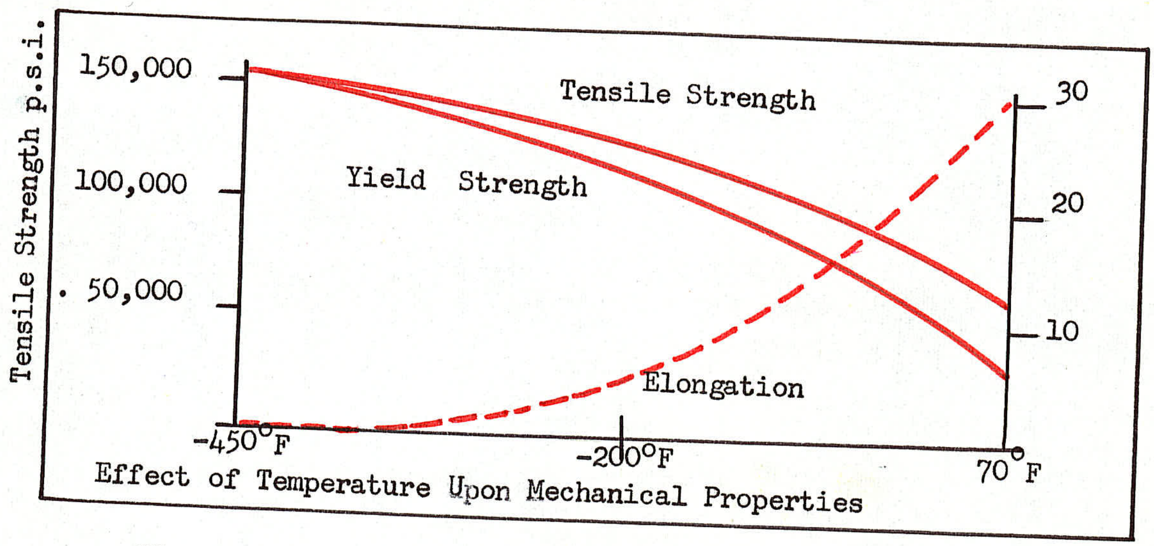
It is known that velocity effects are damaging to materials. For example, "battle damage" on warships was generally accompanied by brittle characteristics in the material. Technically, it is the strain rate which is damaging.

Material - Steel's Resistance to Brittleness

By combining all the brittleness conditions described so far, it would result in the most abusive of all tests, the notched bar impact test. The Charpy test is the best known example of this type.

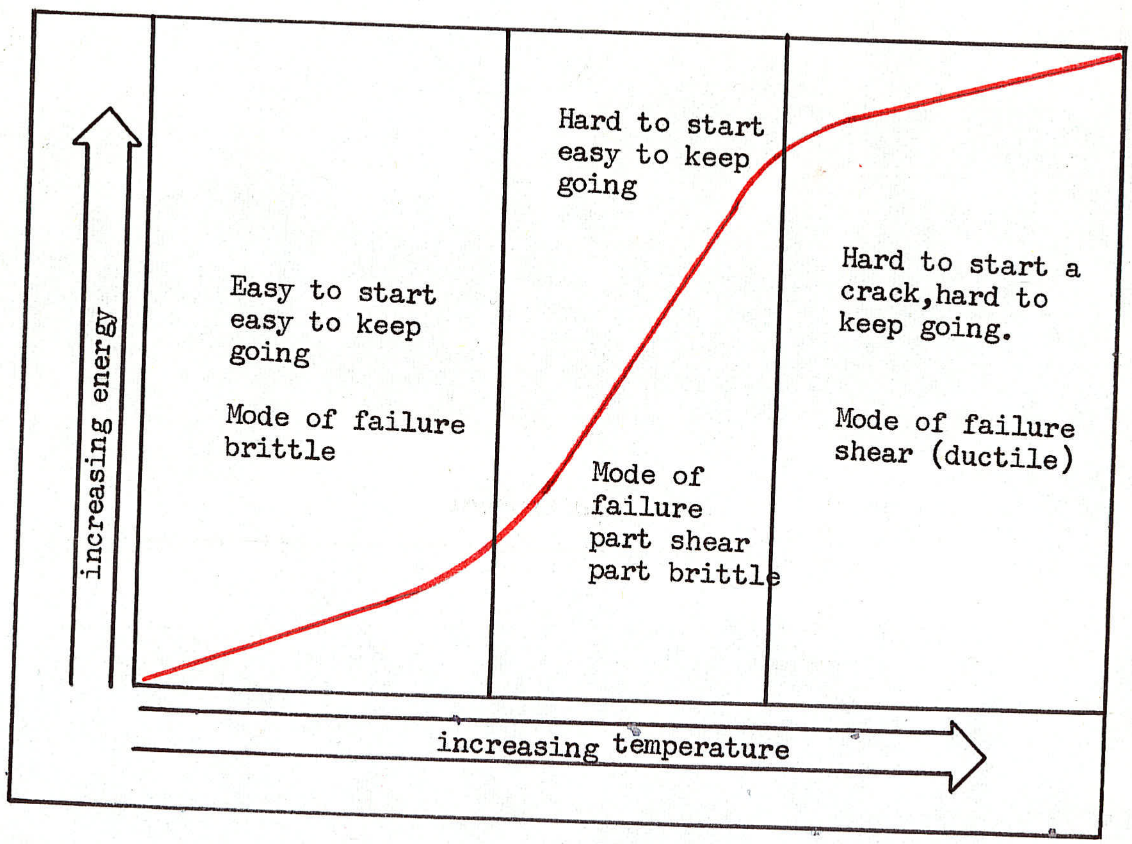
Two Phases of Brittle Fracture

Brittle fracture can be broken down into two phases: crack initiation and crack propagation. The matter of propagation is vital because experience and tests show that brittle cracks, once started, can propagate at the speed of sound - Mach 1 ! Once started, sometimes average stresses as low as five thousand p.s.i. will keep them going.



Tensile Strength p.s.i.
150,000
100,000
50,000
Tensile Strength
Yield Strength
Elongation
30
20
10
Per Cent Elongation
-450°F
-200°F
70°F
Effect of Temperature Upon Mechanical Properties

Fig. 5



increasing energy
Easy to start
easy to keep
going
Mode of failure
brittle
Hard to start
easy to keep
going
Mode of
failure
part shear
part brittle
Hard to start a
crack,hard to
keep going.
Mode of failure
shear (ductile)
increasing temperature

Fig. 6

Charpy Impact Test

The Charpy Impact Test is performed at progressively decreasing temperatures, and the results are plotted as in Figure 6[2].

To the right of the figure it will be noted that the specimen absorbs the most energy and the mode of failure is shear. To the left the lowest absorbed energy and the mode of failure is brittle (cleavage). Of even greater structural significance are the three zones dealing with initiation and propagation. Specimens falling into the category at the right are those in which it is hard to start a crack and hard to keep it going. These specimens do not snap in two pieces in the test. They bend and tear from the notch.

Into the zone at the left fall those specimens in which it is easy to start a crack and easy to keep it going. The pieces literally fly apart in the test. In the middle zone it is difficult to initiate a crack, but once started it is easy to keep it going. The downward break in this zone is called the transition range. The transition is from ductile to brittle. The temperature in this range is called the transition temperature.

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[2] Control of Steel Construction to Avoid Brittle Failure. New York, Welding Research Council 1957, page 21.

Manufacturing Affects Transition Range[3]

The Charpy test (and other tests) evaluates common steels in terms of transition temperature, as affected by chemistry, steel-making practices, and heat-treatment.

The presence of certain elements and their amounts in steel with respect to each other is another variable which affects the ductility and toughness of steel[4].

To sum up

(a) the lower the temperature, the greater the susceptibility to brittle fracture.

(b) brittle fracture can occur only under condition of tensile stress.

(c) the thicker the steel, the greater the susceptibility to brittle fracture.

(d) three-dimensional continuity tends to restrain the steel from yielding and increases susceptibility to brittle fracture.

(e) the presence of sharp notches increases susceptibility to brittle fracture.

(f) Multiaxial stresses will tend to restrain yielding and increase susceptibility to brittle fracture.

---

[3] Parker, Earl R. Brittle Behaviour of Engineering Structures (New York, John Wiley and Sons Inc. 1957) p.44.

[4] Stout, Robert D. and W. D'Orville Doty Weldability of Steels (New York Welding Research Council, 1953) p. 37.

(g) the higher the rate of loading, the greater susceptibility to brittle fracture.

(h) brittle fracture occurs only under conditions of increasing rate of stress.

(j) weld cracks can act as severe notches.

CHAPTER II

STATEMENT OF THE PROBLEM

The purpose of this investigation is to study C.S.A. G40.12 (killed) steel under conditions of reduced ductility. The Standard Tension Test, the Charpy Impact Test, the Kinzel Bend Test and the Large Tension Test were performed on the steel to achieve the necessary results.

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. (See Figure 1). 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 fracture is bright and granular. This is an indication of brittle fracture. A surface resulting from a shear failure is fibrous, grey and silky. This is an indication of a ductile failure[5].

The Standard Charpy Impact Test measures the notch toughness of a material which is a measure of the energy required to cause failure. (See Figure 6).

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

The Kinzel Notch Bend Test is one of the many tests used to determine the effects of welding on the notch toughness of steel[6].

The criteria used to evaluate the transition temperature of the notch bend test consists of the per cent of lateral contraction at the base of the notch and the angle of bend at the maximum load. These are both compared at different temperatures[7].

Large Tension Tests

The Large Tension Tests were performed in an attempt to place the steel under varying service conditions. The conditions considered were temperature, strain rate, prestrain before and after notching, and welding stresses in the presence of a notch.

Limitations of the Investigation

Metals react differently under variables of geometry, temperature, loading condition, and metallergical properties. As a result due to these variables, it is impossible to obtain exact correlation between test results on different specimens.

An attempt has been made to keep these variables down to a minimum in this investigation.

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[6]Robert, D. Stout and W. D'Orville Doty, Weldability of Steels (New York Welding Research Council, 1953), p. 246

[7]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-s, (1960).

Glossary of Terms

Brittleness: A tendency to fracture without appreciable deformation and or energy absorption.

Brittle Fracture: That type of fracture ordinarily characterized by its bright crystalline appearance due to the abrupt splitting open of the metallic crystals or grains on certain crystallographic planes, referred to as cleavage planes.

Cold Working: Plastic deformation of a metal carried out below the metal's recrystallization temperature: work-hardening occurs.

Ductility: That property which is characterized by the ability of a material, subjected to tensile stress, to undergo permanent deformation before fracture.

Ductility Transition Temperature: That temperature above which cleavage fracture can be initiated only after appreciable plastic flow at the base of a notch, and below which cleavage fracture will be initiated with little evidence of notch ductility.

Elastic Behaviour: Behaviour characterized by small deformations or strains which are proportional to stress. The material returns to the original dimensions after release of stress.

Elastic Strain Energy: The energy stored in a metal during the course of elastic deformation.

<u>Electrode Classification</u>: The specified characteristics of an electrode are expressed by the C.S.A. Welding Code classification number of the electrode.

<u>Fibrous Fracture</u>: The term used to designate a ductile shear type fracture of steel. The fracture is characterized by the fibrous or woody appearance of the fractured surface.

<u>Fracture Appearance Transition Temperature</u>: This transition temperature, which is concerned with crack propagation, is associated with the change from a fibrous shear type fracture to a predominantly cleavage type fracture. This term is frequently shortened to <u>Fracture Transition Temperature</u>.

<u>Granular Fracture</u>: A term describing the appearance of a particular type of fractured surface. A granular fracture is one which makes evident the existence of grains. The term is often used to describe the appearance of a fracture that takes place in the cleavage mode.

<u>Heat-Affected Zone</u>: That portion of the base metal which has not been melted but whose mechanical properties or microstructure have been altered by the heat of welding.

<u>Normalizing</u>: Heating to a suitable temperature above the transformation range and subsequently cooling in still air at room temperature.

<u>Notched Bar Transition Temperature</u>: One of several arbitrarily defined transition temperatures determined by the results of notched bar impact or bend test, such as the Charpy test.

Notch Brittleness: The inability of a metal to yield plastically under the action of constraint and high local stresses, as for example, at the root of a notch.

Notch Ductility: The ability and capacity of a metal to yield plastically under constraint and high local stress, as for example, at the root of a notch.

Notch Sensitive: A tendency to brittle behaviour in the presence of a notch, discontinuity or stress concentrator.

Notch Toughness: A tendency to plastic flow with energy absorption even in the presence of a notch, discontinuity or stress concentrator.

Residual Stress: Microscopic stresses remaining in a metal or a structure as a result of nonuniform plastic deformation. This deformation may be caused by mechanical cold working or by temperature effects.

Shear Fracture: A type of fracture in which there is large deformation preceding fracture caused by parallel planes in metal crystals sliding so as to retain their parallel relation to one another.

Shear Lip: The later of surface fracture which often accompanies brittle failure - i.e., ductile edging of the fractured surface. In service failures, the shear lip is usually very thin.

Stress Relieving: A process of reducing the magnitude of residual stressed by heating the object to a suitable temperature and holding for a sufficient time, followed by a controlled rate of cooling.

Thermal Stress: The stresses existing in metals because of nonuniform temperature distribution or because of a temperature change under conditions involving restraint.

Toughness: The property, involving both ductility and strength, of absorbing considerable energy before fracture.

Transition Temperature: That temperature at which a specimen or structure exhibits some change in fracture behaviour, as evidenced by a change in some characteristic, such as energy absorption or fracture appearance.

True Stress: In the tensile test true stress is the axial load divided by the instantaneous area.

Work Hardening: An increase on hardness of a metal during and by the action of plastic deformation.

CHAPTER III

LABORATORY PROCEDURE

The tests performed can be divided into two sections:

1. Standard Tests:

   (a) Standard Tension Test

   (b) Charpy V Notched Impact Test

   (c) Kinzel Notch Bend Test

2. Notched Tension Tests

   Test 1 - tension test with no prestrain

   Test 2 - tension test after tensile prestrain (notch not present during prestraining)

   Test 3 - tension test after compressive prestrain (compressive prestrain was without the notch present)

   Test 4 - tension test after compressive prestrain (compressive prestrain was with the notch present)

   Test 5 - tension test with residual welding stresses present

All specimens were constructed from rolled bar 8 inches by 3/8 of an inch thick. The edges were left as rolled.

The bar material conformed to C.S.A. G40.12 General Purpose Structural Steel. The bar was rolled at the Manitoba Rolling Mills Division of Dominion Bridge Co. Ltd., Selkirk, Manitoba.

I. STANDARD TESTS

Construction of Test Specimens

The Tension specimens, shown in Figure 7, were manufactured according to A.S.T.M. E8-61T[8] except for a change from an 8 inch to a 2 inch gauge length. All specimens were cut parallel to the grain.

The Charpy impact specimens, shown in Figure 8, were manufactured according to A.S.T.M. EGO[9]. 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 tolerances.

The Notch Bend specimen, shown in Figure 9, was constructed to conform to the Kinzel type[10]. 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 E6011 electrode at a rate of 6 inches per minute, acurrent of 110 amps and a voltage of 25 volts. A standard Charpy notch was placed transversely across the specimen and through the weld having the standard notch depth in the base metal.

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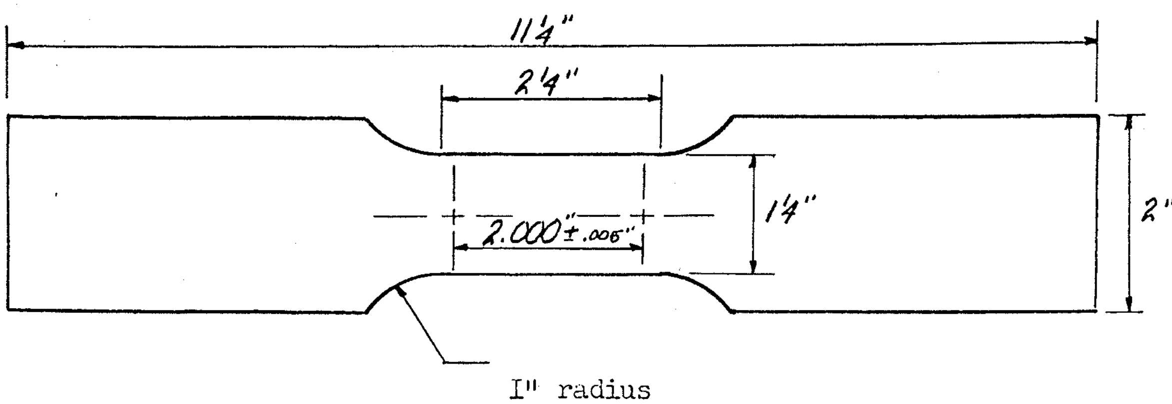
[8] A.S.T.M. Standards 1961 Part 1. Ferrous Metals Specifications, E8-61T p. 165.

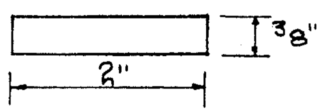
[9] A.S.T.M. Standards 1961 Part 3. Metals Test Methods, E 23-60 p. 79

[10] Stout, Robert D. and W. D'Orville Doty. Weldability of Steels, (New York Welding Research Council, 1953, p. 246)

Fig. 7



Plan View



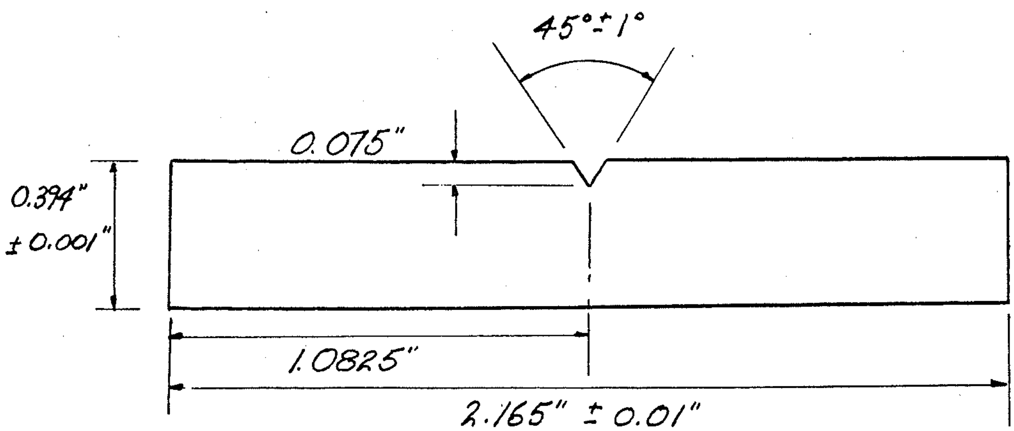
End View

Tension Specimen (A. S. T. M. E 8-61T)

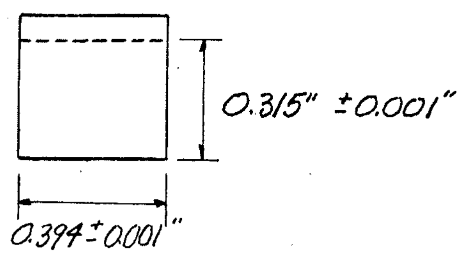
Cut 5 Parallel to grain

Material to conform to C. S. A. Standard G 40.12 See Fig.17

Fig. 8



Elevation View



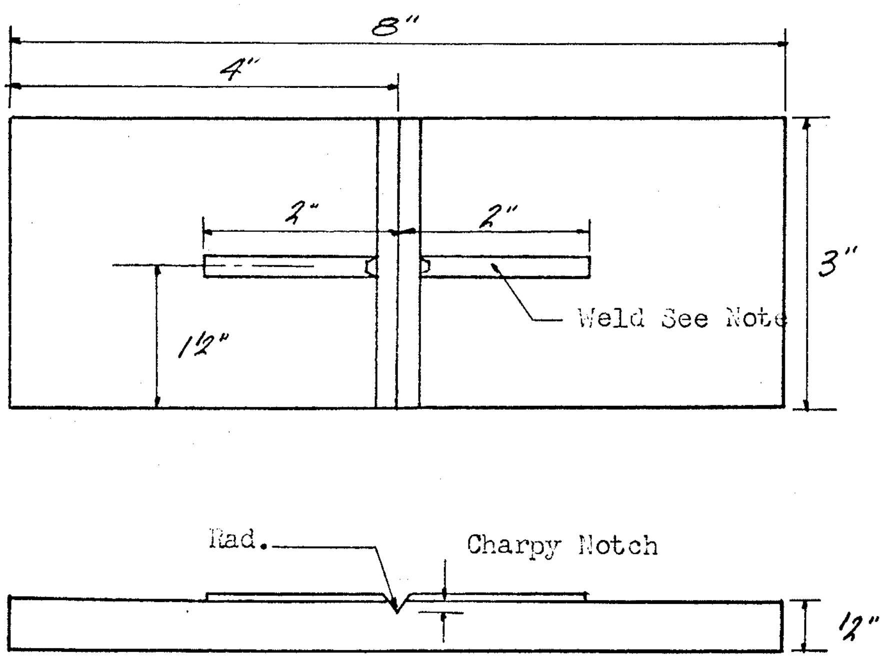
End View

Charpy Impact Specimen (A. S. T. M. E-60)

Cut 27 parallel to grain
Cut 27 perpendicular to grain

Material to conform to C. S. A. Standard G40.12 Steel See Fig.17

Fig. 9



Note - Weld use 3/16" Diam. E6011 electrode at a rate of 6" per minute 110 amps and 25 volts.

