A Comparison of Notch Tests and Notch-Brittleness Criteria.

Lehigh University Bethlehem, Pa.

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A COMPARISON OF NOTCH TESTS
AND
NOTCH-BRITTLENESS CRITERIA

by

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FOREWORD

It is the purpose of this paper to present some of the results obtained in the course of a very comprehensive investigation being performed in the Fritz Laboratory of Lehigh University for the Fabrication Division of the Pressure Vessel Research Committee of the Welding Research Council. This project is concerned primarily with the effect of fabricating processes involving cold work, heat treatment and welding on the physical properties of different types of steel, particularly in regard to the tendency toward brittle behavior at low temperatures. Two steels, one rimming and one aluminum-killed, each in two thicknesses (5/8" and $1\frac{1}{4}$"), have been selected for the over-all test program.

However, in studying the transition temperature at which the mode of failure of a steel changes from shear to cleavage, the difficulty immediately arises that a suitable test must first be chosen from the many recommended for this purpose. Since there is no generally accepted standard test, it was considered necessary, before beginning the main research project, to examine some of the suggested test methods in order to find the one most suitable for such a project.

The present paper deals chiefly with this comparison of tests and most of the results have already been reported[15] in a progress report bearing the same title as this paper.

I. INTRODUCTION

The problem of brittle failure in welded steel storage vessels has many features in common with the failure of welded ships, about which a great deal has been published in recent months. The increasing tendency for a steel structure to fail in a brittle fashion as the temperature is lowered, is known to depend on such factors as the stress distribution at the point of failure, geometrical constraints inherent in the design, the composition, melting and rolling history of the material, and the forming, welding and heat treatment practices employed during fabrication. The precise effects of these factors are individually uncertain and the problem is made more complex by the many variables involved.

Notched test specimens are commonly used to obtain a transition from shear to brittle, or cleavage, failure at temperatures in the region of atmospheric temperature, since it has been evident from service failures that this transition, under service conditions, may occur at temperatures at least as high as atmospheric. The manner in which a notch alters the stress condition and so raises the transition temperature in a test-piece has been demonstrated by Gensamer[1] This principle has been applied to

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1 Numbers refer to references listed at the end of the report.

tension, bend, tear and impact tests, but, while variations in each of these forms are currently in use, the only notched tests to be widely used up to the present time have been the notched bar impact tests of the Charpy and Izod types.

No attempt will be made at this stage to review the voluminous literature on the subject of notched tests. This has been done many times in the literature, for example, by Hollomon[9], Gillett and McGuire[13], and Hoyt[14]. Throughout the following text, however, full reference will be made to the relevant work of earlier investigators.

Unfortunately, much of the early experimental work consisted of notched impact tests at a single temperature, which frequently was not reported. It is now known that a small change in testing temperature may effect a very large change in the notch brittleness characteristics of a steel, so that results at a single temperature, even if that temperature is known, are of limited value. In this connection, the A. S. T. M. Symposium on Impact Testing[18] held in 1938 did much to emphasize the importance of transition temperatures rather than single measurements of different criteria of brittleness. There still remains, however, the difficulty of devising a universally acceptable test method for the determination of transition temperatures.

Recently the notched bar impact tests have been criticized on the basis that the Charpy test fails to differentiate between steels which have distinctly different transition temperatures when tested in wide plate specimens.[4] Through many parallel investigations there has been a wide search for a more satisfactory test method and a variety of slowly loaded notched specimen tests have been suggested as improvements on the impact tests. Three of the most popular of these were selected for a thorough investigation to determine the most satisfactory means of following the transition from shear to brittle failure, as applied to the steels used in this particular investigation.

Initially it was thought that the Lehigh slow notched bend test developed earlier by the Metallurgy Department[2] at Lehigh might not be as satisfactory as certain other tests, particularly in regard to the convenience and significance of the range of testing temperatures in which transition occurred.

For the purposes of the comparison, it was agreed beforehand that final selection of a test should be based on the following considerations:

(a) The results obtained should be reproducible and should show a well-defined transition from shear to cleavage failure in a suitable temperature range. This should apply to both types of brittleness criteria at present in use (see later).

(b) Convenience and cost of the test: test should be simple and rapid to perform; specimen should be economical of material and easily machined; testing rig should be of simple construction.

Attempts to compare and correlate transition temperatures obtained from different tests have been relatively few. It was chiefly the tension tests on wide notched plates, conducted by Boodberg, Davis, Parker and Troxell at the University of California[21] and by Wilson, Hechtman and Bruckner at the University of Illinois[22], which led to a desire to correlate the results of small specimen tests with those of the large and expensive "wide plate tests". While the expense of making wide plate tests prevented a really satisfactory determination of transition temperatures, the work provided the stimulus for the valuable contributions of Kahn and Imbembo[3,11] and of Klier, Wagner and Gensamer[4]. Both of these parties attempted to correlate the results of small specimen tests (to be described later) with Charpy and "wide plate" results. Stout and McGeady[5] made what was probably the most valuable contribution to the literature on comparison of notch tests, when they emphasized the necessity of comparing only those test results obtained using the same type of measurement as the criterion of brittleness. This concept will be discussed in more detail later.

MacGregor and his coworkers[20] achieved an interesting correlation between notched bar tests and biaxial stress tests on thin plates. It is also interesting that Gensamer[1] claims some correlation between Charpy results and the reduction of area in the tensile test, provided that both types of test are conducted with exceptional care. However, the variation in reduction of area results is very slight and usually it is not possible to obtain correlation between the tensile test and notch tests. An investigation just completed[17] will give evidence on this question.

There is perhaps one point which should be clarified before attempting to describe the actual experimental work. The terms "shear" and "cleavage", as used in the literature on fracture, refer to the appearance of a fracture surface. A shear fracture has a dull grey "fibrous" appearance while a cleavage fracture has a bright "crystalline" appearance. The difference between the two types may be seen very clearly from Fig. 10. The terms "shear" and "cleavage" have achieved wide usage because it has been thought that the bright, brittle fracture results from cleavage across certain crystallographic planes and that the shear fracture is a result of separation along slip bands.

Actually, however, there is little evidence that the mechanism of fracture is fundamentally different in the two cases and Hollomon[19] has proposed a simple explanation of the different appearances. He suggests that the cleavage-type fracture only occurs if the deformation in front of the forming crack is negligible when fracture occurs. If appreciable deformation takes place at the base of the growing crack when the fracture occurs, the metal is drawn out and the fracture appears fibrous. Ductile fracture can be thought to occur by a series of steps, further deformation at the base of the crack being required in each step before fracture takes place.

2. EXPERIMENTAL DETAILS

Description of Tests

The three tests chosen for comparison were the Kahn tear test, the Penn State slow notched-bend test and the Lehigh slow notched-bend test. These have been described in the literature previously but the following brief descriptions are given for completeness and to point out where modifications of the original specimens were made.

The Kahn tear test[3] is illustrated in Figs. 1.a, 1.b and 1.c. The specimen shown in Fig. 1.a is held by pins and shackles (Fig. 1.b) attached, through shafts mounted on spherical bearing blocks, to the heads of a standard testing machine, both specimen and shackles being surrounded by an insulated constant temperature bath as illustrated in Fig. 1.c. The only significant modification of the procedure recommended by Kahn was made in testing the heavier ($1\frac{1}{4}$") plate, when 1" pins were necessary to hold the specimens instead of the usual $\frac{3}{4}$" pins. The method of obtaining an autographic record of the load-deflection diagram was to magnify the relative displacement of the heads of the machine by a factor of 4, using a simple pulley and cord arrangement to obtain the magnification and to drive the recorder drum.

The Penn State test[4] is illustrated in Figs. 2.a and 2.b. This test was conducted exactly as it was developed at the Penn State laboratories. An autographic record of the load-deflection diagram was obtained by using a Kenyon-Burns-Young wedge-type extensometer, part of which can be seen in the upper left corner of Fig. 2.b. The insulated tank which surrounds the testing jig and specimen during testing was removed for this photograph in order to show details of the jig.

The Lehigh slow notched bend test[2] is shown in Figs. 3.a and 3.b. The specimen used was somewhat different to that developed as a weldability specimen, the differences being that the specimen in Fig. 3.a has a thickness of 5/8" and uses an Izod notch of only .010" root radius, whereas the weldability specimen is the same thickness as the plate from which it is cut and the notch has a .040" root radius. In the case of the 1 $\frac{1}{4}$" plate, one side was machined to leave a 5/8" thickness and the notches were in the rolled surface. The method of measuring bend angle by protractors clamped to each end of the specimen can be seen from Fig. 3.b and the simple cord and pulley arrangement for magnifying the relative motion of the cross-heads on an autographic load-deflection diagram is partly visible behind the bending jig. In this test the specimen is transferred rapidly from a constant-temperature bath to the testing jig, where it is tested in air. In following this procedure, it is known that the change in temperature of the specimen due to gain or loss of heat to the atmosphere is negligible.

The cross-head speeds used in the three tests were as follows:

Lehigh test:	3 inches per minute
Kahn test:	0.3 inches per minute
Penn State test:	0.1 inches per minute

In addition to the three tests investigated in selecting a slowly loaded notched specimen test, some results[16] will also be presented for the standard Charpy test (conducted according to A. S. T. M. Specification E 23 - 41 T), and for a double width Charpy test.

These two specimens are shown in Fig. 9.

For all tests, elevated testing temperatures were obtained by electrically heating oil or water; low testing temperatures were obtained by adding dry ice or liquid nitrogen to a medium of gasoline or alcohol. Specimens were always held at temperature long enough to ensure that they had reached the temperature of the bath before testing. Transition curves were established by testing four specimens at each of six temperatures.

Measurements Made on Test Specimens

It has recently been emphasized[5] that transition temperatures determined in different tests should only be compared when, in each test, the same criterion of brittleness is used to establish the transition curve. The transition curves for different tests are frequently constructed on the basis of quite different criteria. Thus, in the Penn State test, the appearance of the fracture and the percentage lateral contraction below the drilled hole have been used as criteria of brittleness; in the Kahn test, the appearance of the fracture and the energy absorbed by the specimen after passing the maximum load are the usual criteria; in the Charpy test, the total energy required to break the specimen is measured; in the Lehigh slow notched-bend test, the bend angle at maximum load and percent lateral contraction below the notch have been used; Bagsar[6] used a tear test with the maximum load as criterion; Kinzel[7] recommended a bend test using percent contraction below the notch as the criterion; and so on. However, it was evident in planning the comparison that three tests could be compared only if all measurements commonly made on any one of the tests were made on all three.

This necessitated the following measurements on each test:

1. Appearance of fracture; The percentage of the fracture area which exhibited a brittle, or cleavage type of failure was measured on all specimens.
2. The energy absorbed by the specimen after passing the maximum load until the load had fallen to half the maximum: This was read from the autographic load-deflection curve up to the point of complete failure and an end-point for all specimens was therefore fixed at half the maximum load.
3. The percentage contraction in the width of the specimen at a point 1/32" below the notch after fracture. A pointed micrometer was used for this purpose.
4. The percentage reduction in width at the midpoint of the specimen. In the Penn State

specimen this was measured as the percentage contraction 1/32" below the drill hole.

5. Certain criteria of brittleness which could not be measured identically in all tests. The bend angle at maximum load in the Lehigh test was measured by attaching protractors to the specimen, a procedure which would have been impossible in the Penn State test. However, it was shown that the angle of bend was proportional to the displacement of the plunger in the Lehigh test, and this latter quantity, the bend deflection at maximum load, was read from the load-deflection diagram in the Penn State test.

In the Kahn tear test, the percent elongation on a 2" gauge length ¼" behind the notch was measured also.

In the single and double width Charpy tests the following measurements were made:

(i) total energy absorbed during testing

(ii) % lateral contraction below the notch

(iii) % cleavage in the fracture surface.

Materials

The plates used in the comparison came from two heats of steel for which the complete mill history is known. One heat, aluminum-killed, had been supplied to

A. S. T. M. specification A-201 and the other, a rimming steel to A. S. T. M. specification A-70. Both steels were tested in two plate thicknesses, 5/8" and 1 ¼", and chemical analyses for the four plates are given in Table I.

Each plate was tested in three conditions:

(a) as rolled

(b) after 10% plastic tensile strain

(c) after aging 2 hours at 200° C (392° F) following the 10% tensile strain

All cold worked or strain-aged specimens were tested seven days after the straining or heat-treatment operation.

3. RESULTS

Method of Plotting Results

All of the above-mentioned criteria of brittleness may be plotted against temperature. However, because of the considerable scatter obtained in the results of this type of work, there has been much controversy regarding the method of drawing a curve to represent the results.[4,8] There is little justification for the common procedure of drawing the "best-fitting" smooth curve through a mass of scattered data; on the other hand, the normal scatter of results is so great that attempts at mathematical curve-fitting are not justified unless a large number of points are available. Furthermore, in order to apply Roop's[8] suggested method of analysis, test results are necessary over a wide range of temperatures to ascertain whether the curve approximates the form which he suggests.

In view of these considerations, it was decided that the most satisfactory method of representing the present results was simply to join the mean values for each temperature by straight lines.* This method has the important advantage that it is completely independent of any personal element.

Definition of Transition Temperature

The method of defining transition temperature has been the subject of just as much controversy as has the type of curve to be drawn. Inthis paper the transition temperature is defined as the temperature at which the curve, drawn as described in the previous section, has a value equal to the arithmetic mean of its maximum and minimum values. Thus, if the criterion under consideration is the % cleavage in the fracture surface, the transition temperature is the temperature at which the curve has a value of 50% cleavage.

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*Where, in a very few cases, this method would produce a change in sign of the slope between two adjacent testing temperatures within the transition or scatter zone, the points at each end of this inconsistent section were by-passed and the straight lines drawn to the mid-point of the section.

Recent moves to define the transition temperature, on the basis of fracture appearance, as the highest temperature at which one specimen out of four or five shows more than 50% cleavage, are equivalent to choosing the temperature at which the curve described above has a value of approximately 80% cleavage. There appears to be no valid reason for choosing such a point in preference to the 50% point, which has the following distinct advantages:

(1) The temperature is known to be in the middle of the scatter zone, whereas the most that can be said for an 80% point is that it is probably near the upper limit of the scatter zone.

(2) The slope of the transition curve is a maximum at this point and the temperature is therefore fixed with greater accuracy than at other points on the curve.

The above definition applies in a straight-forward manner to all % cleavage curves as shown for curve E in Fig. 4 and also to % contraction-below-the-notch curves of type A in Fig. 4. However, some curves, such as B and C in Fig. 4, show two definite stages in the transition and for these curves two transition temperatures are defined according to the definition given earlier. It was found experimentally and is shown in Fig. 4 that transition temperatures defined in this way occur at two distinct temperatures for one steel. The temperature determined by curve A and the lower section of B and C will be called T_N and the higher temperature determined by curve E and the upper sections of B and C will be called T_B. The significance of T_N and T_B will be discussed in detail later. Curve D gives evidence of both T_B and T_N but does not have the two sudden transitions of Curve B.

In the energy vs. temperature plots of the Lehigh bend results, some of the curves lack points at temperatures sufficiently high to ensure that maximum energy value had been reached; in this case, therefore, the transition temperature was taken as that giving a prescribed energy level (312.5 ft. lbs.)

Experimental Results

A complete set of transition curves for the A-70, 1 $\frac{1}{4}$" material is given in Figs. 5, 6, 7 and 8. The other three materials showed essentially the same types of curves. Experimental results for all materials are summarized as transition temperatures in Tables 2, 3, 4, and 5.

Since transition temperatures of one material according to different criteria applied to the same type of test may be as much as 200^{o} F apart, it was necessary to test over a wide temperature range with the limited number of specimens available. Testing temperatures were therefore more widely spaced than is usual when only one criterion is being investigated, but it is nevertheless believed that most of the transition temperatures quoted in Tables 2, 3, 4, and 5 are accurate to within $\pm$ 10°F. Additional tests were made for many of the "as-rolled" curves in order to check certain ideas suggested by the original 24 specimens; this accounts for the larger number of points on the "as-rolled" curves in Figs. 5, 6 and 7.

In the case of the three slowly loaded tests, it should be mentioned that autographic load-deflection curves on these tests can only be obtained by using the movement of the heads of the testing machine as a measure of the deformation in the specimen. Particularly in the Penn State and Kahn tests, using high loads and small deflections, the measurement of the energy absorbed after passing the maximum load therefore involves inaccuracies due to elastic deflection in the head of the machine. Also, in all three specimens appreciable deformation occurs in regions removed from the notch, but the energy associated with this deformation is absorbed prior to the maximum load and does not affect the measurement of energy after maximum load.

4. DISCUSSION OF RESULTS

Comparison of Criteria

The results in Table 2 and Fig. 5 show very clearly that the Lehigh bend test divides the brittleness criteria into two distinct groups: Group I, comprising the fracture appearance and the energy after maximum load, giving transition temperatures between 100° F and 200° F higher than Group II, which consists of the bend angle at maximum load and the % contraction below the notch. Group I criteria have a transition curve as in Type E of Fig. 4. The agreement between transition temperature according to different criteria in the same Group is generally good.

In the Penn State test and Kahn tear test similar groups of criteria may be distinguished except that Group II criteria here show curves of types B, C and D in Fig. 4, instead of Type A. Curve B may be regarded as an ideal curve from which experimental curves frequently deviate towards either C or D. Group I criteria invariably show the simple type E curve. (See Figs. 5A, 6A, 7A)

Now, although the actual temperatures vary from test to test, each of the three tests does distinguish two different transition temperatures, one (T_B) some 100-200° F higher than the other (T_N). Group I criteria may be defined as those which show only the high temperature transition at T_B, while Group II criteria are those which are influenced by the transition at T_N. The latter (T_N) is clearly shown in the Lehigh bend test and its existence is demonstrated in both the Penn State and Kahn tests, although here Group II criteria also show evidence of the upper transition (T_B). Consideration may now be turned to the significance of the two temperatures T_B and T_N.

Two important observations may be made on this subject:

(1) In terms of the load-deflection diagram obtained during testing, Group I criteria are measures of the energy absorbed after passing the maximum load, while Group II criteria are either measures of the energy absorbed by the specimen up to the maximum load or are very strongly influenced thereby.

(2) T_B clearly corresponds to the transition in the fracture appearance (curve E in Fig. 4), but at temperatures far below T_B a small zone immediately below the notch continues to fail in a ductile manner. It was verified for each of the three tests investigated, that T_N corresponds to the transition in fracture appearance in this small zone below the notch.

