NACA TN No. 1831

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1831

TENSION PROPERTIES OF ALUMINUM ALLOYS IN THE PRESENCE OF STRESS-RAISERS

II - COMPARISON OF NOTCH STRENGTH PROPERTIES OF 24S-T, 75S-T, AND 24S-T86 ALUMINUM ALLOYS

By E. L. Aul, A. W. Dana, and G. Sachs

Case Institute of Technology

Washington

March 1949

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1831

TENSION PROPERTIES OF ALUMINUM ALLOYS IN THE PRESENCE OF STRESS-RAISERS

II - COMPARISON OF NOTCH STRENGTH PROPERTIES OF 24S-T, 75S-T, AND 24S-T86 ALUMINUM ALLOYS

By E. L. Aul, A. W. Dana, and G. Sachs

SUMMARY

In continuation of part I of this investigation, the effects of triaxial stress states, produced by circumferential V-type notches, on the fracturing characteristics of 24S-T, 75S-T, and 24S-T86 aluminum alloys were investigated.

The actual fracture stresses and ductilities were derived from the test results on mildly notched bars for a considerable range of triaxialities. The results of these tests showed that the fracture stress of the commercial alloys investigated generally increased, whereas the ductility simultaneously decreased, with increasing triaxiality. Over the entire range of triaxiality (including regular tension tests) the actual fracture stress of 75S-T was found to be considerably higher than that of 24S-T86, and that of 24S-T was intermediate. The ductility of 75S-T under conditions present in regular tension tests was higher than that of 24S-T, but it decreased more rapidly than 24S-T (with increasing triaxiality) to considerably smaller values at the highest triaxialities obtainable in notched specimens. The 24S-T86 alloy possessed, over the entire range of triaxialities, ductilities approximately 5 percent lower than the corresponding values of 24S-T.

The preliminary analysis of sharply notched bars indicated that the notch ductility of the different alloys followed the same order as the ductility values derived for high degrees of triaxialities. Although 24S-T retained an appreciable ductility (approximately 5 percent), both 75S-T and 24S-T86 exhibited only a fraction of 1 percent in sharply notched bars. The notch strength, on the other hand, was found to be reduced by sharp notches only for 24S-T, whereas both 75S-T and 24S-T86 were less notch sensitive in regard to strength. The rather different response in this respect of the alloys investigated may be tentatively correlated with their different stress-strain characteristics.

INTRODUCTION

In part I of this investigation (reference 1)[1] a suitable analysis for the problem of the effects of a stress state, possessing rotational symmetry with all three stresses being tensions, on the ductility and strength of 24S-T aluminum alloy was formulated. The method developed restricted the range of notch shapes analyzed to mild notches, that is, negligible stress concentrations. For specimens where fracturing occurred in the center fiber, the fundamental dependence of fracture stress and ductility upon triaxial stress states was established with reasonable accuracy. The fracture stress was found to increase with increasing transverse tension (increasing triaxiality), whereas the ductility decreased correspondingly. The derived relation corresponded almost, but not completely, to the constant shear stress condition of plastic flow. This conclusion confirmed that drawn on the basis of speculation, rather than of rigid analysis, from notched-bar tension tests on steel and other metals (references 2 to 4).

If, on the other hand, fracturing was initiated at the surface of the notch bottom, the test results given in part I of this investigation were found to depend upon the surface condition of the notch. This fact was correlated with the high stress concentrations present in sharply notched bars in the elastic region and the resulting strain concentration after plastic flow began. The sharper the notch and the less ductile the surface condition, the smaller would be the average plastic strain at which the ductility of the outer fiber would be exhausted.

As a result of the work on 24S-T (reference 1), the various notch shapes can be roughly divided into those where fracturing occurred in the center of the test bar (so-called mild notches) and those where fracturing occurred at the surface of the notch bottom (sharp notches). Since the analysis of mild notches appears to be established, a suitable approach to the problem of fracturing in sharply notched bars should be developed.

The properties of sharply notched tension bars have been determined by numerous investigators (references 3 and 5). However, in many instances only one of the three metal characteristics (notch strength, fracture stress, and notch ductility) which can be obtained from such tests has been measured, namely, the average strength of the notched section ("notch strength"). The significance of this quantity is not clear. It depends upon the average strain ("notch ductility") at fracture and, to a certain extent, upon the stress-strain relations at the notched section. In addition, the average stress at fracture ("fracture stress"), which, in turn, is correlated with the notch ductility, has been determined frequently.

---

[1]For an extended reference list on notch testing see the BIBLIOGRAPHY at the end of the paper.

Certain metals which have been subjected to notched-bar tension tests had sufficient ductility to exhibit a maximum load before fracturing for any shape. In addition, the strain at which the maximum load occurs ("necking strain") was found to be practically identical for notched and unnotched specimens (reference 1). This is explained by the fact that the stress-strain curve of any notched specimen is very similar to that of the cylindrical tension test bar, as illustrated schematically in figure 1(a) (conventional stress given as ordinate) and in figure 1(b) (true stress given as ordinate). For a given stress within a considerable range of strain, the average stress required to stretch a specimen provided with a notch is higher than that in a regular tension test by an approximately constant percentage. The ratio of the average stresses for a notched and an unnotched specimen depends considerably upon the notch contour but only slightly upon other variables, such as the metal. This explains the fact that the notch strength, being a particular value of conventional stress, has been found for a variety of metals to be a certain multiple of the tensile strength for a given notch shape.

The notch ductility, according to all experimental evidence, decreases with certain features of the notch shape, namely, an increasing notch sharpness, a decreasing flank angle, and an increasing notch depth. At first glance, the relations between notch ductility and these variables appear rather universal. However, investigations in which the fracture stress has also been determined show that the process of fracturing, which determines both the notch ductility and the fracture stress, is extremely complex. These phenomena have not been clarified up to the present time.

The notch strength of sufficiently ductile specimens is not related to either the notch ductility or the fracture stress, as just discussed. In the stress-strain curves (fig. 1) the point of fracturing is then located at a strain larger than the necking strain. However, the significance of the notch strength changes radically if a metal becomes comparatively brittle upon notching, as illustrated by means of the stress-strain curves in figure 2. If notching reduces the ductility to a value below the necking strain expected from the trend of the stress-strain curves, the notch strength is simply the conventional stress, the true stress of which is the fracture stress. Then, the notch strength is also directly correlated with the notch ductility. If it were possible to vary the notch ductility and keep all other factors identical, a simple relation between notch strength (and fracture stress) and notch ductility should exist. Actually, such a rather simple relation is obtained for a variety of heat-treated steels (fig. 3, from reference 15), if their differences in strength are eliminated by using the ratio of notch strength to tensile strength ("notch strength ratio") rather than the notch strength.

Although the experimental data available illustrate the general dependence of the aforementioned quantities for various materials upon certain components of the notch shape (the curvature of the notch bottom, the notch depth, and the flank angle of the notch), no general relationships are recognized which permit evaluating the "notch sensitivity" of a particular alloy.

Only through a study of groups of similar alloys, varying widely in ductility and other conditions, can the effects of stress concentrations (notch sensitivity) be definitely established. It is the primary purpose of this paper to establish some such relations, which may help to define and measure the notch sensitivity of an alloy.

In order to achieve this purpose, the investigation of specimens, differing widely in notch depth and sharpness, offers according to previous investigations the greatest possibility of studying the effects of stress concentrations. Since variation of the third possible geometric factor, notch angle, results in property changes intermediate between the other two geometric factors, notch depth and sharpness, the notch angle was kept constant. Furthermore, the selected notch angle of 60° yields properties rather close to those resulting from the most severe notching in this respect, namely, a notch angle of zero (references 2, 6, and 7). By applying the method outlined in reference 1, the fundamental dependence of the fracturing characteristics of the investigated alloys could be established.

The two aluminum alloys investigated, 24S-T and 75S-T, varied widely in necking strains. By treating 24S-T to 24S-T86, the necking strain and the strain-hardening rate were reduced. Thus, three similar materials that differed in their strain-hardening characteristics were available.

This paper constitutes part II of the final report on a research program conducted at the Case Institute of Technology under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

Various members of this laboratory have contributed to the previous work done in this field and to the work done on this particular investigation. Particular thanks is due Messrs. M. L. Fried and M. H. Jones for their assistance in the experimentation.

SYMBOLS

R	radius of curvature of notch
a	half the diameter of notched section
s_1, s_2, s_3	principal true stresses (actual)
s_1', s_2', s_3'	principal true stresses (average)
s_f	actual fracture stress for any stress state
s_f'	average fracture stress for any stress state
k	variable flow stress in pure tension

k_f	fracture stress in pure tension
f	variable fracture stress (function of stress and strain state); with subscript zero, in pure tension
e_1, e_2, e_3	principal conventional (unit) strains
ϵ_1, ϵ_2, ϵ_3	principal natural strains ($\epsilon = \log_e(1 + e)$)
q	reduction in area or contraction in area at fracture
ϵ_f	maximum natural strain at fracture under conditions of testing; with additional subscript zero, in pure tension

MATERIAL AND PROCEDURE

Aluminum alloys 24S[2] and 75S were available as $\frac{3}{4}$-inch-diameter rod in the "T" condition. All specimens were re-solution-heat-treated after final machining to yield two alloy conditions: 75S-T and 24S-T86. An electric Lindberg cyclone forced-convection furnace was used for all thermal treatments.

The 75S-T rod was reheat-treated by (a) Soaking for 45 minutes at 900 ± 10° F, (b) quenching in water at room temperature, and (c) artificial step aging as follows: (1) heating at 210 ± 10° F for 5 hours, (2) air cooling, (3) heating at 315 ± 10° F for 10 hours, (4) air cooling.

The 24S-T86 specimens were obtained by (a) Machining cylindrical specimens from the 24S-T rod, (b) solution-heat treating as for 24S-T (see reference 1), (c) reducing cross-section area by 5 to 6 percent by stretching, (d) aging at 375 ± 10° F for $9\frac{1}{2}$ hours,[3] and (e) air cooling.

Figure 4 illustrates the various specimen types. In order to determine the fundamental properties of the various materials, cylindrical specimens were used. Notched specimens had 60°, circumferential V-type notches, with the notch depth and radius at the root of the notch having various values. In every case, however, the diameter of the notched section was machined to 0.212 ± 0.012 inch and the variation in notch depth was obtained by changing the cylindrical outside diameter. Consequently, because of this notching technique, the notch contour was entirely circular for specimens with large radii and/or small notch depths.

---

[2]Data and curves for 24S-T are given in reference 1.

[3]This treatment was started within 3 hours after the solution (standardizing) treatment.

The test procedure is described in part I of this investigation (reference 1). The tests were run at a speed low enough to allow recording of stress–strain curves. In each case, the final diameter was measured by means of a microprojector at a magnification of 10X and the ductility and fracture stress values recorded in tables I and II were obtained in this manner. The ductility values obtained were accurate to ±0.1 percent strain and the load readings were accurate to ±5 pounds. In all, 14 unnotched specimens and 313 notched specimens were tested.

Observed properties for the laboratory reheat–treated specimens are compared with typical values (from the supplier) for the materials investigated in the following table:

Alloy	Typical properties			Observed properties		
	Yield strength (psi)	Tensile strength (psi)	Contraction in area (percent) (1)	Yield strength (psi)	Tensile strength (psi)	Contraction in area (percent)
24S–T	46,000	68,000	------	42,000	70,000	32
75S–T	72,000	82,000	------	69,000	84,500	36
24S–T86	66,000	70,000	------	64,000	75,000	30

[1]Values not available.

The stress–strain curves obtained in regular tension are shown in figure 5. (In this and all following graphical representations an average of two or more tests is used.) The dashed lines added to this graph represent the branches of the flow stress curves after necking occurred. These were determined from the radius at the bottom of the neck at fracture and Bridgman's correction, as previously outlined (reference 1). In figures 6 and 7, stress–strain curves for various notch depths and radii are shown.

The strength properties and ductilities, obtained from unnotched and notched bars of 75S–T alloy are given in table I and of 24S–T86 in table II.

RESULTS AND DISCUSSION

Dependence of Notch Strength Characteristics on Notch Sharpness

The three experimentally determined quantities, the notch ductility, the notch strength, and the average fracture stress for 75S–T, 24S–T86, and 24S-T (see reference 1 for original data on 24S-T) are represented in figures 8 to 10 as functions of notch sharpness.[4]

The notch sharpness greatly affects the notch properties of the investigated alloys. With increasing notch sharpness for any given notch depth both the fracture stress and notch strength first increase, passing through a maximum value at a certain notch sharpness, and then decrease. The notch ductility decreases continuously until, at a certain notch sharpness, it becomes approximately constant.

The initial increase of either fracture stress or notch strength is readily understood as resulting from a progressive increase in the magnitude of the induced transverse tension (triaxiality) by a more severe (sharper) notch. A maximum of induced triaxiality is reached at intermediate notch sharpnesses, after which the fracture stress and notch strength should remain constant. However, the decrease is probably effected by cracking at the surface of the notch or, in the case of notch strength, by a reduction of the ductility to a value below the necking strain, as discussed in the INTRODUCTION. These relations can be correlated with the variation of triaxiality in the elastic state. In the elastic state, the degree of triaxiality is determined primarily by notch sharpness. By using the equations developed by Neuber (reference 8), a curve for the dependence of triaxiality on notch sharpness a/R is obtained for an infinitely deep notch (fig. 11). Again the same type of variation is found. This indicates that the elastic relations still apply qualitatively after plastic flow occurs.

The maximum in the fracture stress can be taken as the rough division between mild and sharp notches. It is of interest to note that the aforementioned maximum occurred at smaller notch sharpnesses, the smaller the notch depth, and was more pronounced in the case of fracture stress than of notch strength.

The ductility, of course, decreases with increasing notch sharpness and then becomes constant after the stress concentration reaches its maximum value at intermediate notch sharpnesses.

The discussed similarity of the curves representing the notch strength characteristics as functions of the notch sharpness does not very clearly reveal the differences among the various materials. They are therefore not further discussed in this paper.

---

[4]In these representations the abscissa scale is based on the quantity $\frac{a/R}{\frac{a}{R} + 10}$. This scale allows the plotting of all sharpnesses from zero to infinity, with a value of 10 at the center of the plot. This scale has no other physical significance.

Dependence of Notch Strength on Notch Depth

In figures 12 to 14, the notch ductility, notch strength, and average fracture stress are shown as functions of notch depth for the investigated alloy.

The dependence of either the notch strength or the fracture stress upon the notch depth is rather complex. It nevertheless follows a comparatively definite trend in agreement with the results of previous tests on heat-treated steels. Thus, the following relations appear to apply generally to metals which are sufficiently ductile in regular tension to exhibit some necking.

The dependence of the notch strength upon notch depth becomes particularly simple if a metal possesses sufficient ductility to exhibit a maximum load on testing sharply notched specimens. These basic relations are schematically illustrated in figure 15. For notch sharpnesses exceeding a certain value, approximately 10 to 15, the notch strength generally increases linearly with the notch depth to a value approximately twice the tensile strength for 100-percent notch depth. For milder notches, the trend curves first follow this straight-line relation and then deviate from it earlier, the milder the notch, the notch strength being practically constant at very deep notches.

For mild notches, the notch strength of all three aluminum alloys corresponds closely to the basic trend curves. For a given notch sharpness, the relative change in notch strength with notch depth is practically identical for the different alloys. This includes the range of notch sharpnesses between 0.05 and 1.8 (R = 2.00 inches to 0.060 inch). Apparently, the ductility of these alloys is sufficiently large that their notch strength is not adversely affected by such mild notches. This means that these notches do not reduce the average ductility below the necking strain for any of these structural alloys. The notch strength then depends only upon the average triaxiality which, for a given notch shape, is apparently almost constant. The effect of notch radius on the notch strength has just been discussed. The peculiar effect of notch depth, for a given notch sharpness, cannot be explained at present.

In the range of sharp notches, the notch strength depends on the notch depth in a different manner for each alloy investigated. This relation has been investigated previously for heat-treated steels (reference 5); the results are illustrated in figure 16. For a given steel and a given notch sharpness, the dependence of the notch strength upon notch depth corresponds to one curve of the family of curves in figure 16. For different steels (different strength levels) the curves for different notch sharpnesses spread more, the lower the ductility of the steel (the higher its strength level).