Kinzel Notch Bend Specimens

Cut 10 parallel to grain (weld 5 only as shown)
Cut 10 perpendiculær to grain (weld 5 only as shown)

Material to conform to C. S. A. Standard G40.12 Steel See Fig. 17

Test Equipment

The machine used for the Standard Tension Test was the Riehle 60,000 pound Precision Hydraulic Universal Testing Machine. The strain gauge used was an Ames indicator Model 272.

The machine used for the Charpy Impact Test was the Olsen Impact Testing Machine. This machine has a Charpy test capacity of 264 foot pounds at a striking velocity of 16.5 feet per second. The coolant used was a mixture of acetone and solidified carbon dioxide. A Farenheit thermometer with a range of +60°F to -110°F was used for the temperature measurements.

The apparatus used to perform the Standard Notch Bend Test is shown in photograph 1. The machine used to supply load was the Baldwin 30,000 pound P.T.E. 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°F to -110°F.

Test Procedure

The standard tension test was performed at room temperature of +70°F. Strain readings were performed at load increments of 1,000 pounds. This rate of loading, to allow for the taking of strain readings, was approximately 4,000 pounds per minute. The yield and ultimate strengths were recorded.

All the Charpy Impact specimens were placed in the anvil with the notch in tension. They were tested at temperatures ranging from +70°F to -100°F. In all cases the testing procedure followed standard A.S.T.M. E23-60 procedures.

In the Notch Bend Test the specimen was placed on the rollers, as shown in Figure 10, 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 +20°F, 0°F, -30°F, -60°F and -80°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. The load was applied at a steady rate of approximately 40,000 pounds per minute. When the ultimate load was reached, the load was rapidly released.

II. LARGE TENSION TEST

Construction of Test Specimens

All specimens were 8 inches wide, 3/8 inch thick and 20 inches long. The specimens had bars welded on the end to provide a grip for pulling in tension. The dimensions of these specimens were such that the width was larger than 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.[11] The notch shown in Figure 12 was used in all the large tension specimens. (See Figure 11 for the construction of the large tension specimens). The jeweller's saw cut was used to provide the initiation of the fracture.

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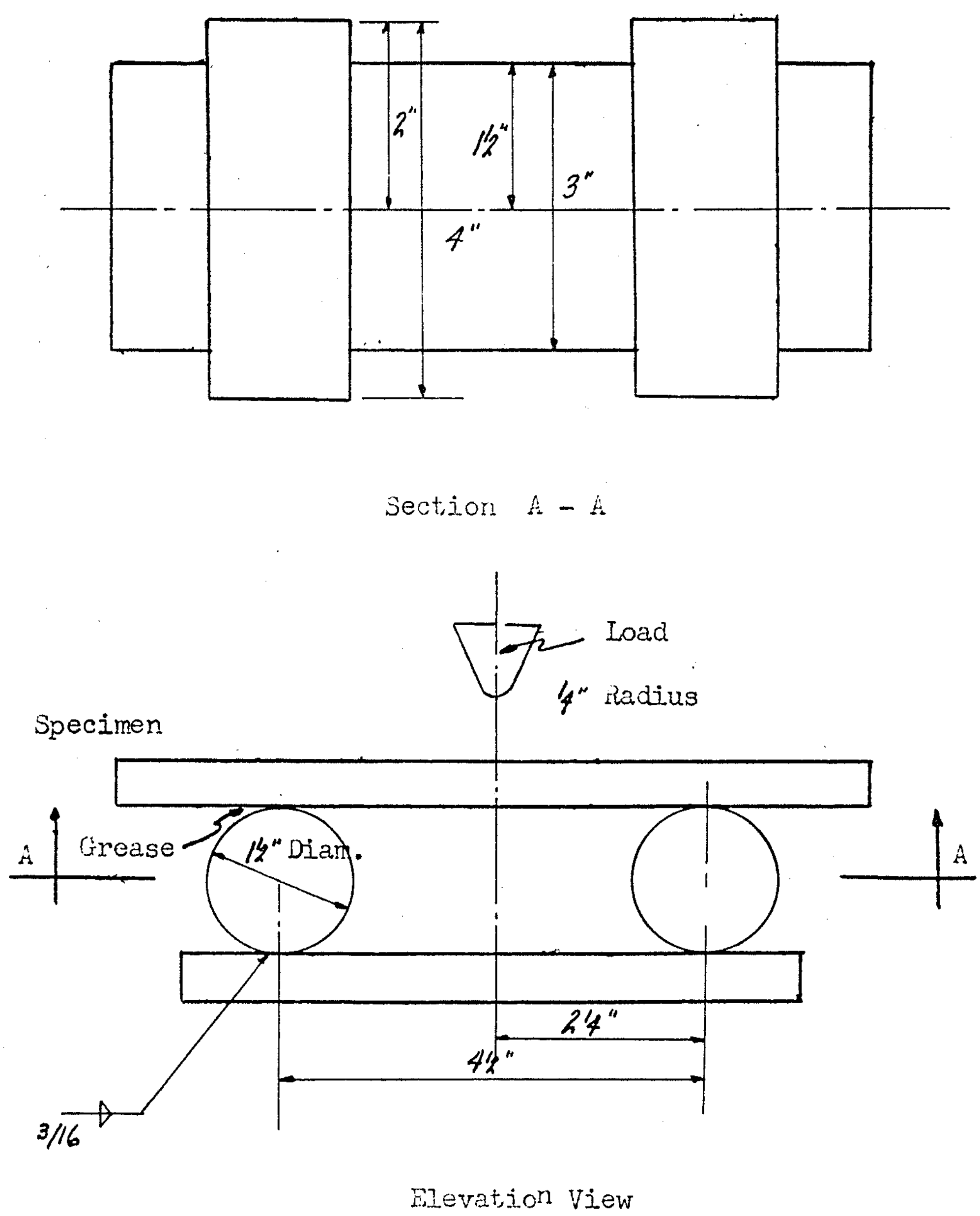
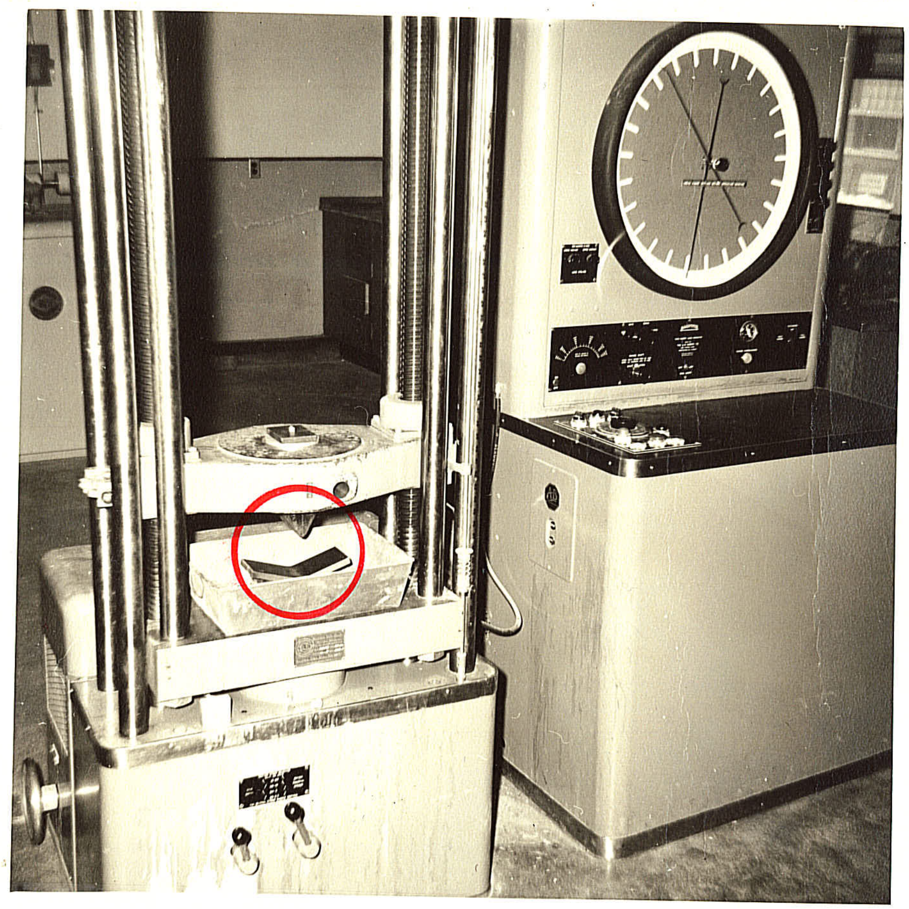
[11] A.S.T.M. Committee on Fracture Testing of High Strength Sheet Materials. Fracture Testing of High Strength Sheet Materials. A.S.T.M. Bulletin, January 1960, No. 243, pages 29 and 31.

Fig. 10



Kinzel Notch Bend Test set up



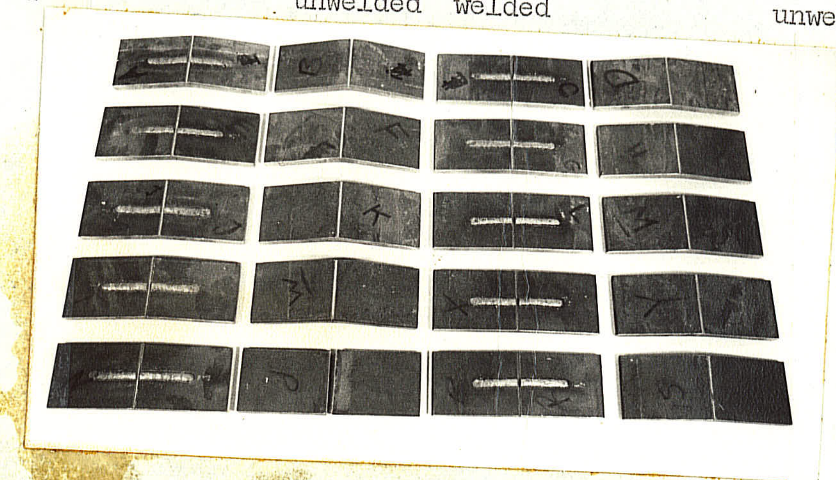
Photograph No. 1

The Kinzel Notch Bend Test set up showing the Baldwin 30,000 pound P.T.E. testing machine.

Cut // to direction of rolling — welded | unwelded
Cut ⊥ to direction of rolling — welded | unwelded

Temperature °F

20°
0°
-30°
-60°
-80°

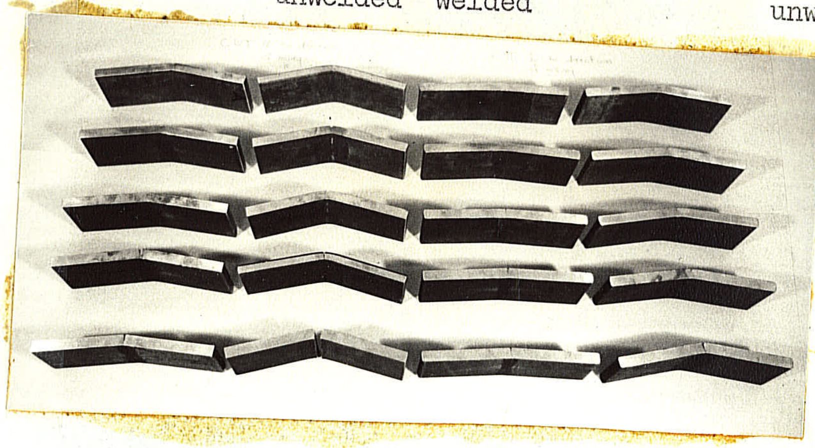


Photograph 2
Kinzel Notch Bend Test specimens after testing - plan view

Cut // to direction of rolling — welded | unwelded
Cut to direction of rolling — welded | unwelded

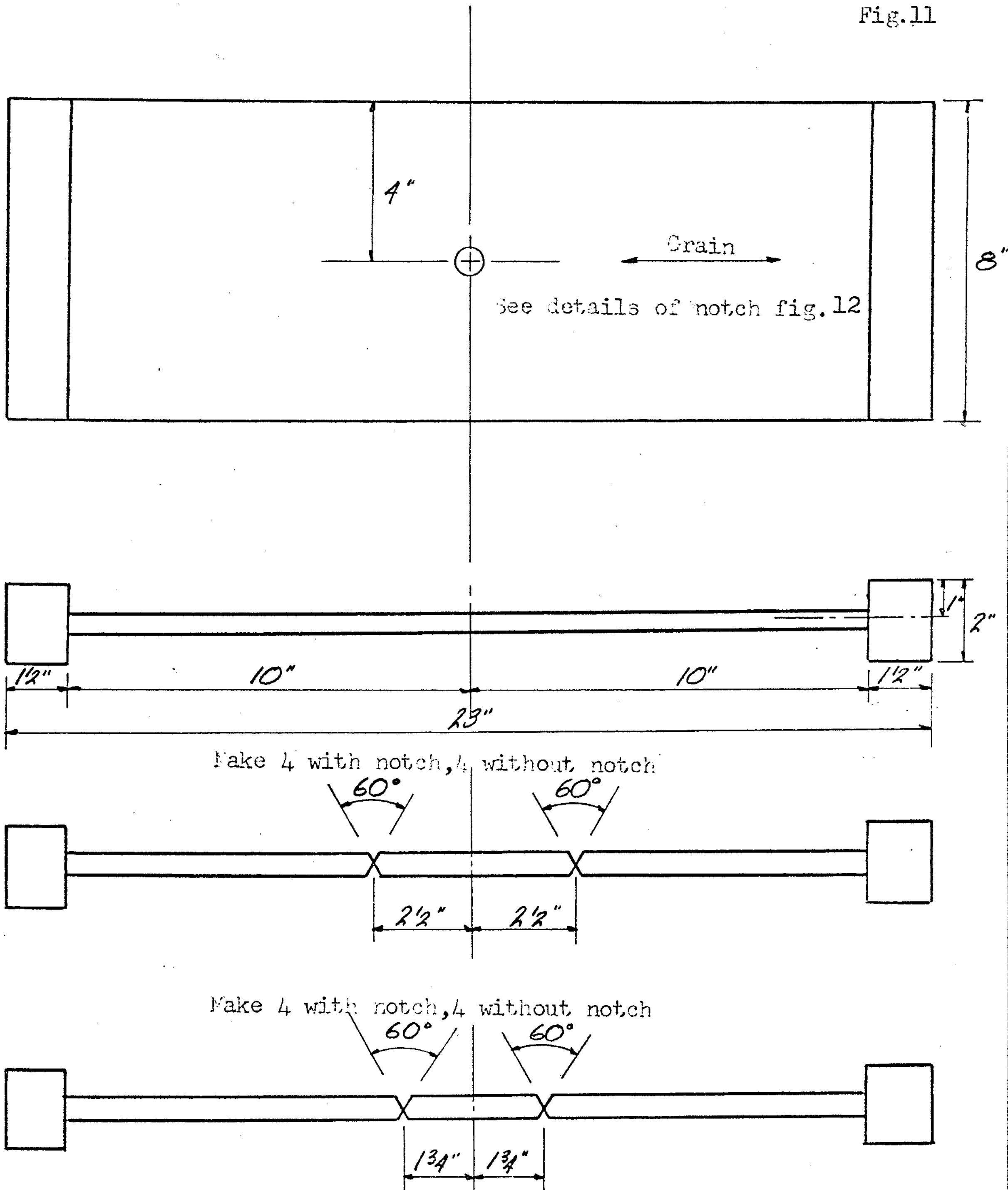
Temperature °F

20°
0°
-30°
-60°
-80°



Photograph 3
Kinzel Notch Bend Test specimens after testing - side elevation

Fig.11

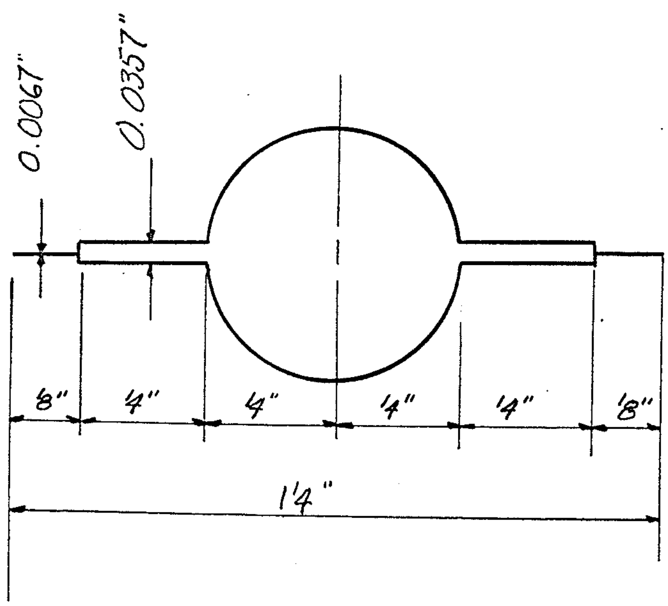


Make 4 with notch

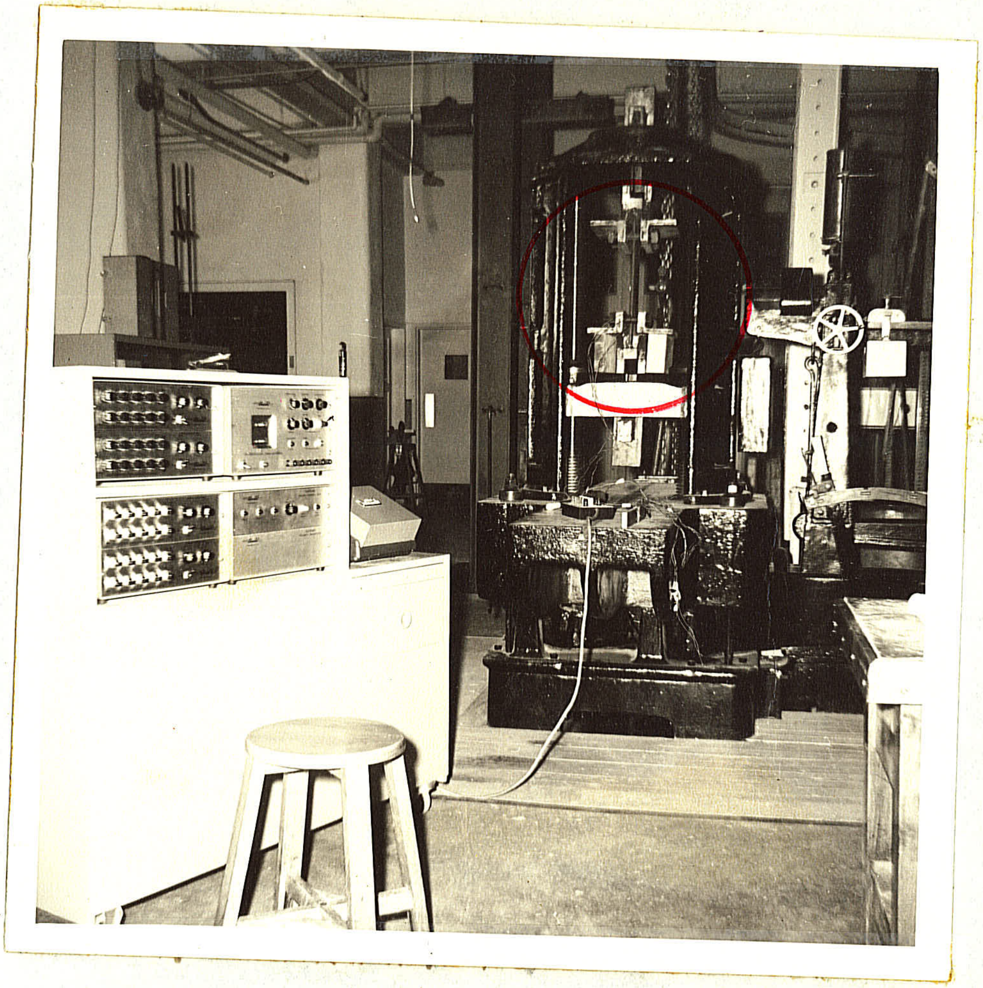
Note- all steel to conform to C. S. A. standard G40.12

Large Tension Specimens

Fig.12



Standard notch for large tension specimens



Photograph 4

Large Tension Test set up showing the Riehle 200,000 pound screw type testing machine and the Dalton Digital Strain Indicator at the left.

The Type 1 series contained no prestrain. The series was tested after the notch was inserted.

The Type 2 series was similar to the Type 1 series, except that a tensile prestrain beyond the yield point was given to the specimen before the notch was inserted.

In the Type 3 series a 5 inch strip was removed centrally from the specimen. The edges of this strip were bevelled with a double V bevel to make it easier to compress and to ensure satisfactory weld.

After the specimen was compressed in the special apparatus shown in Figure 15, and photographs 5 and 6 and passed its yield point, a notch was cut in it and was welded back into the specimen. The weld was made with a 3/16 inch diameter E7018 electrode according to C.S.A. W48.1-1962. Wet cloths were placed against the weld to protect the strain gauges from heat generated during welding.