Thus T_N may logically be considered as the temperature of transition from a shear to cleavage mode of fracture under the stress conditions imposed by the notch machined in the specimen surface, while T_B is a similar transition temperature for the stress condition existing at the base of a sharp crack formed by shear fracture immediately below the notch. The fundamental effects of geometry and stress conditions on transition temperatures have been discussed very fully in the literature[9, 10], and it would be expected from the known principles that T_B, the transition temperature for the sharper effective notch, would be appreciably higher than T_N. The magnitude of this effect may be gauged from the fact that, using the 5/8" Lehigh bend specimen on A-70, $1\frac{1}{4}$" plate, T_N for a notch of 0.010" radius was found to be about 80° F higher than for a notch of 0.040" radius. Stout and McGeady[5] have recently published results of investigations in which T_N varied by as much as 100° F between notches of different severity.

Moreover, since T_B is higher than T_N, the transition at temperature T_B occurs in metal which has been plastically deformed prior to and concurrently with initial shear fracture at the root of the notch. The temperature T_B is therefore a characteristic of deformed metal and not of the metal before it is tested. Table 2 shows that a 10% plastic strain may raise T_N by as much as 100° F, so that this effect together with that of the different effective notch severities can readily account for differences between the temperatures T_B and T_N of the order of magnitude encountered in Tables 2, 3, and 4.

The practical implications of this discussion of the two transition temperatures are very important. The temperature T_B, which is determined when fracture appearance, energy after maximum load, etc., are employed as the brittleness criterion, is the transition temperature of the material after a severe but indeterminate cold deformation. The stress system producing the transition is that obtaining at the base of a crack.

On the other hand, the temperature T_N influences only those criteria which fall in the Group II defined above, and is the transition temperature of the material under the stress system prevailing at the base of a machined notch. It should be pointed out that the root radius of the machined notch changes during a test and the radius at failure is different in different steels. However, Group II criteria possess the important property of being sensitive to notch acuity and other surface or near-surface effects to which T_B and the Group I criteria are completely insensitive. In some cases, such as the Lehigh Weldability Test, welding effects may be regarded as surface or near surface phenomena having little or no effect on T_B and Group I criteria.

There is also evidence[17] that, in the Lehigh test at least, Group I criteria are much less sensitive to the effects of cold work than are the Group II criteria: Steels prestrained 1%, 5% and 10% in tension were tested as Lehigh slow notch bend specimens and, as can be seen from Figs. 11a, 11b, 12a, and 12b, the curves for % cleavage were changed very little compared with those for % contraction, which were shifted to appreciably higher temperatures by the cold work. The results in Table 2 also give some evidence that T_B and the Group I criteria are less sensitive to the effects of cold work. Unfortunately, with the Kahn and Penn State tests, it was not possible to determine T_N for any of the cold-worked materials (see Tables 3 and 4) so that for the present this observation is limited to the Lehigh test.

Significance of Transition Curves and Temperatures

The conslusions reached in the foregoing discussion may now be used to explain briefly the origin and significance of the various transition curves and the two temperatures, T_B and T_N.

Consider first the metal at the surface in the root of the notch, in any of the notch tests under investigation. The as-received metal under the stress conditions obtaining at the root of the notch has a transition temperature of T_S, below which the surface metal will fail without deformation and above which it will fail with shear. This is shown schematically in Fig. 13, Curve A. Two factors prevent the practical realization of Curve A:

(i) If the surface metal is deformed during testing by an amount, x% lateral contraction, the cold work performed raises the transition temperature to T_x and the transition curve becomes Curve B* in Fig. 13.

(ii) Normal scatter of results rounds off the top and bottom of the curve as in Curve C of Fig 13.

These considerations determine the shape of the Group II criteria curves and T_N as defined earlier is shown in Curve C. This discussion neglects the slight effect of changing notch radius during a test.

At temperatures above the range shown in Curve C, the surface metal at the base of the notch deforms to the limit of its ductility before cracking. The crack so formed creates a more severe stress system under which the transition temperature of the metal is much higher than at the base of the notch, particularly as the metal at the base of the crack is already cold worked. However, this higher transition may be treated in a way similar to T_S in Fig. 13 to give a Curve C representing a curve for Group I criteria; the midpoint on this curve would then represent T_B.

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*The curvature of Curve B is derived from Figs. 11a and 12a which suggest that cold work exerts a stronger influence on the transition temperature at high levels of cold work - otherwise the lower sections of the curves for 1%, 5% and 10% prestrain should be parallel.

It is clear that neither T_N nor T_B have a simple fundamental significance such as can be assigned to T_S. The value of T_N lies in the fact that it is largely dependent on T_S but is a more convenient temperature to determine. The value of T_B is its practical significance in the study of propagation of fractures, as distinct from their initiation. Probably the only transition temperature appearing in the literature which has the fundamental significance of T_S, is that determined by MacGregor and his associates[20] on biaxially stressed thin plates; they define the transition temperature as the highest temperature at which the plate breaks without first yielding.

Comparison of Tests

The original object of this investigation was to compare the Kahn, Lehigh and Penn State tests on the basis of the considerations outlined above (Section I). The following conclusions were reached as a result of the experience gained in performing the large number of tests reported herein:

a) Results

(1) Transition Temperatures: As can be seen from Tables 2, 3, and 4, there was little to choose between the tests with respect to the temperature ranges in which

the transitions occurred.

(2) Effect of Criterion: The Lehigh test was the only one to determin T_N satisfactorily. T_B could be determined equally well by all three tests, although the transition zone was wider in the Lehigh test than in the other two.

(3) Reliability: The Penn State results conflicted with those of the other tests and were inconsistent within themselves, in that the 1 ¼" A-201 and 5/8" A-70 plates showed transition temperatures after straining, and sometimes even after strain-aging, which were lower than those of the as-rolled materials.

b) Convenience and Cost of the Test

(1) Machining: There was little to choose between the three tests in the matter of machining time but the Lehigh and Kahn tests probably had an advantage over the Penn State test.

(2) Testing Rig: The Lehigh test set-up was the simplest of the three, but both the bend tests were much simpler than the Kahn test. The latter was the only one in which regular replacements of any parts - in this

case the pins - were necessary.

(3) Ease and Speed of Testing: Here again the bend tests were definitely superior to the Kahn test, with the Lehigh test somewhat quicker and more convenient than the Penn State test.

(4) Size of Specimen: The Penn State test was considerably more economical of material than the Kahn and Lehigh tests, the latter using slightly more than the Kahn.

It was decided on the basis of these findings to adopt the Lehigh slow notched-bend test for future work requiring transition curve determinations. The fact that the Lehigh notch is in the surface is apparently unimportant, even with the A-70 steel, as the Lehigh results conform quite well to the pattern of the Kahn test results.

Values of T_B determined by the Lehigh test were generally slightly higher than those determined by the Kahn test, these in turn being some 50° F or so higher than those of the Penn State test. It seems probably that these differences in T_B can be explained on the basis of specimen geometry, the greater restraint due to the greater width of the Lehigh specimen and the greater notch depth of the Kahn tear specimen being responsible for the higher values of T_B in these tests. However, there are two factors to complicate this simple picture; firstly, the speed of testing is different in each test; secondly, the amount of cold work preseding failure is probably different in the three tests.

The values obtained for T_N were not very reliable in the Kahn and Penn State tests but generally speaking they were both lower than the T_N value given by the Lehigh test. This also is probably due chiefly to differences in geometry.

Charpy Results

The results of a survey of Charpy transition temperatures according to the three different criteria for the two heats of steel are give in Table 5. It is evident that transition temperatures using fracture appearance as the criterion were invariably higher (by as much as 50° F) than those obtained using either of the other criteria. Temperatures taken from the energy or % contraction curves were usually almost equal and it may be that these correspond to the T_N of the slowly loaded tests, while the fracture appearance again determines T_B. However, there is some evidence in Fig. 8 that this is not so, since the transition zone begins at about 0° F for all criteria. This may mean that, because of the comparatively small specimen used in the Charpy test, the transition at the notch (T_N) is associated with a high proportion of shear failure below the notch and around the faces of the specimen. For example, in Fig. 8, at a temperature of 75° F where the % contraction transition is complete, the specimen already exhibits almost 60% shear in the fracture.

As would be expedted from geometrical considerations, transition temperatures determined by the double-width specimens were higher than the corresponding temperatures obtained with sinlge width specimens.

<u>Effect of Materials</u>

The effect of cold work and strain-aging on the transition temperatures of A-70 and A-201 steels will be described more fully in another paper[17] but some conclusions may be drawn from the results presented in Tables 2, 3, and 4.

In all tests T_B was considerably higher for the rimming steel than for the aluminum-killed steel as rolled. In the Lehigh and Penn State tests the difference was very close to 60° F; in the Kahn test it varied from 30 to 50° F. Except for the inconsistencies in the Penn State results mentioned above, T_B generally increased after cold work and increased further after strain aging. The increase in T_B due to strain aging was approximately the same in both steels.

The effects on T_N may be judged only from the results of the Lehigh test in Table 2. It appears fhom these, however, that T_N may not be as susceptible to differences in deoxidation practice as is T_B, but that it is very sensitive to strain-aging effects.

Two chemical factors have been suggested recently as governing the value of T_B; they are the nitrogen content[10] and the Mn:C ratio[11]. It is interesting to note that although the two steels investigated had approximately the same nitrogen content, T_B for the rimming steel was 60° F higher than for the Al-killed steel. It seems probable that nitrogen content is of more significance in strain-aging phenomena than in the consideration of transition temperatures, and in this connection it is of interest to recall that the effect of strain-aging on T_B and T_N was much the same in both steels.

From Table 1 it can be seen that the two steels have Mn:C ratios of almost 2 for the A-70 steel and about 3 ½ for the A-201 steel. According to Barr and Honeyman[11], the higher Mn:C ratio should correspond to a lower value of T_B and it is believed that the higher Mn:C ratio of the A-201 steel contributed to its lower transition temperatures.

Effect of Plate Thickness

In all tests, T_B for the 1 ¼" material was about 60° F higher than for the corresponding 5/8" material. In the Penn State and Kahn tests this may have been partly a result of geometrical differences but since the Lehigh specimens, which were machined to the same geometry, showed the same effect there was clearly a difference in the materials being tested.

Using the Lehigh slow notched-bend test, transition curves were determined on 5/8" thick specimens normalized 1 hour at 1600° F before notching for both steels in both thicknesses. The results are summarized in Table 5. It is evident that while some difference remained between transition temperatures corresponding to parent plates of different thickness, this difference was largely removed by the normalizing treatment. This suggests that such differences were largely the result of the different cooling rates experienced by plates of different thickness in cooling from the finishing temperature after rolling.

Increased cooling rates and higher manganese contents both result in finer pearlite and it seems probable that this is the mechanism by which these factors give lower transition temperatures.

5. CONCLUSIONS

1. In each of the three slowly loaded notch tests investigated, the use of different criteria of brittleness determined two different types of transition temperature.

2. The upper temperature, T_B, is that determined by a group of criteria of which the fracture appearance is usually the most satisfactory; it is the transition temperature of the material after considerable cold work and under the stress conditions pertaining at the base of a sharp crack.

3. The lower temperature, T_N, from 100 to 200° F lower than T_B, is best determined by using the % lateral contraction below the notch as the criterion of brittleness; it is an indication of the transition temperature of the material under the stress system imposed by the machined notch.

4. Charpy tests did not clearly distinguish these two transitions (st T_N and T_B) but transition temperatures determined by different criteria usually showed substantial differences.

5. Of the three notch sensitivity tests examined and compared, the modified Lehigh slow notched-bend test was considered the most satisfactory.

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Table 1. Chemical Composition of Materials

	A-201		A-70	
	5/8"	1 ¼"	5/8"	1 ¼"
C	.17	.15	.19	.18
Mn	.55	.53	.36	.34
P	.020	.020	.019	.018
S	.022	.025	.020	.028
Si	.21	.19	.02	.02
Cu	.06	.08	.13	.15
Al	.041	.026	.028	.038
Al_2O_3	.003	.002	.002	.003
N_2	.005	.003	.003	.003
Ni	.05	.05	.10	.09
Cr	.04	.04	.04	.04
W	.04	.04	.04	.04
V	.02	.02	.02	.02
Mo	.01	.01	.01	.01

Table 2. Transition Temperatures in ^{o}F

Lehigh Slow Notched-Bend Test

	% Brittle	Energy	Bend Angle	% Contraction below notch
	T_B	T_B	T_N	T_N
A-201, 5/8"				
as rolled	41	33	-88	-68
strained	45	43	-72	-44
strain-aged	101	95	-13	30
A-201, 1 ¼"				
as rolled	95	77	-78	-58
strained	123	95	-17	0
strain-aged	156	105	-21	32
A-70, 5/8"				
as rolled	100	85	-74	-76
strained	123	143	5	37
strain-aged	177	197	-22	15
A-70, 1 ¼"				
As rolled	162	103	-46	-42
strained	190	152	12	45
strain-aged	183	138	30	60

Table 3. Transition Temperatures in °F

Penn State Slow Notched-Bend Test

	% Brittle	Energy	% Contraction at drill hole	Bend Deflection		% Contraction at notch	
	T_B	T_B	T_B	T_B	T_N	T_B	T_N
A-201, 5/8"							
as rolled	-23	-15	-11	-32	-100	-9	-100
strained	-19	-26	-13	-30	-	-22	-
strain-aged	-8	-13	-5	-7?	-	-13	-
A-201, 1 ¼"							
as rolled	43	43	43	41	-100	39	-60
strained	22	21	26	18	-	14	-
strain-aged	43	40	47	27	-	27	-
A-70, 5/8"							
as rolled	38	41	42	34	-90	48	-90
strained	16	17	16	7	-	7	-
strain-aged	53	55	58	53	-	60	-
A-70, 1 ¼"							
as rolled	97	98	92	89	-70	53	-70
strained	98	101	99	100	-	94	-
strain-aged	106	108	105	-	-	103	-

Table 4. Transition Temperatures in °F

Kahn Tear Test

	% Brittle	Energy	% Contraction at Mid-point	% Contraction below Notch		Elongation	
	T_B	T_B	T_B	T_B	T_N	T_B	T_N
A-201, 5/8"							
as rolled	28	14	20	-	-120	-	-
strained	60	32	55	-	-	-	-
strain-aged	73	-	65	-	-60	-	-
A-201, 1 ¼"							
as rolled	87	57	87	50	-100	50	-120
strained	102	93	100	86	-	90	-
strain-aged	140	140	138	141	-	140	-
A-70, 5/8"							
as rolled	60	60	58	57	-110	62	-100
strained	88	85	85	85	-	85	-
strain-aged	103	83	95	105	-	110	-
A-70, 1 ¼"							
as rolled	145	156	125	134	-35	142	-45
strained	192	196	182	175	-	175	-
strain-aged	200	205	188	168	-	170	-

Table 5 - Charpy Transition Temperatures (°F) at Various Locations According to 3 Criteria

	Single Width Specimen			Double Width Specimen		
	Energy	% Cleavage	% Contraction	Energy	% Cleavage	% Contraction
A-201 Steel (Aluminum-killed)						
Ingot 1, Top*	-80	-52	-92			
Middle	-50	---	-50			
Bottom	-60	-18	-52			
Ingot 3, Top	-61	-13	-62			
Middle	-61	-33	-66			
Bottom	-70	-42	-69			
Ingot 4, Top*	-47	-28	-44	-29	-19	-35
Middle	-22	+12	-27	-17	+20	-17
Bottom	-35	-10	-38	-17	+14	-32
Ingot 9, Top	-25	+25	-26	+2	+42	-7
Middle	-33	-8	-38	-15	+34	-17
Bottom	-38	-10	-41	+10	+25	+2
A-70 Steel (Rimming)						
Ingot 2, Top	+57	+65	+37	+63	+116	+42
Middle	+56	+68	+31	+50	+92	+31
Bottom	+34	+47	+27	+42	+70	+29
Ingot 7, Top	+8	+48	+8			
Middle	+12	+40	-6			
Bottom	+4	+33	-2			

* Normalized plate

Table 6. Transition Temperatures for Normalized Materials

	T_B (°F)	T_N (°F)
A-201, 5/8"	-55	-110
A-201, 1 1/4"	-25	-115
A-70, 5/8"	51	-91
A-70, 1 1/4"	40	-85

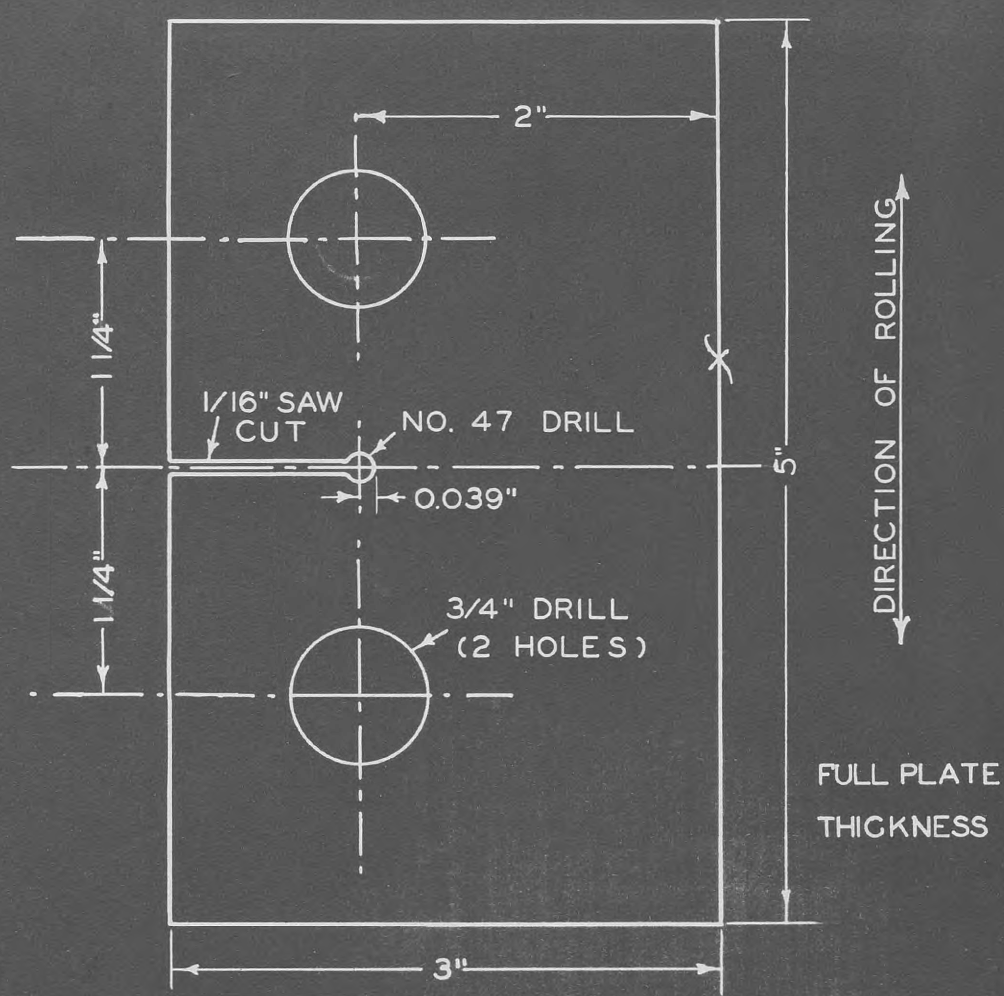


FIG. 1A SPECIMEN USED IN THE KAHN TEAR TEST.