The limited data for the aluminum alloys investigated indicate that similar relations between notch strength and notch depth exist. For a particular alloy, the trend curves for different notch sharpnesses appear to belong again to a family of curves, as illustrated in figures 12 to 14. Generally, a trend curve for any alloy deviates from the limiting straight line more, the sharper the notch. The character of the trend curves, however, is rather different for 24S-T from that for the two other alloys. Sharp, shallow notches reduce the notch strength of 24S-T considerably but increase that of either 75S-T or 24S-T86. This may be correlated with the respective values of necking strain. Because of the large necking strain of 24S-T, a certain ductility below this value will cause a reduction in notch strength, because of premature termination of the stress-strain curve. Such a ductility may, however, exceed the considerably smaller necking strain of 75S-T or 24S-T86 and, therefore, not affect the notch strength. Consequently, the notch strength values for these two alloys follow the straight-line relation to both larger notch depth and larger notch sharpness.

On the contrary, for very deep notches, the deviation from the straight line also becomes pronounced for 75S-T and 24S-T86. The deviation in notch strength from this straight line for different notch sharpnesses is considerably smaller for 75S-T than for 24S-T86 and 24S-T as far as the different shape of the trend curves permits comparison. Regarding the notch strength, therefore, 75S-T is considerably less notch sensitive than 24S-T. On the other hand, 75S-T is the most notch sensitive in regard to ductility and 24S-T86 is notch sensitive in both respects.

General Comparison of Various Alloys on the Basis of Composite Graphs

The notch strength characteristics of a particular material depend to a large extent upon the shape of the notch, other factors such as section size, temperature, and so forth being held constant. This relation between properties and shape is very complex and therefore difficult to evaluate. Many attempts were made to represent the test data in such a manner that different alloys could be compared readily. It appears now that composite graphs in which the strength functions are plotted against the notch ductility serve best the purpose of comparing at a glance the response of different alloys to notching.

The following four strength functions can be derived directly from the tests:

(1) Notch strength

(2) Average fracture stress

(3) Notch strength ratio, that is, ratio of notch strength to tensile strength

(4) Fracture stress ratio, that is, ratio of fracture stresses for a notched and unnotched specimen

The first two quantities permit a direct evaluation of the strength properties, and the last two aid in the comparison of the relative effects of notching.

If this method is applied to the test data previously obtained for heat-treated steels (references 5 and 10), a rather simple classification depending upon notch ductility is obtained for the steels. The resulting graphs are shown schematically in figure 17.[5] In each graph, the test data for a particular material, that is, a steel heat-treated to a certain tensile strength, fill a certain area. This area is bounded at the right side by a curve representing the results for comparatively mild notches (large radii), that is, the highest stress values for a given ductility or the highest ductility for a given stress. The other boundaries conform to the most severe notches. The tests on the various heat-treated steels now show a very definite dependence of the shape of the areas or of the relative stress values upon the smallest values of ductility obtained in severely notched bars. The absolute stress values, of course, also depend upon the tensile strength of the particular material.[6] In general, the notch ductilities decrease with increasing tensile strength. This decrease is evidenced by a relative shift of both the right and left boundaries simultaneously to smaller ductility values in figure 17. The upper boundary changed only slightly regarding the relative stress values, whereas the lower boundary moved at an increasing rate (with decreasing notch ductility) to low stress values; the result was a corresponding enlargement of the area. In other words, a particular notch generally resulted in a certain reduction in ductility, which was determined by the minimum ductility exhibited by the steel and by the notch shape. On the contrary, the stress values first increased with both the notch radius and the notch depth (according to an almost universal function) and then followed the ductility, if it decreased below a certain value.

Similar curves for the aluminum alloys[7] investigated are presented in figure 18. The shapes and relative positions of the areas for the various alloys in contrast with those for the steels are not determined by the

---

[5]These graphs refer to SAE 3140 steel. The previous test data are not sufficient to construct quantitative rather than schematic representations.

[6]The ductility of unnotched bars (contraction in area) could be correlated with the notch sensitivity of a steel condition. Comparatively large differences in contraction in area were frequently observed in steels with almost identical notch sensitivities, and vice versa.

[7]These representations are rather sensitive in respect to the accuracy and consistency of the test data. The values for 24S-T were found to be sufficiently consistent to outline accurately the boundaries for this alloy. On the contrary, average values obtained from two to four presumably identical, parallel tests left the boundary lines for 75S-T and 24S-T86 somewhat indeterminate. Apparently, it will be necessary to control the heat treating more closely and to average a larger number of tests to obtain more accurate test data for these alloys.

minimum values of notch ductility. As was expected from commercial experience, 24S-T retained a considerably higher ductility after severe notching than the other two alloys. This, however, was not associated with a correspondingly small notch sensitivity in respect to the stress values. On the contrary, both 75S-T and, to a lesser extent, 24S-T86 retained their strength after most severe notching and also exhibited a larger strength increase in mildly notched bars than 24S-T.

Of the relations discussed for steel, only one appears to remain valid for the aluminum alloys. The change in ductility observed by notching to a given shape is continuous and, consequently, results in a comparatively small ductility if the ductility in severely notched bars is small. Again, the ductility of the unnotched specimens was not correlated with the notch sensitivity in any way. Thus, 75S-T exhibited the largest contraction in area in the tensile tests but the smallest ductility in severely notched bars of the three alloys investigated.

Regarding the absolute stress values, 75S-T ranges considerably above both 24S-T and 24S-T86, both in respect to notch strength and to fracture stress (fig. 18). The 24S-T86 alloy yielded considerably higher notch strength values but only slightly higher fracture stress values than 24S-T.

In the following sections, an attempt is made to analyze further the discussed notch strength characteristics.

Effects of Geometrical Variables in Composite Graphs

The composite graphs (figs. 19 and 20) illustrate primarily the limiting combinations of ductility and either notch strength or fracture stress obtainable with bars provided with notches of varying contour.

The notch contour can be represented rather completely by three of its components, the notch sharpness, the notch depth, and the notch flank angle. If one of these factors is varied while the others are kept constant, characteristic families of curves are obtained.

Considering that a number of previous publications report the notch strength and ductility, the effects of a single variable (component of the notch shape) on only the notch strength ratio (as a function of notch ductility) are discussed herein (figs. 19 and 20).

It must be noted first that any such trend curve originates in the point for the regular tensile tests. Consequently, any family of curves, with a second component of the notch shape as the parameter, fans out from the regular tension point, each curve terminating at a different position on the boundaries of the areas representing all possible notch shapes. In figures 19 and 20, these families of curves are shown for 24S-T. These curves are derived from the data presented in reference 1 and are complemented by some previously published test results (references 7 and 11). The dotted lines in these graphs represent the boundaries transferred from figure 18(b). These boundary lines in figure 18(b) were obtained from tests with notches having a depth up to 80 percent, sharpnesses up to approximately infinity, and a constant flank angle of close to 60°. If specimens with greater notch depth and smaller flank angles had been investigated, the left and lower boundaries would be found to be slightly shifted to smaller notch strength ratios and notch ductilities, whereas the upper boundary would have moved slightly upward. Therefore, some test data reported in the literature may be expected to extend beyond the boundaries in figures 19 and 20 for an identical material.

Varying the two components of the notch shape investigated in this report, the depth and the sharpness, yields for a constant flank angle of 60° (or less) practically all strength and ductility combinations obtainable with circumferential notches. Therefore, the family of trend curves, for either notch depth or notch sharpness as the variable and the other as parameter, completely covers the area between the boundary lines in figures 19 and 20. On the contrary, if the notch angle and only one of the other two components of the notch shape are varied (the third being constant), a considerably smaller range of notch properties is obtained. It appears, therefore, that, in order to establish a comparatively complete picture of the notch effects, it is necessary to vary at least both the notch sharpness and the notch depth over a wide range. The effects of flank angle probably are more complex than those of one of the other two variables, which yield certain ranges in which either the stress concentration or the triaxiality vary only to a slight extent.

Thus, if the notch sharpness is increased (fig. 19(a)) the values follow first the right boundary, then deviate from it at a value which is higher, the deeper the notch and probably the smaller the flank angle. Each such curve then reaches or passes through a maximum to terminate at the left boundary. Tests in which the notch sharpness was varied have been also reported by Doan and McDonald (reference 12) for a commercial 24S-T extrusion. Their results show a similar trend. However, for a given increase in notch strength ratio, their loss in ductility was smaller than that observed in this investigation. A few tests by McAdam (reference 6), in which both the notch depth and flank angle were held constant, are added to figure 19(a). These also agree with the trend curves established for 24S-T regarding the effects of notch sharpness.

In figure 19(b), some additional data by McAdam (reference 6) show the effect of notch sharpness for different flank angles and a constant notch depth. These trend curves appear to be similar to those obtained with variation in depth. (See fig. 19(a).)

If the notch depth is increased (fig. 20(a)), curves are obtained which terminate at the lower and left boundaries for sharper notches and at the right boundary for all notches below a certain sharpness. A few tests by Schapiro and North (reference 11) on 24S-T extrusions provided with sharp notches of varying depth confirm the reduction in notch strength ratio resulting from sharp notching, this decrease being, however, twice as large (0.78 for 15-percent notch depth) as that observed in this investigation. No notch ductility values were reported by Schapiro and North to render a more complete comparison possible.

The effects of variations in flank angle have not been studied in this investigation, because a large amount of such experimentation has been carried out by McAdam (reference 6) on 24S-T. The trend curves for his tests appear similar to those for notch depth. Additional data (reference 13) showing approximately the same trend are plotted in figure 20(b) for an aluminum alloy containing 4 percent copper, similar to 25S-T (being less strong and more ductile than 24S-T).

Effect of Triaxiality on Fracturing Characteristics

Composite graphs similar to those discussed in the preceding section can be prepared by plotting the actual longitudinal stress (true stress at the locus of fracture) present at the moment of fracturing as a function of the notch ductility (figs. 21 to 23). This stress is obtained by means of the analysis outlined in part I of this investigation (reference 1).

If fracturing occurs in the center rather than at the notch bottom, this stress assumes the physical significance of an actual fracture stress. It has been shown that such a condition can be assumed to apply, if the test data deviate from the right boundary not more than is to be expected from general scattering. Only a few values for 75S-T and 24S-T86 conform to this requirement, according to figures 21 and 22. Also, the test results for these alloys were rather inconsistent and, therefore, render the location of the right boundary uncertain.

Specimens in which fracturing is considered to be initiated at the center yield a corresponding number of pairs of fracturing characteristics, that is, fracture stress and ductility. Furthermore, by knowing the fracture stress, which is simultaneously the stress required for plastic flow for a strain equal to the ductility and the flow stress in uniaxial tension for the same strain (taken from fig. 5), the triaxiality present at the moment of fracturing is obtained from the following equation:

$$\frac{s_3}{s_f} = 1 - \frac{k}{s_f} \qquad (1)$$

This equation is derived from the condition of plastic flow (see reference 1):

$$s_f - s_3 = k \qquad (2)$$

By this method the dependence of fracture stress and ductility upon triaxiality has been determined for the alloys investigated (figs. 24 and 25). For a given triaxiality, the fracture stress of 75S-T is approximately 15 percent higher than that of 24S-T over the entire range, whereas the fracture stress of 24S-T86 is approximately 15 percent lower than that of 24S-T at low triaxialities (high ductilities) but less than 10 percent lower for high triaxialities.[8] In view of the fact that the rod used for these tests possessed properties close to the typical values, these differences appear to be representative for the investigated alloys.

The dependence of the ductility upon triaxiality has not been established to date with sufficient accuracy for 75S-T and 24S-T86. However, the test data for 24S-T86 conform to ductility values which are approximately 5 percent below those of 24S-T for the entire range of triaxialities investigated. The ductility of 75S-T was found to be slightly larger than that of 24S-T at low triaxialities (regular tension). With increasing triaxiality, however, the ductility of 75S-T distinctly decreased more rapidly and became lower at high triaxialities than that of 24S-T.

The test data available for heat-treated steels (reference 5) indicate that their ductility varies with triaxiality much more rapidly than that of any of the aluminum alloys. No real explanation can be given for this peculiar relation. Possibly it may be correlated with the general shape of the stress-strain curves for these materials. The heat-treated steels exhibit little strain hardening. A small change in fracture stress, therefore, corresponds to a considerably larger decrease in ductility than that for a metal which strain-hardens more extensively. Consequently, if it is assumed that the quantitative effect of triaxiality on the fracture stress conforms to some universal law, its effect on ductility should vary with the stress-strain characteristics of a metal.

Significance of Tests on Sharply Notched Bars

According to all available evidence, the embrittlement caused by a sharp notch is considerably more pronounced than that resulting from a mild notch. The previous investigations on heat-treated steels (references 5 and 10) and the present work on aluminum alloys establish a rather definite parallelism of these two effects. Whenever a sharply notched bar is liable to fracture after very small over-all strains, its ductility will be also reduced to comparatively small values by mild notches.

The average ductility values determined for sharply notched bars are of course no direct measure of their actual ductility.[9] It has been

[8] It is rather surprising that the test values outline very accurately these relations between fracture stress and triaxiality. It is not quite clear why, in this respect, the large variations in the direct test results have such little influence on the accuracy.

[9] The value of strain at the locus of failure, expressed as $\epsilon_f = -\log_e(1 - q)$.

shown that rather brittle appearing fractures are associated with quite large strains (reference 14). The large strains, however, appear to be very localized, presumably in the vicinity of the locus of fracture (notch bottom). On the other hand, the average strain and the actual surface strain must be correlated in some simple manner. Consequently, the extremely small average ductilities frequently observed in notched tests must also indicate a rather small actual ductility. In other words, if some factor causes a large decrease in average ductility, it should be expected that the actual ductility is reduced correspondingly. Certainly, the spectacular reductions in over-all strength, which have been observed repeatedly to be associated with very small average ductilities (reference 15), cannot be explained simply by extreme localization of large strains. Even if this were true, no reason is apparent why the strain distribution after fracturing for the so-called brittle fractures should be radically different from those for ductile fractures.

On the other hand, it is rather probable that the function which correlates the average ductility with the actual ductility is of such a nature that a reduction in actual ductility below a certain value results in very small average ductilities. Figure 26 illustrates schematically such a possible relation for both an extremely sharp notch and a somewhat less sharp notch. This figure attempts to summarize the following general conclusions which may be drawn from the evidence available at present. The sharper the notch, the larger is the initial stress concentration (in the elastic state) and the higher should be the ratio of actual to average strain in the early phases of plastic flow. On the other hand, if the entire section is plastic, the stress concentration becomes insignificant, and the strain increments for a given increase in load should be practically constant for the entire section. The problem then reduces itself to an explanation of the phenomenon that average ductilities below a certain critical value, say, 1 percent (fig. 26), are associated with brittle or sudden failures. In the present state of knowledge, it is not clear whether this is simply a mechanical process, such as the inability of the metal to relieve the elastic energy stored without failure. However, it is also possible that the crack propagation occurs under physical conditions conducive to further embrittlement of the metal and, therefore, assumes an instantaneous character. Actually, the only difference which can be established definitely between so-called brittle and ductile failures is that the first type is of the self-accelerating type, whereas the second type needs additional outside energy to sustain its progress.

On the basis of these discussions, it may, therefore, be assumed that the embrittlement observed in sharply notched bars is determined by a corresponding decrease in actual ductility. The stress conditions at the notch bottom are in the following two respects different from those in uniaxial tension (or in a mildly notched or necked test bar) in the early stages of plastic flow. First, a high stress concentration or stress gradient is present and second, considerably large tangential tensions must be present in the surface layer, because of the inability of the notched cross section to change diameter against the resistance of the still elastic core. In other words, a biaxial stress state[10] rather close to plane strain should exist, the transverse tension then being one-half of the longitudinal tension.

It has definitely been established that the ductility decreases with increasing biaxiality in the range between uniaxial tension and plane strain. In particular, tests on tubes subjected simultaneously to internal pressure and to longitudinal tension (references 16 to 18) and bending tests on rectangular bars of various breadth-to-heighth ratios (references 18 to 20) have shown this to be a general law for various metals. According to these tests, also, the fracture stress is little affected by biaxiality.

Thus, a varying degree of biaxiality appears to be the only factor which may explain variations in the actual ductility of sharply notched bars. If this were true, the average ductility observed in sharply notched bars should also be a measure of the actual ductility, under conditions approaching those of plane strain. Consequently, a large reduction in ductility from an unnotched to a sharply notched bar would be explained by a corresponding general difference in actual ductility observed between uniaxial tension and plane strain, other conditions being identical. (For metals, such as steels, differences in speed and temperature also may exert a large effect.) It should be possible to correlate the effects of sharp notching on the ductility with those observed in the other tests in which the biaxiality can be varied.

Shape and Significance of Stress-Strain Curves for Notched Specimens

Valuable conclusions can be drawn from the over-all stress-strain relations for notched bars. The general shape of the stress-strain curve for a notched specimen appears to be related to that of an unnotched test bar of the same metal in a rather universal manner. However, at present, the termination point of a particular stress-strain curve cannot be predicted by means of any simple rule.