The construction of the Type 4 specimen were similar to that used for the Type 3 specimen except that the notch was inserted in the central strip before it was compressed.

In the Type 5 series a 3.5 inch strip was removed from the centre of the specimen and welded back. The 3.5 inches was selected because research has shown that maximum residual stresses occur from one to two inches from the weld.[12]

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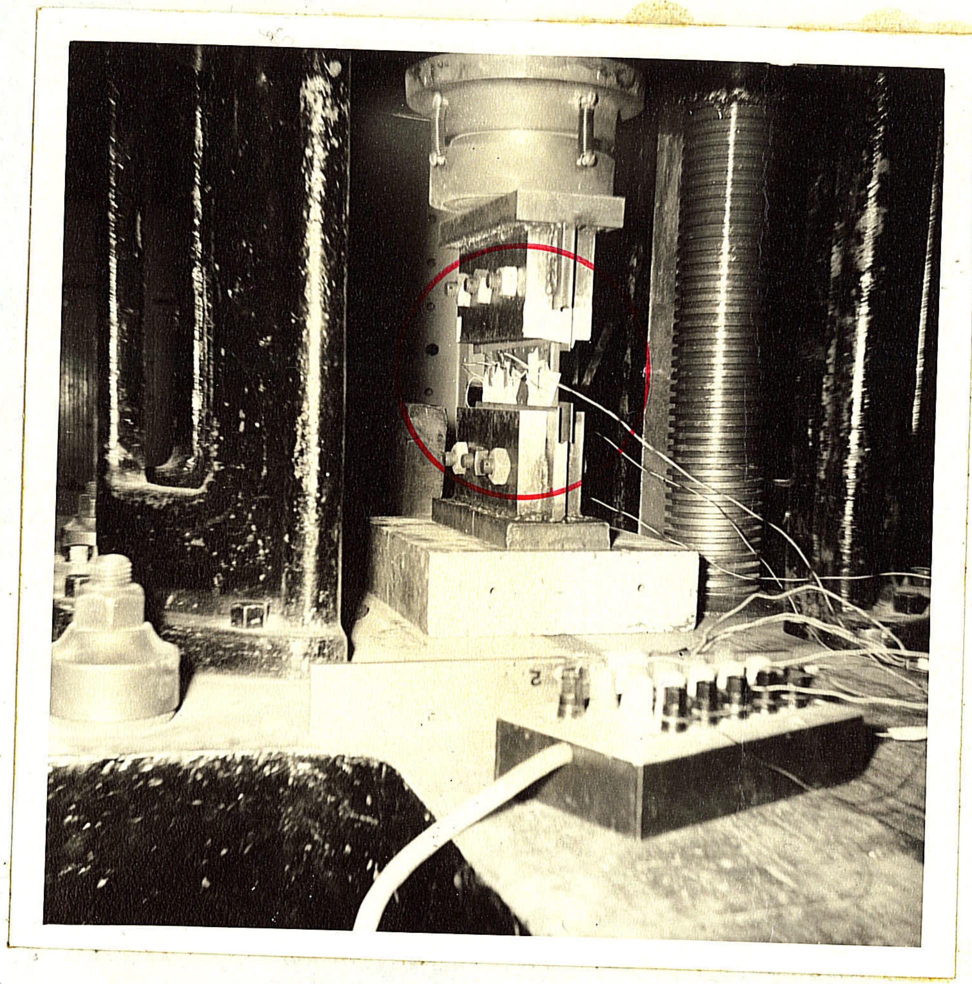
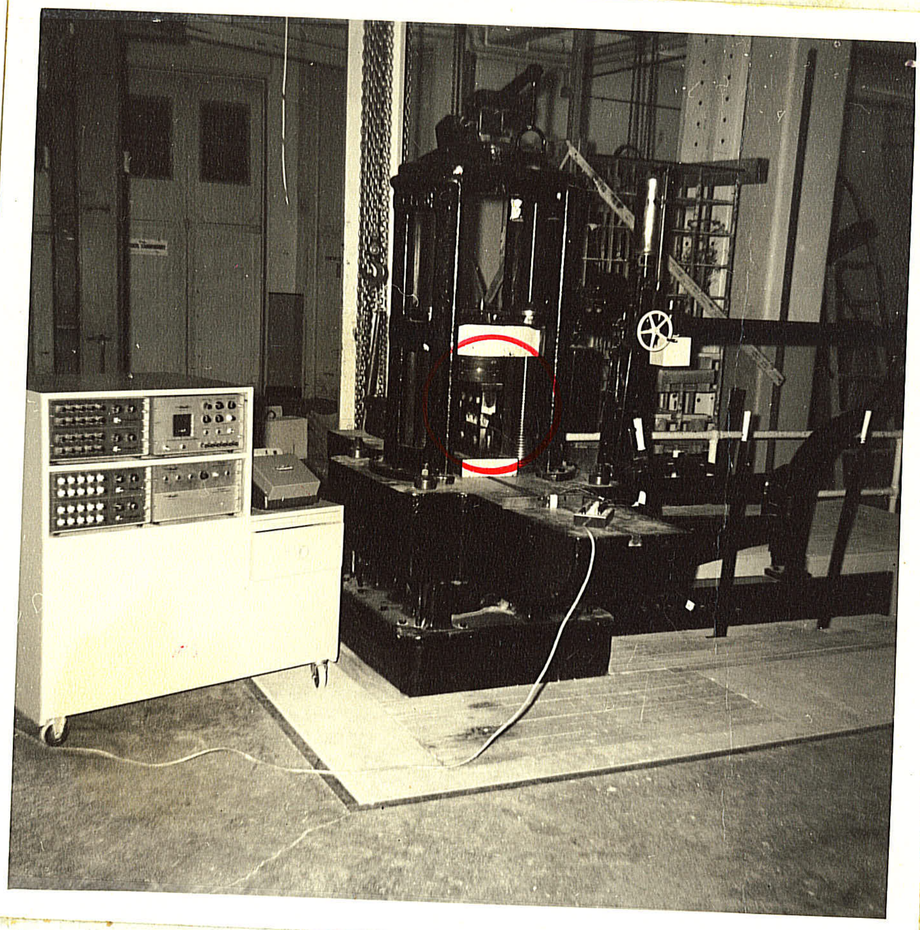
[12]Nagaraja Rao, N.R. and Lambert Tall. Residual Stresses in Welding Plates. The Welding Journal 40 (10) Research Supplement, 468-S to 480-S (1961).



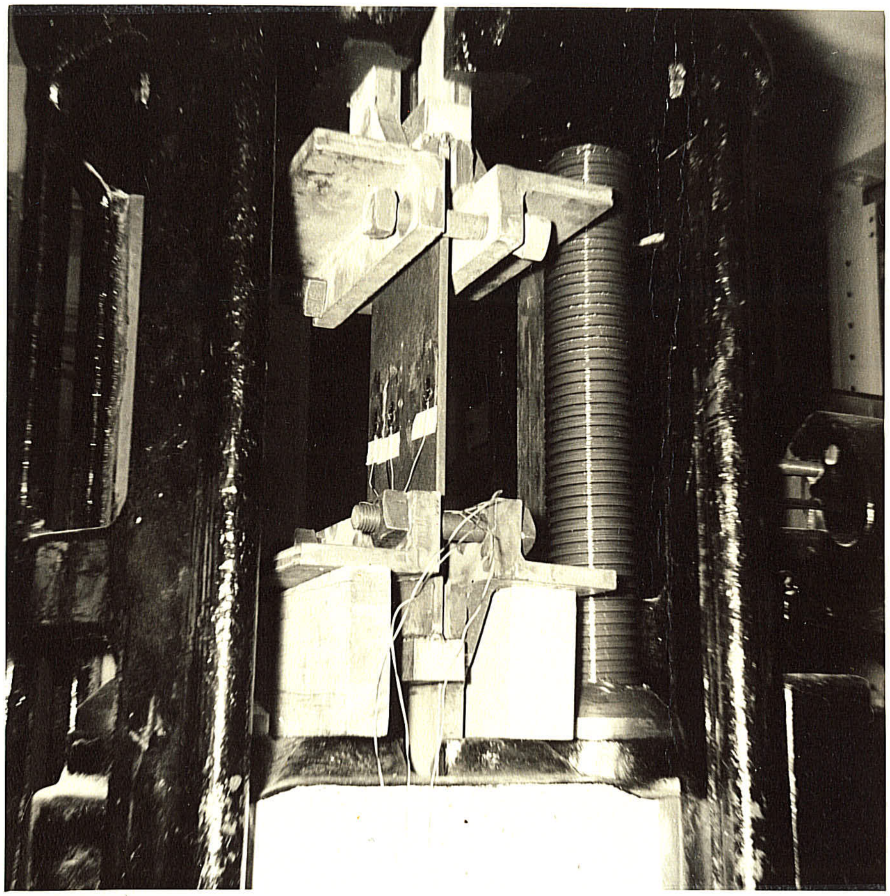
Photograph 5

Close up of the precompression of a large tension test specimen.



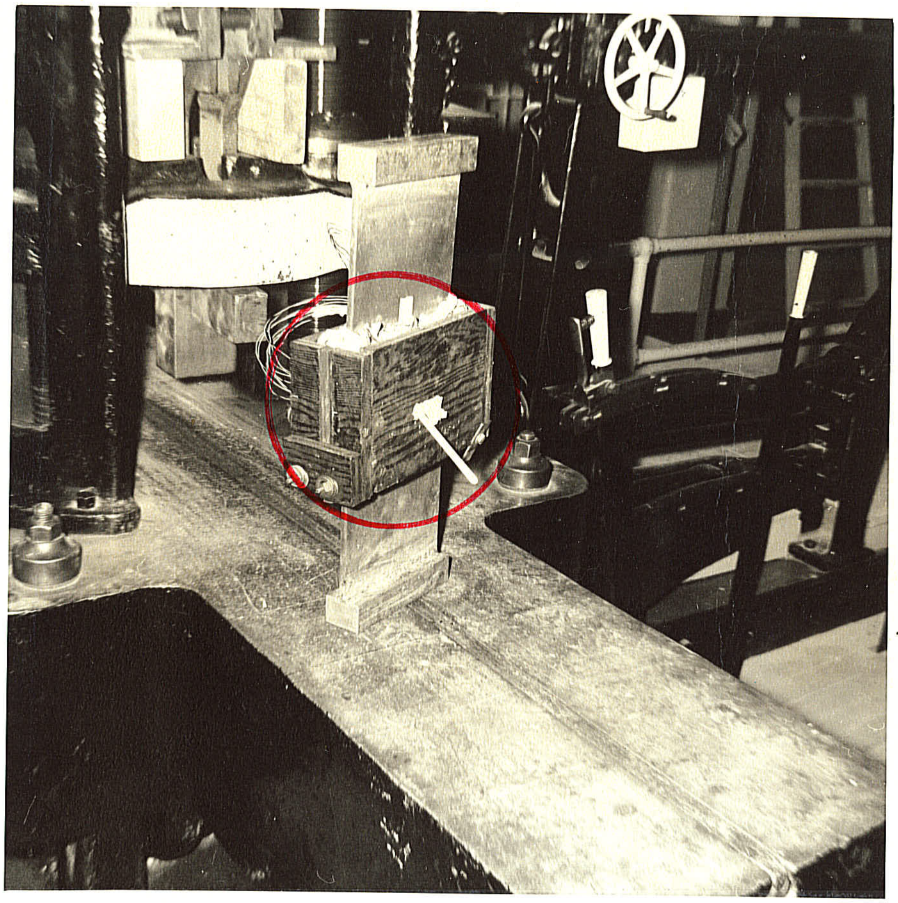
Photograph 6

Overall view of the test set up of Photograph 5.



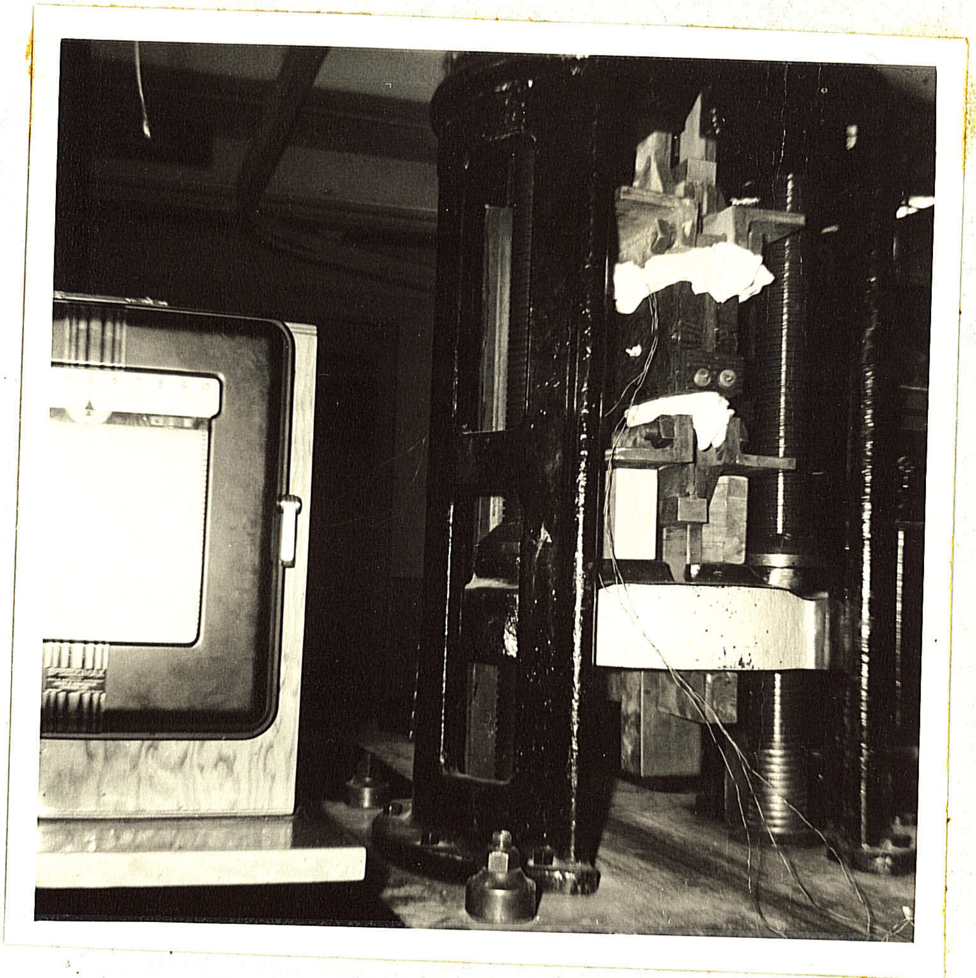
Photograph 7

Close up of a specimen for test series one of the Large Tension Tests.



Photograph 8

Cooling of Large Tension Test specimen.



Photograph 9

A Large Tension Test specimen set up in the testing machine ready for loading. Note the Speedomax type 6 temperature recording instrument.

During welding the other end of the test specimen was immersed in water to prevent the heat damaging the strain gauges. All welding was done with 3/16 inch diameter E7018 electrode according to C.S.A. W42.1-1962.

Instrumentation

The instrumentation shown in Figure 13, remained identical for each type series tested. The SR-4 type PA-3 post yieldstrain 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 GW-1 was placed over the gauge and leads. All strain readings were made by Darton Digital Strain Indicator.

For measurement of residual strain due to welding in the Type 5 series SR4 type A7 strain gauges were attached to the specimen and read by the portable strain indicator Model P-350.

Thermo-couples, used for temperature measurement, were constructed from 24 gauge copper construction wire and were oriented on the specimen as shown in Figure 13. A compound called Thermon was used to set the thermo-couples into the specimens. 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°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 specimen to the heads of the machine and to precompress the specimen were constructed from A7 steel as shown in Figures 14 and 15.

These were constructed for a previous study.[13]

The coolant used was solidified carbon dioxide. The cooling chamber was constructed as shown in Figure 16. The box was filled with the solid carbon dioxide. Direct contact between the coolant and the steel was prevented by insulating sheets between the steel and the solid carbon dioxide coolant.

Test Procedure

In each series of the tests, except test series 5, one plate was tested at +70°F, two at 0°F and one at -30°F. For test series 5, one plate was tested at +70°F, two at 0°F and one at -60°F. At 0°F one test was carried out at a faster rate than the other in order to see if this made a difference in the results. Each specimen was taken to destruction.

In test 3 and 4 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 5, 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.

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[13]Butterfield, William Henry. A Study of Brittle Fracture Initiation in Prestrained Notched Steel Tension Specimens

Fig. 13

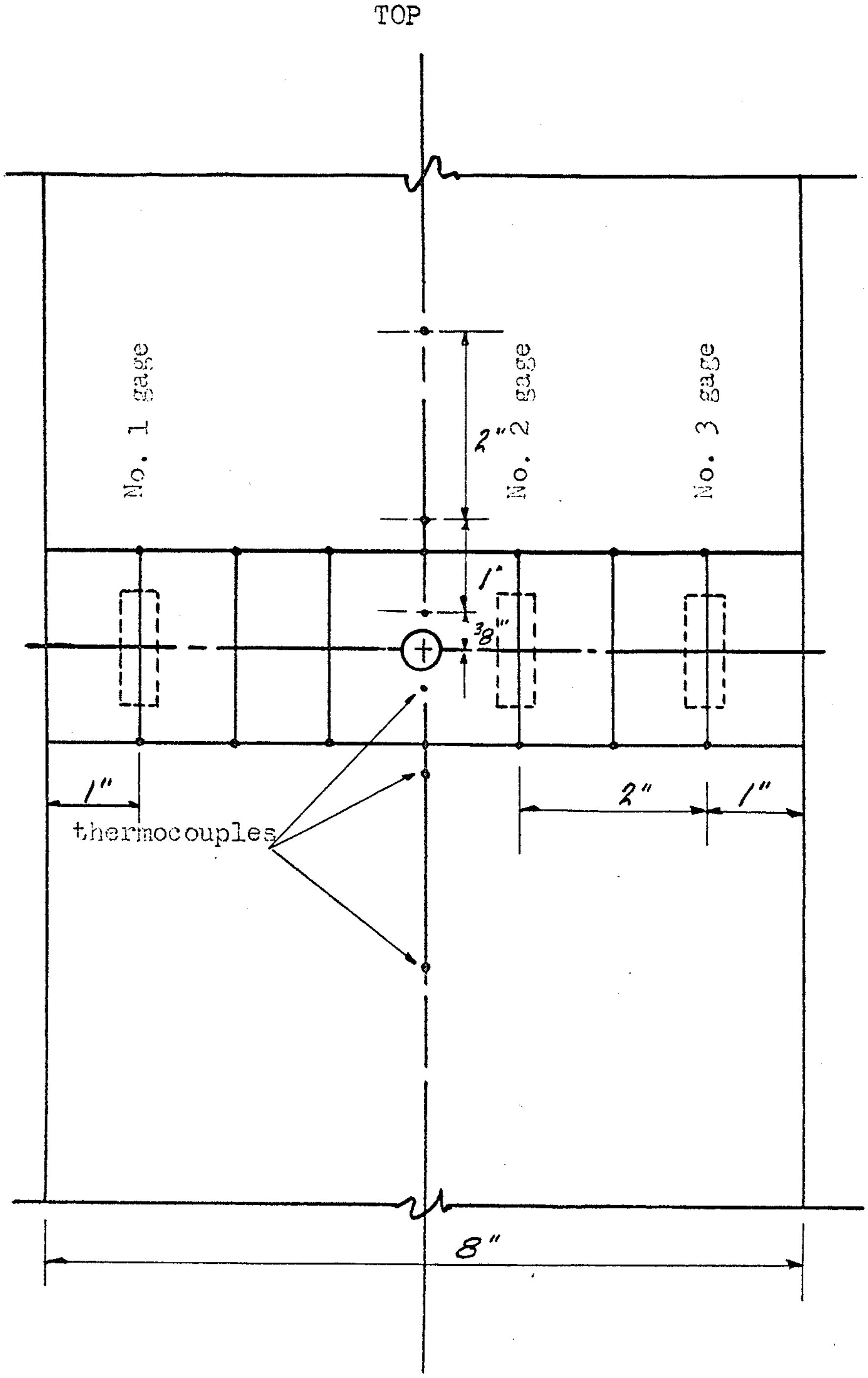
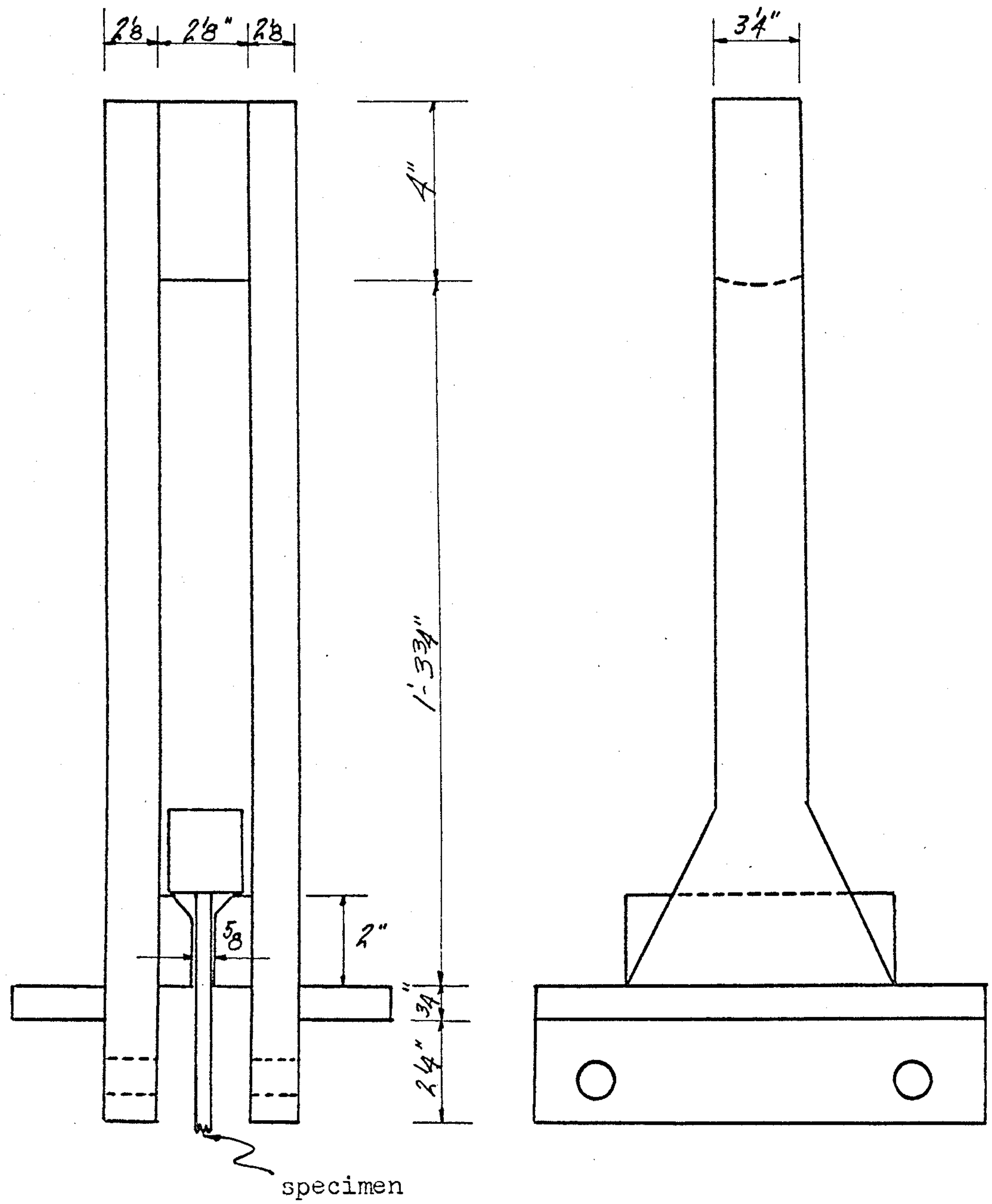