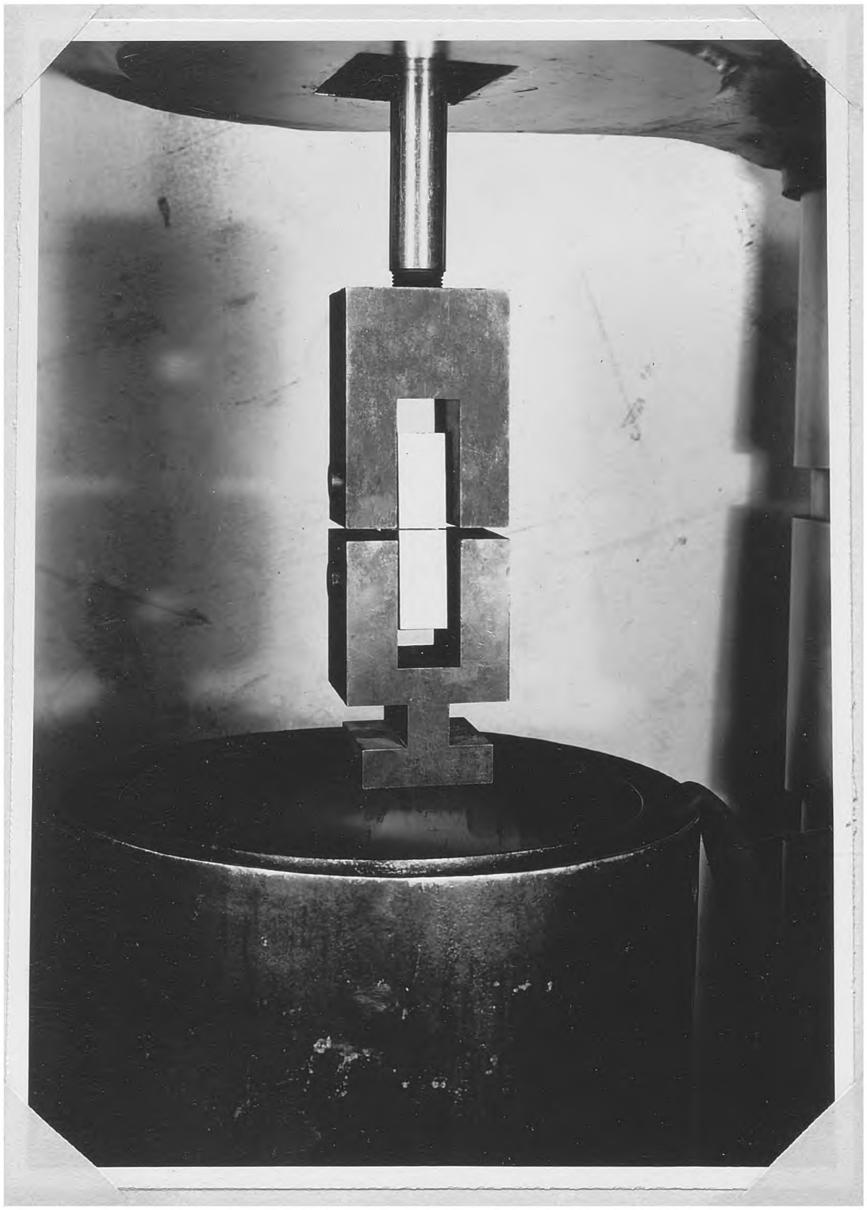


Fig. 1.b Kahn Tear Test, showing method of holding specimen by pins and shackles.

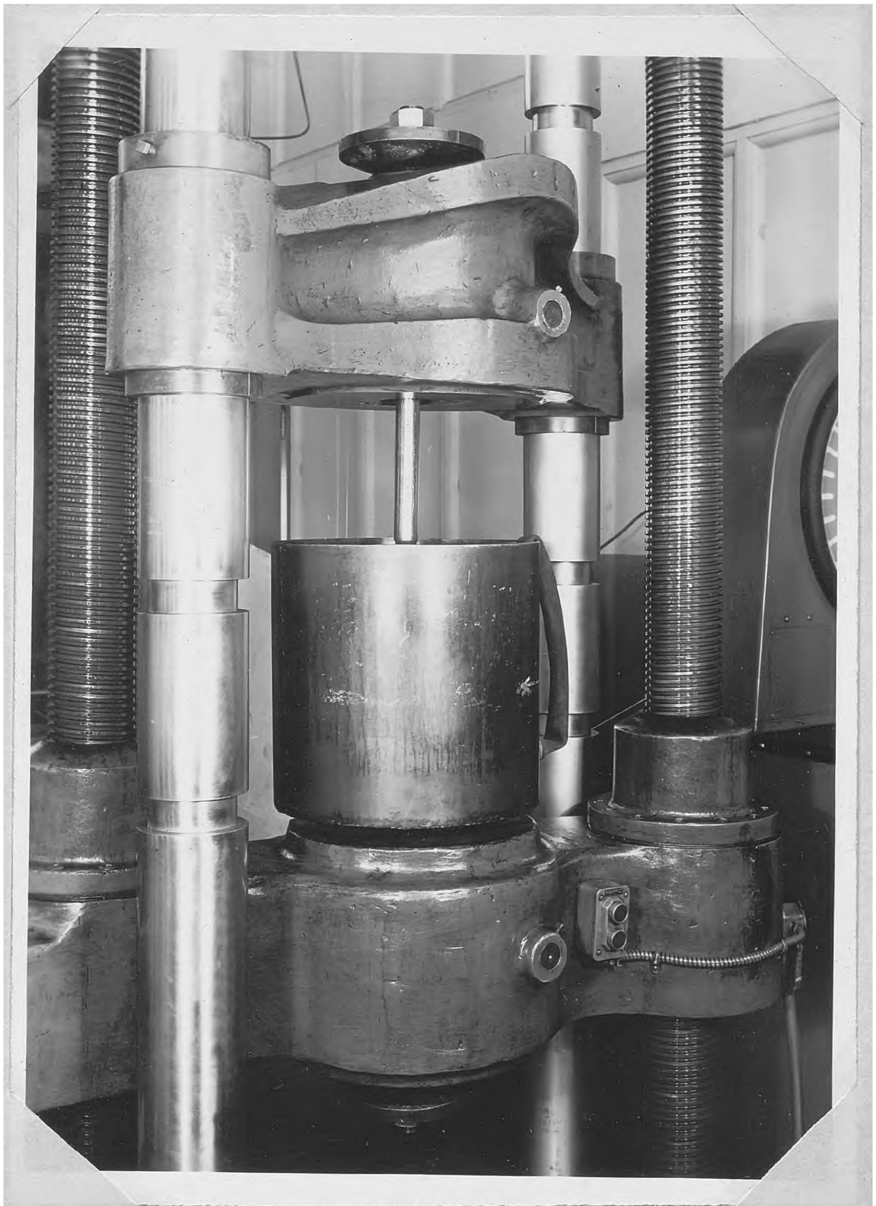


Fig. 1.c Kahn Tear Test, showing method of loading and the constant-temperature bath. Note spherical bearing blocks to insure axial loading.

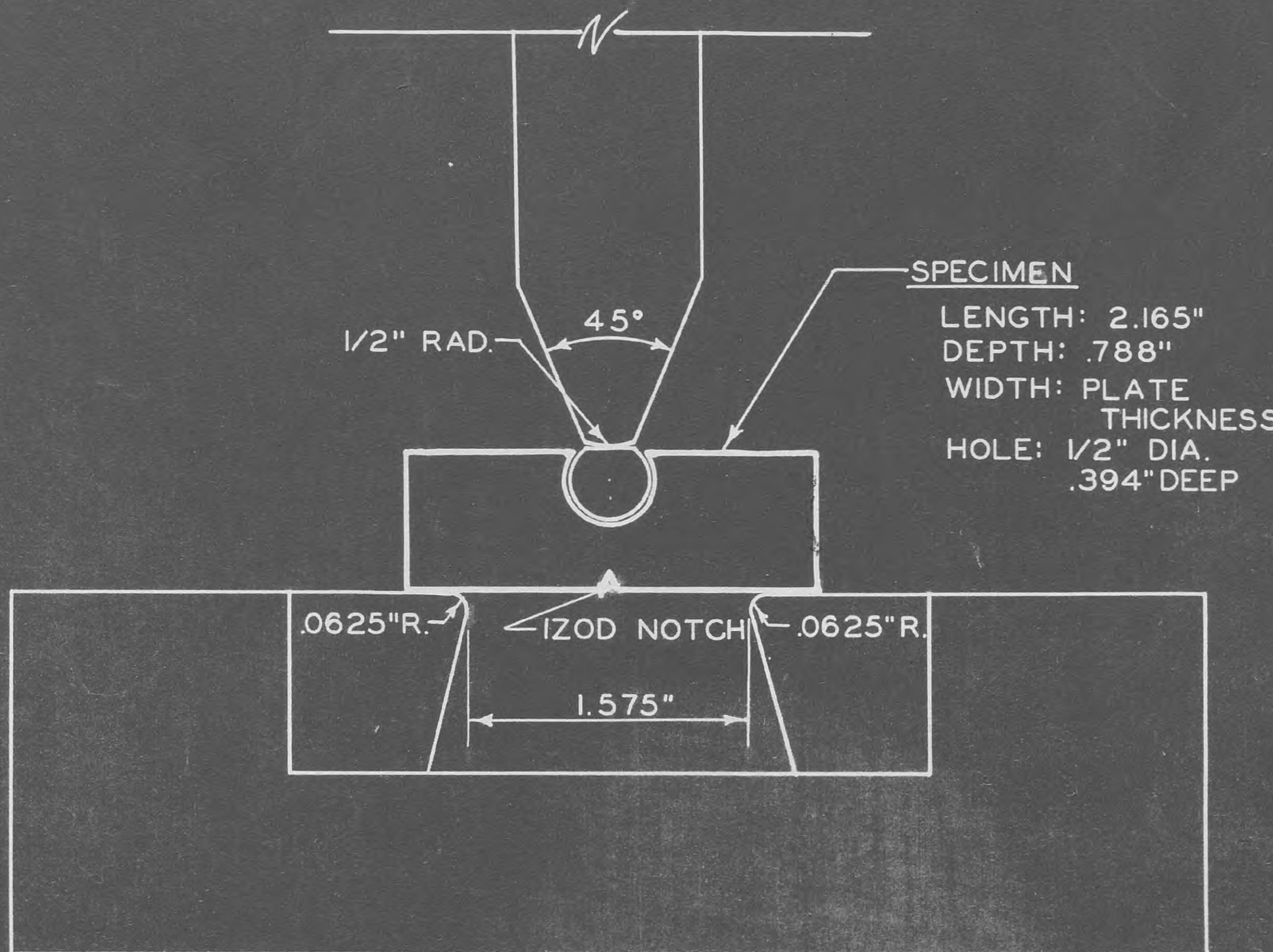


FIG.2A THE PENN STATE SLOW NOTCHED BEND TEST WITH COMPRESSION ZONE OF SPECIMEN REPLACED BY HARDENED DRILL ROD.

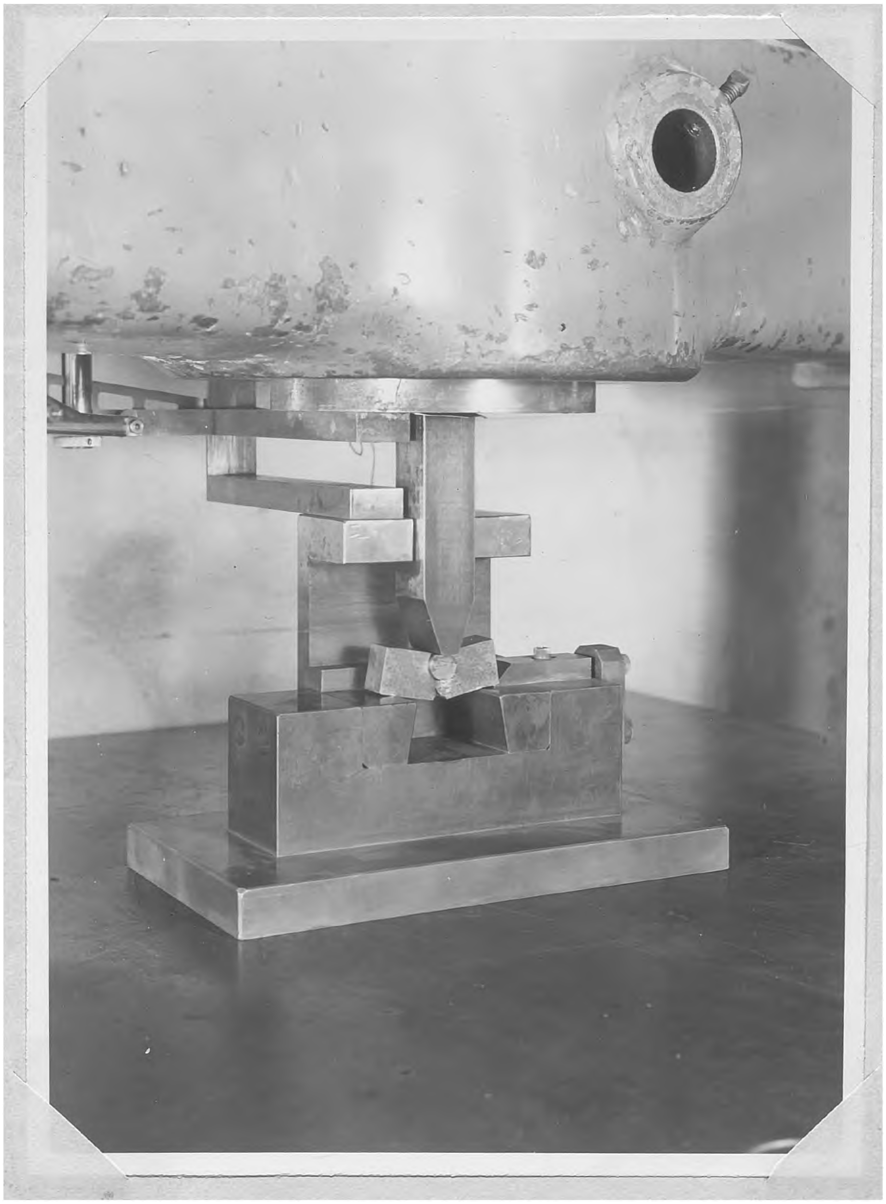


Fig. 2.b Penn State Slow Notched-Bend Test, showing specimen partly broken. Kenyon-Burns-Young extensometer visible in upper left.