The following discussion is restricted to stress-strain curves in which the true (average) stress is plotted as a function of the average natural strain of the notched section. Such a basic curve, for any particular notch shape, can be obtained, as a rough first approximation, from the flow stress curve f of the metal by multiplication of the stresses by a constant factor c (fig. 27). The actual curve then deviates from this basic curve in either two or three respects for mild notches or in three or four respects for sharp notches. The first deviation (I in fig. 27) consists of a depression in the stress values, which is reduced rapidly with increasing strain to become insignificant

[10]Biaxial stress states are those in which tension stresses are present in two principal directions, the stress in the third principal direction having some small value (or zero).

at strains above 1 to 2 percent (reference 5). This effect is larger the sharper the notch, being determined by the initial stress concentration. The second deviation (II in fig. 27) also occurs to lower stress values. It increases slowly with straining, not exceeding a small fraction of the difference between the stress-strain curve and the flow stress curve. This effect is attributed to a slight progressing change in average triaxiality from its elastic value. The third deviation (III in fig. 27) is observed only if the conventional stress-strain curve exhibits a maximum. It comprises a gradual increase in stress, starting at the maximum load strain or "necking strain." This effect has been discussed repeatedly for unnotched specimens, being caused by a gradual increase in triaxiality. The increase in triaxiality is determined by the curvature of the neck which develops at decreasing loads (reference 21). Usually, this effect is noticeable only in mildly notched, comparatively ductile specimens. On the contrary, the last deviation (IV in fig. 27) is restricted to sharply notched bars (reference 1), extending over a certain strain immediately preceding fracturing. This effect may assume an appreciable magnitude at fracturing, being related to the development and propagation of cracking.

These various effects can be recognized more distinctly if the ratio of average longitudinal stress s_1' to flow stress k is formed and plotted as a function of the strain. Experimental data evaluated by this process then result in several types of such reduced stress-strain curves, which are schematically represented in figure 28. A number of such curves, for 24S-T, are shown in part I of this investigation (reference 1). The location of a curve, that is, the magnitude of the values s_1'/k, has no direct influence on its shape, being dependent primarily upon the initial triaxiality.

Crack Propagation

The fracturing of sharply notched test bars is a process which is very difficult to analyze in detail. In this investigation attempts were made to determine accurately both the load and the change in diameter at the moment of fracturing. Because of the small ductility of the sharply notched specimen, the change in load following initial cracking at the notch bottom was rather distinct. These observations revealed the somewhat unexpected result that in all instances the specimens failed suddenly at a maximum load. It was not possible to take any load or strain readings at gradually decreasing loads. Consequently, the last readings (extrapolated to fracturing) relate to some obscure, intermediate moment during the cracking process at which the load-carrying capacity of the specimen has reached a maximum. This applies not only to the aluminum alloys investigated herein but also to the previously investigated heat-treated steels.[11]

[11]It is probable that a metal which possesses a high notch ductility cracks more slowly. Such a metal would then permit following the load changes during cracking much further. However, it would also exhibit necking, and it would be rather difficult to separate effects of necking from those of cracking.

Some additional information regarding the process of cracking can be obtained by further analyzing the stress-strain relations as follows. In each of figures 29 to 31, the stresses s_1' for a particular metal and a particular notch depth are plotted as functions of the notch sharpness, with the strain as parameter. For any given strain sufficiently lower than the average fracture ductility, this stress follows a rather peculiar relation. The longitudinal stress increases with increasing notch sharpness at a gradually decreasing rate. It then becomes practically constant for a considerable range of high notch sharpnesses. This relation confirms previous conclusions drawn from tests on heat-treated steels.

If cracking precedes final fracturing, however, the observed longitudinal stress becomes progressively smaller than that required by the aforementioned relation. This permits an estimate of the strains at which cracking begins. In figures 29 to 31, the ranges of stresses and strains which are then considered to be measured after the beginning of cracking are represented by shaded areas. This shaded area extends over the largest range of stress and strain at the sharpest notch and with decreasing notch sharpness gradually fades out at a certain notch sharpness, as discussed previously (reference 1).

A comparison of the three aluminum alloys investigated (figs. 29 to 31) shows that considerably large increases in stress and strain are observed in both 24S-T and, to a lesser extent, in 24S-T86 after the beginning of cracking. On the contrary, the test data for 75S-T indicate that the load-carrying capacity of this metal terminated suddenly at the moment a crack developed. The heat-treated steels investigated previously (reference 5) also seem to be subject to such sudden crack propagation.

As was to be expected and as discussed previously (reference 1), machining of the surface after heat treating results in an earlier appearance of the crack. On the contrary, the final fracturing was found to be only slightly accelerated by such machining of 24S-T. This explains the considerable extension of the shaded region in figure 31, representing the phase of crack propagation.

CONCLUSIONS

The following conclusions have been drawn from the investigation of tensile test bars of 75S-T, 24S-T86, and 24S-T aluminum alloys provided with circumferential V-type notches of various contours:

1. Notching of a metal subjected to tension generally reduces the ductility. For a given notch shape, the decrease in ductility from the value for regular tension is very different for various metals. The ductility of the aluminum alloys is considerably less affected by notching than that of heat-treated steels. For the investigated aluminum alloys, the absolute decrease in ductility was largest for 75S-T and approximately equal for 24S-T and 24S-T86.

2. The relative magnitude of the reduction in ductility is similar for mildly and for sharply notched bars. It is believed that it is caused in mildly notched bars by the presence of transverse tensions, or a triaxial stress state, in the center of the specimen. Similarly, in sharply notched bars, a biaxial stress state must be assumed to be present at the surface of the notch to explain the decrease in ductility. Thus, for a particular metal, the response of the ductility to either triaxial or biaxial tensions is of a corresponding magnitude. This effect can be considered as a measure of notch sensitivity.

3. The notch sensitivity regarding ductility is not related in a simple manner to the notch sensitivity regarding strength. Only if materials are very similar regarding their stress-strain characteristics (such as heat-treated steels of various hardness) do the notch strength and the fracture stress become universal (but very complex) functions of the notch ductility. No definite relation between ductility and strength can be derived at present for aluminum alloys.

Case Institute of Technology
Cleveland, Ohio, June 11, 1947

REFERENCES

1. Dana, A. W., Aul, E. L., and Sachs, G.: Tension Properties of Aluminum Alloys in the Presence of Stress-Raisers. I - Effects of Triaxial Stress States on the Fracturing Characteristics of 24S-T Aluminum Alloy. NACA TN No. 1830, 1949.

2. Sachs, G., and Lubahn, J.: Effects of Notching on Strained Metals. The Iron Age, vol. 150, Oct. 8, 1942, pp. 31-38; Oct. 15, 1942, pp. 48-52.

3. McAdam, D. J., Jr., and Mebs, R. W.: An Investigation of the Technical Cohesive Strength of Metals. Metals Tech., vol. 10, 1943; A.I.M.E. Tech. Pub. No. 1615.

4. Sachs, George, and Lubahn, J. D.: The Effect of Triaxiality on the Technical Cohesive Strength of Steels. Jour. Appl. Mech., vol. 12, no. 4, Dec. 1945, pp. A-241 - A-252.

5. Sachs, G., Lubahn, J. D., and Ebert, L. J.: The Effect of Notches of Varying Depth on the Strength of Heat Treated Low Alloy Steels. Trans. Am. Soc. Metals, vol. 34, 1945, pp. 517-544.

6. McAdam, D. J., Mebs, R. W., and Geil, G. W.: The Technical Cohesive Strength of Some Steels and Light Alloys at Low Temperatures. A.S.T.M., vol. 44, 1944, pp. 593-624.

7. McAdam, D. J., Geil, G. W., and Mebs, R. W.: The Effect of Combined Stresses and Low Temperatures on the Mechanical Properties of Some Nonferrous Metals. Trans. Am. Soc. Metals, vol. 37, 1946, pp. 497-537.

8. Neuber, H.: Theory of Notch Stresses: Principles for Exact Stress Calculation. Translation 74, The David W. Taylor Model Basin, U. S. Navy, Nov. 1945. (Kerbspannungslehre: Grundlagen für genaue Spannungsrechnung, Julius Springer (Berlin), 1937.)

9. Dudley, W. M.: Preliminary Rep. No. 1 on Curves and Formulas for Elastic Stresses. Issued under ONR Contract No. N6ori-273, T.O.1., Feb. 19, 1947.

10. Sachs, G., Lubahn, J. D., and Ebert, L. J.: Notched Bar Tensile Test Characteristics of Heat Treated Low Alloy Steels. Trans. Am. Soc. Metals, vol. 33, 1944, pp. 340-395.

11. Schapiro, L., and North, H. E.: Symposium on Notch Effects in High-Strength Aluminum Alloys. Part I. Notch Sensitivity in High-Strength Aluminum Alloys - Theoretical Aspects. Jour. Aero. Sci., vol. 13, no. 8, Aug. 1946, pp. 391-395.

12. Doan, J. P., and McDonald, J. C.: The Notch Sensitivity in Static and Impact Loading of Some Magnesium-Base and Aluminum-Base Alloys. A.S.T.M., vol. 46, 1946.

13. Kuntze, W.: Cohesive Strength. Julius Springer (Berlin), 1932.

14. Ruark, A. E., Kramer, I. R., Shearin, P. E., et al.: Ductility and Fracture Resistance of Ship Plate. Naval Res. Lab. Rep. 0-2796, Nov. 22, 1946.

15. Sachs, G., Ebert, L. J., and Brown, W. F., Jr.: Comparison of Various Structural Alloy Steels by Means of the Static Notch Bar Tensile Test. A.I.M.E. Tech. Pub. No. 2110.

16. Sachs, G., and Lubahn, J. D.: Bursting Tests on Notched Alloy Steel Tubing. Trans. Am. Soc. Metals, vol. 31, 1943, pp. 71-87.

17. Espey, G.: Instability of Thin Walled Tubes Subjected to Internal Pressure. A.S.M.E., vol. 68, 1946, pp. 281-285.

18. Thomsen, E. G., and Dorn, J. E.: The Effect of Combined Stresses on the Ductility and Rupture Strength of Magnesium-Alloy Extrusions. Jour. Aero. Sci., vol. 11, no. 2, Apr. 1944, pp. 125-136.

19. Sachs, George, Lubahn, J. D., and Taub, J. M.: Correlation of Information Available on the Fabrication of Aluminum Alloys (NA-126): Section V - Formability of Aluminum Alloys for Use in Military Aircraft. Part V - Simple Bending of Rectangular Shapes by Means of Dies. OSRD No. 5014, Serial No. M-487, War Metallurgy Div., NDRC, Apr. 26, 1945.

20. Maier, A. F.: The Effect of Stress State on Ductility of Metallic Materials. V.D.I. Verlag, Stuttgart, 1935.

21. Bridgman, P. W.: The Stress Distribution at the Neck of a Tensile Specimen. Trans. Am. Soc. Metals, vol. 32, 1944, pp. 553-572.

BIBLIOGRAPHY

Books

Cocker, E. G., and Filon, L. N. G.: Photoelasticity. London, 1931, pp. 362–397.

Neuber, H.: Theory of Notch Stresses: Principles for Exact Stress Calculation. Translation 74, The David W. Taylor Model Basin, U. S. Navy, Nov. 1945. (Kerbspannungslehre: Grundlagen für genaue Spannungsrechnung, Julius Springer (Berlin), 1937.)

Gensamer, M.: Strength of Metals under Combined Stresses. Am. Soc. Metals, 1940.

Articles

Martens, A.: Tensile Tests on Notched Specimens. Z.V.D.I., vol. 45, 1901, pp. 805–812.

Rudeloff, M.: Testing of Iron and Steel by Means of Notched Pieces. Stahl u. Eisen, vol. 22, 1902, pp. 374–380.

Preuss, E.: Experiments Regarding the Stress Distribution in Notched Tensile Test Bars. Z.V.D.I., vol. 57, 1913, pp. 664–667.

Ludwik, P., and Scheu, R.: Effect of Notches on Soft Iron. Stahl u. Eisen, vol. 43, 1923, pp. 999–1001.

Siebel, E.: Report of the Special Committee of the Association of German Ironworkers. Werkstoffaus, vol. 71, Nov. 1925.

Ludwik, P.: Yield Point, Cold and Hot Shortness. Z.V.D.I., vol. 70, 1926, pp. 379–386.

Timoshenko, S.: Stress Concentration Produced by Fillets and Holes. Proc. 2nd Int. Cong. Appl. Mach., Zürich, Sept. 12–17, 1926, Orell Füssli (Zürich and Leipzig), 1927, pp. 419–426.

Ludwik, P.: The Meaning of Flow and Rupture Resistance in Material Testing. Z.V.D.I., vol. 71, no. 44, 1927, pp. 1532–1538.

Foeppl, L.: Investigations of Plain Stress States with the Help of Photoelasticity. Verlag d. Bay. Akad. d. Wiss., 1928, pp. 247–265.

Kuntze, W.: Statistical Basis for Failure by Vibration. Z.V.D.I., vol. 72, no. 42, Oct. 20, 1928, pp. 1488–1492.

László, F.: The Notch. Z.V.D.I., vol. 72, no. 24, June 16, 1928, pp. 851–856.

Kuntze, W.: The Fracture of Notched Test Specimens. Arch. Eisenhuettenw., vol. 2, 1928–29, pp. 109–117.

Kuntze, W.: Impact Strength and Conventional Mechanical Properties. Arch. Eisenhuettenw., vol. 2, 1928–29, pp. 538–593.

Kuntze, W.: Critical Notch Strength Values. Metallwirtschaft, vol. 8, 1929, pp. 992–998.

Kuntze, W.: The Strength of Threads. Z.V.D.I., vol. 73, no. 14, Apr. 6, 1929, pp. 469–471.

Berg, S.: The Stresses and Strains in the Repeated Impact Test. Forschungsarb. Ing. Wesen, no. 331, 1930, pp. 1–28.

Kuntze, W.: The Meaning and Evaluation of Fracturing in Metals. Z. Metallkunde, vol. 22, 1930, pp. 14–22.

Kuntze, W.: On the Notch Danger. Z.V.D.I., vol. 74, no. 3, Jan. 18, 1930, pp. 78–82.

Kuntze, W.: The Problems of Cohesion. Z. Metallkunde, vol. 22, 1930, pp. 264–268.

Docherty, J. G.: The Effect of the Rate of Bending in Notched Bar Bending Tests. Engineering, vol. CXXXI, no. 3400, March 13, 1931, pp. 347–350.

Foetscher, F.: Regarding the Choice of Working Tensions in Machine Pieces. Maschinenbau, vol. 3, 1931, pp. 79–83.

Kuntze, W.: Transverse Elastic Strain and Triaxial Stress States in Notched Specimens. Z. Phys., vol. 72, 1931, pp. 785–792.

Docherty, J. G.: Bending Tests on Geometrically Similar Notched Bar Specimens. Engineering, vol. CXXXIII, no. 3464, June 3, 1932, pp. 645–647.

Kuntze, W.: Cohesive Strength. Julius Springer (Berlin), 1932.

Kuntze, W.: Ductility and Strength of Notched Specimens. Z. Phys., vol. 74, 1932, pp. 45-65.

Kuntze, W.: The Practical Procedure for Notched Bar Tensile Tests. Metallwirtschaft, vol. 11, 1932, pp. 179-184.

Kuntze, W.: The Procedure of Determining the Cohesive Strength. Metallwirtschaft, vol. 11, 1932, pp. 343-347.

Neuendorff, G. G.: Izett Steel. Metals & Alloys, vol. 3, no. 3, March 1932, pp. 61-68.

Kuntze, W.: The Evaluation of the Influence of Non-Uniform Stress and Cross-Section on the Yield Point. Der Stahlbau, vol. 7, 1933, pp. 37-44.

Neuber, H.: Exact Elastic Solutions Concerning the Notch Effect on Plates and Bodies of Rotational Symmetry. Z.f.a.M.M., vol. 13, 1933, pp. 439-442.

Roetscher, R.: Determination of the Stress Distribution in Constitutional Parts by Elongation Measurements. Z.V.D.I., vol. 77, 1933, pp. 373-378.

Siebel, E., and Maier, A.: Effect of Multiaxial Stress States on the Ductility. Z.V.D.I., vol. 77, no. 51, Dec. 23, 1933, pp. 1345-1349.

Davidenkov, N., and Schewandin, H. M.: The Cohesive Strength of Previously Stretched and Compressed Test Specimens. Z. Metallkunde, vol. 26, 1934, pp. 193-196.

Kuntze, W.: Relations between Cohesion and Plasticity. Z. Metallkunde, vol. 26, 1934, pp. 197-198.

Nadai, A., and MacGregor, C. W.: Concerning the Effect of Notches and Laws of Similitude in Material Testing. Proc. A.S.T.M., vol. 34, II, 1934, pp. 216-228.