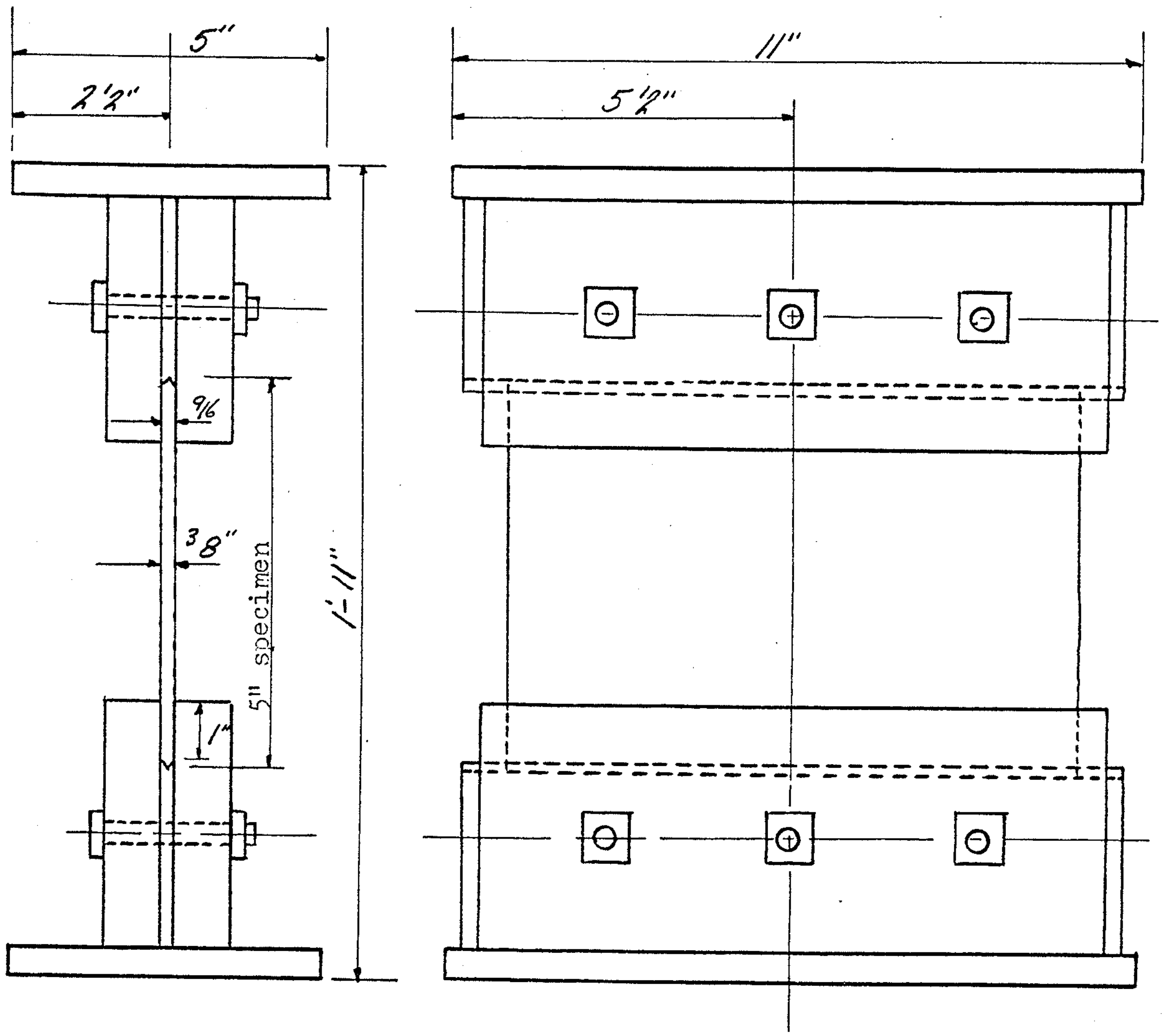
Diagram showing strain gage and thermocouple layout for large tension specimens

Fig. 14



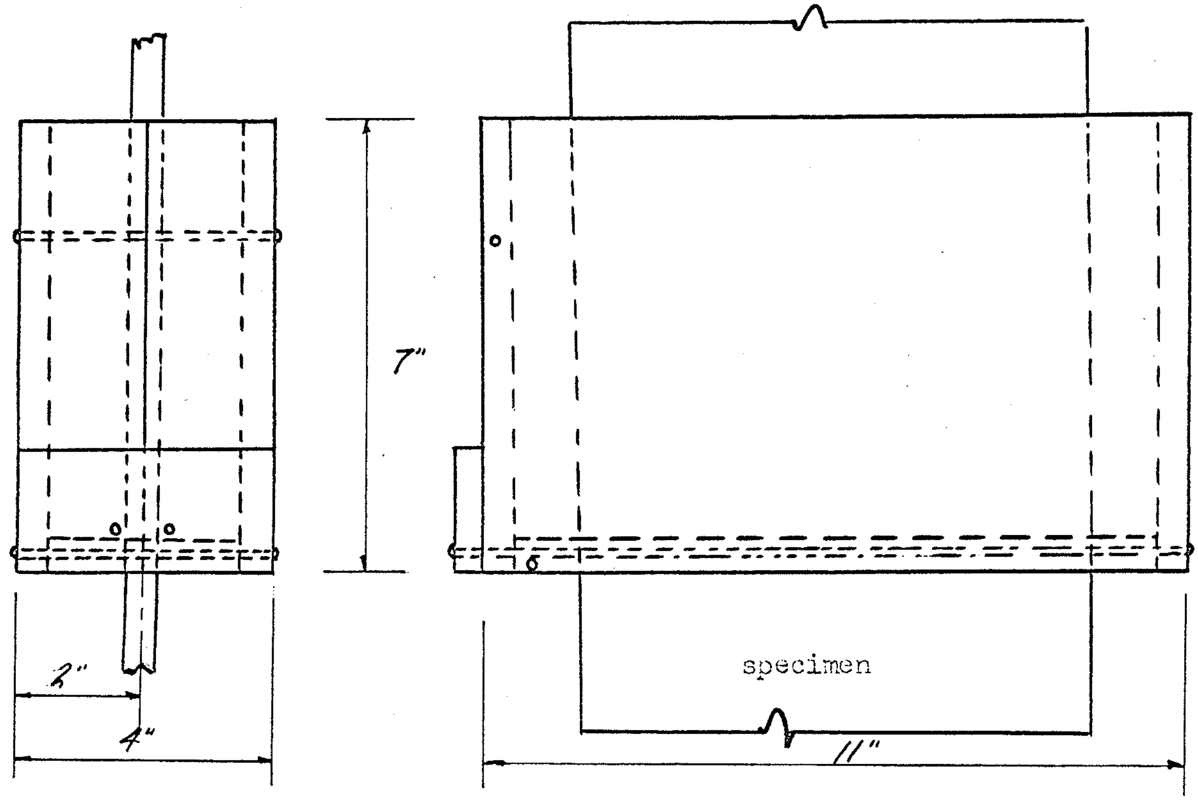
Details of grips used to pull large tension specimens

Fig. 15



Details of the compression apparatus for prestraining specimens types 111 and 1V

Fig. 16



Details of cooling jacket for large tension specimen.

CHAPTER IV

RECORDED TEST DATA

Standard Tension Test

Five specimens were tested. The strain readings were tabulated for each one thousand pound load increment. The areas of each specimen were calculated and an average value of yield stress and ultimate tensile strength for the material was attained as shown in Figure 17.

Charpy Impact Test

The energy in foot pounds at each temperature was recorded and graphically shown in Figure 18.

Kinzel Notch Bend Test

The test data 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 at different temperatures.

This data was plotted as shown in Figure 19.

Notched Tension Tests

From tables 5 to 8, 13 to 16, 21 to 24, 29 to 33 and 37 to 39 inclusive, the load was measured in pounds and the gauge readings were measured in micro-inches per inch. The gauge readings were taken until the gauges failed. The temperatures indicated on the table were the average temperature of the specimen during the test.

Temperature Readings

The Standard Tension Tests were taken at room temperature of +70°F. The temperature was taken by a Fahrenheit thermometer.

For the Charpy Impact Tests, the temperatures taken were the temperatures of the bath that the specimen was in. The specimens were left to cool in the bath for ten minutes before they were tested. Temperatures were taken by a Fahrenheit thermometer.

For the Kinzel Notch Bend Tests, the specimens were placed in a bath and allowed to cool for ten minutes before testing. The temperature was kept constant during the tests. Temperatures were taken by a Fahrenheit thermometer.

For the Notched Tension test, the temperatures were taken by thermocouples. The thermocouples were placed in holes that were drilled into the steel specimens. The temperature was kept constant throughout the tests.

TABLE I

STANDARD TENSION TEST ON G40.12 STEEL

TEMPERATURE +70°F

Mark Number	Thickness(inches)	Width(inches)	Area(square inches)
A	1.243	0.376	0.467
B	1.243	0.377	0.469
C	1.241	0.376	0.467
D	1.243	0.377	0.469
E	1.243	0.377	0.469

TABLE II

STANDARD TENSION TEST ON G40.12 STEEL

Gauge Readings in Micro-Inches per Inch

Load Pounds	A	B	C	D	E
1,000	0	10	0	0	60
2,000	25	60	10	20	200
3,000	90	110	90	100	310
4,000	150	160	190	120	550
5,000	200	210	280	150	690
6,000	250	275	370	180	800
7,000	310	340	460	220	900
8,000	380	390	550	260	970
9,000	450	450	650	310	1,060
10,000	520	510	760	360	1,150
11,000	590	580	850	410	1,250
12,000	650	620	940	470	1,340
13,000	700	680	1,010	510	1,420
14,000	760	750	1,090	570	1,540
15,000	820	810	1,150	650	1,630
16,000	890	900	1,210	740	1,900
17,000	950	980	1,290	850	2,200
18,000	1,010	1,050	1,400	1,000	2,650
19,000	1,030	1,175	1,600	1,250	3,300
20,000	1,030	9,700	12,500	10,600	13,500
21,000	12,850	10,950	14,900	12,350	15,000
22,000	14,750		17,200	14,100	16,500
23,000	16,900		18,700		17,900
24,000	19,150		20,070		24,000
25,000					28,300
Yield Load Pounds	20,000	19,500	19,700	19,200	19,600
Ultimate Load Pounds	34,000	34,350	34,200	34,350	34,200
Elongation in 2 inches % at Rupture	36.0%	36.0%	36.5%	37.0%	37.0%

Speed of Load Application 0.05"/min.

TABLE III

CHARPY IMPACT TEST ON G40.12 STEEL

Parallel to Grain			Transverse to Grain		
Temperature °F	Absorbed Energy Ft. Lbs. Test 1	Test 2	Temperature °F	Absorbed Energy Ft. Lbs. Test 1	Test 2
70	120	118	70	42	38
60	138	128	60	46	38
50	124	128	50	34	42
40	130	102	40	34	28
30	114	130	30	32	32
20	108	106	20	26	28
10	106	62	10	26	24
0	126	92	0	18	24
-10	70	70	-10	22	20
-20	36	80	-20	18	24
-30	44	-	-30	16	-
-40	14	-	-40	14	-
-50	8	-	-50	8	8
-60	6	-	-60	4	-
-70	8	-	-70	3	-
-80	4	-	-80	0	-
-90	0	-	-90		
-100			-100		

TABLE IV

Kinzel Notch Bend Test on G40.12 Steel

Parallel to Grain

Welded

Temperature °F	Mark Number	Ultimate Load Lbs.	% Lateral Contraction at Ultimate Load	Angle of Bend at Ultimate Load
+20	A	12,750	0.67%	19°50'
0	E*	12,900	0.77%	15°15'
-30	J	11,750	0.60%	13°55'
-60	T	12,100	0.97%	17°50'
-80	N	11,225	0.44%	16°50'

Unwelded

Temperature °F	Mark Number	Ultimate Load Lbs.	% Lateral Contraction at Ultimate Load	Angle of Bend at Ultimate Load
+20	B	13,300	1.25%	30°35'
0	F	13,450	0.68%	29°05'
-30	K	13,900	1.08%	29°05'
-60	W*	13,850	1.68%	39°50'
-80	P*	13,850	1.80%	39°00'

*Fracture

Yield for specimens at temperatures of +20°, 0° and -30° is 6,750#

" " " " " " -60° and 80° is 7,750#

Load applied at 40,000 pounds/minute

TABLE IV (CONT'D.)

Kinzel Notch Bend Test on G40.12 Steel

Perpendicular to Grain

Welded

Temperature °F	Mark Number	Ultimate Load Lbs.	% Lateral Contraction at Ultimate Load	Angle of Bend at Ultimate Load
+20	C	10,300	0.33%	5°05'
0	G	11,450	0.67%	9°10'
-30	L	9,950	0.40%	6°05'
-60	X	9,875	0.30%	5°55'
-80	R	9,750	0.20%	6°10'

Unwelded

Temperature °F	Mark Number	Ultimate Load Lbs.	% Lateral Contraction at Ultimate Load	Angle of Bend at Ultimate Load
+20	D	11,650	0.44%	15°55'
0	H	11,550	0.64%	15°30'
-30	M	11,900	0.84%	15°45'
-60	Y	12,100	0.85%	15°55'
-80	S	12,450	1.07%	17°20'

*Fracture

Yield for specimens at temperatures of +20°, 0° and -30° is 6,750#

" " " " " " -60° and 80° is 7,750#

Load applied at 40,000 pounds/minute

STRAIN READINGS FOR TENSION TEST WITH NO PRESTRAIN

TABLE V

Specimen T1-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load Pounds	1	2	3
0,000	-1	-1	0
5,000	-40	-44	-18
25,000	171	198	184
35,000	294	368	330
46,000	429	573	502
56,000	548	798	668
60,000	606	923	744
65,500	678	1,130	842
71,000	752	1,396	938
75,000	808	1,548	1,012
80,000	886	1,820	1,096
85,000	968	2,104	1,184
95,000	1,156	3,144	1,424
100,000	1,300	4,630	2,670
105,000	2,510	9,240	9,100
110,000	5,430	11,600	14,400
115,000	12,800	-	15,600
120,000	15,800	-	17,100
125,000	19,100	-	-
130,000	27,400	-	-

Ultimate Load - 131,585

TABLE VI

T1-OF Temperature 0°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-2	-2	0
5,000	-180	-238	-172
10,000	-112	-150	-106
18,000	-020	-028	-021
35,000	200	238	187
40,000	363	472	364
51,000	494	672	519
79,500	920	1,828	964
94,000	1,210	3,760	1,220
108,500	1,400	6,600	1,500
114,500	2,400	8,600	3,700
119,000	10,100	13,800	7,400
130,000	19,500	-	20,200
135,000	21,400	-	23,400
139,500	22,000	-	28,000

Ultimate Load - 139,690

TABLE VII

T1-OS

Temperature $0^{\circ}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	-002	-002
5,000	0	-005	008
10,000	45	52	56
15,000	106	129	123
25,000	234	309	248
35,300	370	514	380
45,000	698	744	496
55,000	630	1,032	616
60,000	688	1,168	680
65,000	764	1,328	740
70,000	840	1,456	804
75,000	920	1,592	876
80,000	984	1,608	920
85,000	1,040	1,924	992
90,000	1,120	2,160	1,080
95,000	1,240	2,580	1,130
100,000	1,300	3,100	1,240
105,000	1,420	3,880	1,340
110,000	1,540	5,000	1,450
115,000	1,800	6,780	1,680
119,000	5,800	-	3,280
120,000	12,100	8,200	7,200
124,000	12,600	-	10,200
126,500	13,200	-	10,400
130,000	14,000	-	13,000
135,000	14,400	-	20,000
140,000	14,200	-	23,200

Ultimate Load - 141,920

TABLE VIII

Specimen T1-N30 Temperature $-30^{o}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-001	-002	-002
5,500	-292	-432	-313
25,000	-138	-298	-178
35,000	16	-114	- 25
45,000	177	062	128
55,000	337	246	282
65,000	510	490	444
70,000	582	632	514
75,000	681	842	608
80,000	748	1,100	680
85,000	872	1,520	772
90,000	960	2,092	848
95,000	1,032	2,816	952
100,000	1,136	3,692	1,040
105,000	1,600	4,400	-
110,000	2,600	6,700	1,400
115,000	5,600	11,100	2,900
120,000	10,600	-	9,600
125,000	15,600	-	15,200
130,000	17,500	-	16,600
135,000	-	-	21,700

Ultimate Load - 141,000

STRAIN READINGS FOR PRETENSION WITHOUT THE NOTCH PRESENT

TABLE IX

Speciman T2-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-2	-4	-5
5,000	34	30	33
15,000	141	144	148
26,000	270	282	284
35,000	380	401	401
46,000	509	540	544
55,000	619	661	670
65,000	729	786	801
75,000	840	924	944
85,000	956	1,088	1,090
95,000	1,064	1,268	1,228
100,000	1,120	1,348	1,296
105,000	1,182	1,460	1,372
110,000	1,252	1,686	1,470
115,000	1,372	2,116	1,584
119,000	1,536	3,320	1,624
Set			
0,000	168	1,988	200

TABLE X

T2-OS

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	001	001
5,000	102	132	136
15,000	201	270	280
25,500	310	404	419
35,500	414	543	546
45,500	519	684	672
55,000	616	944	906
65,000	728	944	906
75,000	832	1,092	1,028
85,000	948	1,248	1,154
95,000	1,072	1,472	1,280
100,000	1,144	1,656	1,344
105,000	1,224	1,840	1,392
110,000	1,308	2,200	1,496
115,000	1,384	2,752	1,592
120,000	1,530	5,460	2,060
Set 0,000	230	5,160	1,480

TABLE XI

T2-OF

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-002	000
5,000	238	241	226
15,000	390	382	356
25,000	496	486	445
35,000	597	574	525
46,000	704	678	615
55,000	796	765	692
65,000	917	863	777
76,000	1,044	996	872
85,000	1,140	1,100	958
95,000	1,276	1,260	1,052
105,000	1,420	1,754	1,148
110,000	1,548	2,520	1,200
115,000	1,680	3,536	1,320
120,000	5,440	6,340	2,440
Set 0,000	5,250	5,040	1,200