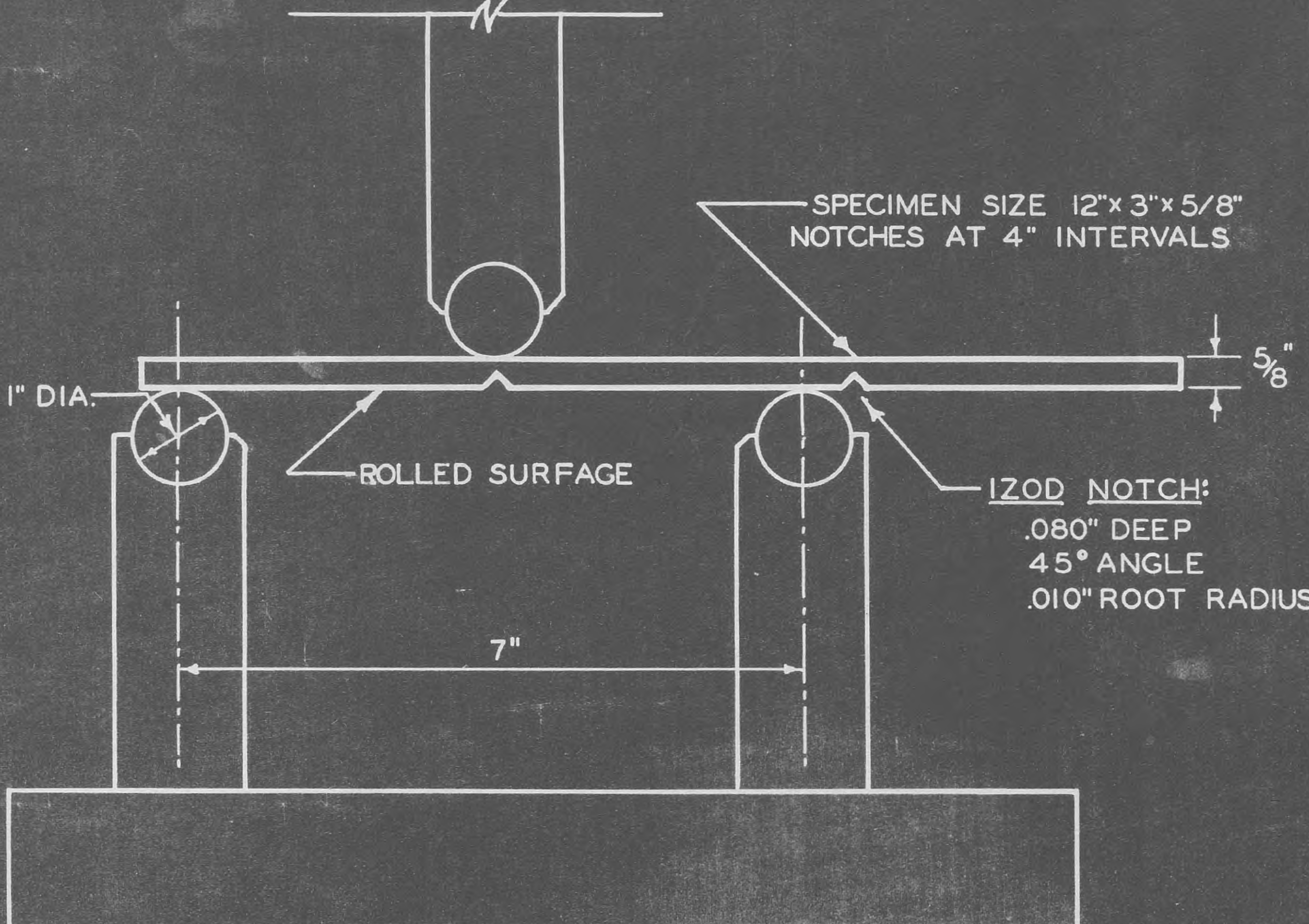


FIG. 3A THE LEHIGH SLOW NOTCHED BEND TEST

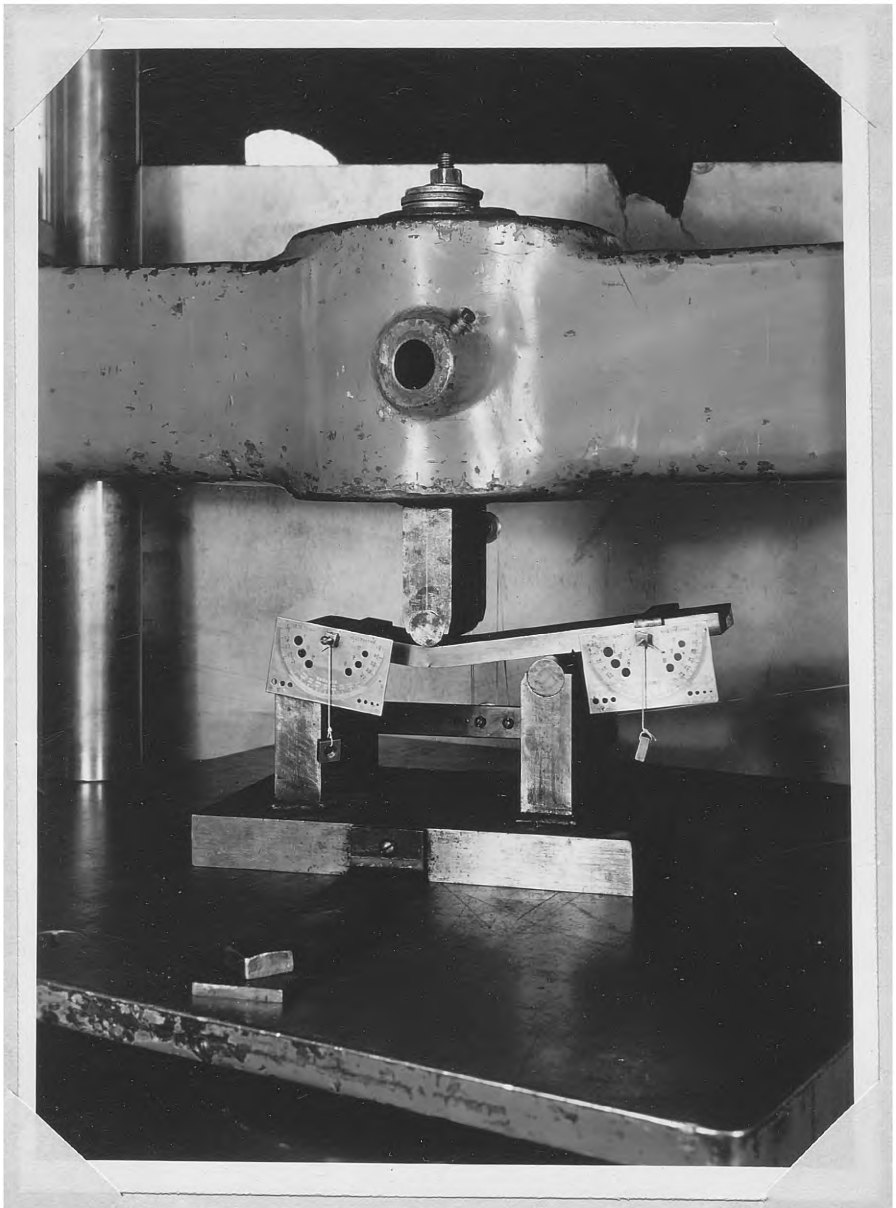


Fig. 3.b Lehigh Slow Notched Bend Test, showing test in progress.

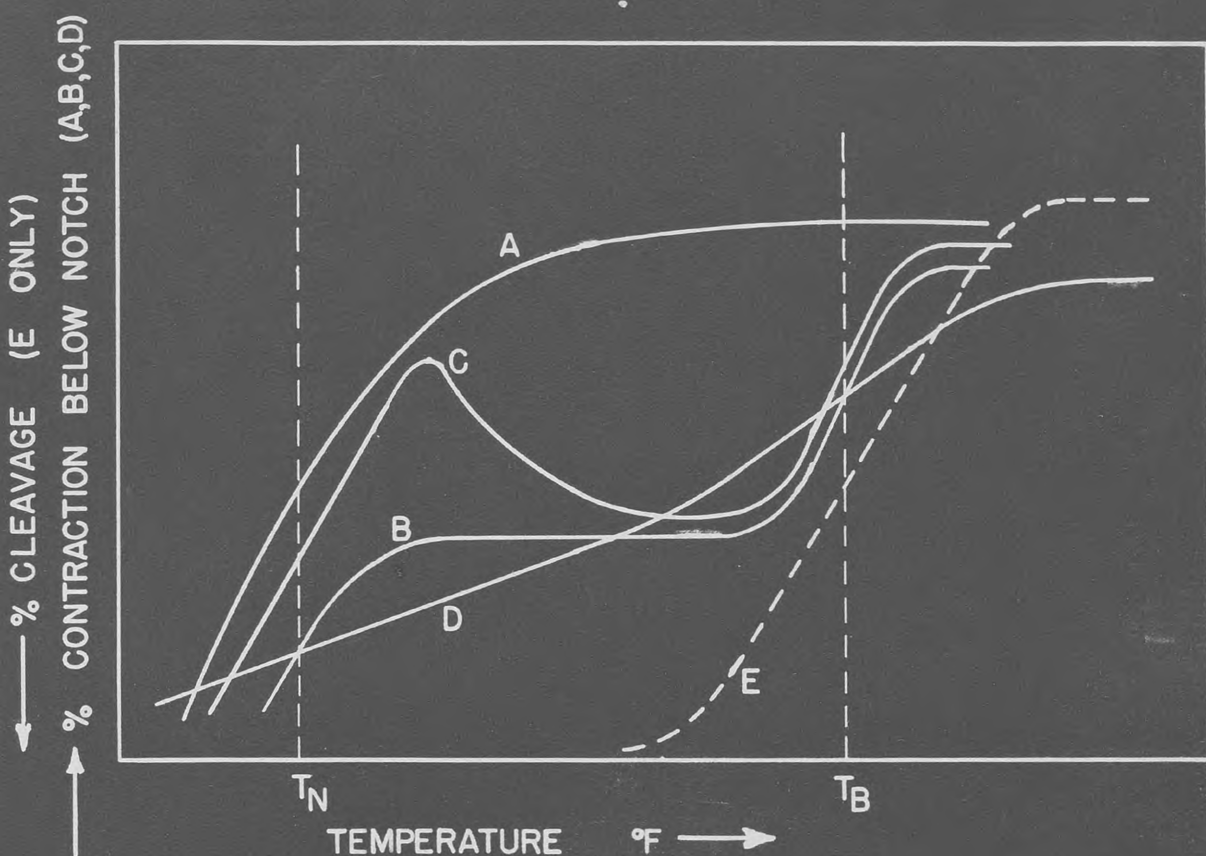


FIG. 4 DIAGRAM SHOWING TYPES OF TRANSITION CURVES OBTAINED ON NOTCHED SPECIMENS, USING % CONTRACTION BELOW THE NOTCH IN A, B, C AND D; % CLEAVAGE IN E.