Wahl, A. M., and Beeuwkes, R., Jr.: Stress Concentration Produced by Holes and Notches. Trans. A.S.M.E., vol. 56, no. 8, Aug. 1934, pp. 617-625.

Davidenkov, N.: Kuntze's Method and Its Critical Evaluation. J. Tech. Phys. (U.S.S.R.). vol. 5, 1935, pp. 915-927.

Docherty, J. G.: Notch Brittleness in Large Bars. Engineering, vol. CXXXIX, no. 3609, March 15, 1935, pp. 285-286.

Docherty, J. G.: Slow Bending Tests on Large Notched Bars. Engineering, vol. CXXXIX, no. 3606, Feb. 22, 1935, pp. 211-213.

Frocht, Max M.: Factors of Stress Concentration Photoelastically Determined. Jour. Appl. Mech., vol. 2, no. 2, June 1935, pp. A-67 – A-68.

Kuntze, W.: Modern Strength Questions. Der Stahlbau, vol. 2, 1935, pp. 1-6.

Maier, A. F.: Effect of Stress State on Ductility of Metallic Materials. Mitt. Mat. Anst. Stuttgart, 1935.

Wittmann, F., and Davidenkov, N.: A New Method of Centering Specimens. Tech. Phys., vol. 5, 1935, pp. 1760-1767.

Frocht, Max M.: The Behavior of a Brittle Material at Failure. Jour. Appl. Mech., vol. 3, no. 3, Sept. 1936, pp. A-99 – A-103.

Kuntze, W.: Notch Shape and Elastic Elongation Distribution. Der Stahlbau, vol. 9, 1936, pp. 121-124.

Siebel, E.: Static and Dynamic Notch Toughness. Jahrb. L.G.L., 1936, pp. 383 6.

Davidenkov, N., and Wittmann, F.: Mechanical Analysis of Impact Brittleness. Tech. Phys. (U.S.S.R.), vol. 4, no. 4, 1937, pp. 1-17.

Kuntze, W.: Concerning the Question of Strength in Relation to Triaxial Tension States. Der Stahlbau, vol. 23, 1937, pp. 1-5.

Wittmann, F.: The Influence of Surface Plastic Deformations on the Impact Cold-Brittleness of Steel. Tech. Phys. (U.S.S.R.), vol. 4, no. 3, 1937, pp. 1-15.

Pfender, M.: The Behavior of Materials with Restraint to Possible Flow. Arch. Eisenhuettenw., vol. 11, 1937-38, pp. 595-606.

Davidenkov, N., and Sakharov, P.: On the Influence of Cold Working upon the Brittleness of Steel. Tech. Phys. (U.S.S.R.), vol. 5, 1938, 743-758.

Hoyt, S. L.: Notched-Bar Testing and Impact Testing. Proc. A.S.T.M., vol. 38, 1938, pp. 141-156.

McAdam, D. J., and Clyne, R. W.: The Theory of Impact Testing – Influence of Temperature, Velocity of Deformation. Proc. A.S.T.M., vol. 38, II, 1938, pp. 112-134.

Matthaes, K.: Notch Effects under Static Stress. Luftfahrtforschung, vol. 14, 1938, pp. 28-40; English Metal Treatment, vol. 4, 1938, Spring Issue, pp. 15-23.

Kuntze, W.: Mechanical Testing of Materials with Concern of Their Specific Uses. Arch. Eisenhuettenw., vol. 12, 1938-39, pp. 329-334.

Koerber, F., and Hempel, M.: The Effect of the Type of Stress on Fatigue Strength of Drilled and Notched Steel Test-Pieces. Arch. Eisenhuettenw., vol. 12, 1939, pp. 433-444.

Kraechter, H.: X-Ray Determination of the Stress Concentration Factor of Notched Cylindrical Test Bars. Z. Metallkunde, vol. 31, 1939, pp. 114-115.

Kuntze, W.: The Safety against Rupture of Welded Constructions. Wiss. Abb. D. Material pruefungs., no. 2, 1939, pp. 11-18.

Pomp, A., Krisch, A., and Haupt, G.: The Notched Bar Sensitivity of Alloy Steels at Temperatures between 20° C and -253° C. Mitt. Kaiser-Wilhelm Inst., vol. 21, 1939, pp. 219-230.

Siebel, E., and Wellinger, K.: Testing of Steels Regarding Embrittlement at Elevated Temperatures. Arch. Eisenhuettenw., vol. 13, 1939-40, pp. 387-392.

Davis, E. A.: Combined Tension-Torsion Tests on 0.35 Percent Carbon Steel. Trans. A.S.M.E., vol. 62, 1940, pp. 577-586.

Frocht, M. M., and Hill, H. N.: Stress-Concentration Factors around a Central Circular Hole in a Plate Loaded through Pin in the Hole. Jour. App. Mech., vol. 7, no. 1, Mar. 1940, pp. A-5 - A-9.

Gensamer, Maxwell: Static Crack Strength of Metals. Metal Progress, vol. 38, no. 1, July 1940, pp. 59-64.

Gensamer, M., Pearsall, E. B., and Smith, G. V.: The Mechanical Properties of the Isothermal Decomposition Products of Austenite. Trans. Am. Soc. Metals, vol. 28, 1940, pp. 380-398.

Goodier, J. N.: The Distribution of Load on the Threads of Screws. Jour. Appl. Mech., vol. 7, no. 1, Mar. 1940, pp. A-10 - A-16.

Lee, O. R.: The Notched Bar Test. Jour. Inst. Mech. Eng., vol. 143, 1940, pp. 114-121.

Sachs, G.: Stress Raisers. The Iron Age, vol. 146, Aug. 1, 1940, pp. 31-34; Aug. 8, pp. 34-37.

Keissler, H., and Connert, W.: Notched Bar Tensile Tests with Superimposed Bending Strain. Arch. Eisenhuettenw., vol. 14, 1940-41, pp. 555-560.

Haas, B.: The Behavior of Materials and Structures under Static and Dynamic Stresses. Luftwissen, vol. 8, 1941, pp. 338-343.

McAdam, D. J., Jr.: The Technical Cohesive Strength of Metals. Jour. Appl. Mech., vol. 8, no. 4, Dec. 1941, pp. A-155 - A-165.

Sachs, George: Some Fundamentals of the Flow and Rupture of Metals. Case School of Applied Science. (Reprinted from Tech. Pub. No. 1335, Am. Inst. Mining Met. Engrs., Metals Tech., June 1941, pp. 12-29.)

Scheele, H.: Tensile Tests with Resistance to Transverse Strain. Arch. Eisenhuettenw., vol. 14, no. 10, 1941, pp. 513-520.

Gensamer, M., Pearsall, E. B., Pellini, W. S., and Low, T. R.: The Tensile Properties of Pearlite, Bainite and Spheroidite. Trans. Am. Soc. Metals, vol. 30, 1942, pp. 983-1020.

McAdam, D. J.: The Technical Cohesive Strength and Yield Strength of Metals. Am. Inst. Mining Met. Engrs., vol. 150, 1942, pp. 311-357.

Sachs, G., and Lubahn, J. D.: Effects of Notching on Strained Metals. The Iron Age, vol. 150, Oct. 8, 1942, pp. 31-38; Oct. 15, 1942, pp. 48-52.

Dorn, John E., and Meriam, J. L.: Properties and Heat Treatment of Magnesium Alloys: Part II - Notch Sensitivity of Magnesium Alloys (NA-144). OSRD No. 1819, Serial No. M-104, War Metallurgy Div., NDRC, Sept. 3, 1943.

Henry, O. H., and Farmer, James G.: An Investigation of the Static Notched Bar Behavior of Steel with Reference to Tri-Axial Stress and the Technical Cohesive Strength. Jour. Am. Welding Soc. Supp., vol. 8, Apr. 1943, pp. 150s-162s.

Jones, P. G.: On the Transition from a Ductile to a Brittle Type of Fracture in Several Low-Alloy Steels. Proc. A.S.T.M., vol. 43, 1943, pp. 547-553.

McAdam, D. J., and Mebs, R. W.: An Investigation of the Technical Cohesive Strength of Metals. Metals Tech., vol. 10, 1943; Tech. Pub. No. 1615.

McAdam, D. J., and Mebs, R. W.: The Technical Cohesive Strength and Other Mechanical Properties of Metals at Low Temperatures. Proc. A.S.T.M., vol. 43, 1943, pp. 661-703.

Sachs, G., and Lubahn, J. D.: Notched Bar Tensile Tests on Heat Treated Low Alloy Steels. Trans. Am. Soc. Metals, vol. 31, 1943, pp. 125-160.

Anon.: Development and Testing of Triaxial Tension Specimens. The Welding Jour., vol. 23, Dec. 1944, pp. 642s–647s.

Anon.: Symposium on Cohesive Strength. Am. Inst. Mining Met. Engrs., T.P. 1782, Metals Tech., Dec. 1944.

Dorn, J. E., and Thomsen, E. G.: The Effect of Combined Stresses on the Ductility of Metals. OSRD No. 3218, Serial No. M-213, War Metallurgy Div., NDRC, Feb. 2, 1944.

Hollomon, J. H.: The Notched-Bar Impact Test. Metals Tech., vol. 11, Apr. 1944; Tech. Pub. No. 1667.

Isenburger, H. R.: Failures in Cold-Heated Machine Bolts. Steel, Sept. 18, 1944.

Jackson, C. E., Pugaoz, M. A., and McKenna, F. S.: Variables Affecting the Results of Notched-Bar Impact Tests on Steels. Trans. Am. Inst. Mining Met. Engrs., vol. 158, 1944, pp. 263–282.

McAdam, D. J.: The Technical Cohesive Strength of Metals in Terms of the Principal Stresses. Metals Tech., vol. 11, 1944, pp. 5–31.

McAdam, D. J., Mebs, R. W., and Geil, G. W.: The Technical Cohesive Strength of Some Steels and Light Alloys at Low Temperatures. A.S.T.M., vol. 44, 1944, pp. 593–624.

MacGregor, C. W., and Fisher, J. C.: Relations between the Notched Beam Impact Test and the Static Tension Test. Jour. Appl. Mech., vol. 11, no. 1, Mar. 1944, pp. A-28 – A-34.

Morkovin, D.: Completely Brittle Failure and the Technical Cohesive Strength. Doctor's Thesis, University of Illinois, 1944.

Sachs, G., Cole, P. S., and Roth, R. A.: The Strength of Heat Treated Alloy Steel Bolts. Trans. Am. Soc. Metals, vol. 33, 1944, pp. 396–410.

Sachs, G., Lubahn, J. D., and Ebert, L. J.: Notched Bar Tensile Test Characteristics of Heat Treated Alloy Steels. Trans. Am. Soc. Metals, vol. 33, 1944, pp. 340–395.

Davis, E. A.: Yielding and Fracture of Medium-Carbon Steel under Combined Stress. Jour. Appl. Mech., vol. 12, no. 1, Mar. 1945, pp. A-13 – A-24.

Fisher, A.: A Discussion of the Notch Impact Test and Its Interpretations. Metallurgia, vol. 32, 1945, pp. 192–195, 281–284.

McAdam, D. J., Jr.: Fracture of Metals under Combined Stresses. Am. Soc. Metals Preprint No. 29, 1945. Also, Trans. Am. Soc. Metals, vol. 37, 1946, pp. 538-566.

McAdam, D. J., Geil, G. W., and Mebs, R. W.: The Effect of Combined Stresses on the Mechanical Properties of Steels between Room Temperature and -188° C. A.S.T.M. Preprint No. 22, 1945.

Sachs, George, and Lubahn, J. D.: The Effect of Triaxiality on the Technical Cohesive Strength of Steels. Jour. Appl. Mech., vol. 12, no. 4, Dec. 1945, pp. A-241 - A-252.

Sachs, G., Lubahn, J. D., and Ebert, L. J.: The Effect of Notches of Varying Depth on the Strength of Heat Treated Alloy Steels. Trans. Am. Soc. Metals, vol. 34, 1945, pp. 517-544.

Sachs, G., Lubahn, J. D., Ebert, L. J., and Aul, E. L.: The Effect of Fiber on Notched Bar Tensile Strength Properties of a Heat Treated Low Alloy Steel. Trans. Am. Soc. Metals, vol. 34, 1945, pp. 505-516.

Smith, C. S.: The Mechanism of Brittle Fracture. Metallurgia, vol. 33, Dec. 1945, pp. 55-58.

Windenburg, D. F., and Roop, W. P.: Notes of the Conditions of Fracture of Medium Steel Ship Plates. The Welding Jour. Res. Supp., vol. 24, 1945, pp. 580s-587s.

Doan, J. P., and McDonald, J. C.: The Notch Sensitivity in Static and Impact Loading of Some Magnesium-Base and Aluminum-Base Alloys. A.S.T.M., vol. 46, 1946.

Drake, D. W.: The Effect of Notches on Static and Fatigue Strength. Jour. Aero. Sci., vol. 13, no. 5, May 1946, pp. 259-269.

Fisher, A.: The Importance of Ultimate Extension as an Engineering Property of Materials. Metallurgia, vol. 34, June 1946, pp. 77-84.

McAdam, D. J., Geil, G. W., and Mebs, R. W.: Effects of Combined Stresses and Low Temperatures on the Mechanical Properties of Some Nonferrous Metals. Am. Soc. Metals, vol. 37, 1946, pp. 497-537.

McAdam, D. J., Geil, G. W., and Woodard, D. H.: Influence of Strain Rate and Temperature on the Mechanical Properties of Monel Metal and Copper. A.S.T.M. Preprint 54, 1946.

Moseley, D. L.: Symposium on Notch Effects in High-Strength Aluminum Alloys. Part III. Notch Effects in High-Strength Aluminum-Alloy Spar Caps. Jour. Aero. Sci., vol. 13, no. 8, Aug. 1946, pp. 397-401.

Norton, J. T., Rosenthal, D., and Maloof, S. B.: X-Ray Diffraction Study of Notch-Bend Test. The Welding Jour. Res. Supp., vol. 25, May 1946, pp. 269s-276s.

Orowan, E.: Notch Brittleness and the Strength of Metals. Trans. Inst. Eng. Ship. (Scotland), vol. 89, 1946, pp. 165-215.

Sachs, G., Ebert, L. J., and Brown, W. F., Jr.: Comparison of Various Structural Alloy Steels by Means of the Static Notch-Bar Tensile Test. Am. Inst. Mining Met. Engrs., Metals Tech., Tech. Pub. No. 2110, Dec. 1946.

Sachs, George, Smith, Charles S., Lubahn, Jack D., Davis, Gordon E., and Ebert, Lynn J.: Nondestructive Measurement of Residual and Enforced Stresses by Means of X-Ray Diffraction. I – Correlated Abstract of the Literature. NACA TN No. 986, 1945. Also, The Welding Jour. Res. Supp., 1946, pp. 400s-412s.

Schàpiro, L., and North, H. E.: Symposium on Notch Effects in High-Strength Aluminum Alloys. Part I. Notch Sensitivity in High-Strength Aluminum Alloys – Theoretical Aspects. Jour. Aero. Sci., vol. 13, no. 8, Aug. 1946, pp. 391-395.

Schaub, C.: Brittle Fracture of Steel under Sustained Load at Elevated Temperature. Jernkontorets Ann., vol. 130, 1946, pp. 1-26; The Engineer's Digest, vol. 7, no. 7, July 1946, pp. 205-206.

Shepler, Paul R.: DeForest Brittle Temperature Research. The Welding Jour. Res. Supp., vol. 25, June 1946, pp. 321s-332s.

Stevenson, C. H.: Symposium on Notch Effects in High-Strength Aluminum Alloys. Part II. Notch Effects of Open Holes on the Tensile Strength of Some Aluminum Alloys. Jour. Aero. Sci., vol. 13, no. 8, Aug. 1946, pp. 395-397.

Welter, G.: Ductility of Metals and Alloys Used in Construction. Part I. Metallurgia, vol. 34, 1946, pp. 233-237; Part II, pp. 304-310.

Wheelon, O. A., and Barrett, St. J.: Symposium on Notch Effects in High-Strength Aluminum Alloys. Part IV. The Effect of Notches upon Limiting Strain in High-Strength Aluminum Alloys. Jour. Aero. Sci., vol. 13, no. 8, Aug. 1946, pp. 401-404.