TABLE XII

T2-N30

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	000	-002
5,000	85	96	109
15,000	188	217	270
25,000	274	326	422
35,000	381	447	580
45,000	478	561	730
55,000	588	690	894
65,000	688	812	1,048
75,000	800	940	1,200
95,000	1,044	1,260	1,498
105,000	1,178	1,546	1,644
110,000	1,284	2,900	2,736
115,000	1,600	7,600	12,800
Set			
0,000	400	5,800	11,400

STRAIN READINGS FOR TENSION TEST AFTER TENSILE PRESTRAIN

TABLE XIII

Specimen T2-70

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-002	-008
5,000	88	113	81
25,000	329	428	347
35,000	441	612	490
45,000	545	746	622
55,000	646	904	752
60,000	701	-	822
65,000	752	1,084	884
70,000	804	1,182	952
75,000	862	1,322	1,032
80,000	920	1,500	1,092
85,000	968	1,726	1,156
90,000	1,028	2,008	1,240
100,000	1,180	3,230	1,480
105,000	1,400	6,090	1,900
110,000	2,200	-	10,000
115,000	3,800	-	13,400
120,000	6,000	-	14,800
125,000	-	-	15,700

Ultimate Load - 135,000

TABLE XIV

T2-0S

Temperature $0^{\circ}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	2	-2	-2
5,000	48	72	66
26,000	256	392	354
35,000	345	528	474
46,000	444	688	618
55,000	536	832	744
65,000	632	1,000	880
70,500	692	1,110	956
77,000	756	1,248	1,044
80,000	792	1,348	1,088
85,000	852	1,506	1,160
90,500	912	1,761	1,236
95,000	960	2,128	1,296
105,000	1,110	3,240	1,560
110,000	1,140	4,080	2,670
115,000	1,400	10,600	8,400
120,000	3,200	-	12,600
125,000	6,000	-	14,400
135,000	19,000	-	91,600

Ultimate Load -139,030

TABLE XV

T2-OF Temperature $0^{o}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	000	-002
5,000	206	274	220
21,000	355	452	376
35,000	444	560	436
45,000	580	736	612
55,000	684	860	716
60,000	720	924	768
65,000	780	996	824
70,000	826	1,006	862
75,000	876	1,148	920
80,000	928	1,252	988
90,000	1,016	1,572	1,032
95,000	1,080	1,868	1,148
100,000	1,140	2,356	1,224
105,000	1,216	2,928	1,296
110,000	1,310	3,800	2,120
115,000	1,640	5,420	4,300
120,000	7,000	9,200	13,900
125,000	8,400	-	15,200
128,000	9,000	-	16,400
130,000	8,800	-	17,000
135,000	13,700	-	18,600
140,000	17,600	-	20,200
142,000	18,200	-	20,500

TABLE XVI

T2-N30 Temperature -30°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	002	001	223
5,000	-69	-107	153
25,000	213	254	474
36,000	348	436	646
45,000	456	584	786
57,500	604	793	977
65,500	700	936	1,104
70,000	750	1,016	1,172
75,500	816	1,132	1,256
80,500	880	1,280	1,332
85,000	930	1,494	1,400
90,000	996	1,744	1,484
95,000	1,056	2,160	1,592
100,000	1,152	2,720	1,672
105,000	1,212	3,592	1,792
110,000	1,680	6,400	2,040
115,000	3,700	11,300	3,600
120,000	6,600	19,200	5,200
130,000	15,300	-	7,200

Ultimate Load - 143,810

STRAIN READINGS FOR PRECOMPRESSION WITHOUT THE NOTCH PRESENT

TABLE XVII

Specimen T3-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-001	000	000
5,000	-94	-78	-41
25,000	-380	-334	-181
45,000	-518	-582	-412
66,000	-605	-759	-724
85,000	-676	-910	-1,428
105,000	-1,110	-1,680	-6,460
110,000	-1,200	-2,400	-11,800
115,000	-1,600	-3,500	-15,000
Set			
0,000	-300	-2,000	-13,800

TABLE XVIII

Specimen T3-OS Temperature $70^{\circ}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-001	000
5,000	-48	108	86
15,000	-136	128	60
43,000	-499	-30	-178
55,000	-635	-156	-288
75,000	-830	-459	-486
95,000	-932	-1,052	-716
100,000	-896	-1,812	-708
105,000	-928	-	-804

Yielding occurring (some buckling)

TABLE XIX

Specimen T3-OF

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-001	000
5,000	-110	108	90
26,000	-578	-18	-194
46,000	-884	-232	-522
65,000	-1,126	-520	-828
85,000	-1,296	-960	-1,156
105,000	-1,774	-	-1,378
Set	-424	-	-36

TABLE XX

Specimen T3-N30

Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-500	000	000
5,000	-592	58	58
27,000	-900	-12	-22
45,000	-1,140	-208	-204
65,000	-1,380	-516	-582
85,000	-1,584	-1,236	-632
105,000	-3,100	-10,000	-1,600
Set			
	-1,370	-8,780	-0,380

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

TABLE XXI

Specimen T3-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	002	-003	-003
5,000	212	290	248
10,000	262	372	334
15,000	299	444	396
20,000	344	534	469
25,000	377	617	524
35,000	477	736	645
46,000	592	773	768
55,000	722	916	896
65,000	878	1,114	1,060
75,000	1,042	1,364	1,208
80,000	1,152	1,580	1,312
85,000	1,252	1,828	1,398
95,000	1,648	3,272	1,632
99,000	2,040	5,220	1,740
105,000	2,720	6,980	1,940
110,000	3,900	10,400	2,200
115,000	5,400	19,200	3,000
120,000	7,800	29,800	4,500
125,000	13,200	40,000	7,000
130,000	15,300	49,000	-
135,000	24,000	40,600	-

Ultimate Load - 135,000

TABLE XXII

Specimen T3-OF

Temperature $0^{o}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	002	-306	001
5,000	-94	-447	-117
25,000	-231	-683	-306
50,000	104	-242	022
75,000	494	564	341
95,000	975	-	644
122,000	8,800	32,600	2,800
135,000	29,700	-	28,700

Ultimate - 146,330 pounds

TABLE XXIII

Specimen T3-OS

Temperature $0^{o}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	-001	-002
5,000	108	176	91
25,000	112	151	60
46,000	203	480	87
71,000	400	1,310	320
99,000	840	2,800	640
114,000	1,800	9,600	1,300
119,000	1,600	19,200	2,200
124,000	2,400	28,000	3,900
130,000	6,600	43,500	12,600
135,000	16,800	59,600	17,200
140,000	22,200	-	22,100

Weld failed at 140,930 pounds

TABLE XXIV

Specimen T3-N30 Temperature $-30^{\circ}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	-003	-002
11,500	-67	-50	-32
48,000	-930	63	310
58,000	-930	97	520
65,000	139	820	470
70,000	165	1,180	550
75,000	200	1,500	650
80,000	262	1,950	790
85,000	320	2,500	910
90,000	388	3,170	1,040
95,000	510	4,600	1,230
100,000	620	6,200	1,420
105,000	760	12,150	2,090
110,000	1,520	23,200	4,550
115,000	2,940	29,800	7,900
120,000	3,320	37,850	12,000
125,000	8,550	53,000	15,000
130,000	13,500	-	18,800

STRAIN READINGS FOR PRECOMPRESSION WITH THE NOTCH PRESENT

TABLE XXV

Specimen T4-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	000	000
5,000	-70	-70	-87
25,000	-366	-296	-365
45,000	-650	-497	-540
65,000	-901	-712	-606
85,000	-1,100	-904	-668
105,000	-1,228	-1,282	-848
111,000	-1,238	-1,512	-920
113,000	-1,256	-1,620	-944
115,000	-1,388	-1,854	-972
Set	-153	-600	152

TABLE XXVI

Specimen T4-OS

Temperature 70°F

Gage Reading in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-002	-002
5,000	-102	76	75
25,000	-402	91	-182
45,000	-647	-031	-426
65,000	-860	-196	-670
85,000	-1,036	-426	-888
106,000	-1,248	-776	-1,238
124,000	-1,430	-4,640	-1,320
Set	-120	-3,592	24

TABLE XXVII

Specimen T4-OF | Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	500	000	000
5,000	442	-10	-144
25,000	38	-164	-664
46,000	-352	-488	-906
65,000	-634	-808	-1,068
85,000	-916	-1,182	-1,232
105,000	-926	-1,438	-1,356
119,000	-840	-6,140	-1,740
Set	510	-5,140	-440

TABLE XXVIII

Specimen T4-N30 | Temperature 70°F

0,000	000	-002	-001
5,000	-120	-26	-104
25,000	-458	-135	-402
45,000	-720	-337	-698
65,000	-908	-600	-962
85,000	-1,072	-878	-1,188
105,000	-1,172	-1,216	-1,384
117,000	-1,270	-4,960	-1,360
Set	310	-3,900	-20

STRAIN READINGS FOR TENSION TEST AFTER COMPRESSIVE PRESTRAIN

TABLE XXIX

Specimen T4-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-001	-002
5,000	136	179	186
10,000	210	286	341
21,000	332	498	431
25,000	377	548	600
35,000	519	780	834
45,000	668	856	1,036
55,000	828	1,200	1,416
65,000	996	1,408	1,832
75,000	1,184	1,648	2,880
85,000	1,460	1,840	5,290
95,000	1,610	2,000	8,370
100,000	1,800	1,900	11,200
105,000	1,800	2,000	15,200
110,000	1,600	2,100	24,300
115,000	1,800	2,500	33,200
120,000	3,200	4,200	38,700
125,000	15,400	8,000	48,600
130,000	19,800	16,000	48,600
135,000	28,400	26,700	—

Ultimate Load - 136,000

TABLE XXX

Specimen T4-OF

Temperature $0^{o}F$

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-1	-1	-1
5,000	-75	-52	-26
15,000	-101	-42	12
25,000	-178	-51	90
35,000	-207	-15	243
45,000	-214	52	421
55,000	-184	93	636
87,000	72	2,564	2,160
111,000	2,000	-	9,800
118,000	2,000	-	15,200
123,000	3,200	6,800	19,000
126,000	3,000	6,100	19,900
129,000	5,200	5,400	20,200
136,000	16,400	4,100	23,800

Ultimate Load - 141,720

TABLE XXXI

Specimen T4-OS

Temperature 0°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	000	-002	001
5,000	-20	34	26
10,000	-28	59	63
15,000	-40	52	82
25,000	-68	45	128
35,000	-82	375	226
45,000	-58	616	340
55,000	-13	884	476
65,000	24	1,388	616
75,000	86	2,084	790
85,000	148	3,296	1,052
95,000	253	4,880	1,316
100,000	378	7,140	1,580
105,000	496	10,100	1,700
110,000	795	17,400	2,192
115,000	1,160	-	2,920
120,000	1,600	30,200	4,600
125,000	2,100	37,600	10,800
130,000	14,800	47,400	15,800
135,000	19,000	50,800	19,600
140,000	23,300	49,600	25,600
145,000	33,800	45,400	35,600

Ultimate Load - 145,300

TABLE XXXII

Specimen T40-OS Temperature 0°

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-002	-002	000
30,000	32	71	14
50,000	248	573	239
85,000	704	2,640	604
101,000	1,016	-	1,056
115,000	2,000	14,600	1,600
120,000	4,000	23,600	2,000
122,000	6,600	30,100	2,900
123,000	7,000	33,000	2,800
125,000	8,200	35,800	5,000
126,000	8,100	39,400	7,400
127,000	8,600	41,400	10,800
128,000	9,600	43,500	11,500
130,000	11,200	46,100	12,700
132,000	12,000	49,600	15,000
133,000	13,400	52,900	17,000
135,000	15,200	57,200	19,400
141,000	23,400	-	26,500
143,000	26,600	-	30,000
144,000	30,100	-	33,000

Ultimate Load - 144,990

TABLE XXXIII

Specimen T4-N30 Temperature -30°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2
0,000	004	003
5,000	-156	-150
10,000	-202	-182
16,000	-225	-186
20,000	-238	-167
25,000	-248	-132
30,000	-259	-85
35,000	-268	-020
45,000	-278	58
55,000	-260	108
65,000	-218	220
75,000	-133	584
85,000	25	1,428
95,000	368	3,112
100,000	524	-
105,000	796	8,150
110,000	1,190	12,200
115,000	2,000	18,200
120,000	4,500	24,600
125,000	7,000	33,400
130,000	11,700	43,100
135,000	13,700	35,400
140,000	15,600	35,400

Ultimate Load - 143,430

STRESS READINGS FOR RESIDUAL STRESSES DUE TO WELDING

TABLE XXXIV

Specimen T5-70 Temperature 71°F

	Gage 1	Gage 2	Gage 3
Initial Reading	20	1,071	-151
Final Reading	217	1,255	-159
Residual Stress in p.s.i.	6,300	5,900	-253

TABLE XXXV

Specimen T5-OF Temperature 71°F

	Gage 1	Gage 2	Gage 3
Initial Reading	25	1,340	-267
Final Reading	441	1,733	63
Residual Stress in p.s.i.	13,300	12,600	10,600

TABLE XXXVI

Specimen T5-N30 Temperature 71°F

	Gage 1	Gage 2	Gage 3
Initial Reading	1,953	382	707
Final Reading	2,190	923	813
Residual Stress in p.s.i.	7,600	17,300	3,400

STRAIN READINGS FOR TENSION TEST WITH RESIDUAL WELDING STRESSES PRESENT

TABLE XXXVII

Specimen T5-70 Temperature 70°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
5,000	-310	-392	-294
10,000	-412	-502	-359
15,000	-	-564	-394
25,000	-459	-545	-390
35,000	-465	-390	-350
45,000	-424	-153	-294
55,000	-370	132	-216
65,000	-280	460	-118
76,000	-114	960	039
85,000	116	1,734	264
95,000	560	4,290	740
105,000	1,120	-	1,660
110,000	1,800	22,800	2,800
115,000	5,600	33,000	6,100
120,000	12,600	44,800	13,800
125,000	18,700	64,600	20,100
130,000	23,700	78,600	23,600
135,000	30,600	-	-

TABLE XXXVIII

Specimen T5-OF

Temperatue 0^oF

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	-2	-1	-4
12,000	8	19	7
21,000	44	168	164
43,000	162	620	502
100,000	840	9,070	2,740
105,000	1,000	23,000	4,800
110,000	1,400	32,600	10,400
117,000	2,800	38,800	16,200
121,000	3,600	41,200	18,200
123,000	4,600	42,900	19,000
125,000	5,800	46,100	19,400
127,000	7,800	49,500	19,600
130,000	13,000	48,800	20,100
134,000	22,200	54,300	22,500
138,000	24,400	56,200	24,400
141,000	26,400	-	-

Ultimate Load - 143,790

TABLE XXXIX

Specimen T5-N30

Temperature -60°F

Gage Readings in Micro-Inches per Inch

Load in Pounds	1	2	3
0,000	004	001	001
5,000	-363	-467	-360
10,000	-394	-480	-360
15,000	-396	-450	-334
20,000	-384	-390	-288
25,000	-360	-288	-226
35,000	-271	-114	-094
45,000	-163	72	44
55,000	-138	257	188
65,000	109	483	342
76,000	294	798	549
85,000	475	1,456	858
95,000	744	2,944	1,388
100,000	872	3,792	1,568
105,000	1,064	7,160	2,210
110,000	1,280	14,200	3,800
115,000	1,560	19,700	6,440
120,000	2,100	-	10,800
125,000	2,960	-	16,100
130,000	5,040	-	20,200
135,000	12,400	-	22,100
140,000	20,000	-	27,500
145,000	27,900	-	30,200

Ultimate Load - 149,000

CHAPTER V

PRESENTATION AND DISCUSSION

I. PRESENTATION

Standard Test Results

For the Standard Tension Test results see Figure 17.

For the Charpy V Notch Impact Test see Figure 18.

For the Kinzel Notch Bend Test results see Figure 19.

Notched Tension Tests Results

Test 1 For load versus strain reading results of the tension tests with no prestrain tested at temperatures of $70^{o}F$, $0^{o}F$ and $-30^{o}F$, see Figure 20.

Test 2 For load versus strain reading results of tension tests after tensile prestrain at temperatures of $70^{o}F$, $0^{o}F$ and $-30^{o}F$ see Figure 21.

The notch was not present in the specimen during prestraining.

Test 3 For load versus strain reading results of tension tests after compressive prestrain tested temperatures of $70^{o}F$, $0^{o}F$, and $-30^{o}F$ see Figure 22.

Test 4 For load versus strain reading results of tension tests after compressive prestrain tested at temperatures of $70^{o}F$, $0^{o}F$ and $-30^{o}F$, see Figure 23. The compressive prestrain was with the notch present.

Test 5 For load versus strain reading results of tensile tests with residual welding stresses present tested at temperatures of 70°F, 0°F and -60°F, see Figure 24.

The above load versus strain reading graphs compare the effects of temperature in the presence of a notch on the different specimens.

For the comparison of tests one to five inclusive of the load versus strain reading results for the notched tension tests at temperatures of 70°F, 0°F and -30°F see Figures 25 to 27.

DISCUSSION OF RESULTS

Standard Tests

A check analysis on the chemical properties of this steel revealed:

Carbon 0.17% (C.S.A. G40.12 specification 0.25% Max.)

An increase in carbon increases the strength, but the ductility is reduced in almost a direct ratio. Carbon hardens welding. Carbon is probably the most important single element affecting notch toughness. It raises the ductility transition temperature in steel about two to four Fahrenheit degrees for each 0.01% of carbon in the steel.[14]

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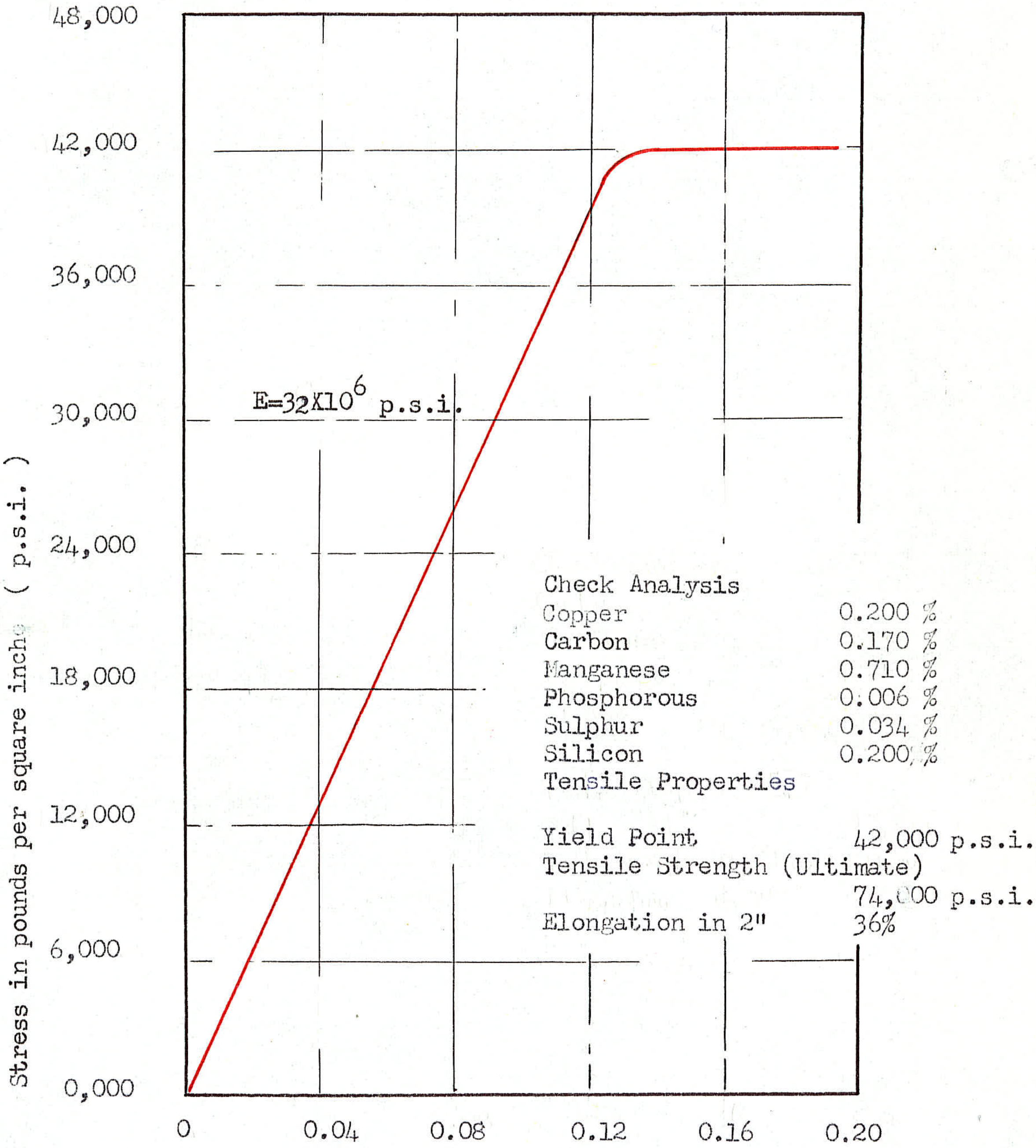
[14]Wheeler, John Structural Steel Material Specifications C.I.S.C. Inc. Vancouver.