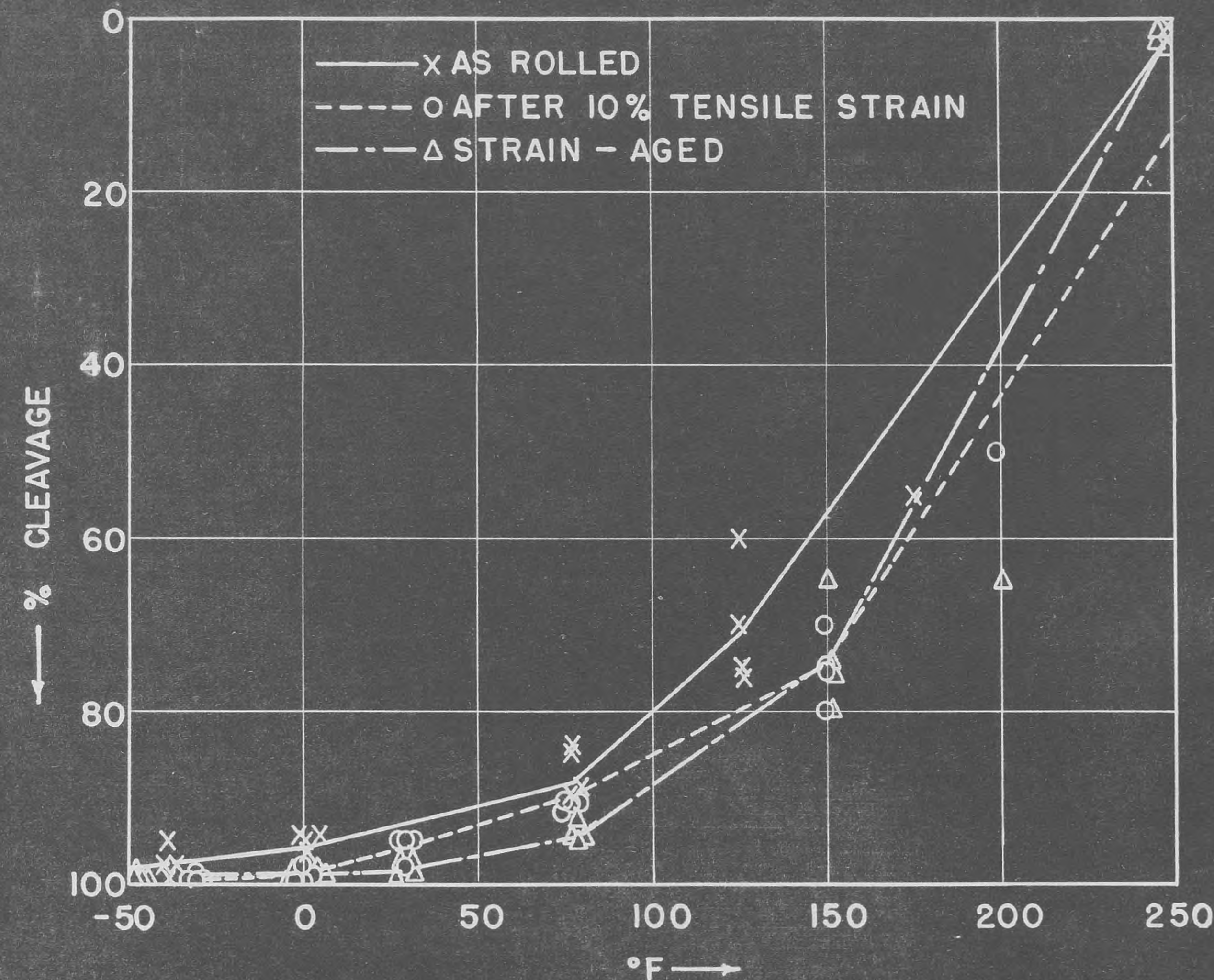


FIG.5-A TRANSITION CURVES FOR A-70 1 1/4" MATERIAL

LEHIGH BEND TEST

CRITERION : % CLEAVAGE

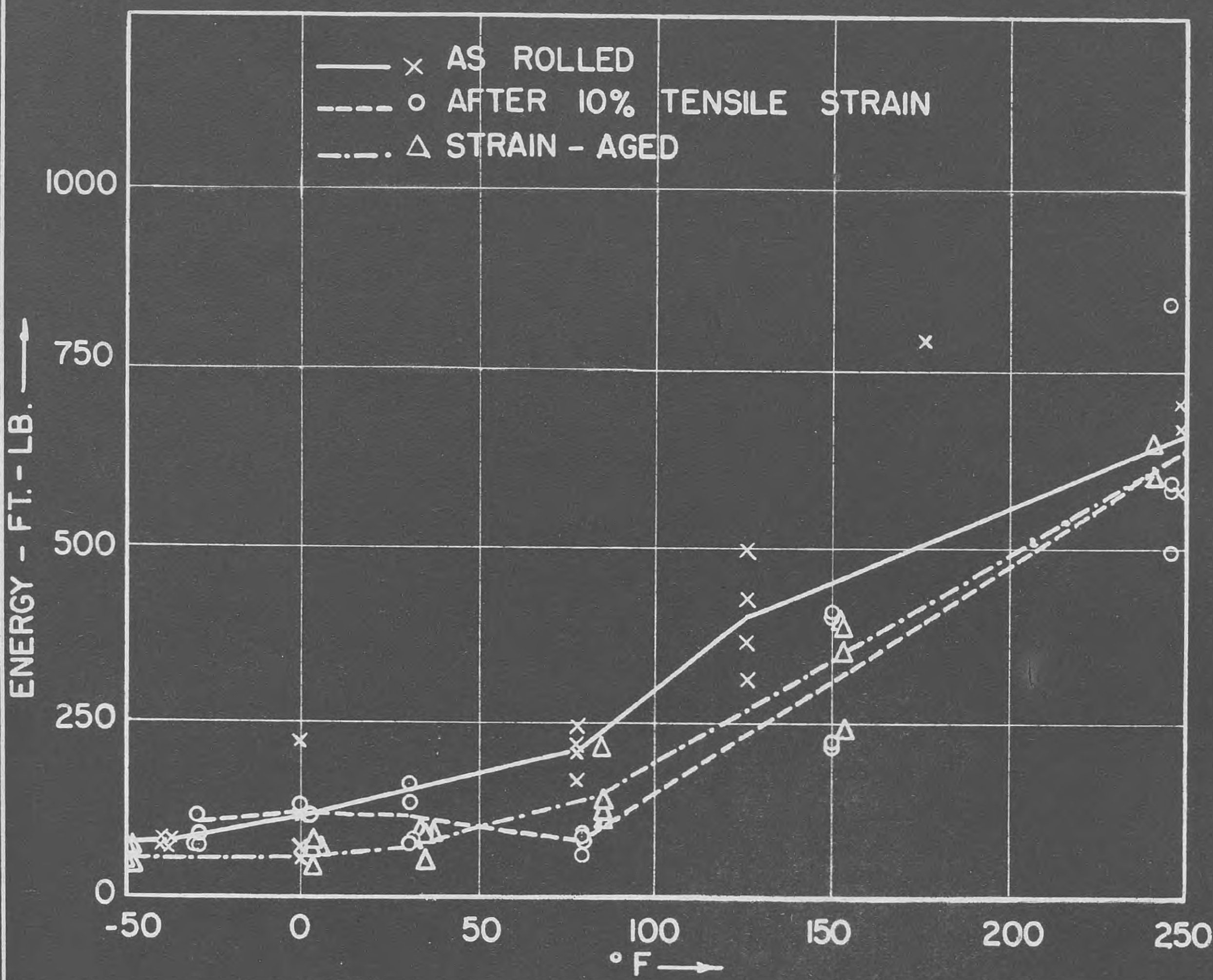


FIG. 5-B. TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

LEHIGH BEND TEST

CRITERION: ENERGY AFTER MAXIMUM LOAD

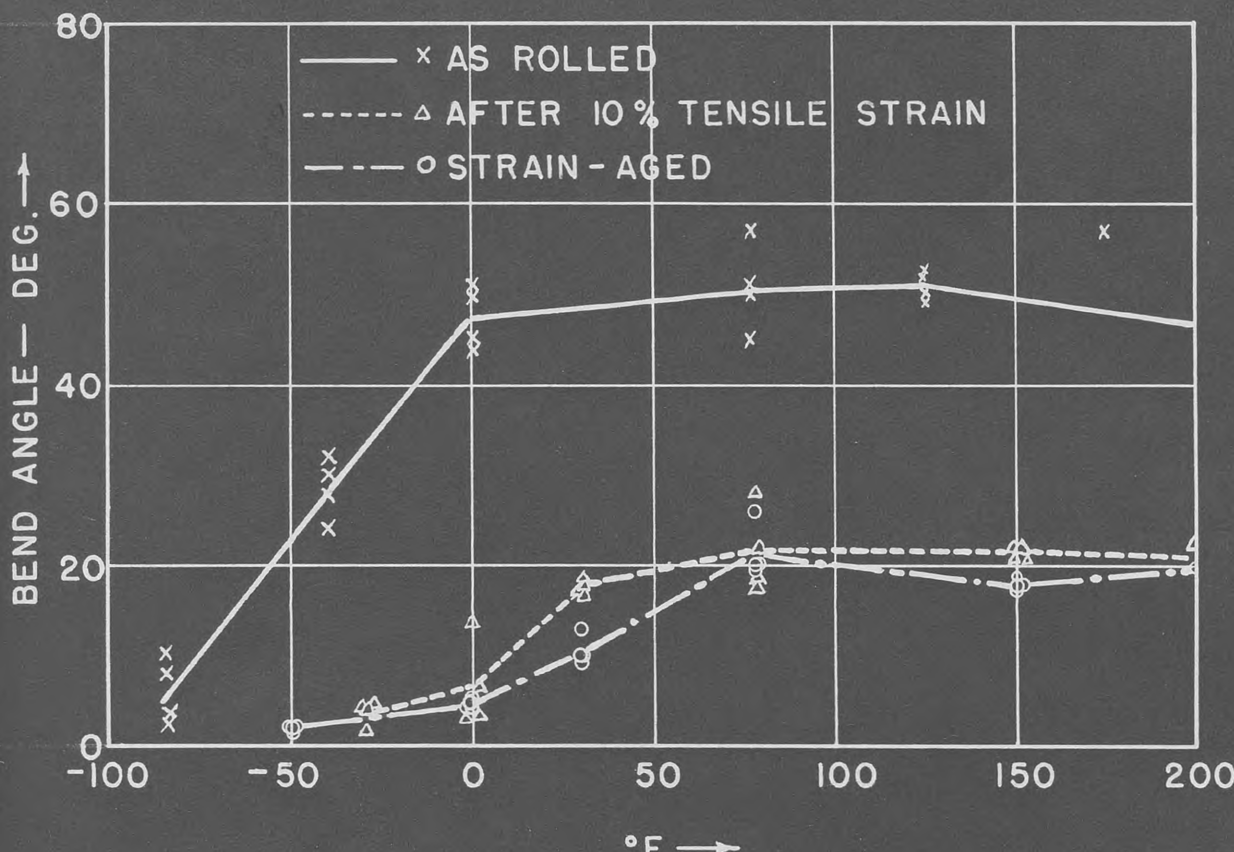


FIG.5-C TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

LEHIGH BEND TEST

CRITERION : BEND ANGLE

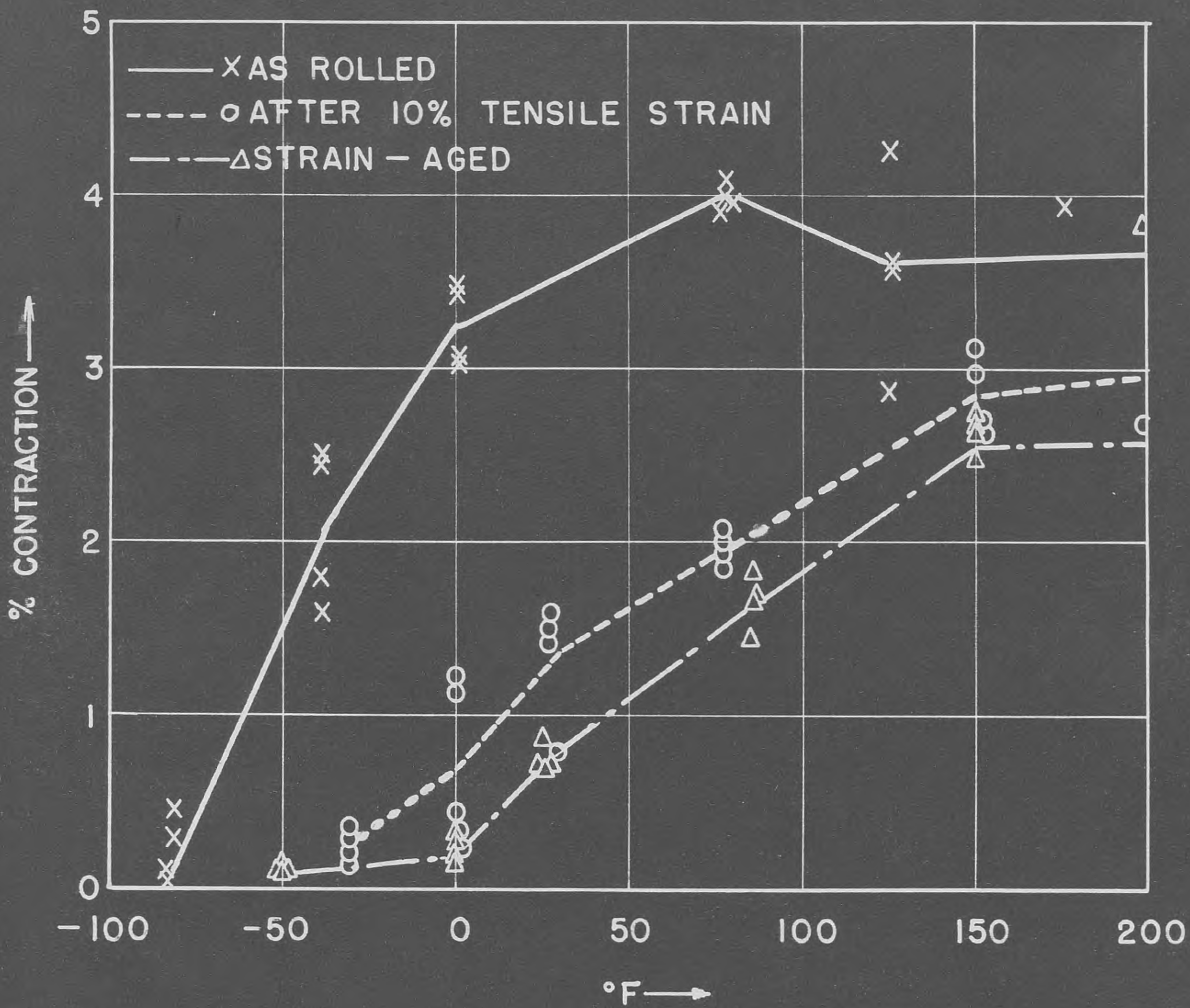


FIG. 5-D TRANSITION CURVES FOR A-70 1 1/4" MATERIAL

LEHIGH BEND TEST

CRITERION: % CONTRACTION BELOW NOTCH

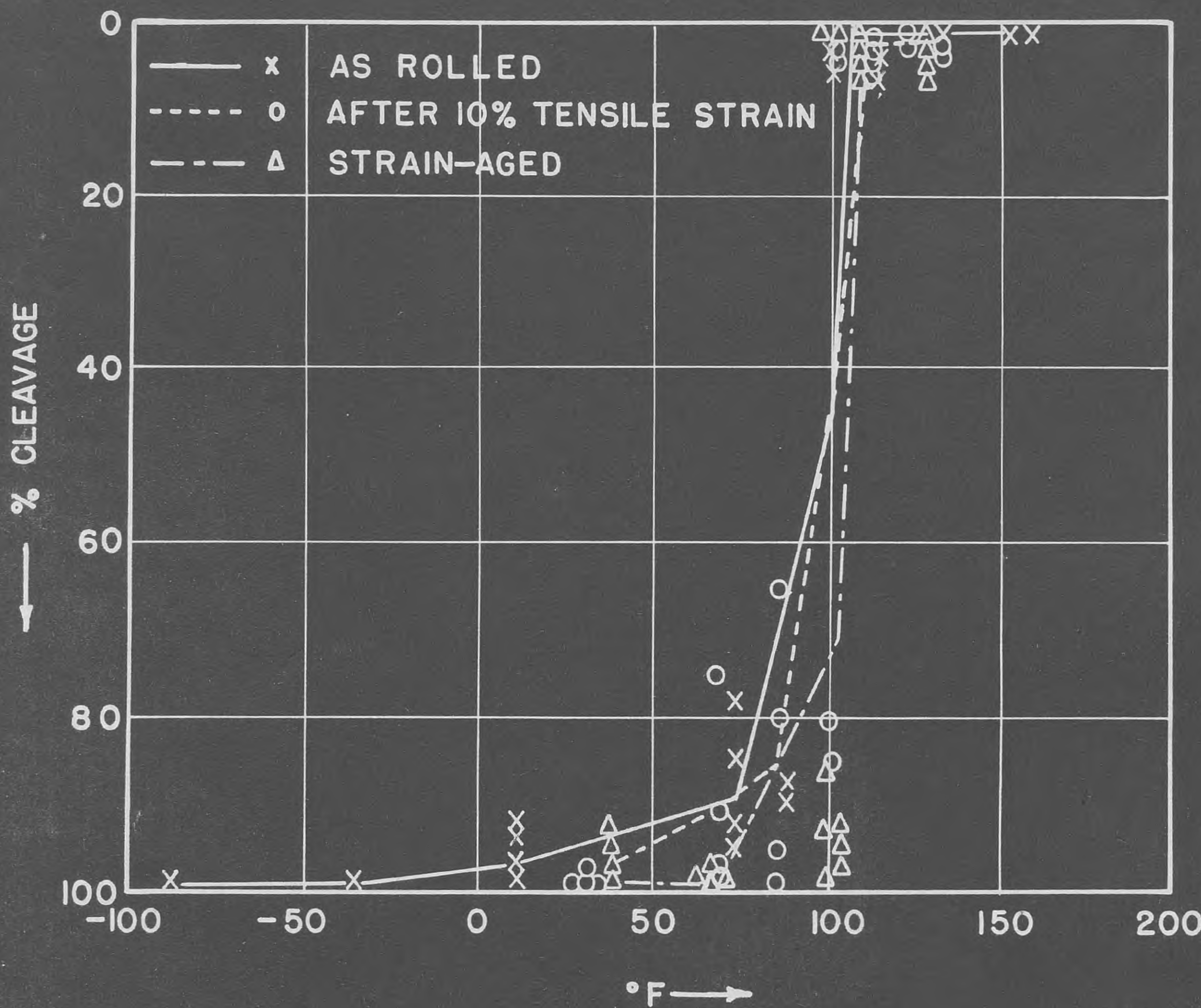


FIG. 6-A TRANSITION CURVES FOR A-70 1 1/4" MATERIAL

PENN. STATE TEST

CRITERION: % CLEAVAGE

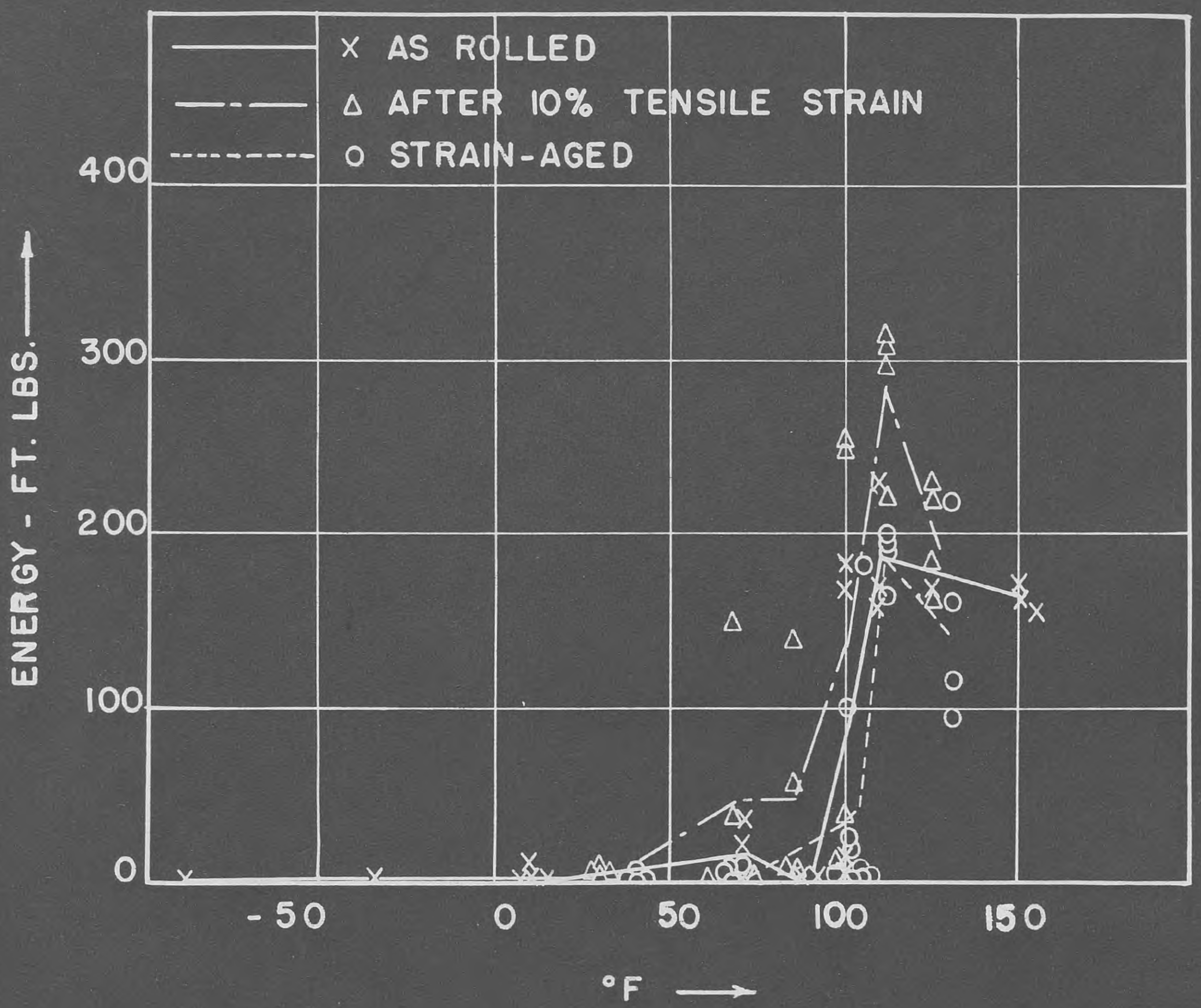


FIG. 6-B TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

PENN. STATE TEST

CRITERION: ENERGY AFTER MAXIMUM LOAD

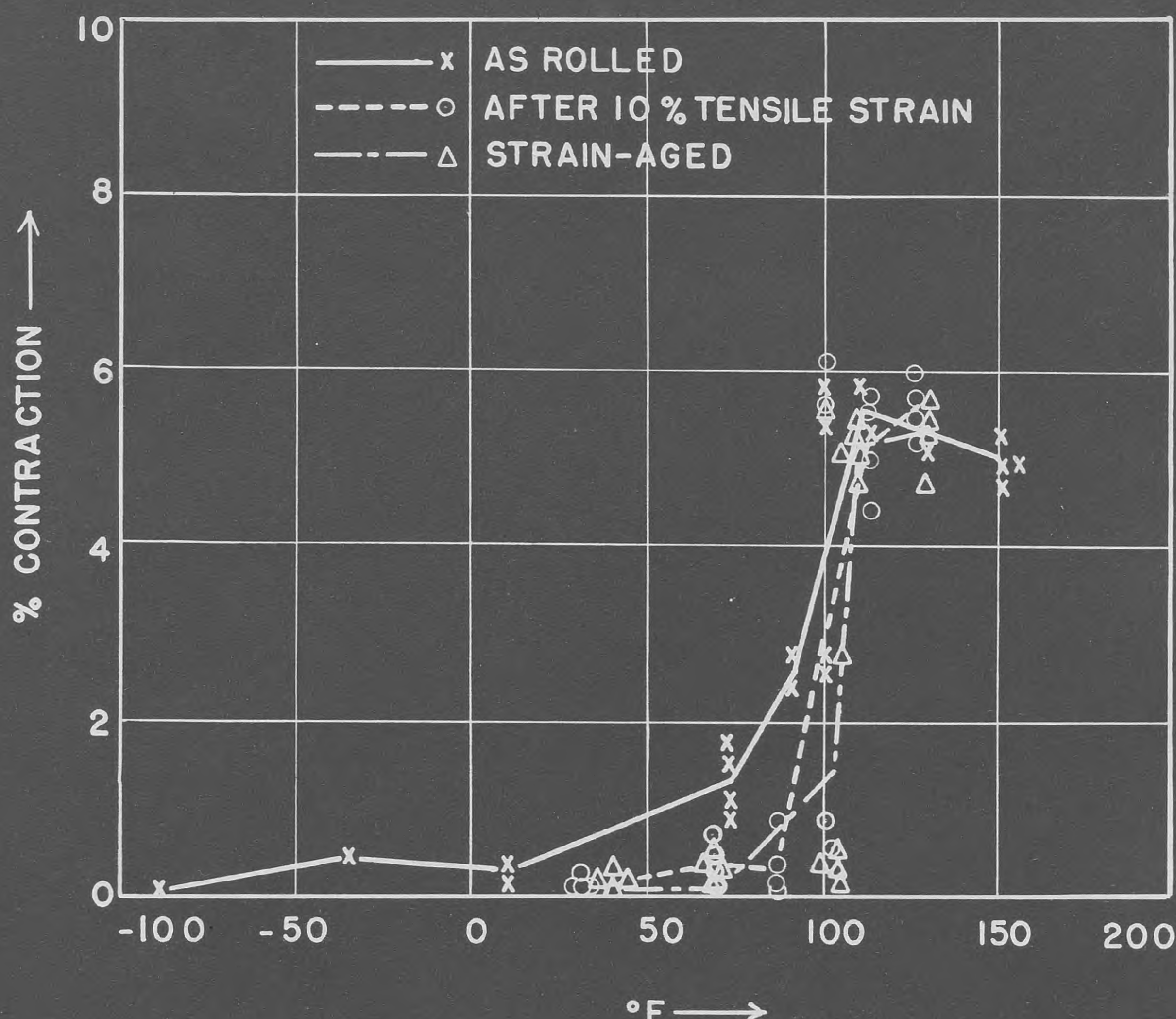


FIG. 6-C TRANSITION CURVES FOR A-70, 11/4" MATERIAL