TABLE I.– RESULTS OF NOTCHED-BAR TENSILE TESTS ON 75S-T ROD

[$\frac{3}{4}$-inch rod re-solution-heat-treated after machining; a = 0.106 inch]

Notch diameter (in.)	Notch depth (percent)	Notch radius (in.)	Notch sharpness, a/R	Notch strength (psi)	Fracture stress (psi)	Notch ductility (percent)
0.224	0	∞	0	86.4×10^3	119.6×10^3	36.0
.224	0	∞	0	86.1	119.5	35.8
.213	0	∞	0	83.6	114.6	36.2
.212	0	∞	0	83.8	115.1	36.6
.212	0	∞	0	82.9	114.1	38.0
.212	2.6	<.0005	∞	84.4	102.5	22.2
.222	12.4	<.0005	∞	92.0	101.3	9.4
.220	12.1	<.0005	∞	91.8	99.7	8.1
.222	11.4	.010	10.6	93.1	103.4	10.2
.222	10.7	.010	10.6	91.9	100.9	9.8
.222	11.5	.023	4.6	92.9	106.9	13.7
.221	13.0	.023	4.6	93.2	106.4	13.3
.219	14.3	.060	1.8	94.8	112.2	16.8
.219	14.0	.060	1.8	94.9	114.0	17.5
.221	13.0	.125	.85	92.2	122.1	29.1
.223	10.0	.125	.85	90.7	120.0	29.5
.225	9.0	2.00	.05	85.4	113.9	31.7
.224	9.8	2.00	.05	85.3	114.0	32.7
.222	20.9	<.0005	∞	97.8	101.8	3.9
.222	21.9	<.0005	∞	97.2	101.2	4.0
.220	22.1	.010	10.6	106.0	109.0	5.0
.221	22.1	.010	10.6	99.8	105.0	4.9
.221	22.1	.023	4.6	101.2	111.9	9.6
.222	20.9	.023	4.6	101.4	112.0	9.6
.218	24.1	.060	1.8	103.0	117.2	12.4
.219	23.2	.060	1.8	102.4	118.2	13.8
.219	23.1	.125	.85	99.5	129.1	20.1
.220	22.7	.125	.85	99.7	120.0	19.2
.225	19.0	2.00	.05	84.9	117.0	32.2
.225	18.8	2.00	.05	84.8	113.0	32.2

NACA

TABLE I.– RESULTS OF NOTCHED-BAR TENSILE TESTS ON 75S-T ROD – Concluded

Notch diameter (in.)	Notch depth (percent)	Notch radius (in.)	Notch sharpness, a/R	Notch strength (psi)	Fracture stress (psi)	Notch ductility (percent)
0.223	50.5	0	∞	112.2 × 10³	115.2 × 10³	2.3
.223	50.4	0	∞	112.3	116.1	2.3
.221	51.2	0	∞	114.6	115.0	.6
.222	50.9	0	∞	111.8	113.8	1.8
.223	50.4	.010	10.6	125.4	127.9	1.8
.224	49.9	.010	10.6	125.0	127.0	1.5
.219	52.4	.010	10.6	124.0	126.4	1.8
.218	52.8	.010	10.6	124.2	125.1	.8
.223	50.5	.023	4.6	127.5	136.1	6.5
.224	49.6	.023	4.6	126.5	136.9	7.7
.222	50.4	.023	4.6	124.2	138.1	10.0
.221	51.0	.023	4.6	125.0	135.4	8.0
.224	50.1	.060	1.8	121.3	140.5	14.0
.223	50.4	.060	1.8	121.9	139.6	13.4
.220	51.4	.060	1.8	118.2	139.8	16.5
.219	51.9	.060	1.8	119.3	138.8	15.6
.221	51.5	.060	1.8	119.5	136.4	14.4
.220	51.5	.060	1.8	119.0	140.7	17.3
.217	52.1	.125	.85	111.9	131.4	14.9
.222	50.8	.125	.85	111.3	131.3	16.0
.220	51.9	.125	.85	110.4	128.5	15.0
.221	51.2	.125	.85	110.0	126.8	14.1
.222	51.1	2.00	.05	89.0	118.9	30.9
.221	51.1	2.00	.05	88.8	118.8	31.3
.226	49.0	2.00	.05	84.7	113.6	33.2
.226	49.0	2.00	.05	84.9	113.4	32.7
.219	80.9	0	∞	121.9	122.1	.3
.219	80.9	0	∞	124.0	124.1	.0
.220	80.6	.010	10.6	142.8	145.5	1.8
.221	80.5	.010	10.6	136.1	148.3	2.1
.221	80.5	.029	3.8	141.1	150.5	6.7
.222	80.4	.029	3.8	142.4	153.1	7.0
.226	79.5	.060	1.8	121.6	143.8	15.5
.226	79.5	.060	1.8	121.8	143.8	15.2
.226	79.8	.125	.85	108.7	128.0	15.0
.225	79.7	.125	.85	108.2	129.5	16.6
.223	79.9	.125	.85	106.6	124.0	14.0
.224	79.8	.125	.85	105.7	124.0	15.0
.226	86.2	2.00	.05	87.4	119.1	32.5
.226	86.3	2.00	.05	87.0	118.3	32.5

NACA

TABLE II.- RESULTS OF NOTCHED-BAR TENSILE TESTS ON 24S-T86 ROD

[$\frac{3}{4}$-inch 24S-T rod stretched and heat-treated to 24S-T86; a = 0.106 inch]

Notch diameter (in.)	Notch depth (percent)	Notch radius (in.)	Notch sharpness, a/R	Notch strength (psi)	Fracture stress (psi)	Notch ductility (percent)
0.225	0	∞	0	74.5×10^3	88.9×10^3	29.5
.225	0	∞	0	74.6	88.1	29.7
.211	0	∞	0	75.2	91.2	32.1
.212	12.6	<.0005	∞	82.6	89.6	8.2
.213	12.2	<.0005	∞	81.5	88.0	7.9
.214	10.2	.010	10.6	79.8	86.4	8.4
.214	11.0	.010	10.6	80.7	88.1	9.1
.215	10.3	.023	4.6	80.6	86.9	8.0
.216	10.2	.023	4.6	79.6	85.0	8.1
.211	13.5	.060	1.8	84.9	96.8	13.8
.203	19.0	.060	1.8	88.8	97.5	9.2
.214	10.7	.125	.85	79.6	91.0	17.2
.216	8.9	.125	.85	77.5	90.8	18.0
.214	15.9	.125	.85	85.8	103.0	23.6
.213	16.8	.125	.85	85.5	104.8	25.4
.208	12.0	.125	.85	83.0	100.8	24.0
.210	12.7	.125	.85	84.3	99.0	17.6
.214	10.9	2.00	.05	77.1	91.8	27.8
.214	10.8	2.00	.05	77.5	93.9	27.3
.215	20.1	<.0005	∞	83.3	88.2	5.5
.213	21.6	<.0005	∞	94.4	98.5	4.3
.214	20.2	.010	10.6	85.5	90.8	6.0
.214	20.7	.010	10.6	84.7	89.9	6.0
.214	19.4	.023	4.6	85.0	90.4	6.1
.213	21.2	.023	4.6	84.8	89.5	5.4
.210	22.9	.060	1.8	89.1	100.7	12.6
.211	24.3	.060	1.8	90.6	103.4	13.0
.216	19.2	.125	.85	83.6	97.3	17.5
.213	22.0	.125	.85	84.5	94.0	11.5
.214	23.7	.125	.85	89.3	107.2	23.5
.214	23.3	.125	.85	88.5	107.1	24.2
.211	22.6	.125	.85	91.1	108.6	19.7
.212	20.0	.125	.85	89.5	110.1	24.8
.213	21.3	2.00	.05	76.8	92.0	27.8
.213	21.7	2.00	.05	76.5	93.0	28.2

NACA

TABLE II.- RESULTS OF NOTCHED-BAR TENSILE TESTS ON 24S-T86 ROD - Concluded

Notch diameter (in.)	Notch depth (percent)	Notch radius (in.)	Notch sharpness, a/R	Notch strength (psi)	Fracture stress (psi)	Notch ductility (percent)
0.211	52.2	<0.0005	∞	98.5 × 10³	101.4 × 10³	2.9
.211	52.0	<.0005	∞	89.0	90.5	1.8
.215	50.2	.010	10.6	103.9	107.0	3.0
.213	51.5	.010	10.6	101.7	106.1	4.1
.212	52.0	.023	4.6	107.3	110.8	3.2
.214	50.6	.023	4.6	104.2	108.9	4.3
.214	50.1	.060	1.8	101.2	120.1	15.8
.213	50.6	.060	1.8	101.7	118.6	14.3
.212	49.8	.060	1.8	107.0	118.0	12.8
.214	49.1	.060	1.8	107.4	123.0	13.6
.214	51.2	.125	.85	97.8	107.9	10.0
.212	51.5	.125	.85	96.5	106.4	10.1
.214	48.8	.125	.85	97.3	111.9	14.1
.213	49.7	.125	.85	95.0	108.0	13.5
.213	50.8	2.00	.05	76.2	92.4	27.8
.213	50.7	2.00	.05	77.5	92.6	27.5
.214	80.7	<.0005	∞	92.5	95.1	2.8
.214	80.9	<.0005	∞	96.6	96.6	0
.216	80.5	.010	10.6	114.1	117.3	2.7
.214	80.9	.010	10.6	115.4	118.2	2.5
.213	81.0	.023	4.6	116.8	120.1	2.8
.214	80.9	.023	4.6	118.5	123.6	4.2
.210	80.2	.060	1.8	109.0	120.9	9.7
.211	80.1	.060	1.8	110.0	121.1	9.2
.218	80.0	.125	.85	94.8	106.1	11.4
.217	80.3	.125	.85	95.0	106.6	11.4
.214	87.7	2.00	.05	77.8	87.9	24.0
.212	87.8	2.00	.05	78.0	92.3	26.5

NACA

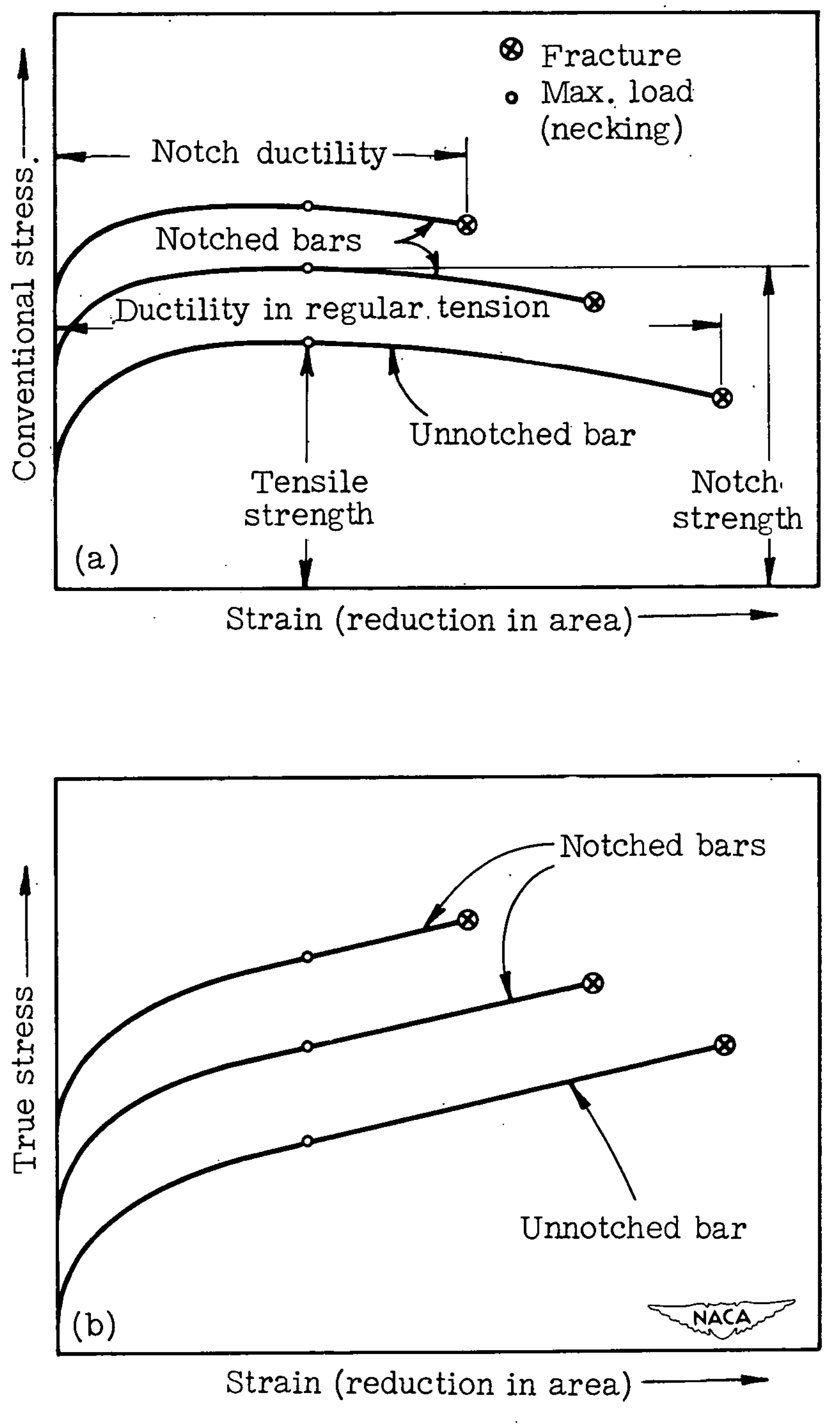


Figure 1.- Schematic stress-strain curves for notched and unnotched bars of a ductile metal.

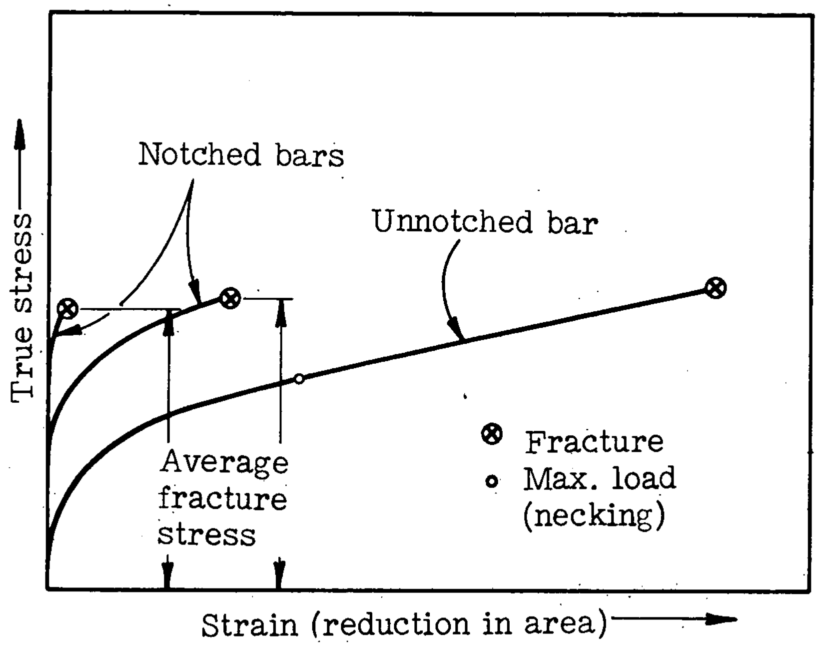


Figure 2.- Schematic stress-strain curves for notched and unnotched bars of a notch-brittle metal.