Fig. 17

Stress - Strain Curve - G 40.12 Steel



Unit Strain - Percent

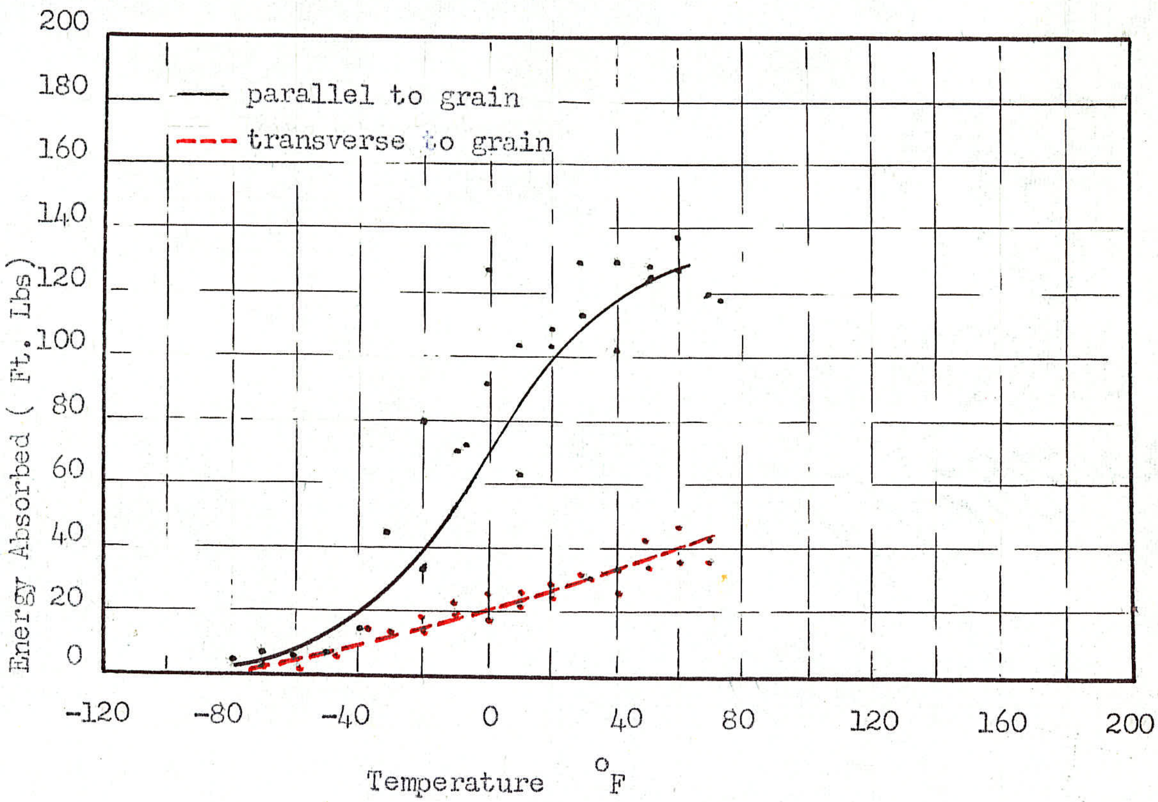
Fig. 18

Check Analysis

Carbon	0.170 %
Manganese	0.710 %
Posphorous	0.006 %
Sulphur	0.034 %
Silicon	0.200 %
Copper	0.200 %

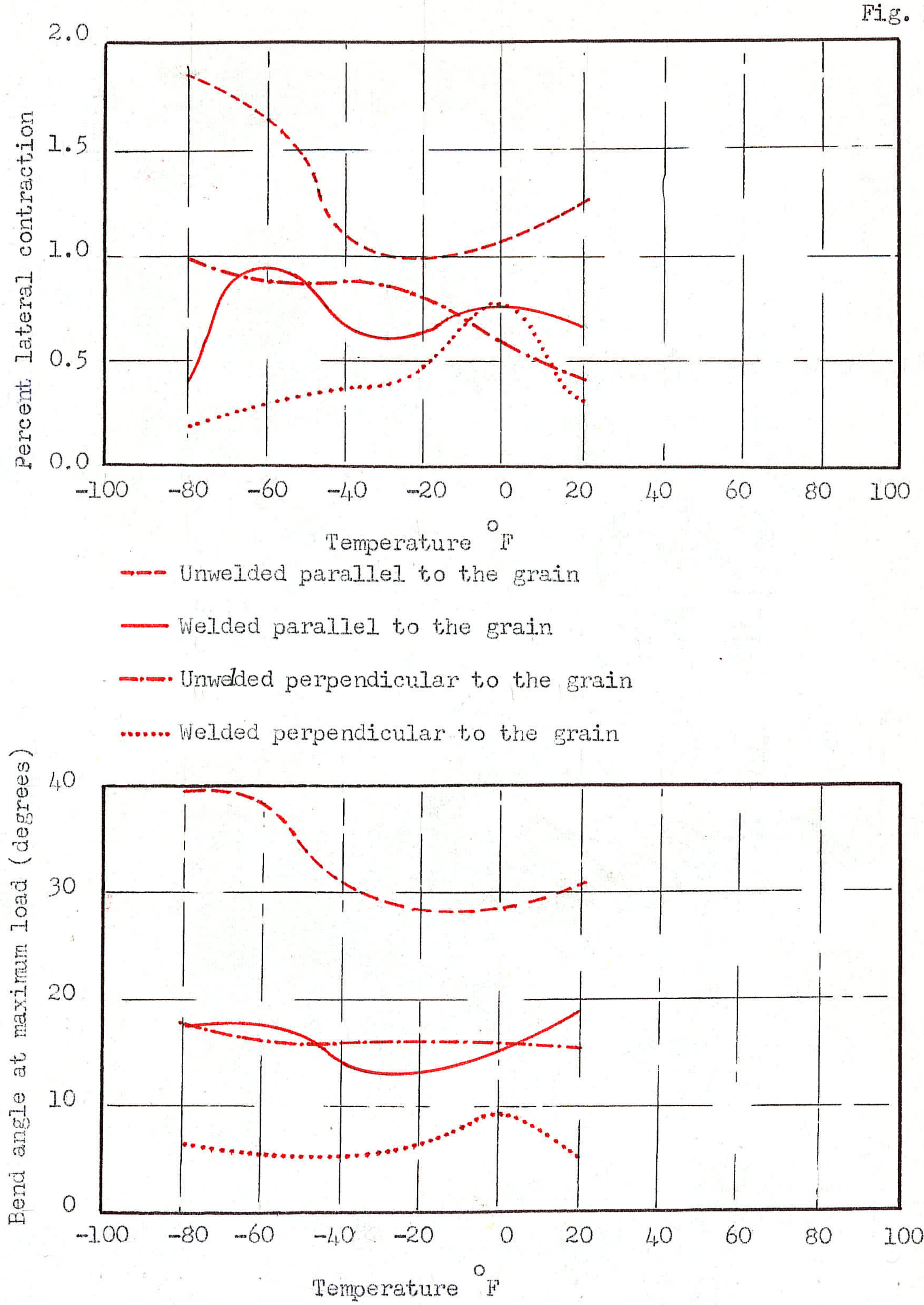
Tensile Properties (See Fig. 17)

Yield Point	42,000 p.s.i.
Tensile Strength (Ultimate)	74,000 p.s.i.
Elongation in 2"	36%



Charpy V Notch Impact Curve (G40.12 Steel)

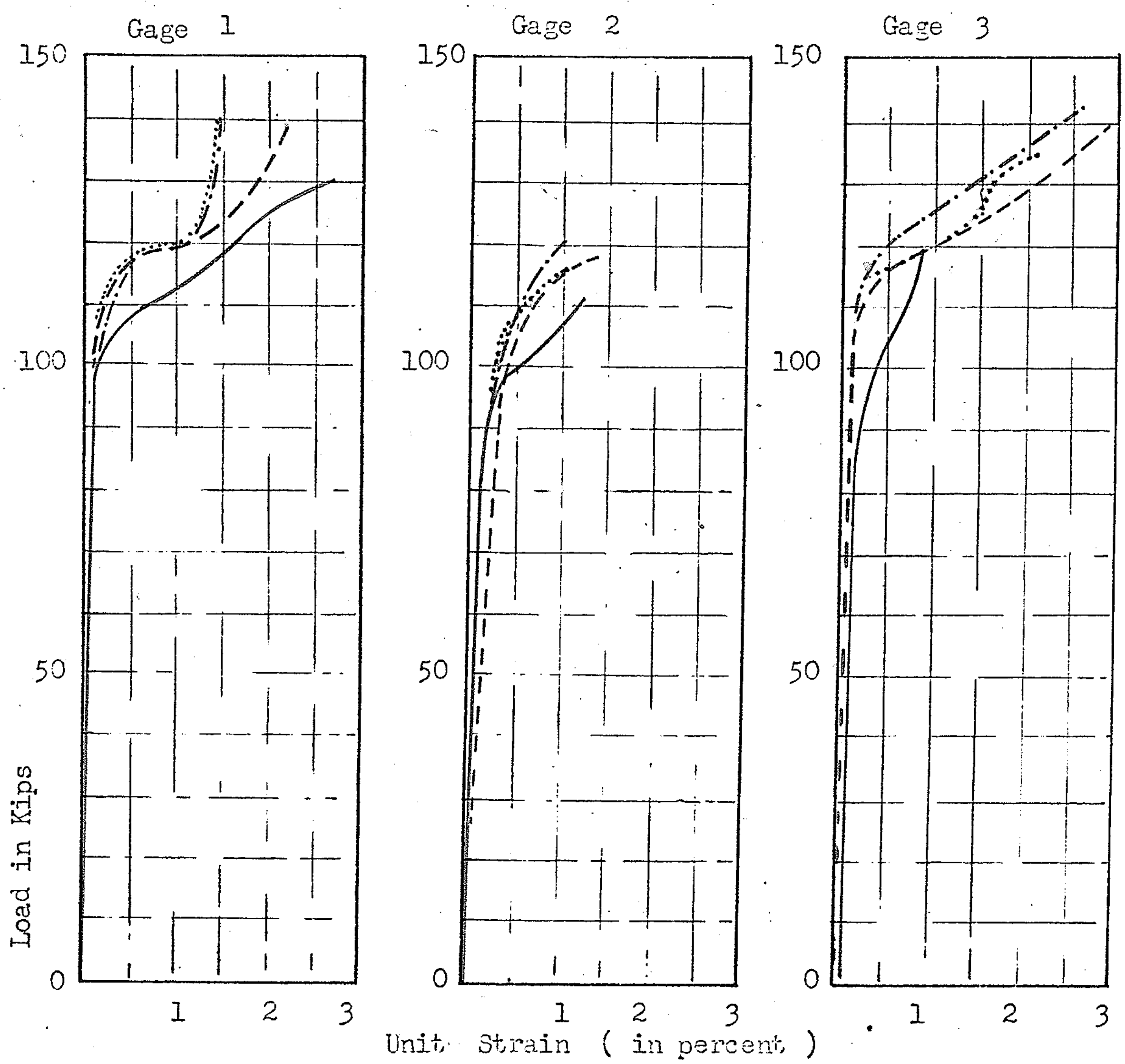
Fig. 19



Kinzel notch bend test transition curves based on percent lateral contraction and bend angle at maximum load for G40.12 steel.

Fig. 20

Test 1...Load- Strain readings for tension test with no prestrain



——— temperature 70°F

– – – " 0°F (fast rate of loading)

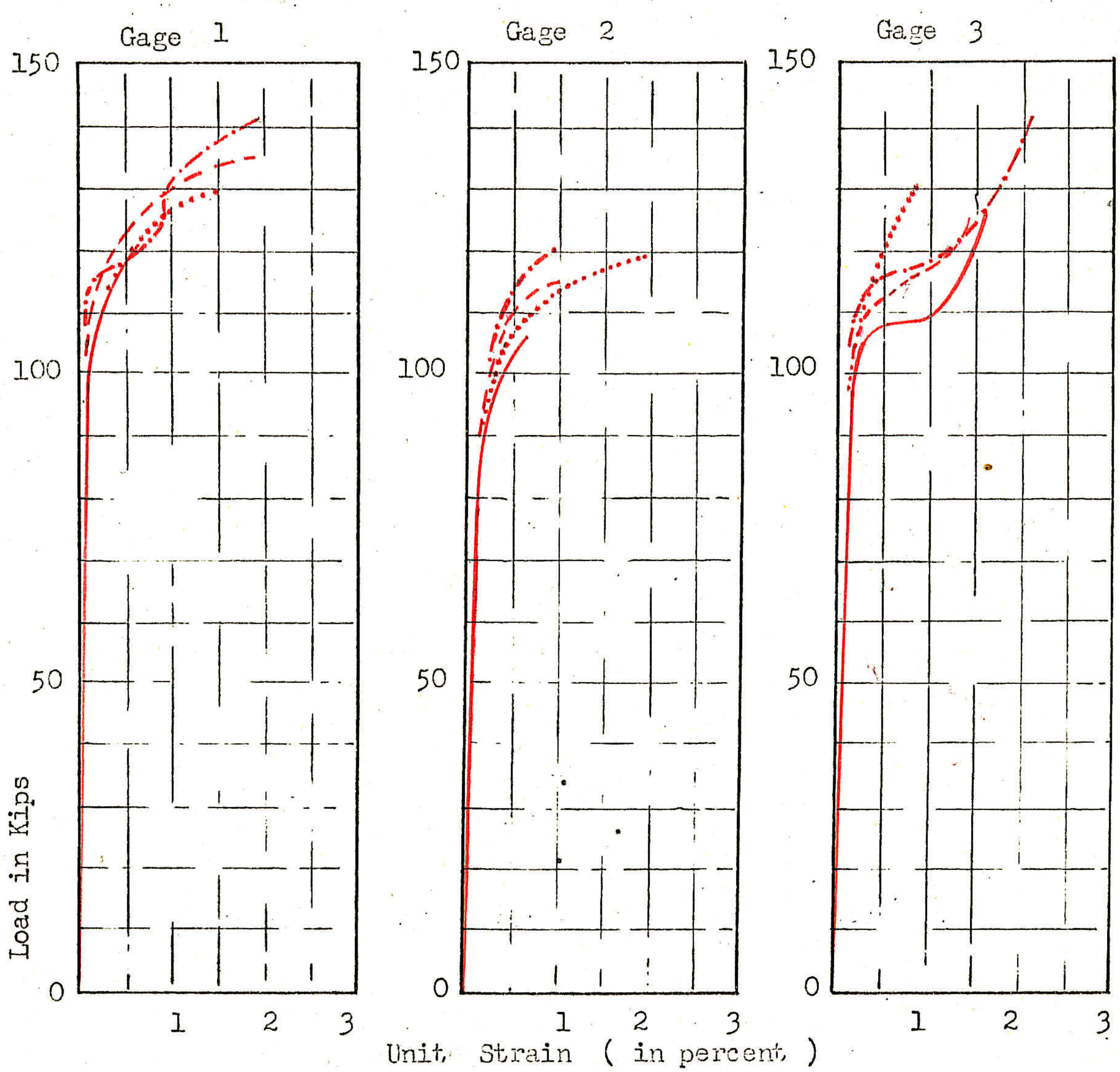
–·–·– " 0°F (slow rate of loading)

······ " -30°F

106 kips calculated yield load of all test specimens

Fig. 21

Test 2...Load-Strain readings for tension test after tensile prestrain.(notch not present during prestraining)



temperature 70°F

" 0°F (slow rate of loading)

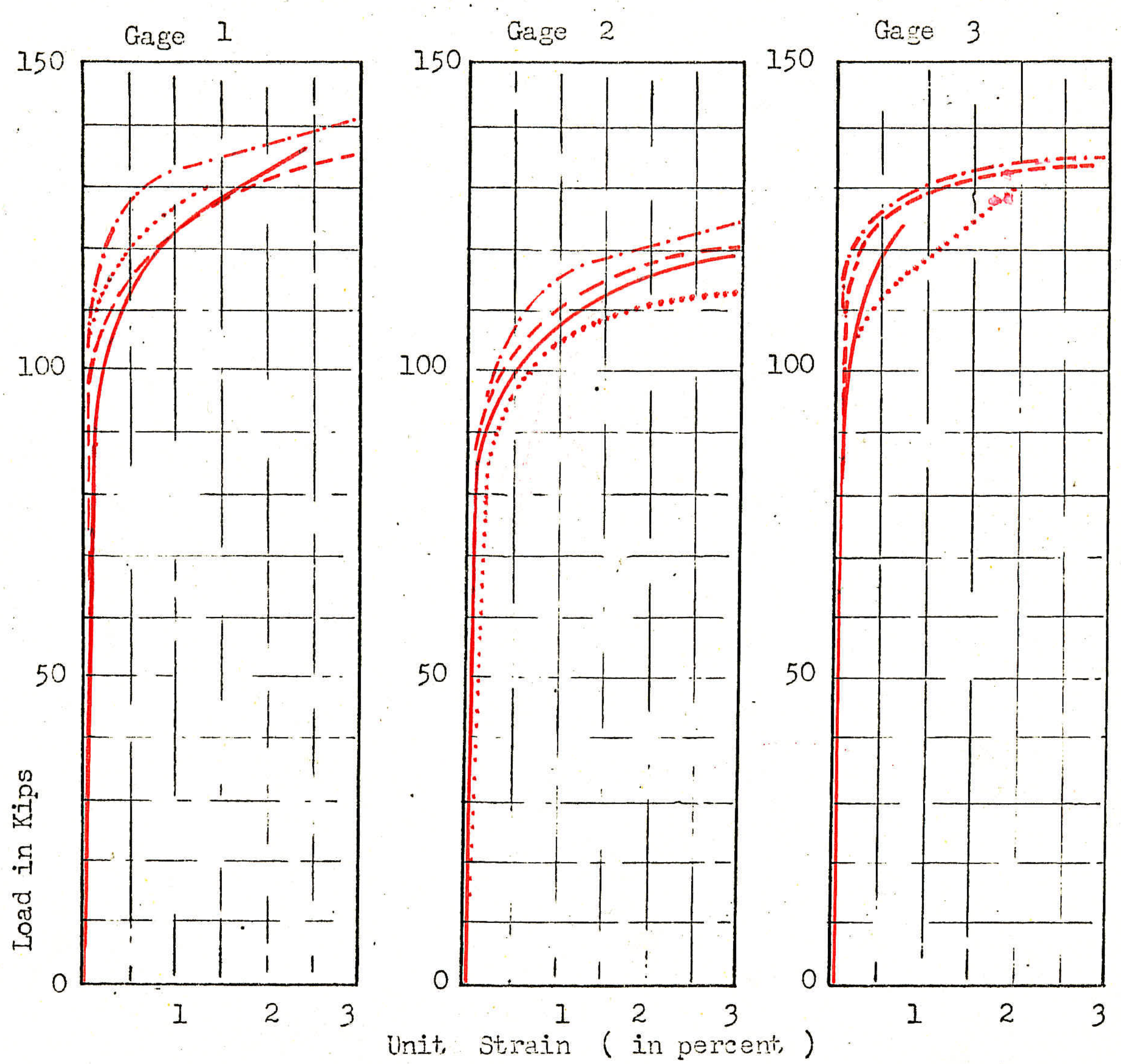
" 0°F (fast rate of loading)

" -30°F

106 kips calculated yield load of all test specimens

Fig. 22

Test 3...Load-Strain readings for tension test after compressive prestrain. (Compressive prestrain was without the notch present)



temperature 70°F

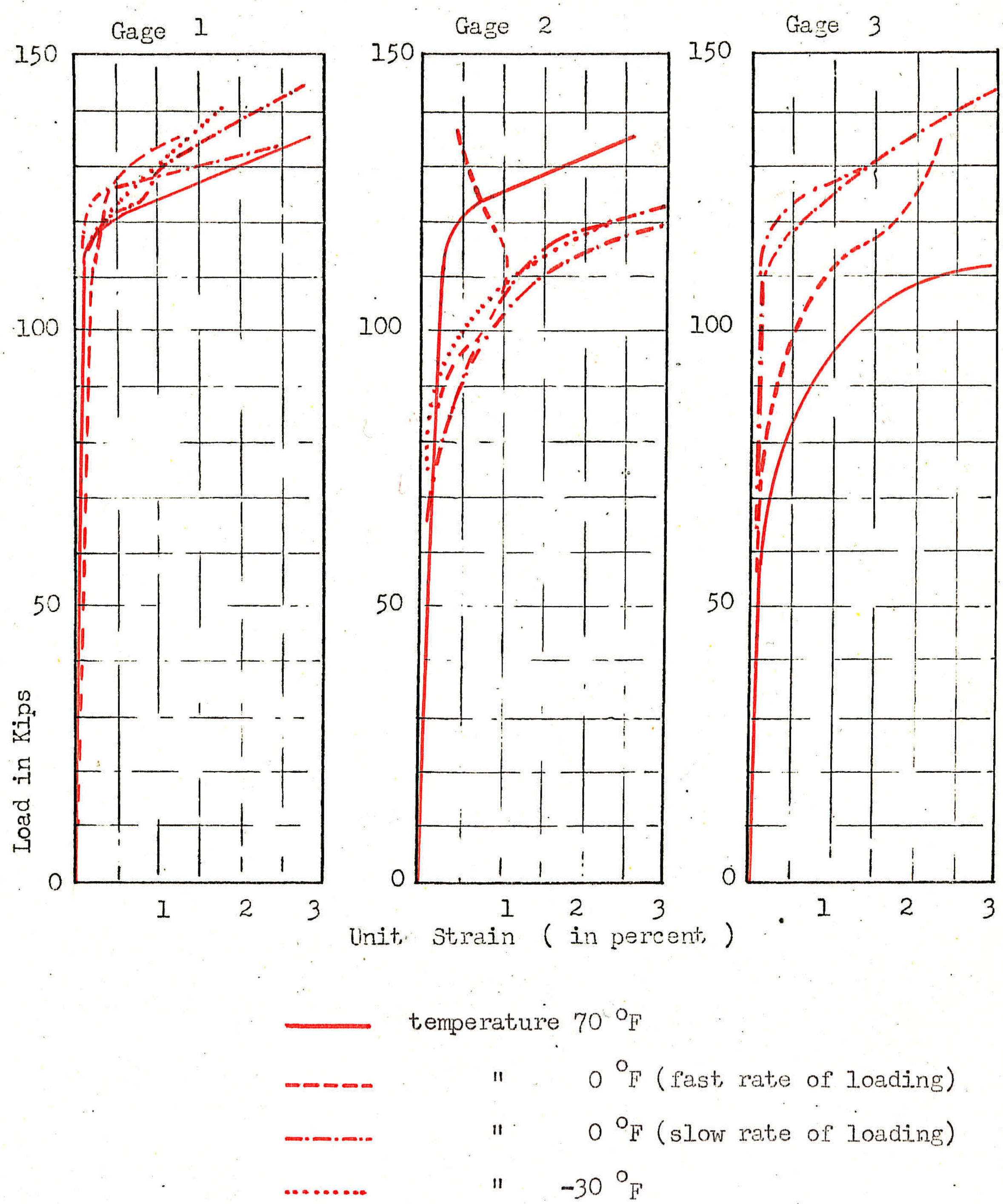
" 0°F (fast rate of loading)