PENN. STATE TEST

CRITERION: % CONTRACTION BELOW DRILL HOLE

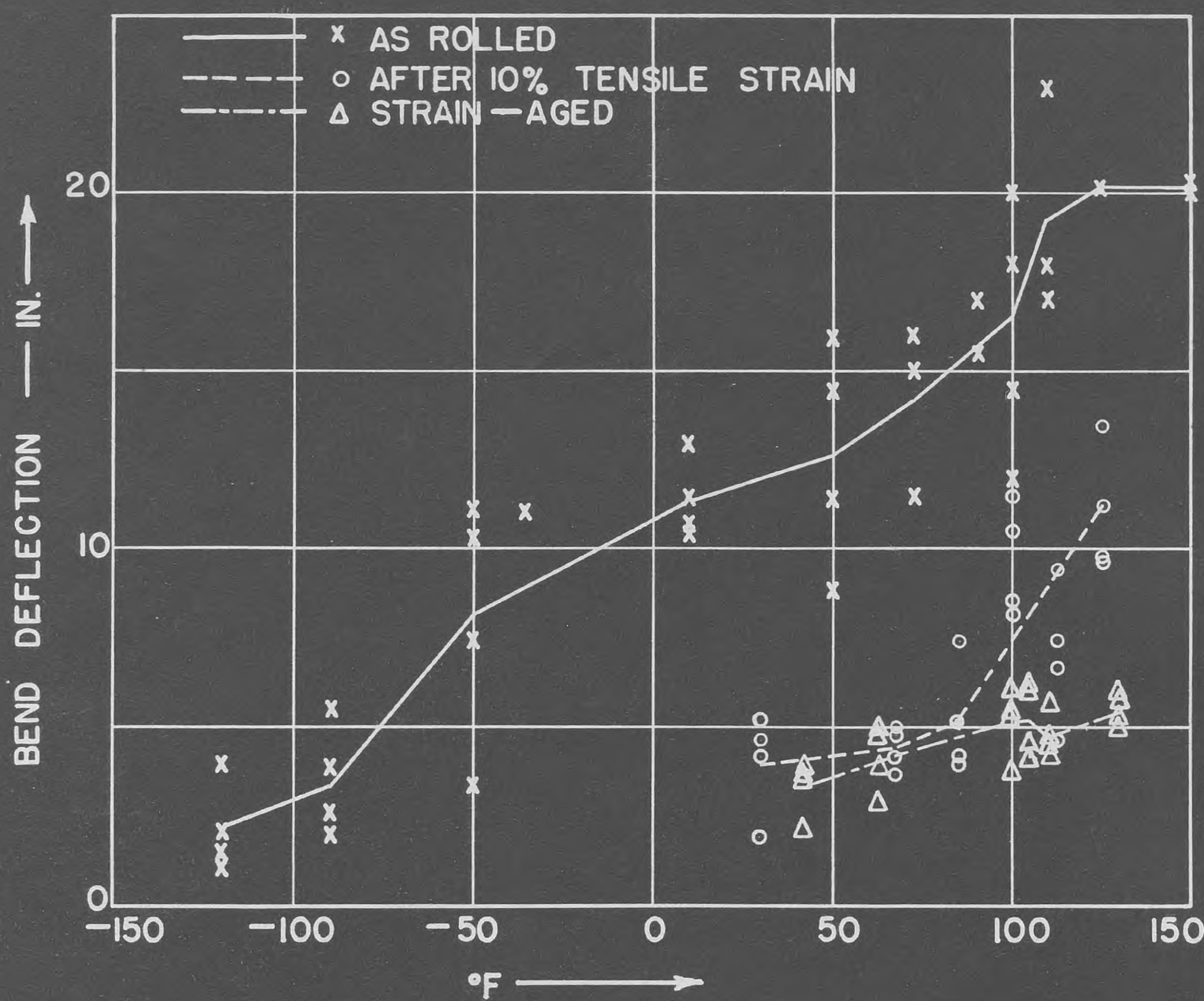


FIG. 6-D TRANSITION CURVES FOR A—70, 1 1/4" MATERIAL

PENN. STATE TEST

CRITERION: BEND DEFLECTION

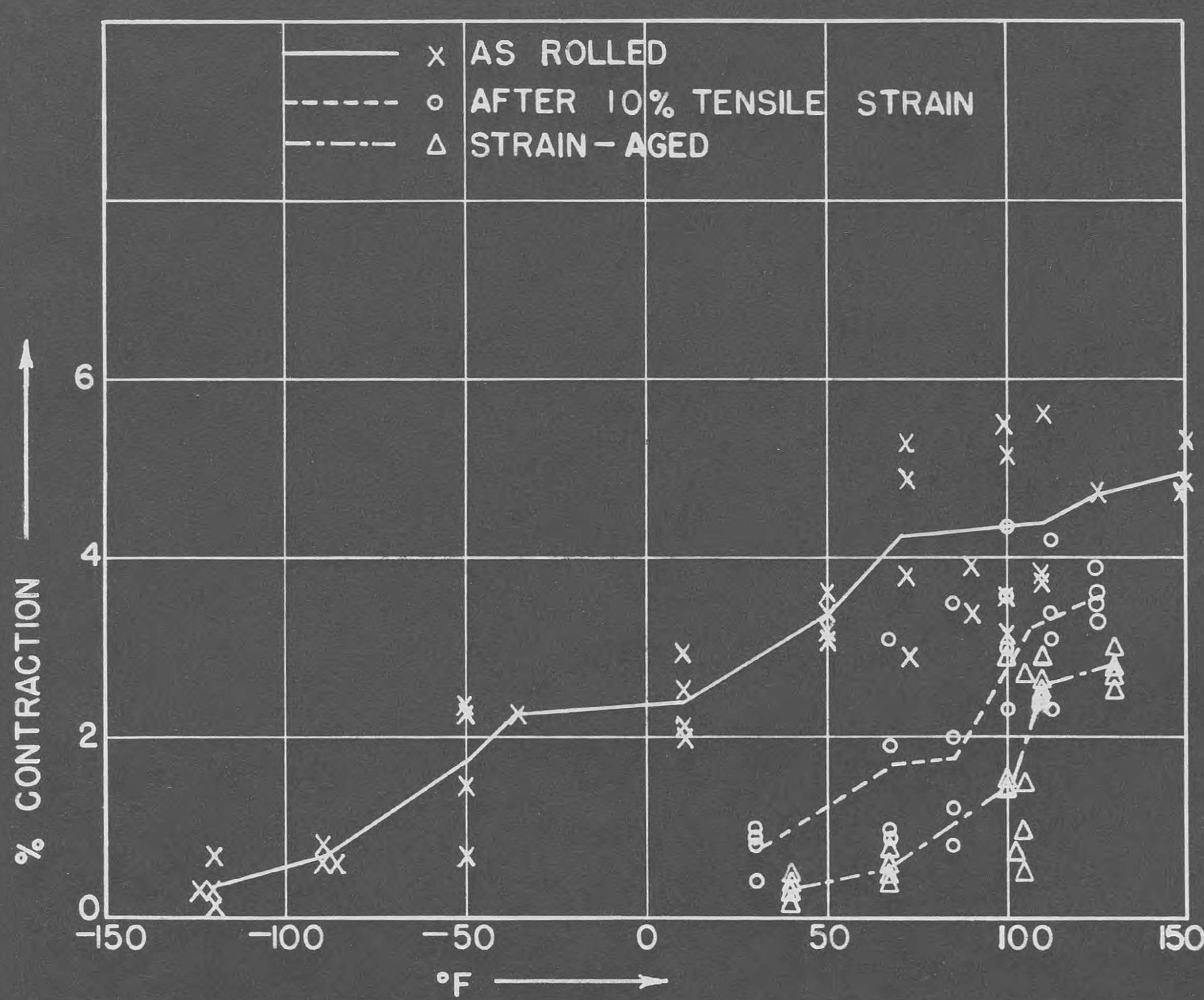


FIG. 6-E TRANSITION CURVE FOR A-70, 1 1/4" MATERIAL

PENN. STATE TEST

CRITERION: % CONTRACTION BELOW NOTCH

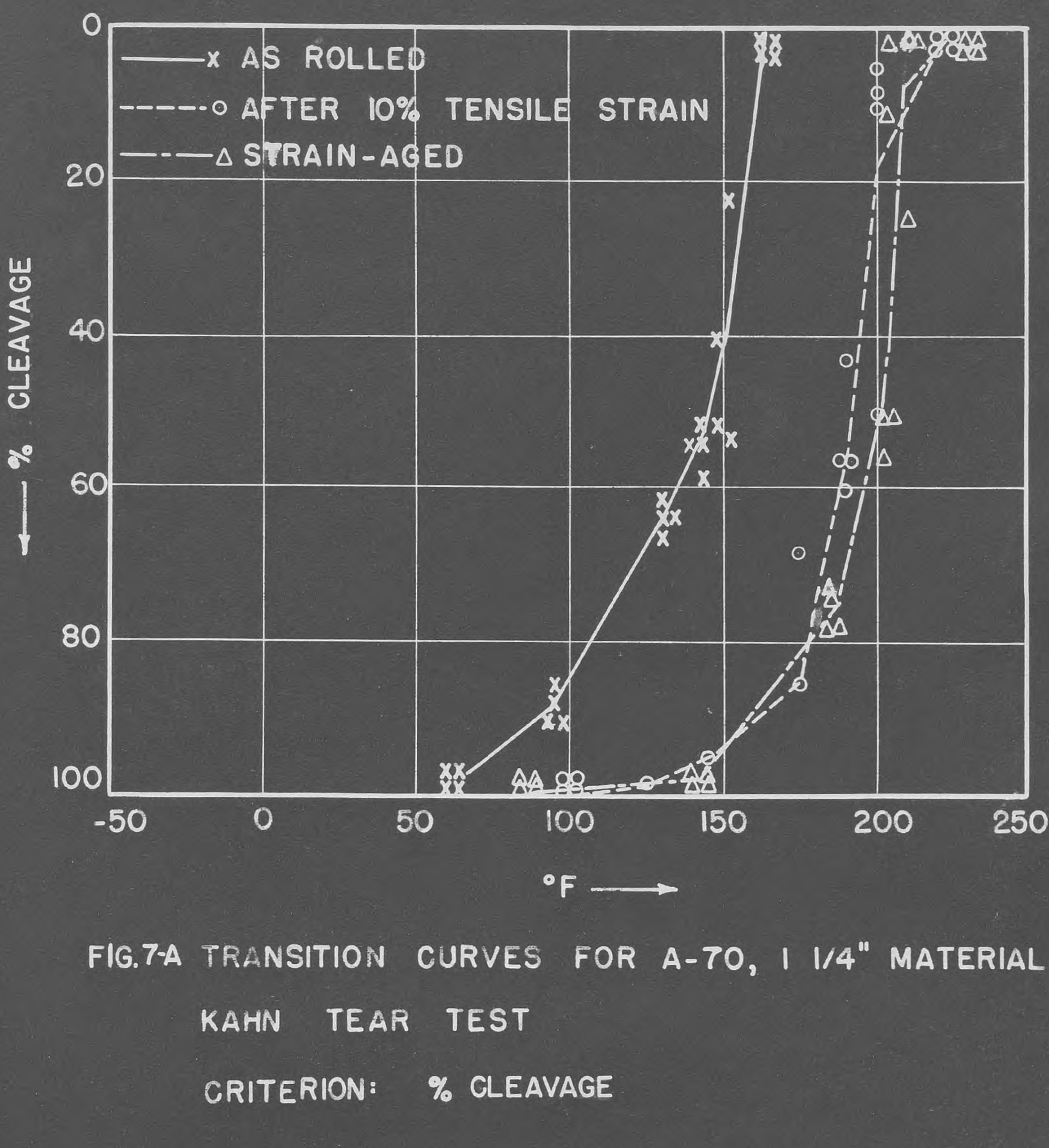


FIG. 7-A TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

KAHN TEAR TEST

CRITERION: % CLEAVAGE

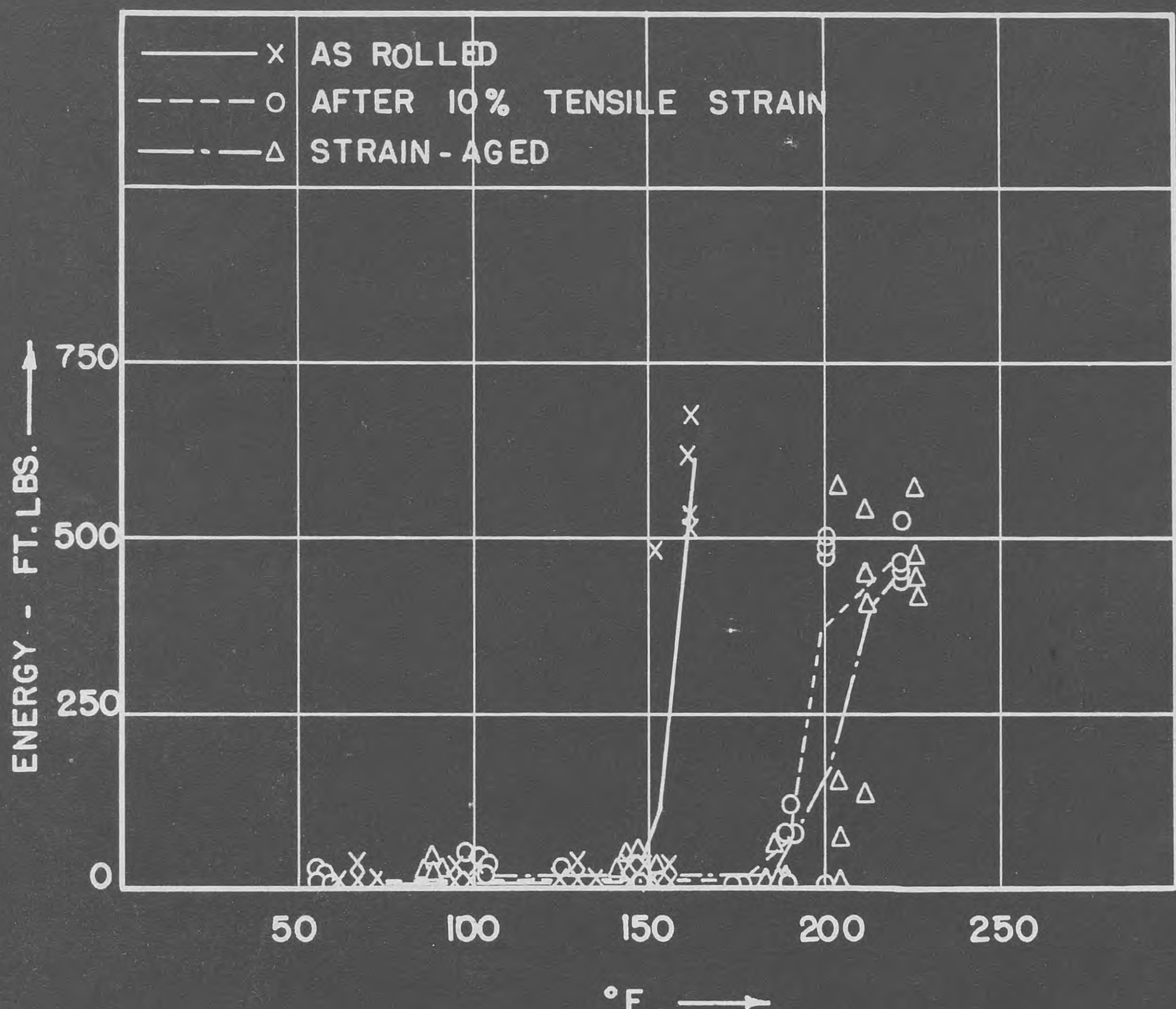


FIG. 7-B TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

KAHN TEAR TEST

CRITERION: ENERGY AFTER MAXIMUM LOAD

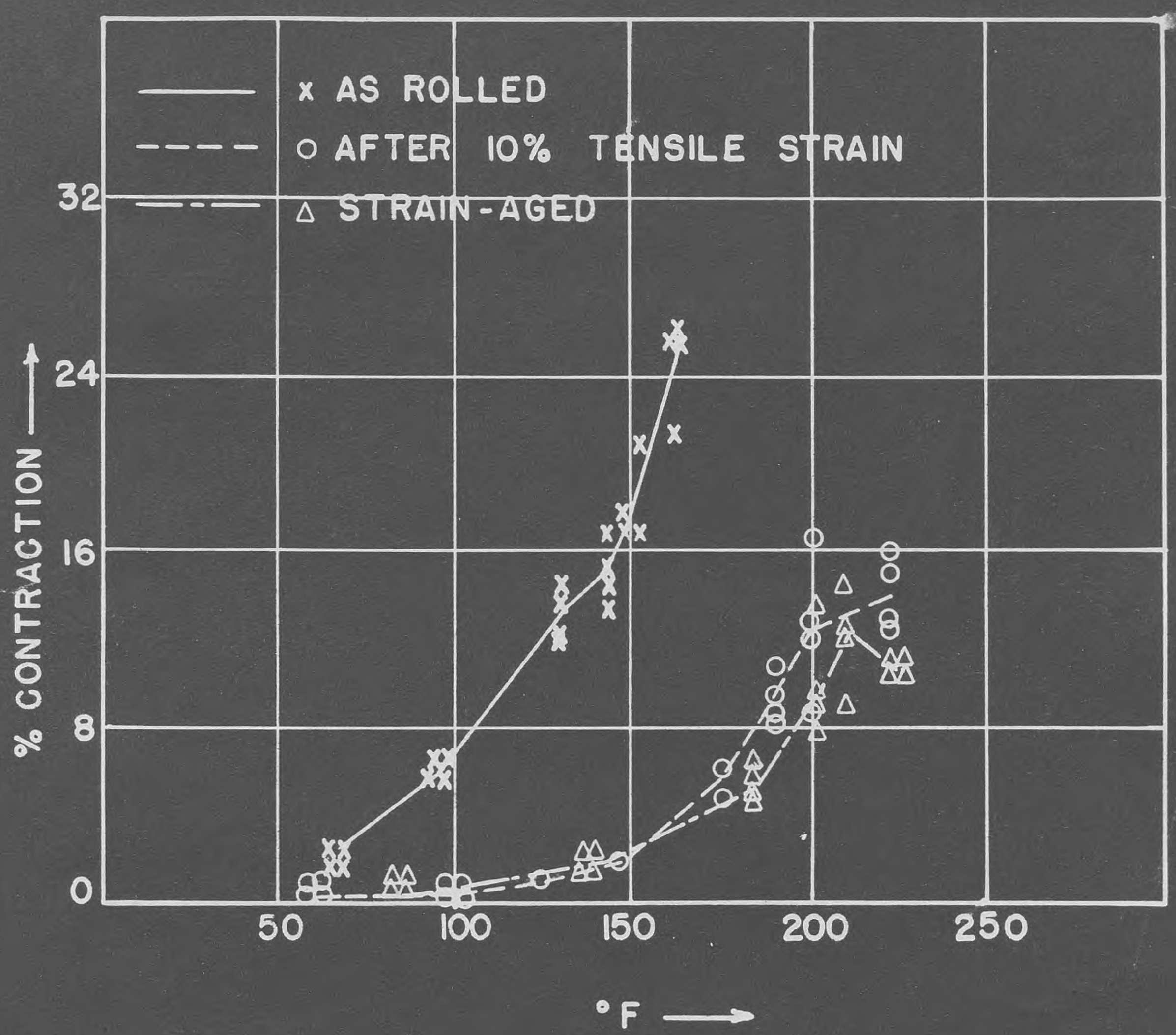


FIG. 7-C TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

KAHN TEAR TEST

CRITERION: % CONTRACTION AT MIDPOINT

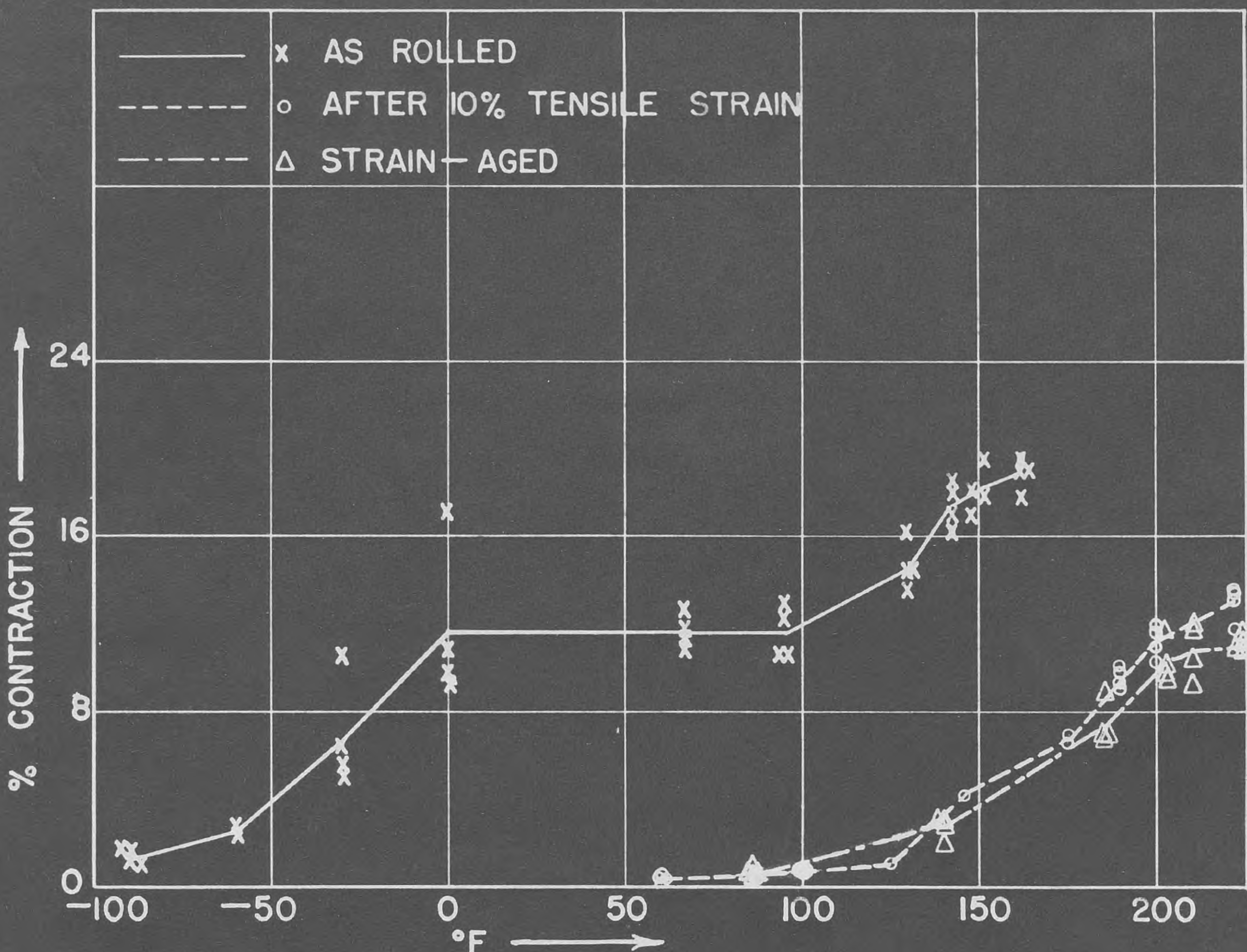


FIG. 7-D TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

KAHN TEAR TEST

CRITERION: % CONTRACTION BELOW NOTCH