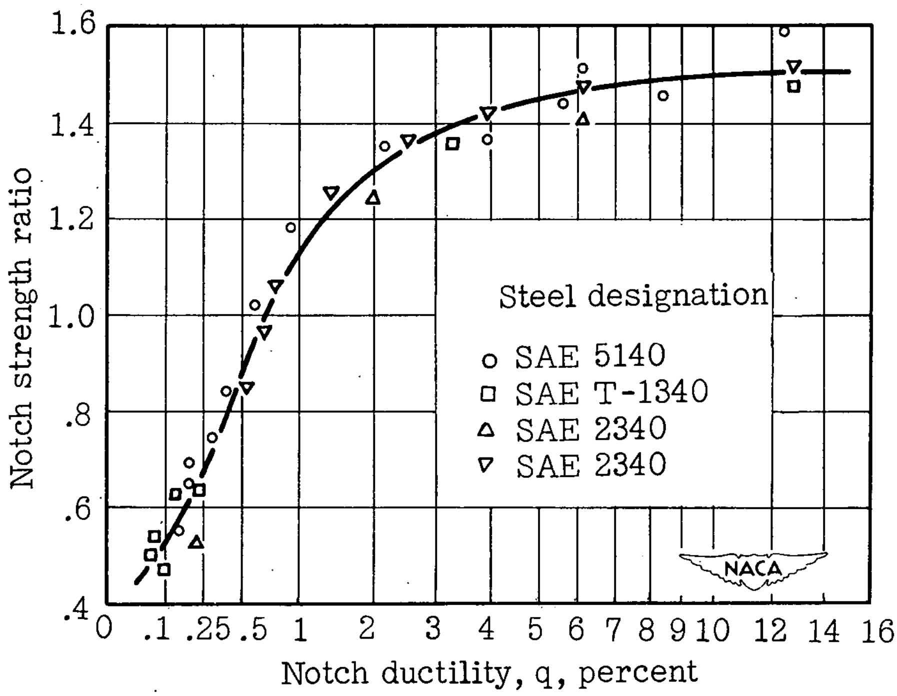
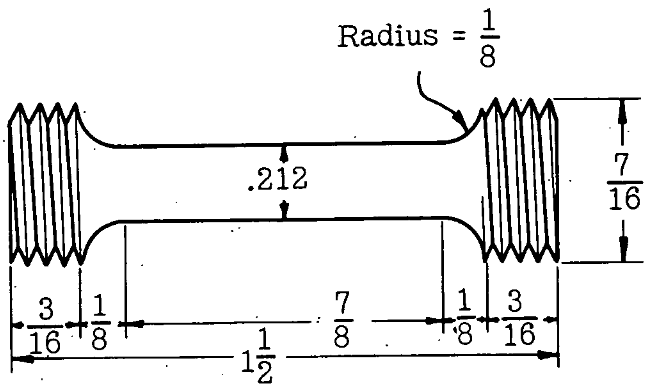
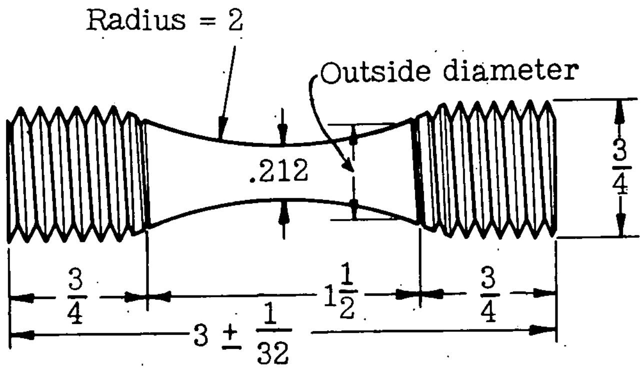


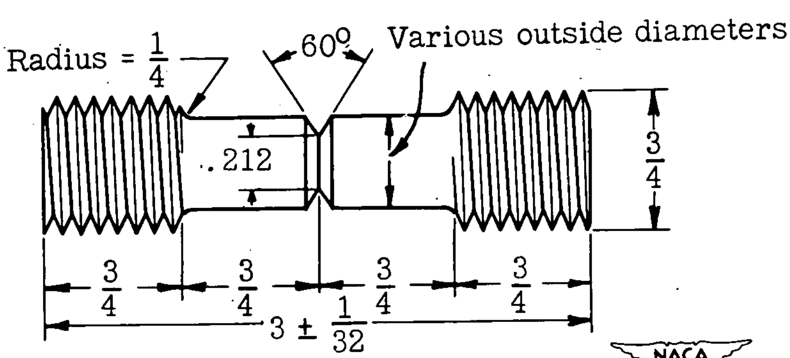
Figure 3.- Relation between notch strength ratio and notch ductility for various low-alloy steels (Sachs, Ebert, and Brown).



(a) Unnotched specimen.



(b) Notched specimen with large radius.



(c) Typical notched specimen.

Figure 4.- Test specimens. All dimensions are in inches.

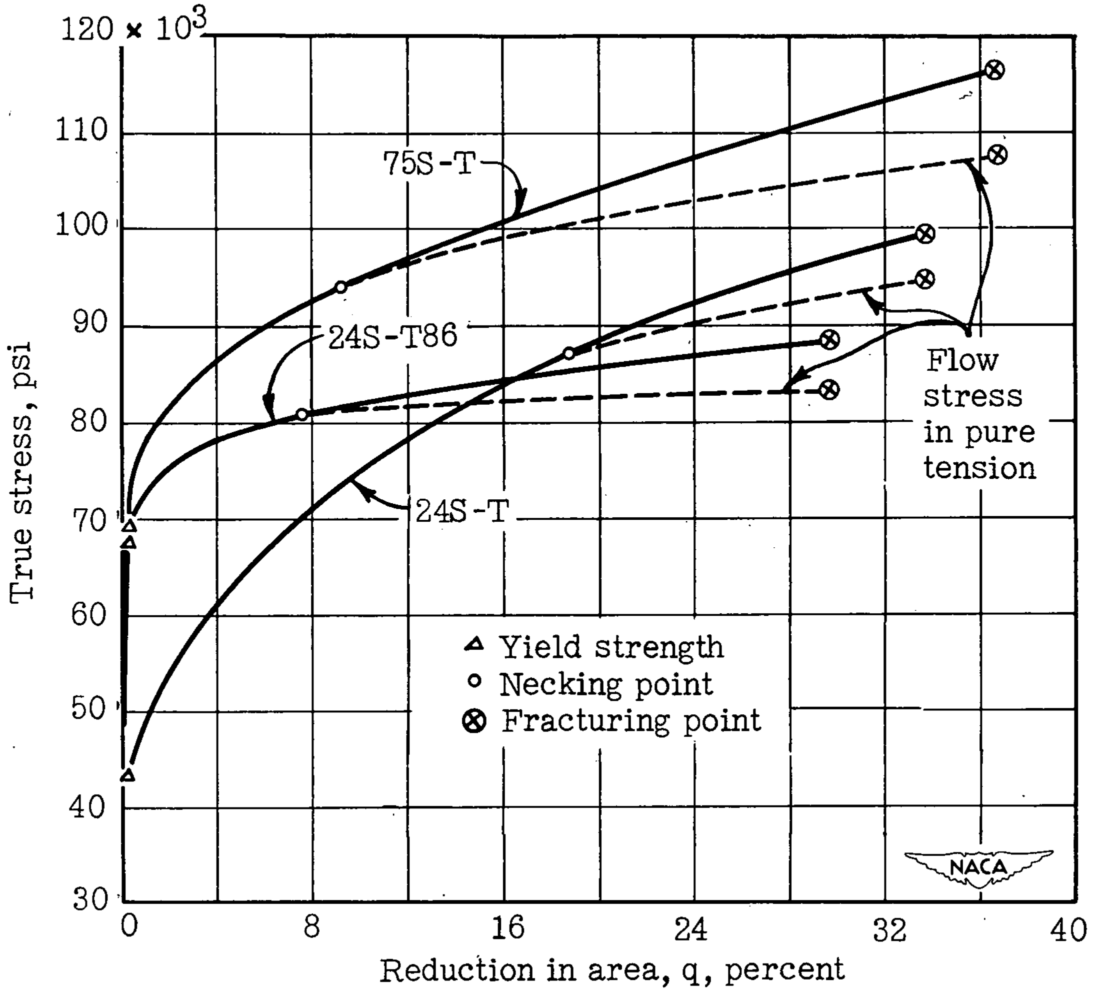


Figure 5.- True stress-strain curves for 75S-T, 24S-T86, and 24S-T aluminum alloys. Unnotched specimens. Material re-solution-heat-treated.

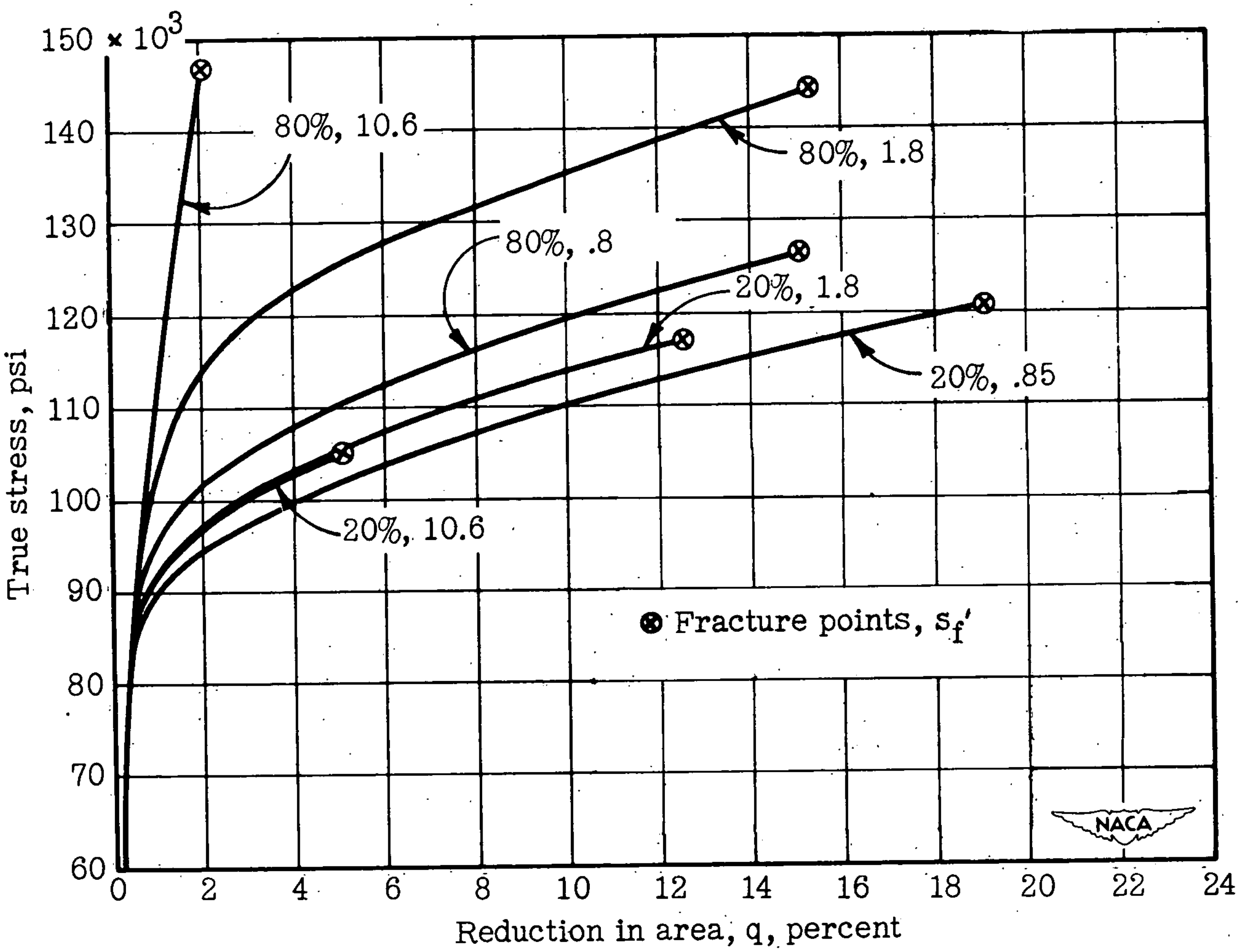


Figure 6.- Stress-strain curves for re-solution-heat-treated 75S-T aluminum-alloy rod. Various notch depths and notch sharpnesses. 60°, V-type notches. First value of curve labels indicates notch depth; second value indicates notch sharpness.

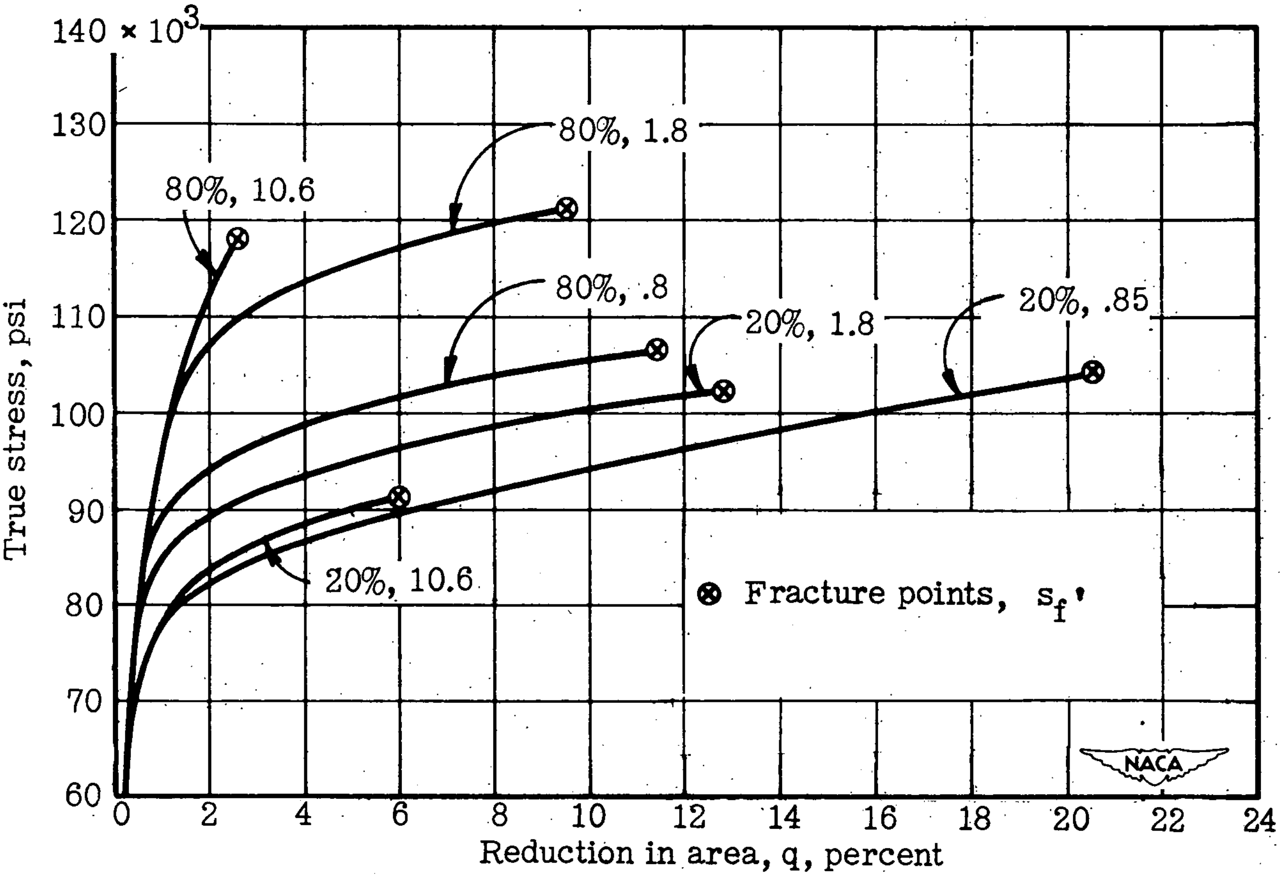


Figure 7.- Stress-strain curves for 24S-T86 aluminum-alloy rod. Various notch depths and notch sharpnesses. 60°, V-type notches. First value of curve labels indicates notch depth; second value indicates notch sharpness.

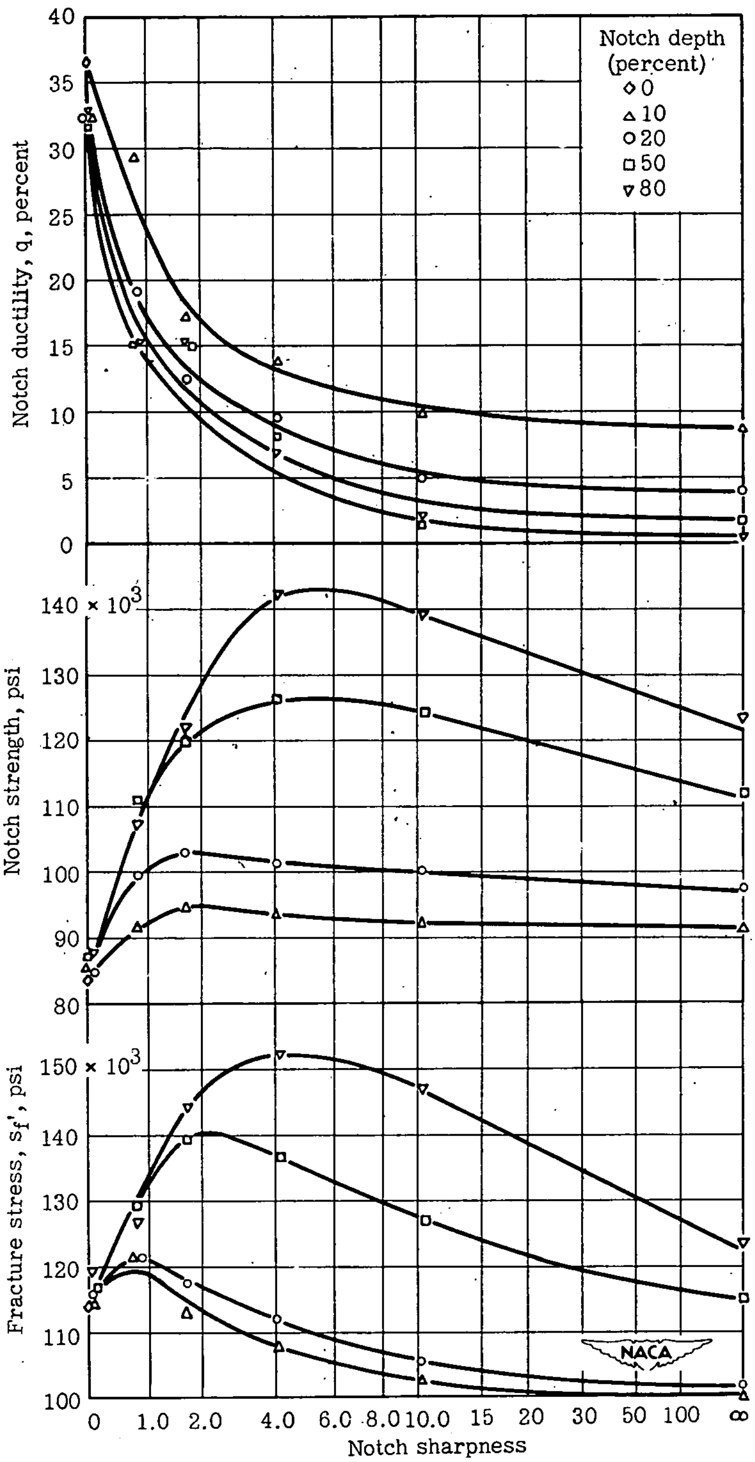


Figure 8.- Effect of notch sharpness on fracture stress, notch strength, and notch ductility of 75S-T aluminum-alloy rod re-solution-heat-treated. 60°, V-type notches. a = 0.106 inch.