" 0°F (slow rate of loading)

" -30°F

106 kips calculated yield load of all test specimens

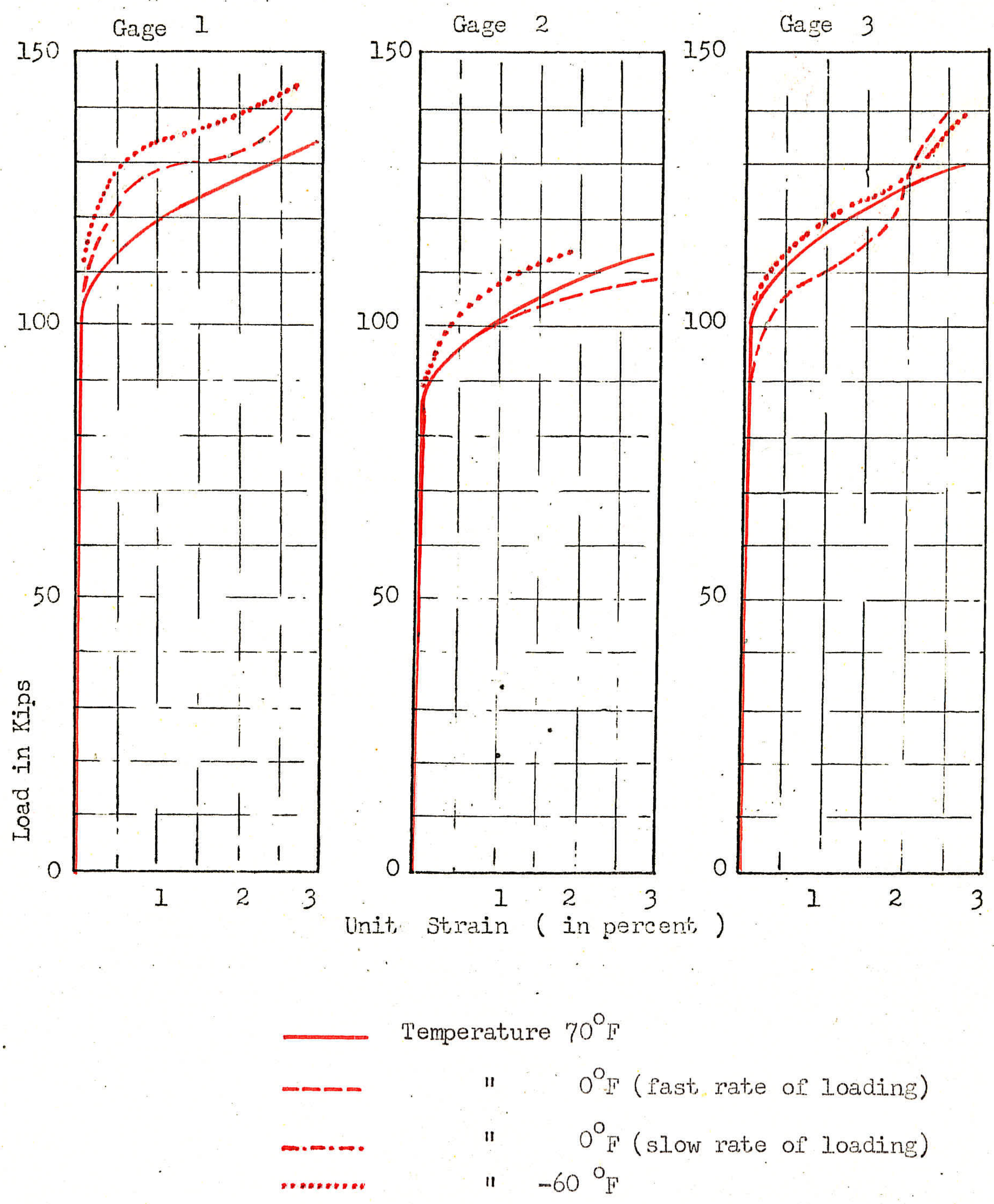
Test 4...Load-Strain readings for tension test after compressive prestrain.(Compressive prestrain was with the notch present) Fig. 23



106 kips calculated yield load of all test specimens

Fig. 24

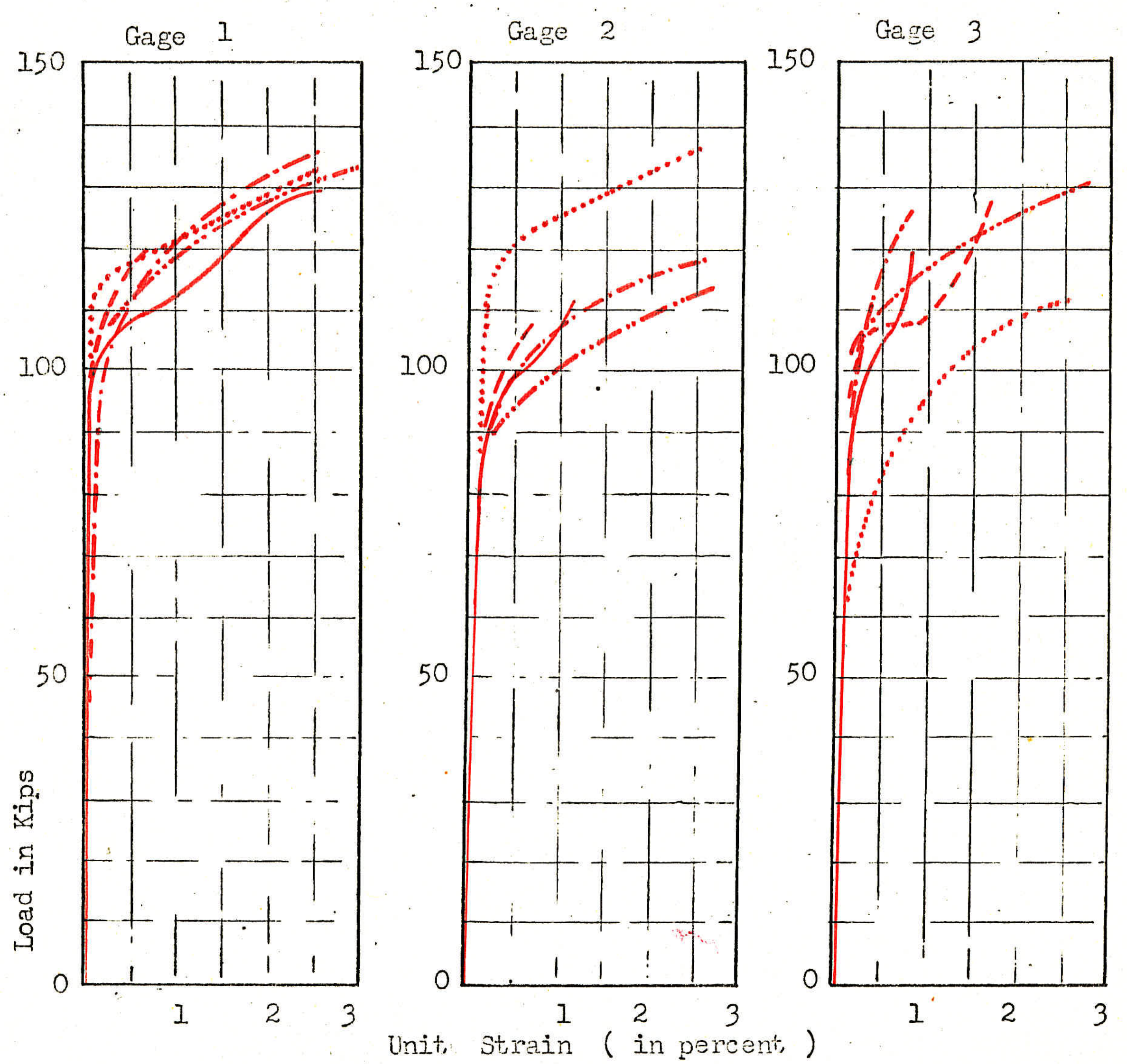
Test 5...Load-Strain readings for tensile test with residual welding stresses present



106 kips calculated yield load of all test specimens

Fig. 25

Load-Strain readings for the tension tests tested at 70°F



Test 1...Load-Strain readings for tension tests with no prestrain

Test 2...Load-Strain readings for tension tests after tensile prestrain (notch not present during prestraining)

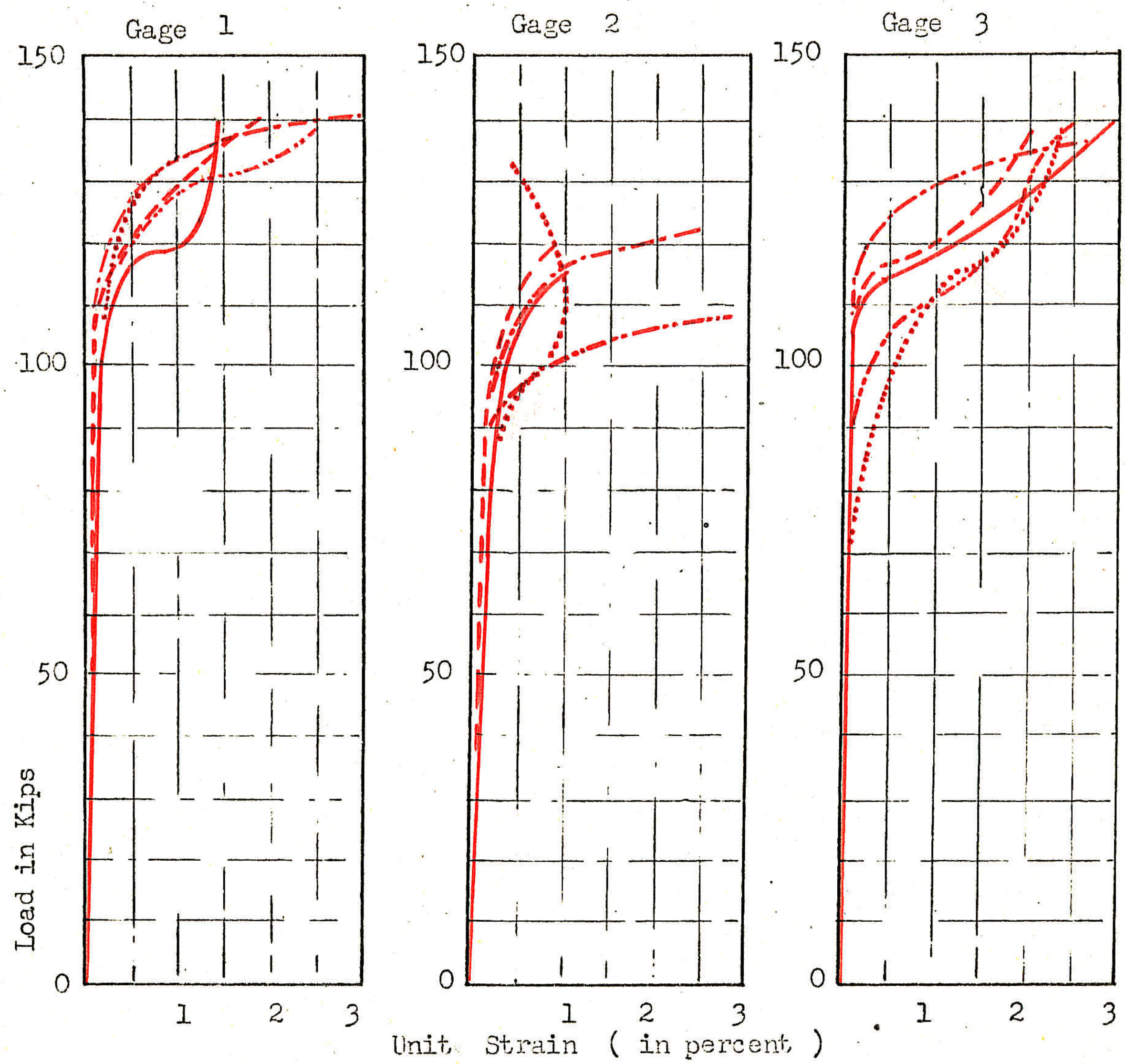
Test 3...Load-Strain readings for tension tests after compressive prestrain (Compressive prestrain was without the notch present)

Test 4...Load-Strain readings for tension tests after compressive prestrain (Compressive prestrain was with the notch present)

Test 5...Load-Strain readings for tension tests with residual welding stresses present

Fig. 26

Load-Strain readings for the tension tests tested at $0^{o}F$(slow rate of loading)



Test 1...Load-Strain readings for tension tests with no prestrain

Test 2...Load-Strain readings for tension tests after tensile prestrain (notch not present during prestraining)

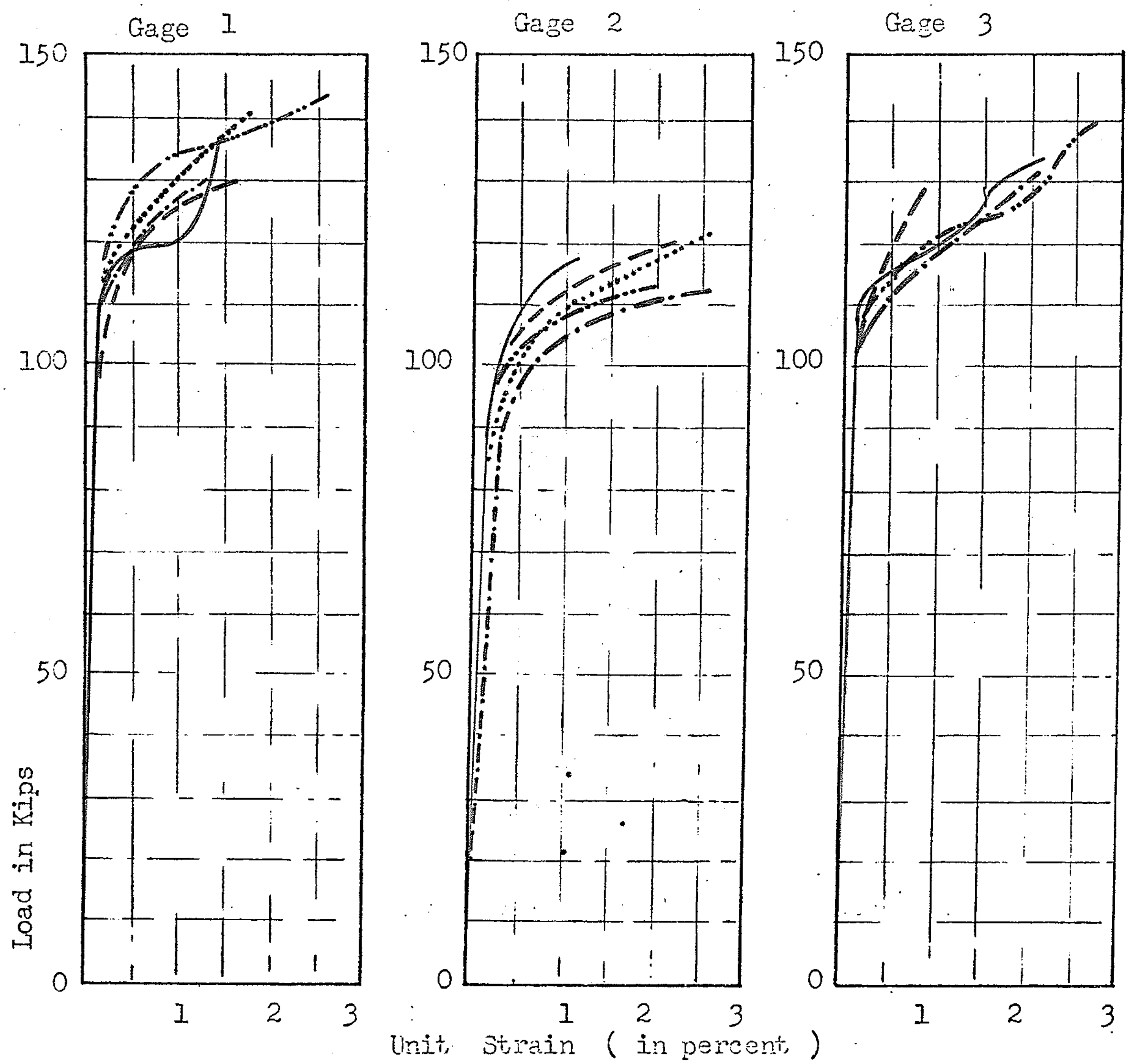
Test 3...Load-Strain readings for tension tests after compressive prestrain (Compressive prestrain was without the notch present)

Test 4...Load-Strain readings for tension tests after compressive prestrain (Compressive prestrain was with the notch present)

Test 5...Load-Strain readings for tension tests with residual welding stresses present

Fig. 27

Load-Strain readings for the tension tests tested at -30°F*



———— Test 1...Load-Strain readings for tension tests with no prestrain

- - - - - Test 2...Load-Strain readings for tension tests after tensile prestrain (notch not present during prestraining)

—·—·— Test 3...Load-Strain readings for tension test after compressive prestrain (Compressive prestrain was without the notch present

············ Test 4...Load-Strain readings for tension tests after compressive prestrain (Compressive prestrain was with the notch present)

—··—··— Test 5...Load-Strain readings for tension tests with residual welding stresses present (tested at -60°F)*

Manganese 0.710% (C.S.A. G40.12 specification 1.55% Max.)

Manganese increases the strength and the hardenability of the steel. It also greatly improves the rolling properties. An increase in Manganese up to 1.5 0% lowers the ductility. Such lowering is believed to be about one Fahrenheit degree for every 0.01% increase of Manganese. British steel makers suggest that for improved resistance to brittleness, the manganese content must be more than three times the carbon content.[15] This condition was met and this influenced the material's ductile behaviour under the tests.

Phosphorous 0.006% (C.S.A. G40.2 specification 0.05% max.)

Phosphorous's effect on the transition temperature is more potent than carbon's effect. It is estimated that phosphorous increases the transition temperature between seven and thirteen Fahrenheit degress for each 0.01% increase of phosphorous.

Sulphur 0.034% (C.S.A. G40.12 specification 0.06% Max.)

Sulphur has no effect on the transition temperatures.

Silicon 0.200% (C.S.A. G40.12 specification - no control)

Up to 0.3% silicon content in the steel, silicon seems to have a favourable effect on the ductility transition temperature.[16]

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[15] Ibid

[16] Ibid

Copper 0.200% (C.S.A. G40.12 specification - no control)

Copper has no effect on the ductility transition temperature. It is mostly used to prevent corrosive action in the steel.

Standard Tests

The Standard Tension Test revealed a yield point of 42,000 p.s.i., a tensile strength of 74,000 p.s.i., and an elongation in gauge length of two inches of thirty six percent. All fractures were of the cup-cone, silky grey shear type with a necking down of the material at the fracture plain. There was a large reduction in the load prior to failure. This was an indication of the inherent ductility of the steel.

The Charpy Impact Test showed a sharp increase in energy absorption above -40°F indicating a ductility transition point. From the two curves it can be seen that the material cut parallel to the direction of rolling is stronger and more ductile. From this test it is shown within reasonable limits that the ductility transition lies in the region of -40°F at an energy of ten foot-pounds.

The Kinzel Notch Bend Test shows that welding and bending the specimen perpendicular to the direction of rolling increase the brittleness of the steel.