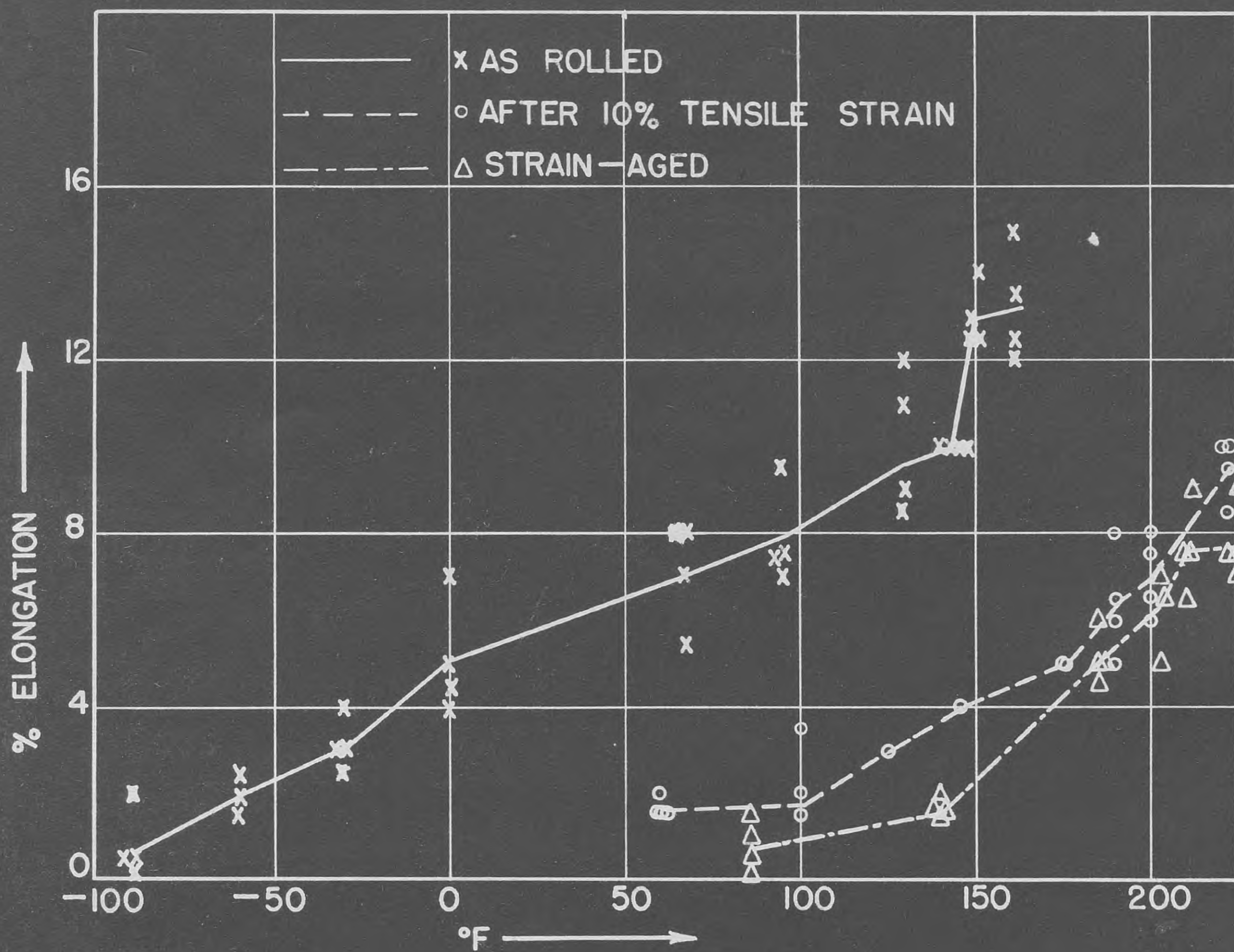


FIG. 7-E TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL

KAHN TEAR TEST

CRITERION: % ELONGATION 1/4" BELOW NOTCH

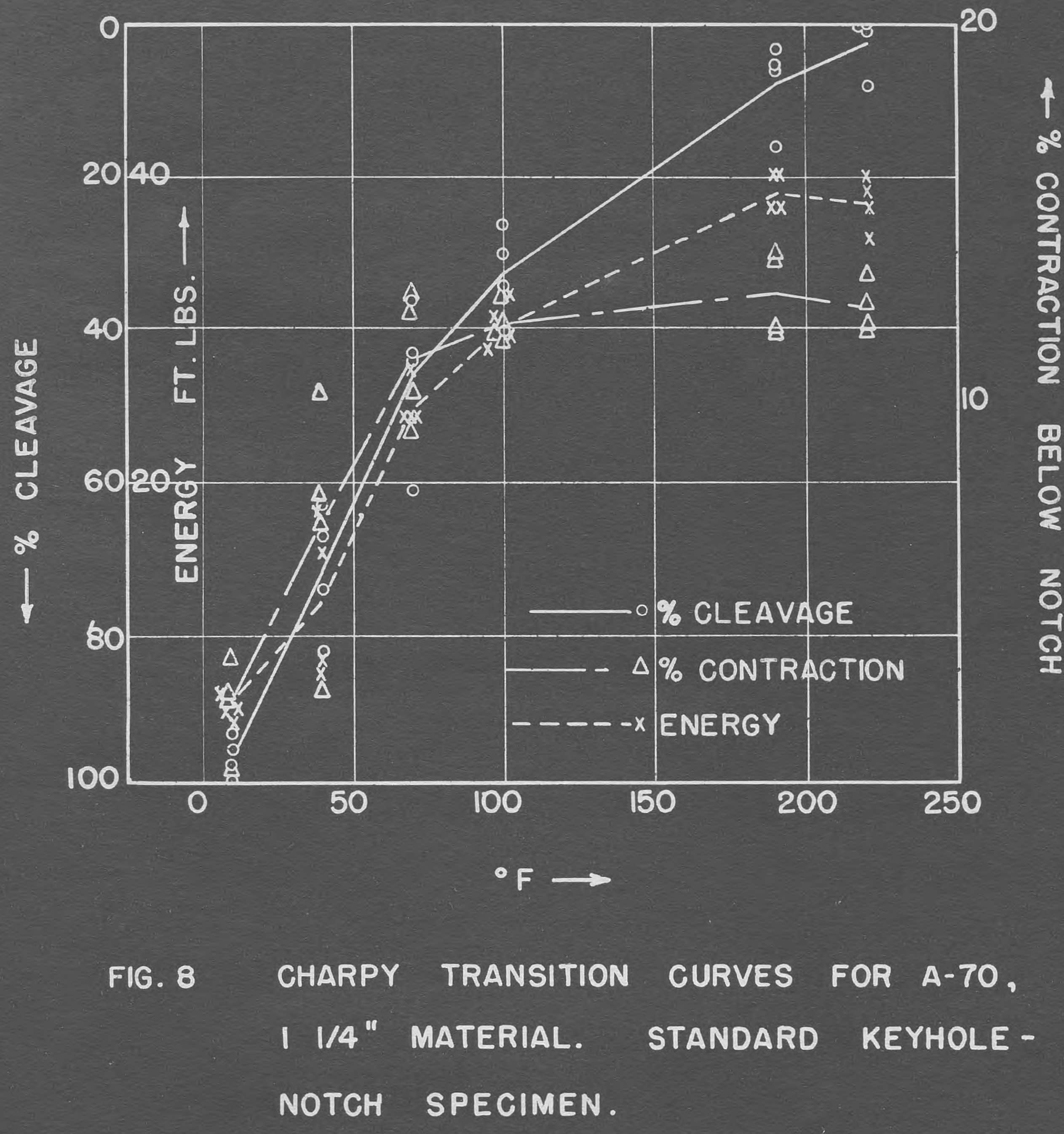


FIG. 8 CHARPY TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL. STANDARD KEYHOLE-NOTCH SPECIMEN.

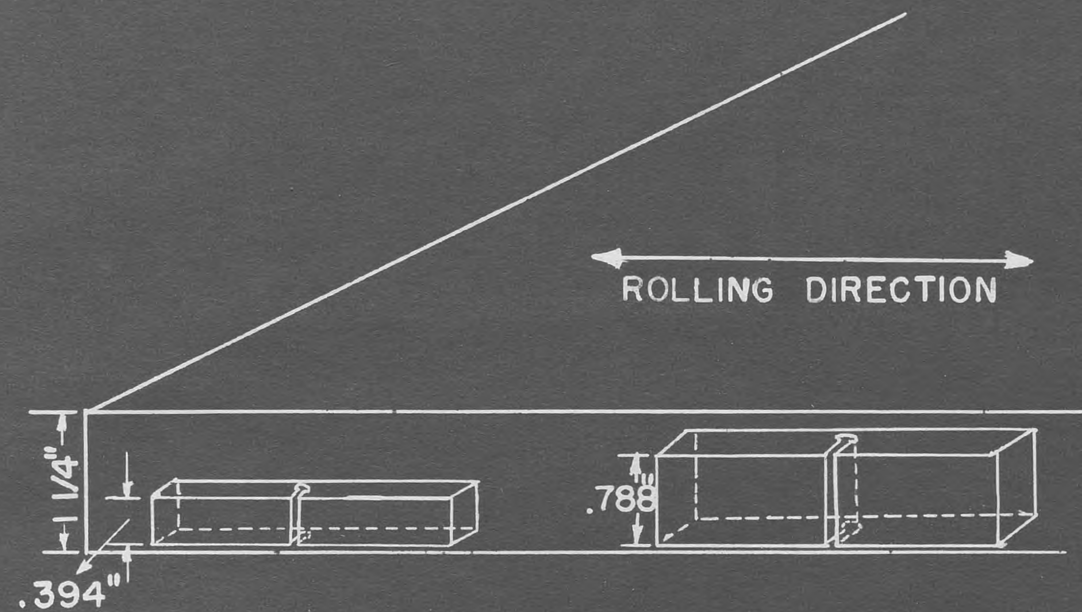
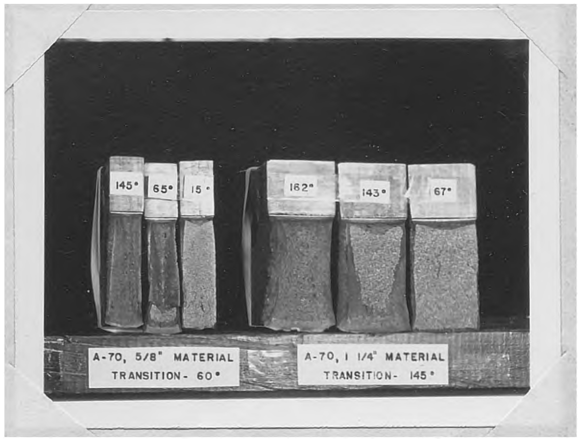
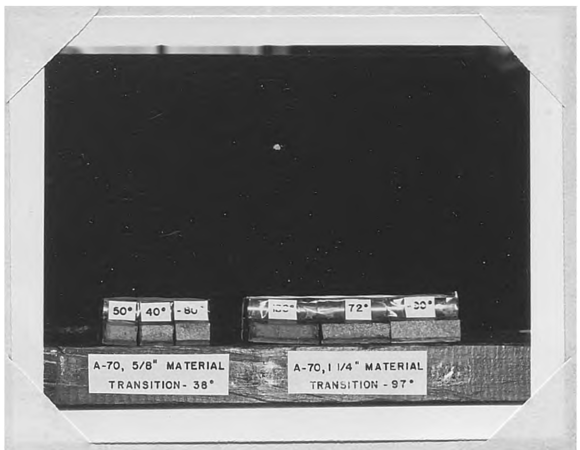


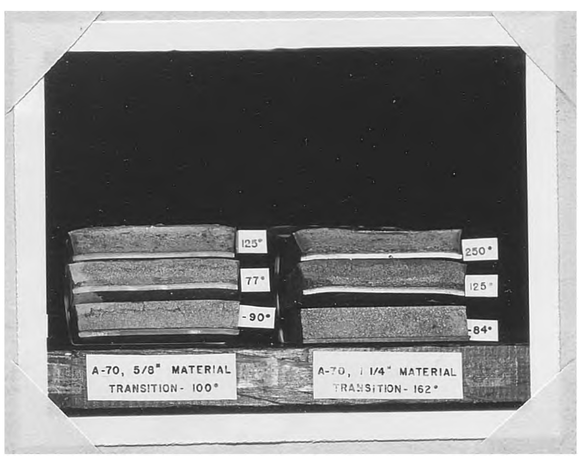
FIG. 9 ORIENTATION OF SINGLE AND DOUBLE-WIDTH CHARPY SPECIMENS IN 1 1/4" PLATE. EXCEPT FOR DOUBLE WIDTH AS SHOWN, THESE ARE STANDARD KEYHOLE-NOTCH SPECIMENS (A.S.T.M. E23-41T).



Kahn Specimen



Penn State Specimen



Lehigh Specimen

Fig. 10 Photographs of fracture surfaces in three types of test specimen, showing shear, mixed and cleavage fractures for each test.

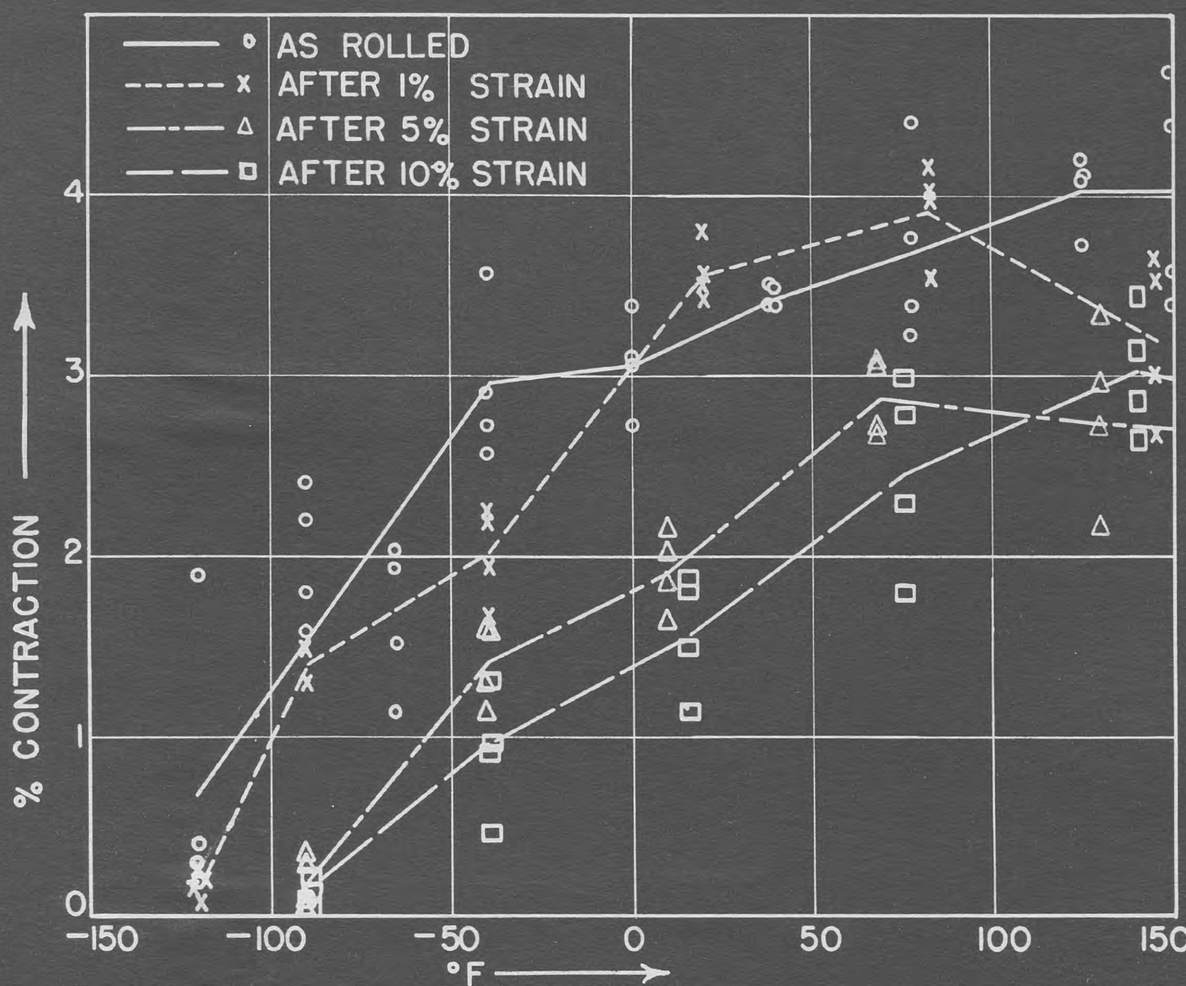


FIG. 11 a. TRANSITION CURVES FOR A-201, 1 1/4" MATERIAL, SHOWING EFFECT OF PLASTIC TENSILE STRAINS PARALLEL TO ROLLING DIRECTION