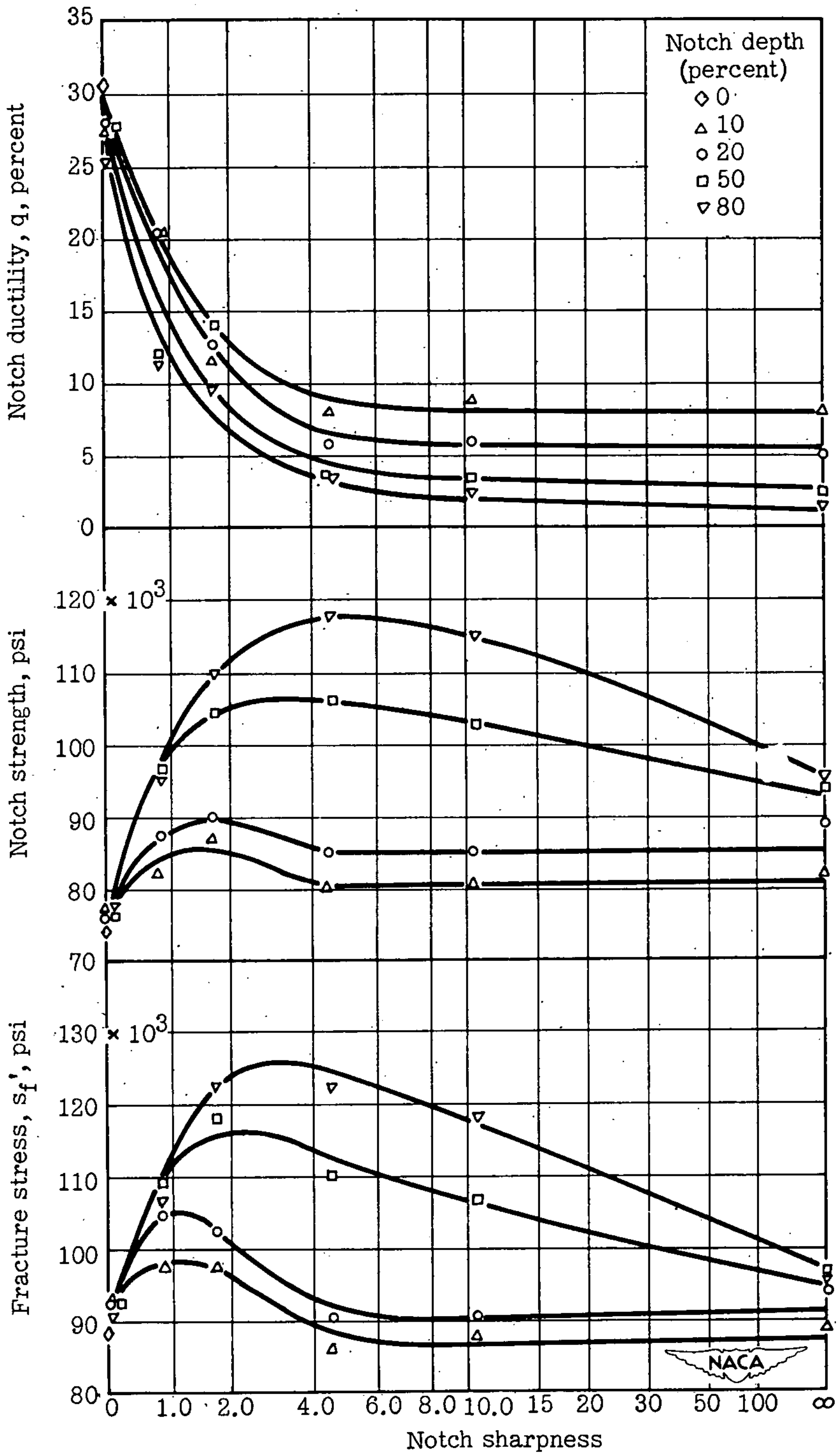


Figure 9.- Effect of notch sharpness on fracture stress, notch strength, and notch ductility of 24S-T86 aluminum-alloy rod re-solution-heat-treated. 60°, V-type notches. a = 0.106 inch.

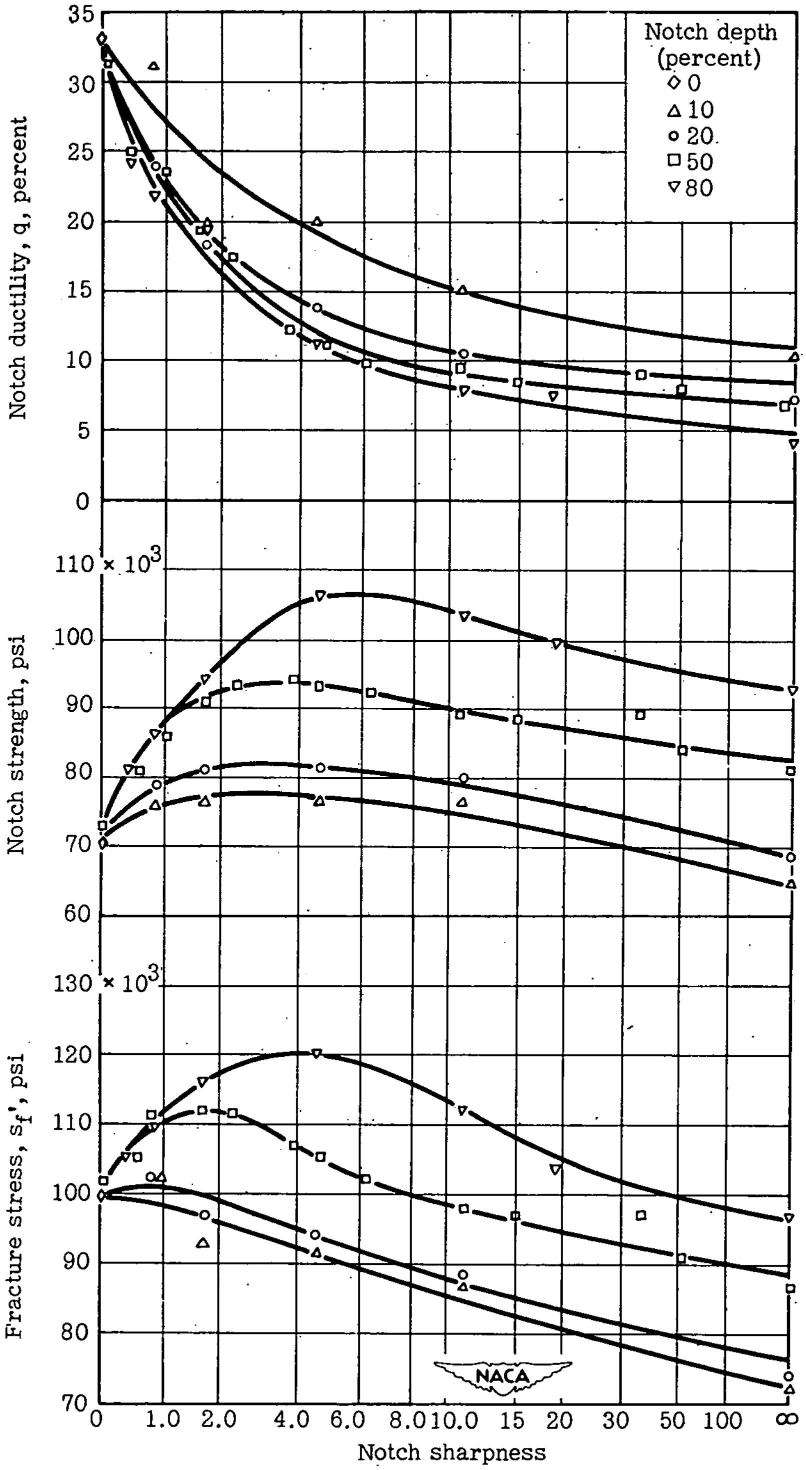


Figure 10.- Effect of notch sharpness on fracture stress, notch strength, and notch ductility of 24S-T aluminum-alloy rod re-solution-heat-treated. 60°, V-type notches. a = 0.106 inch.

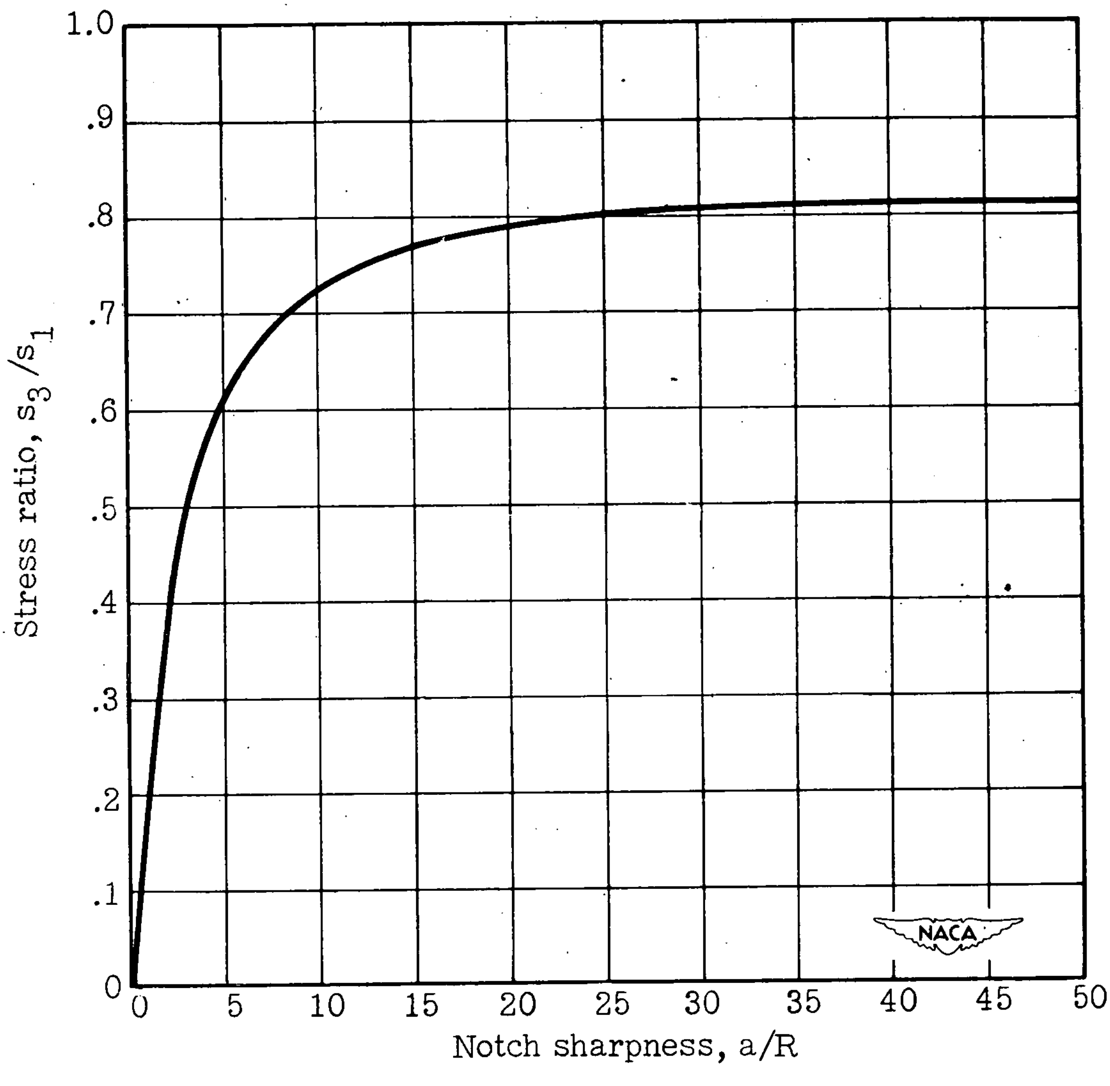


Figure 11.- Effect of notch sharpness on triaxiality at center of an infinitely deep notch in elastic region. Calculated from Neuber's equations (reference 21). Calculated for center of bar with Poisson's ratio = 0.3.

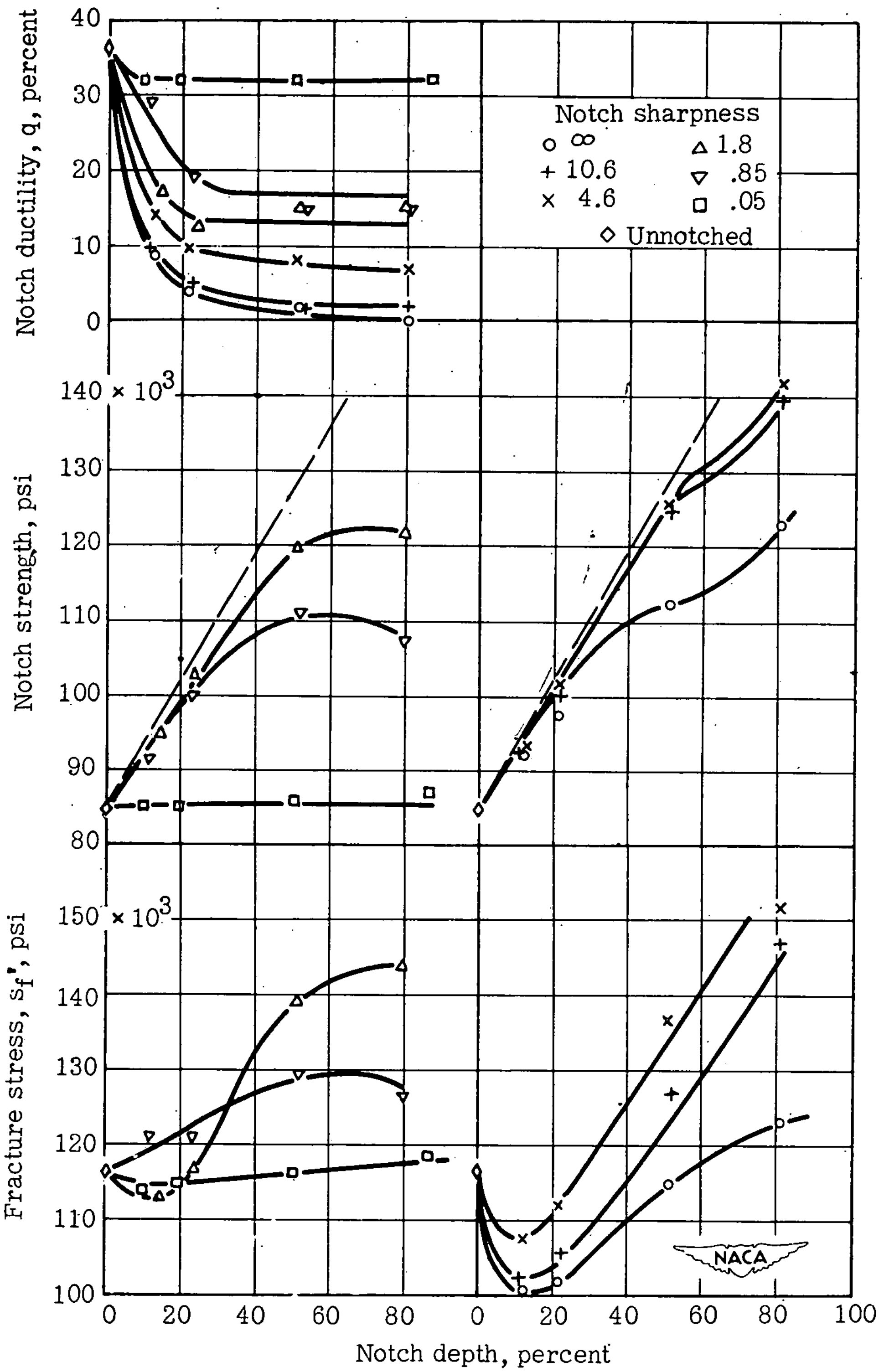


Figure 12.- Effect of notch depth on fracture stress, notch strength, and notch ductility of 75S-T rod. 60°, V-type notches. a = 0.106 inch.