The series of curves show that there is a transition stage at -20°F to -40°F temperature range. This is signified by the dip in both curves at this region.

The specimens that were cut parallel to the direction of rolling cracked at a lower temperature as did the specimens that were cut perpendicular to the direction of rolling. Where the specimens cracked, the unwelded ones cracked all along the width of the specimens where as the welded ones cracked near the weld. All cracked portions were cleavage fractures.

From the recorded data, the unwelded specimens that were cut parallel to the grain were stronger and more ductile. The test revealed that welding in the presence of a notch does reduce the strength of the material. The material is weaker in the direction perpendicular to the direction of rolling (as revealed in the Charpy Impact Test).

Summary of Standard Test Results

The check analysis revealed that the material more than met the minimum requirements of the C.S.A. G40.12 specifications. Elements benefiting ductility were present in the proper percentage.

The Standard Tension Tests illustrated that the material was ductile and that the yield point was somewhat lower than the required minimum. This could have been due to improper placing of the specimens in the testing machine.

The Charpy Impact Test indicated that difficulty can be expected in inducing a brittle failure in materials when the temperature of the material is above -40°F. The effect of notches, welding, strain rate, and of prestrain, will be the controlling factors in initiating brittle fractures above this temperature.

The Kinzel Notch Bend Test as well as the Charpy V Notch Impact Test illustrated that the transition temperature is in the proximity of $-40^{\circ}F$. The test illustrated not only that the direction of rolling has an effect on the strength of steel but also that welding in the presence of notches tends to initiate brittle fractures at the ultimate loads.

Notched Tension Tests

The condition of static loading was investigated because the rate of loading could not be considered as impact value. However, as some specimens failed in tension, one side of the notch failed before the other side. At that moment the total load was placed on the other side creating an impact load. When this was observed to happen, the remaining portion of the specimen failed in a brittle manner.

An increase in loading rate at a constant temperature did give some comparable results. Where the specimens were prestrained, the specimens were brought past the yield point of the material (indicated by an increase in strain with no addition of load). The specimens were prestrained across the total width of the specimen. Where the notch was present during prestraining, the strain rate increased in the region surrounding the notch. Some buckling occurred during precompression. This was noticed by the erratic gauge readings at the start of the tension tests. The erratic gauge readings were also due to improper allignment of the welded portion in the test specimens.

The following tests failed with a ductile grey silky failure (See Photographs 10, 11, 12, 14 and 16):

Test 1 - Test one at a temperature of 70°F and 0°F (slow rate of loading).

Test 2 - Test two at a temperature of 70°F and 0°F (fast rate of loading).

Test 3 - Test three at a temperature of 70°F and 0°F (fast rate of loading).

Test 4 - Test four at a temperature of 70°F and 0°F (slow rate of loading).

Test 5 - Test five at a temperature of 70°F and 0°F (fast rate of loading).

The following tests thatwere yielding in a ductile manner then failed in a sudden brittle fracture when one side sheared away completely thus placing an impact load on the other side. (See Photographs 14, 15 and 16):

Test 1 - Test one failed at temperatures of 0°F (fast rate of loading) and at -30°F.

Test 2 - Test two failed at temperatures of 0°F (slow rate of loading) and at -30°F.

Test 3 - Test three failed at a temperature of -30°F.

Test 4 - Test four failed at temperatures of 0°F (fast rate of loading) and at -30°F.

The following tests started to fail in a ductile manner but suddenly failed in a brittle manner initiated in the weld connecting the prestrained specimen in the test piece. (See Photographs 12, 17, 19, 20, 21 and 22):

Test 5 - Test five failed at a temperature of $0^{o}F$ (slow rate of loading).

Test 3 - Test three failed at a temperature of $0^{o}F$ (slow rate of loading).

Test five that failed at a temperature of $-60^{o}F$ started to fail in ductile shear failure for about one half inch on either side of the notch and then suddenly failed in a brittle manner. (See Photographs 17, 23 and 24).

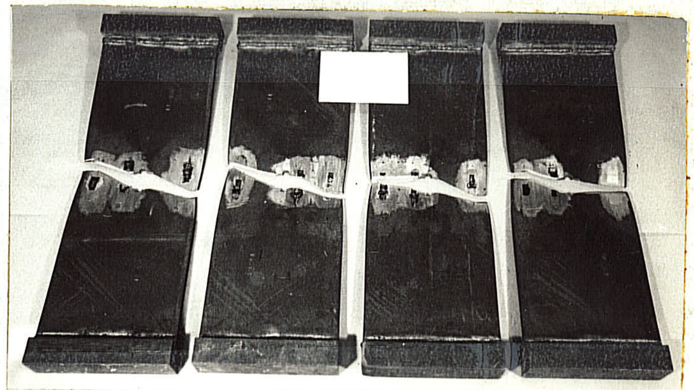
From figures 20 to 24, except for test four, one cannot tell if there was an effect on ductility in the temperature range tested. In test four at temperatures of $70^{o}F$ and $0^{o}F$ (slow rate of loading) and gauge readings of two and three, figures 23 illustrates a marked deviation with respect to the other tests. This can be attributed to the eccentric loading due to improper allignment when the specimen was welded into the test set up.

The effect of the notch is noticeable. The steel yielded below the calculated yield load of the specimen in this area as shown by gauge two (see figures 20 to 24).

Introducing prestrain by compressing the specimen with the notch present (figure 23) was shown to have the greatest influence as far as prestrain was concerned.

Temperature ^{o}F

-30° | 0° Fast Loading | 0° Slow Loading | 70°

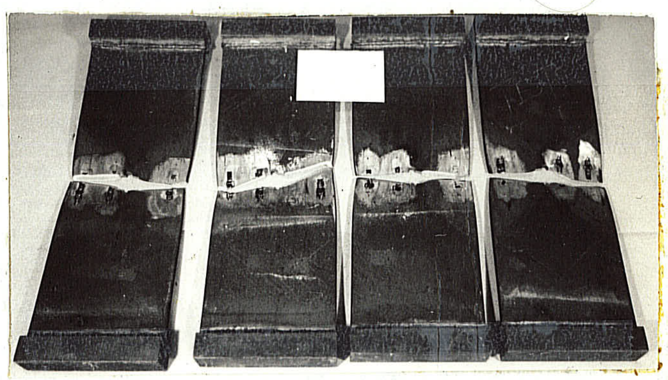


Photograph 10

Large Tension Test specimens - Test I after failure

Temperature ^{o}F

-30° | 0° Fast Loading | 0° Slow Loading | 70°

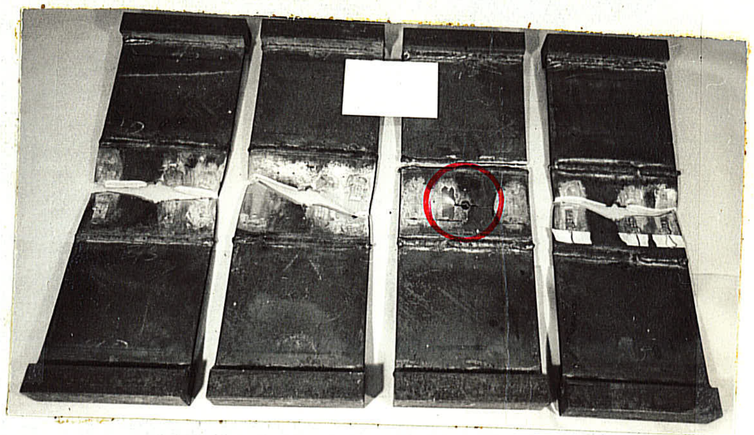


Photograph 11

Large Tension Test specimens - Test II after failure

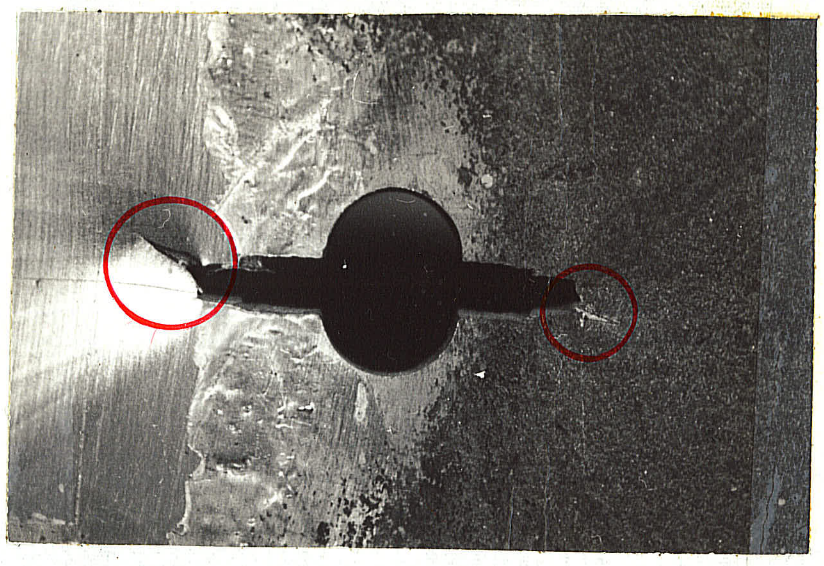
Temperature ^{o}F

-30°	0° Fast Loading	0° Slow Loading	70°



Photograph 12

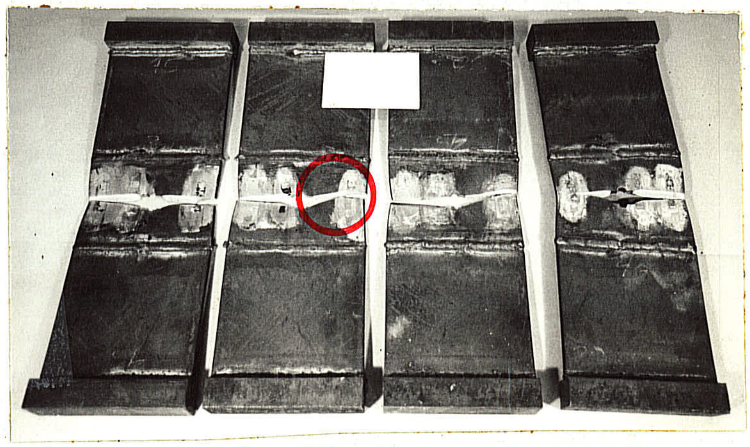
Large Tension Test specimens - Test 3 after failure



Photograph 13

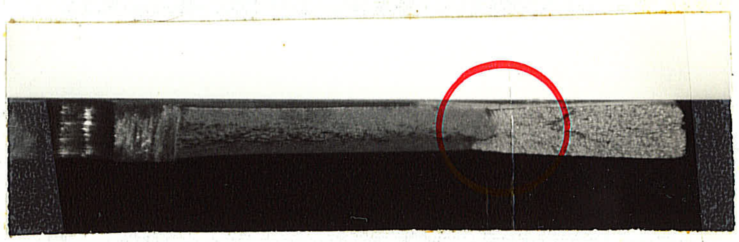
Close up of notch of test series 3 specimen tested at $0^{o}F$ slow rate of loading. This is after considerable yielding and plastic flow at the notch.

	Temperature ^{o}F		
	0^{o}	0^{o}	
	Fast	Slow	
-30^{o}	Loading	Loading	70^{o}



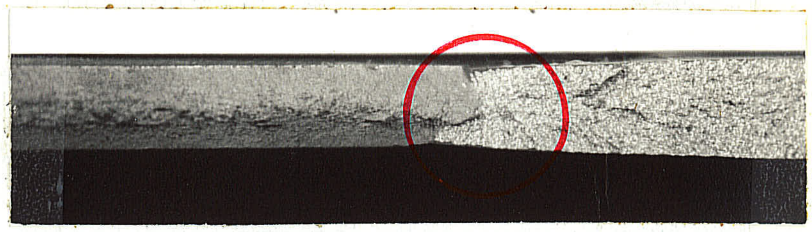
Photograph 14

Large Tension Test specimens - Test 4 after failure



Photograph 15

End view of fracture showing one side of the fractured test specimen of test series 4 tested at 0^{o}F fast rate of loading. Note the change from a ductile to a brittle failure.

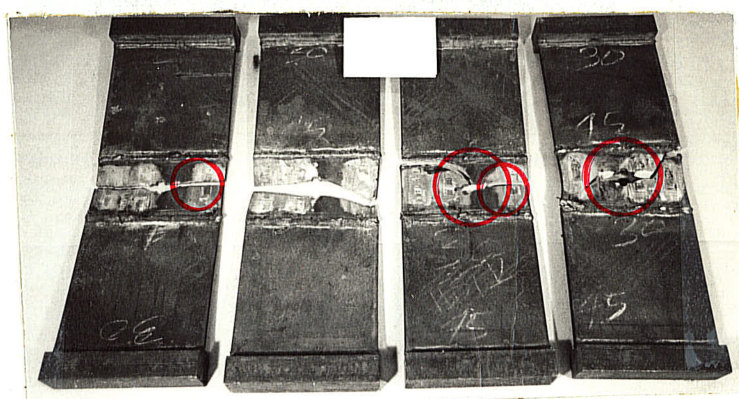


Photograph 16

End view of fracture. Close up of the transition zone mentioned at Photograph 15

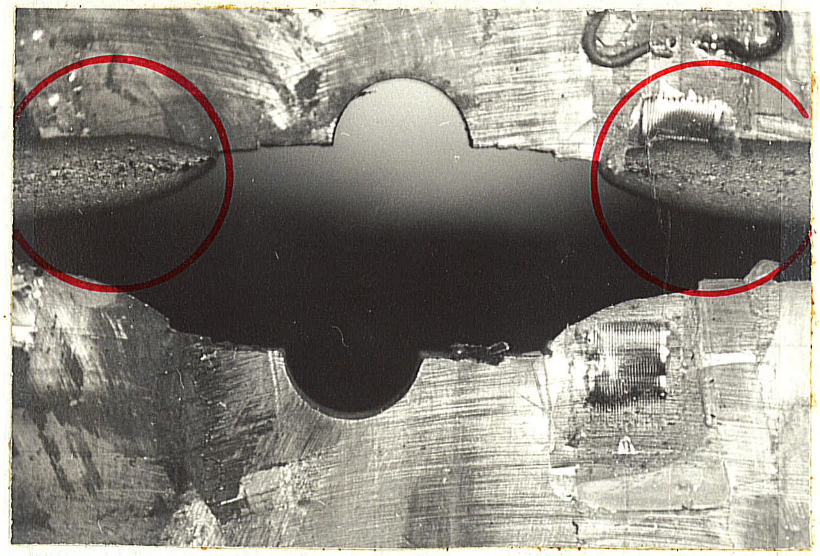
Temperature $^{\circ}F$

-60°	0° Fast Loading	0° Slow Loading	70°



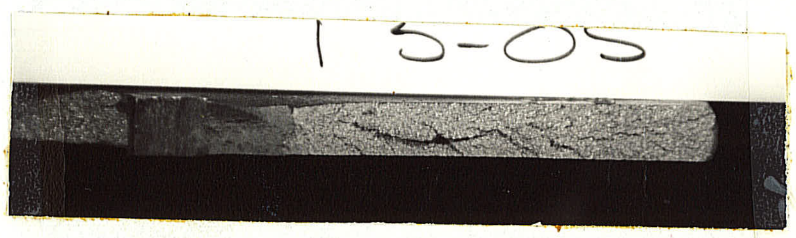
Photograph 17

Large Tension Test specimens - Test 5 after fracture



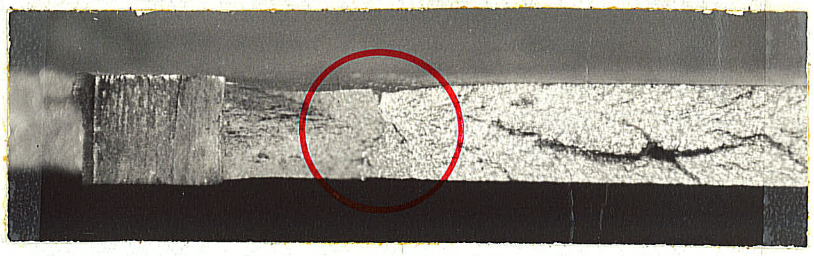
Photograph 18

Close up of notch of test series 5, specimen tested at 70°F. Note shear lip on both sides of the notch.



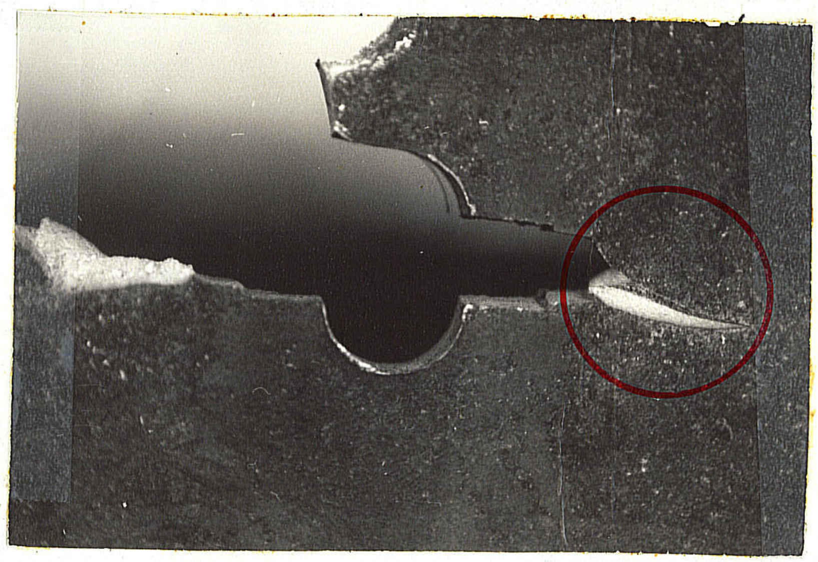
Photograph 19

End view of fracture showing one side of test series 5 specimen tested at 0°F slow rate of loading. Note the typical cleavage failure.



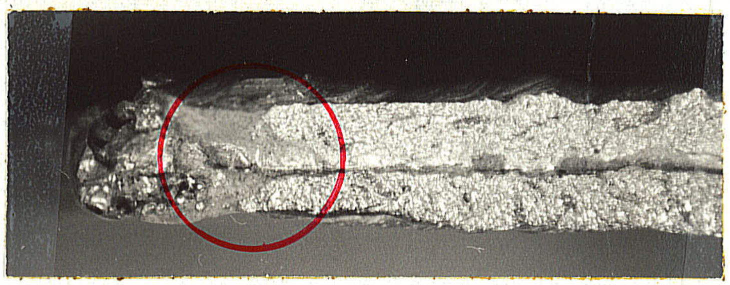
Photograph 20

End view of fracture. Close up of the transition to cleavage failure after the weld initiated failure.



Photograph 21

Close up of the notch of above photograph 20 and 19. The notch did yield with plastic flow before the weld failed.

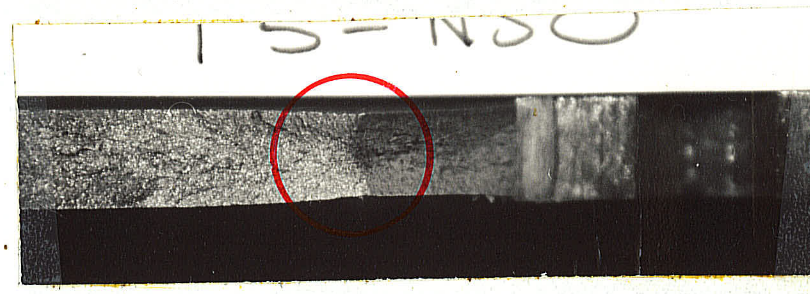


Photograph 22

End view of weld where the fracture was initiated in the specimen shown in Photographs 19, 20 and 21.

Photograph 23

End view of fracture - one side of the specimen of test series 5 that was tested at -60°F. Note the shear failure at the notch before the brittle fracture.



Photograph 24

Close up of the transition from shear to brittle failure mentioned at Photograph 23.

From figures 25 to 27 inclusive, it was observed that the ductility of the steel was becoming less as the temperature was lowered.

Summary of the Notched Tension Tests

The presence of the notches and prestraining in the temperature range of -30^{o}F did not produce brittle failures in this steel.

The presence of impact loading and welding did however, produce brittle failures. Poor welds produced brittle failures in this case.

One specimen, with prestrain due to welding with a notch present, was tested at -60^{o}F and produced a brittle failure. This illustrated that below the ductility transition temperature the steel will fail in a brittle manner, but not without some plastic flow at the base of the notch.

Comparison of the Standard Test and the Notched Tension Tests

Both series of test proved that:

a) A brittle failure in the steel was difficult to initiate above the -40^{o}F temperature.

b) Welding had a marked effect on the steel as far as introducing brittle failures.

Conclusions

1) The steel has a ductility transition temperature of $-40^{\circ}F$, with an energy value of ten foot-pounds.
2) It is very difficult to initiate a brittle failure in tension members of this steel in the presence of a notch above the steel's transition temperature of $-40^{\circ}F$.
3) The effect of preyielding with or without notches did not produce brittle failures above $-40^{\circ}F$.
4) Impact loading did produce brittle failures above the transition temperature.
5) Welding can initiate brittle failures in this steel.
6) Brittle failures can occur in this steel only with the occurance of large plastic flows at the base of the notch.

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