LEHIGH BEND TEST

CRITERION: % CONTRACTION BELOW NOTCH

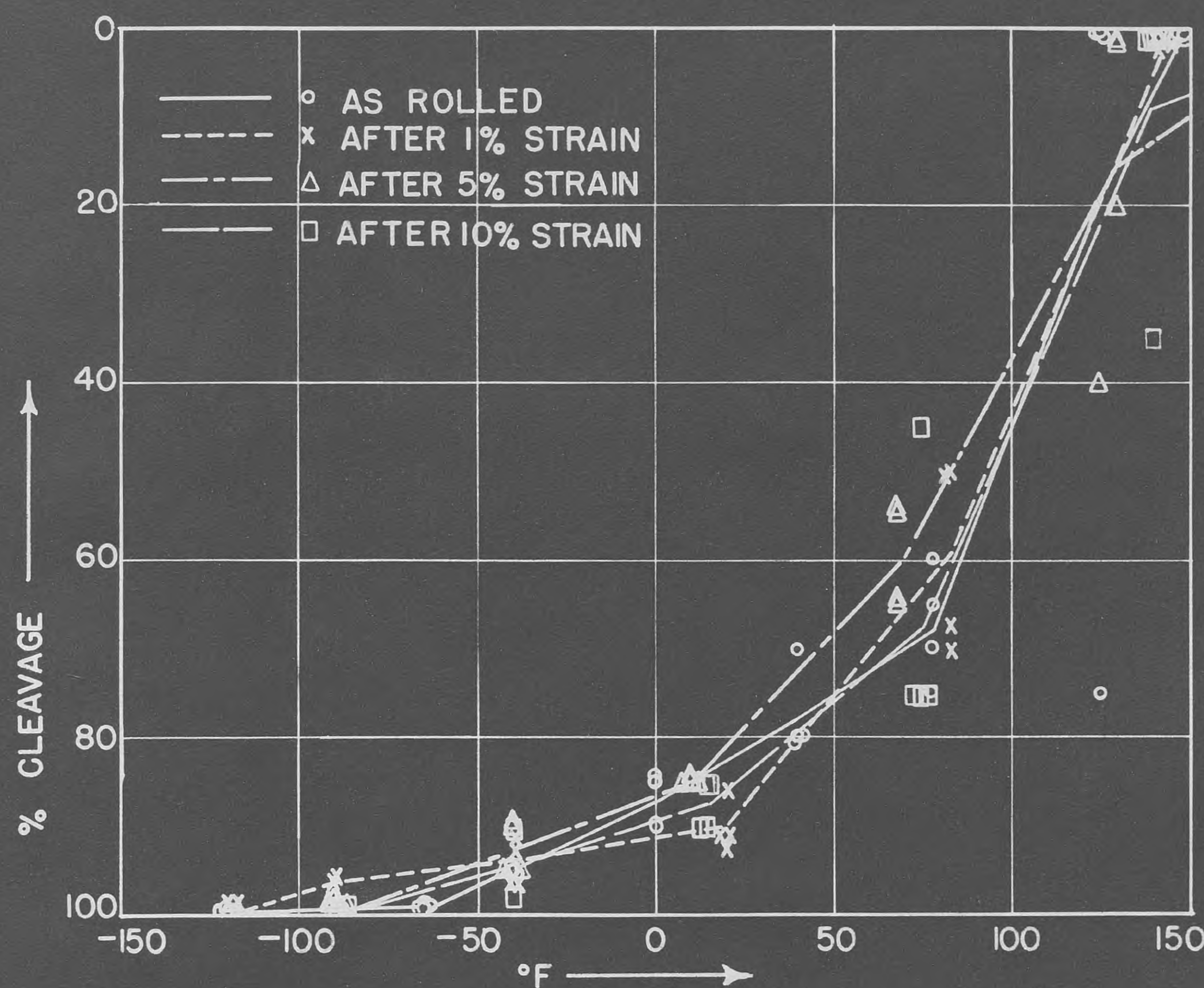


FIG. 11 b. TRANSITION CURVES FOR A-201, 1 1/4" MATERIAL, SHOWING EFFECT OF PLASTIC TENSILE STRAINS PARALLEL TO ROLLING DIRECTION

LEHIGH BEND TEST

CRITERION: % CLEAVAGE

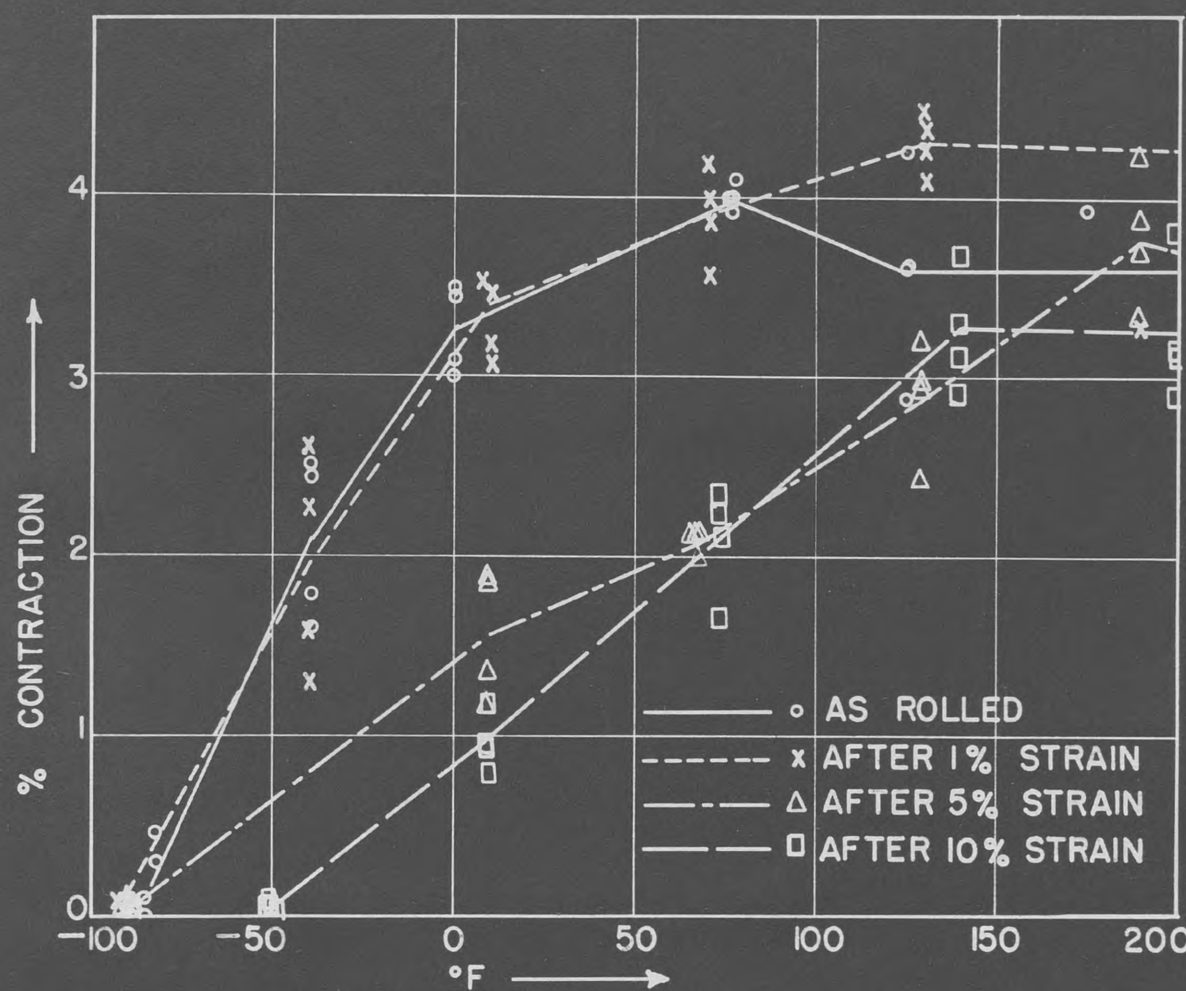


FIG. 12 a. TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL, SHOWING EFFECT OF PLASTIC TENSILE STRAINS PARALLEL TO ROLLING DIRECTION

LEHIGH BEND TEST

CRITERION: % CONTRACTION BELOW NOTCH

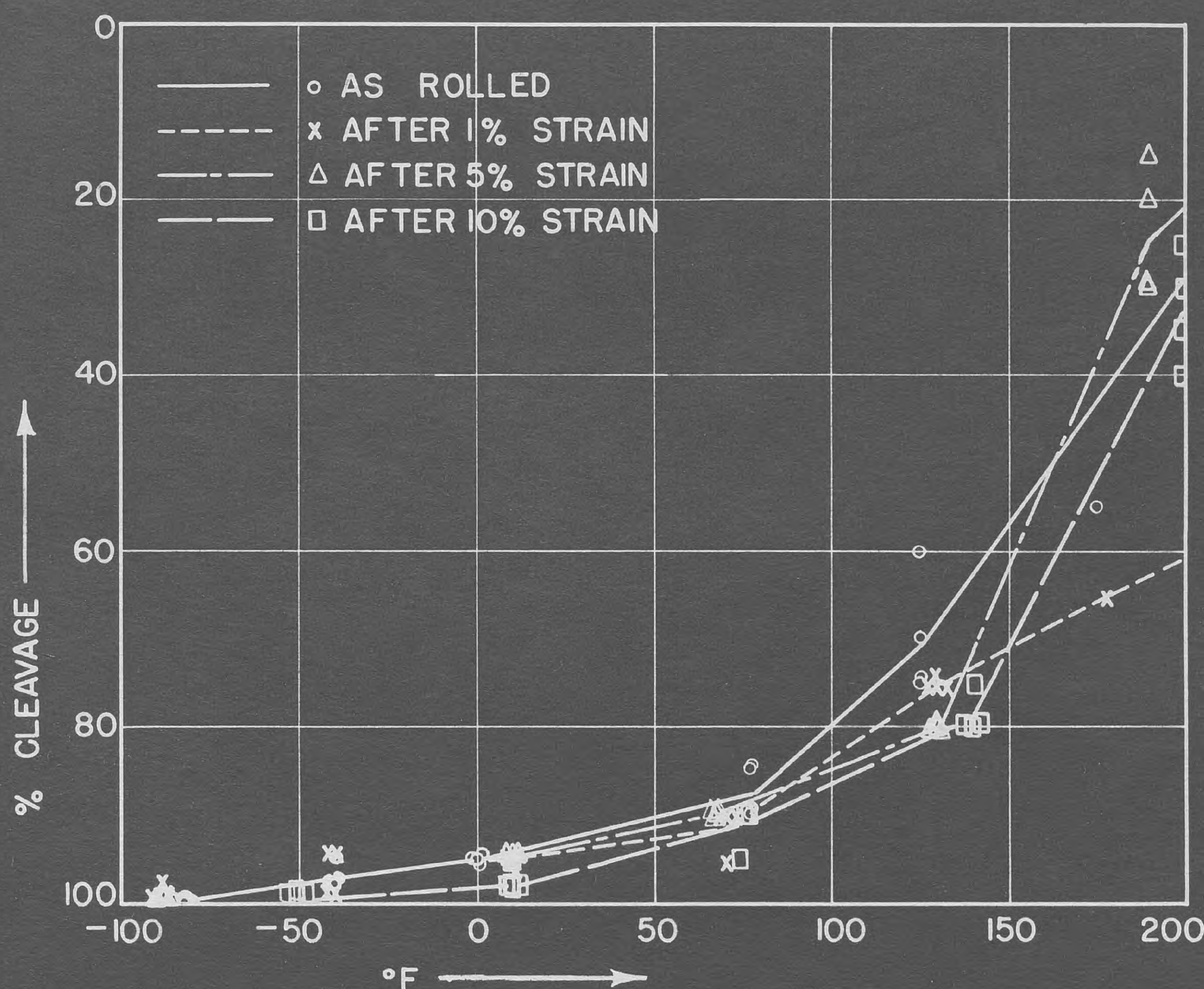


FIG. 12 b. TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL, SHOWING EFFECT OF PLASTIC TENSILE STRAINS PARALLEL TO ROLLING DIRECTION

LEHIGH BEND TEST

CRITERION; % CLEAVAGE

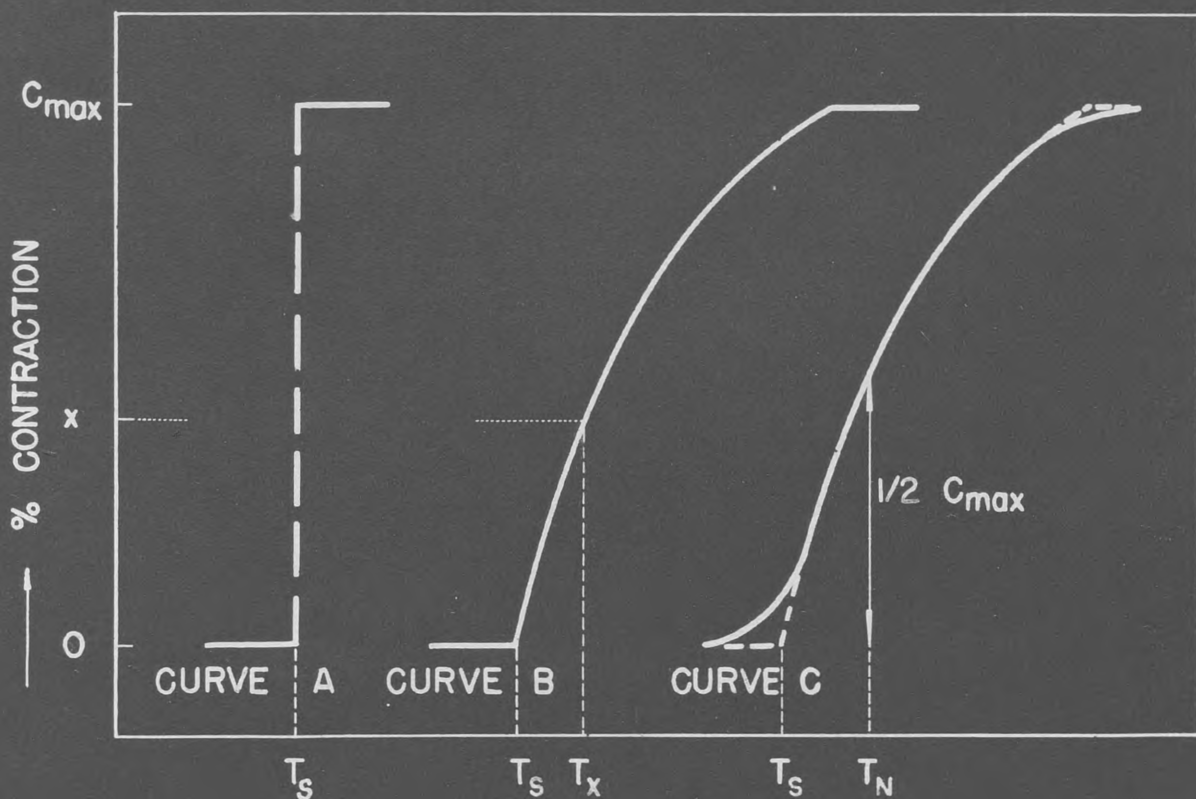


FIG. 13. SCHEMATIC CURVES FOR % LATERAL CONTRACTION AT NOTCH AFTER FRACTURE OF A NOTCHED SPECIMEN.

SUMMARY

The paper is based on a comprehensive comparative study of three notched-specimen tests on mild steel plates--the Kahn tear test and the Penn State and Lehigh slow notched bend tests. In each test, the use of different criteria of brittleness gave transition curves at different temperatures, but it is shown that the transition temperatures fall in one of two narrow temperature ranges 100° F to 200° F apart.

Evidence is produced that those criteria which indicate a transition temperature in the lower of these ranges, are following a transition in metal immediately below the notch and under the stress conditions imposed by the notch geometry. The higher transition temperatures correspond to the transition under the stress system imposed by a crack in heavily cold-worked metal. The origin and significance of the two temperatures are discussed in detail.

Data are presented and discussed for the use of different criteria in the standard and double-width Charpy tests.

The investigation indicated that the Lehigh test was generally the most satisfactory of the three tests examined.

Some evidence concerning the influence of chemical composition and plate thickness on transition temperatures is presented and discussed.

Vita

The author, Cyril John Osborn, was born on February 28, 1921, in Melbourne, Australia. He is the eldest son of William Francis Osborn and Hilda Pearl Osborn (nee Gamlen), both of Melbourne, Australia. On August 21, 1948, he married Elizabeth Anne Howell of Bethlehem, Pennsylvania.

From Wesley College, Melbourne, (1935-37) he went to the University of Melbourne and graduated from this institution with 1st Class Final Honours as Bachelor of Metallurgical Engineering (March, 1942).

From December, 1941 to July, 1942 he was employed as the Assistant Metallurgist, Steel Company of Australia, in Melbourne, where his duties involved electric furnace operation and routine chemical analyses.

From July, 1942 to July, 1946 he was employed as a Research Officer, Australian Council for Scientific and Industrial Research, Division of Aeronautics, also in Melbourne. Here he gained experience in the metallography of aircraft materials, the weldability of aircraft steels and as supervisor of the heat-treatment shop. He also carried out some unpublished research on the furnace brazing of steel. He is at present on leave of absence from this position.

From February, 1943 to July, 1946 he was a part-time lecturer at the Melbourne Technical College, where he taught courses in Advanced Heat-treatment Theory, and Metallurgy for Aero Engineers.

Since July, 1946 he has been a Pressure Vessel Research Committee Fellow at the Fritz Engineering Laboratory, Lehigh University.

He was elected an active member of the Lehigh Chapter of the Society of Sigma Xi, in May 1948.

He has published the following technical papers:

"The Fatigue of Welded Steel Tubing in Aircraft Structures", Symposium: The Failure of Metals by Fatigue, P. 290, Melbourne, 1946.

"Transformations in Ferrous Alloys", Australasian Engineer, Dec. 7, 1944, P. 26.