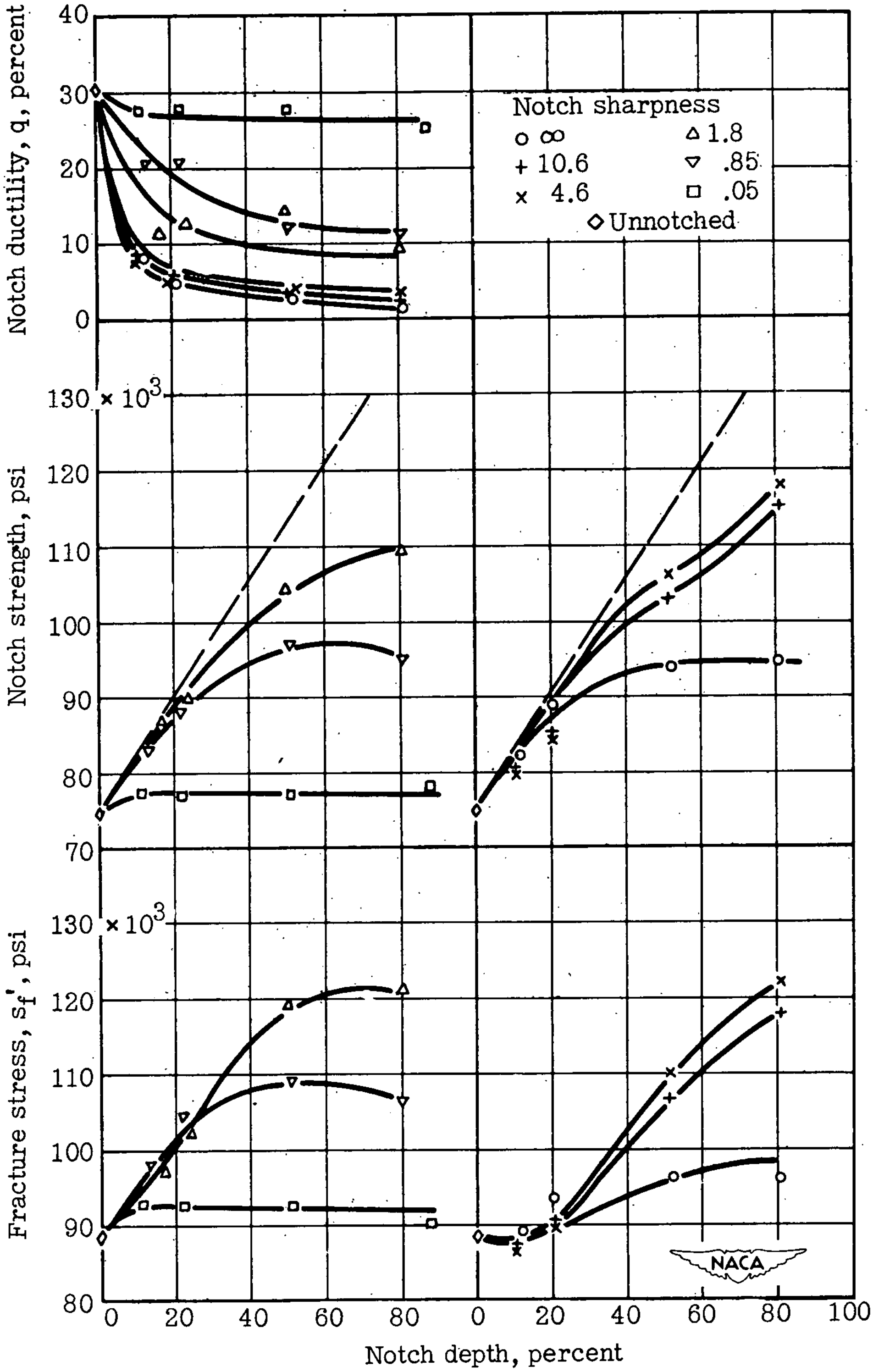


Figure 13.- Effect of notch depth on fracture stress, notch strength, and notch ductility of 24S-T86 rod. 60°, V-type notches. a = 0.106 inch.

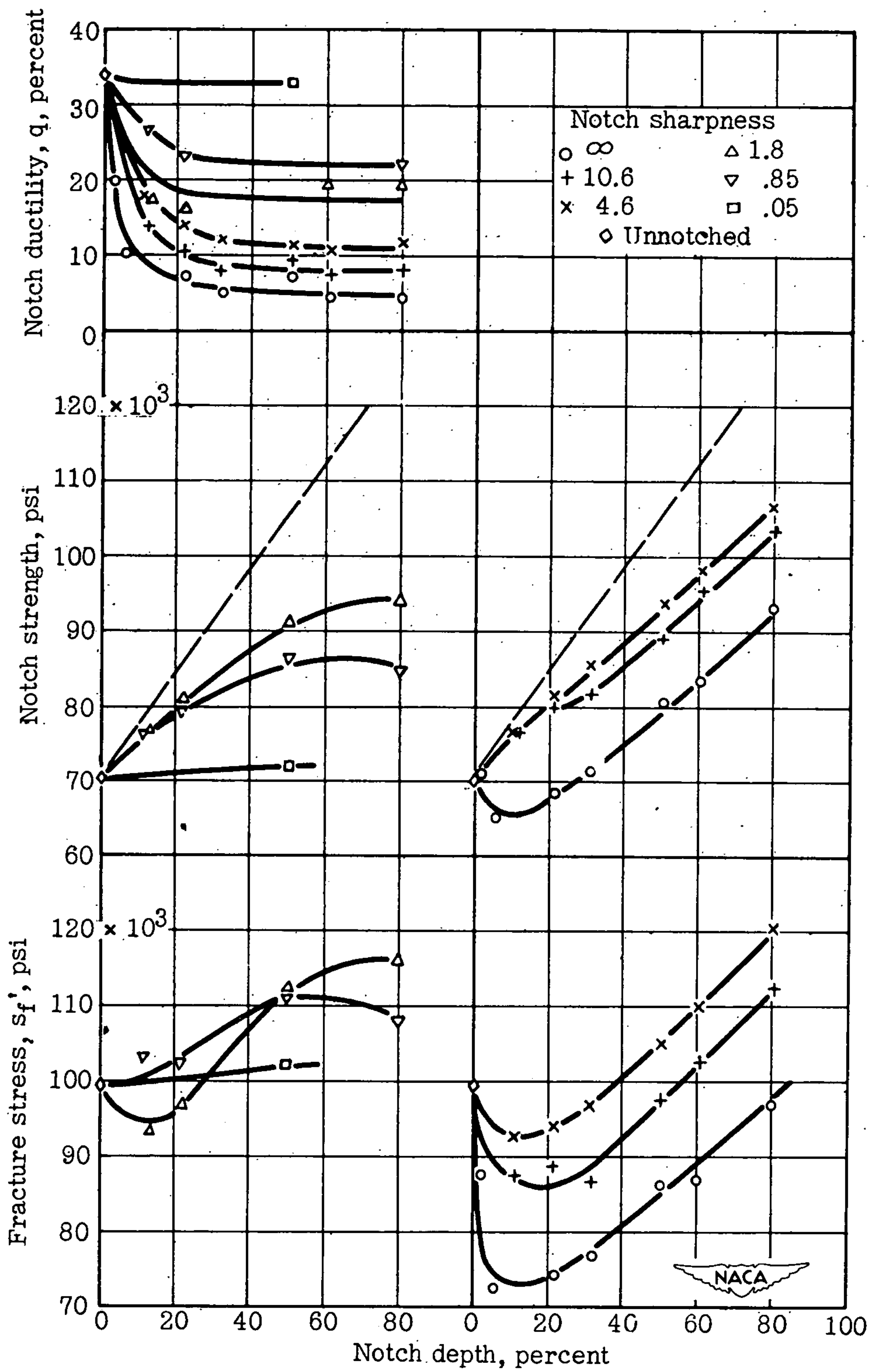


Figure 14.- Effect of notch depth on fracture stress, notch strength, and notch ductility of 24S-T rod. 60°, V-type notches. a = 0.106 inch.

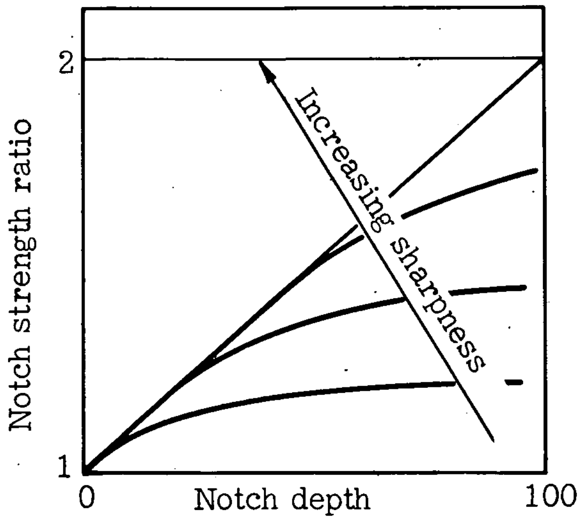


Figure 15.- Schematic representation of dependency of notch strength ratio upon notch depth for various mild notches. Notch-ductile metals.

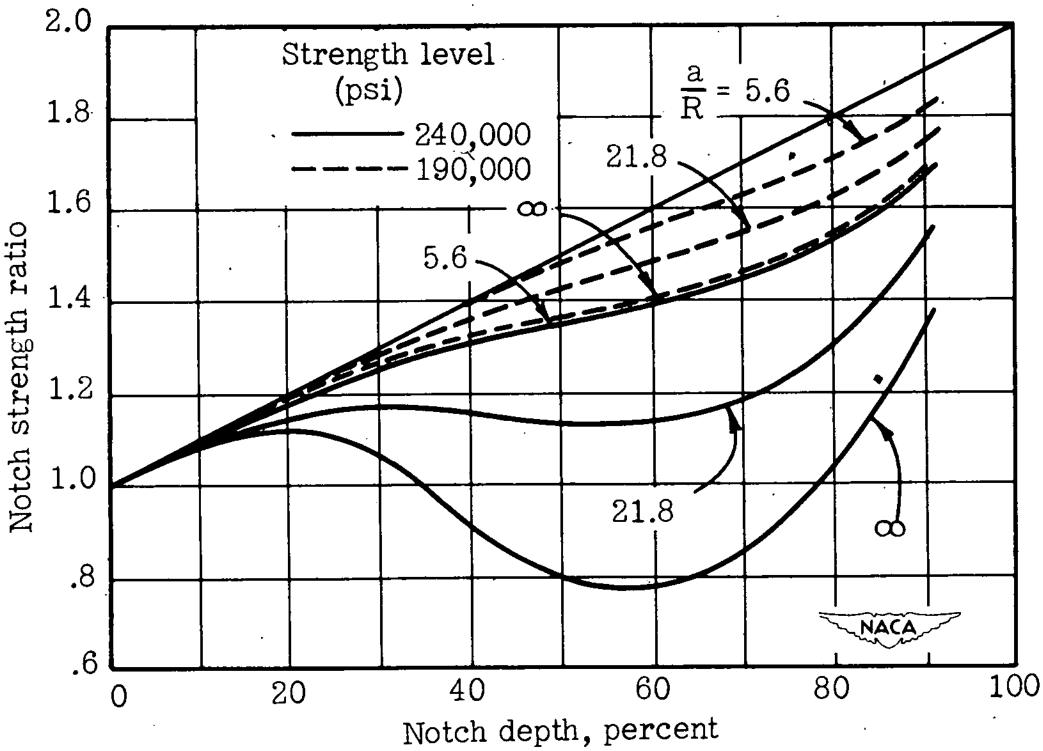


Figure 16.- Derived curves showing effect of notch depth, strength level, and notch sharpness on notch strength ratio (Sachs, Lubahn, and Ebert).

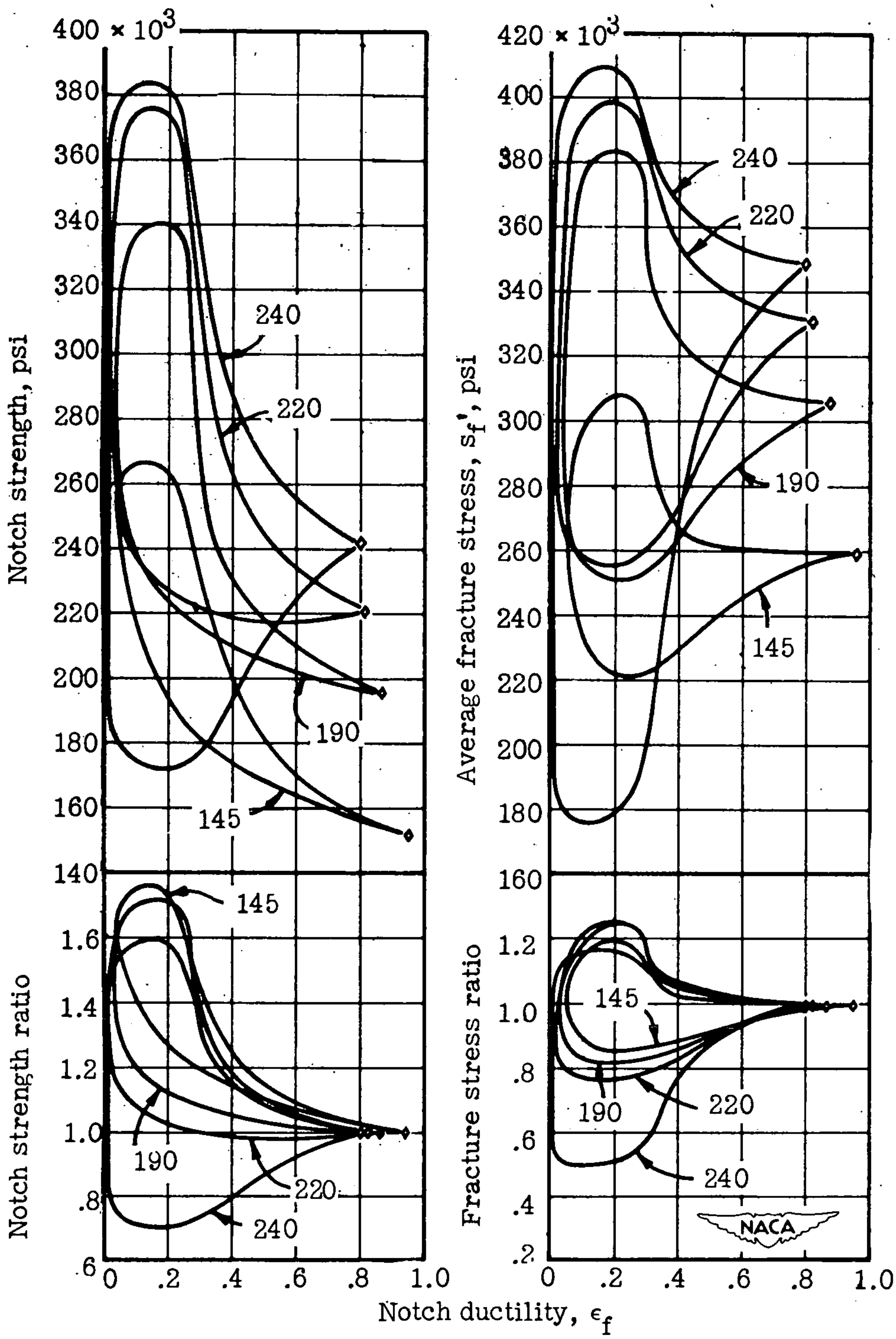


Figure 17.- Schematic relation between notch ductility and notch strength, notch strength ratio, average fracture stress, and fracture stress ratio for SAE 3140 steel (Sachs, Lubahn, and Ebert). Curve labels indicate strength level in 1000 psi.

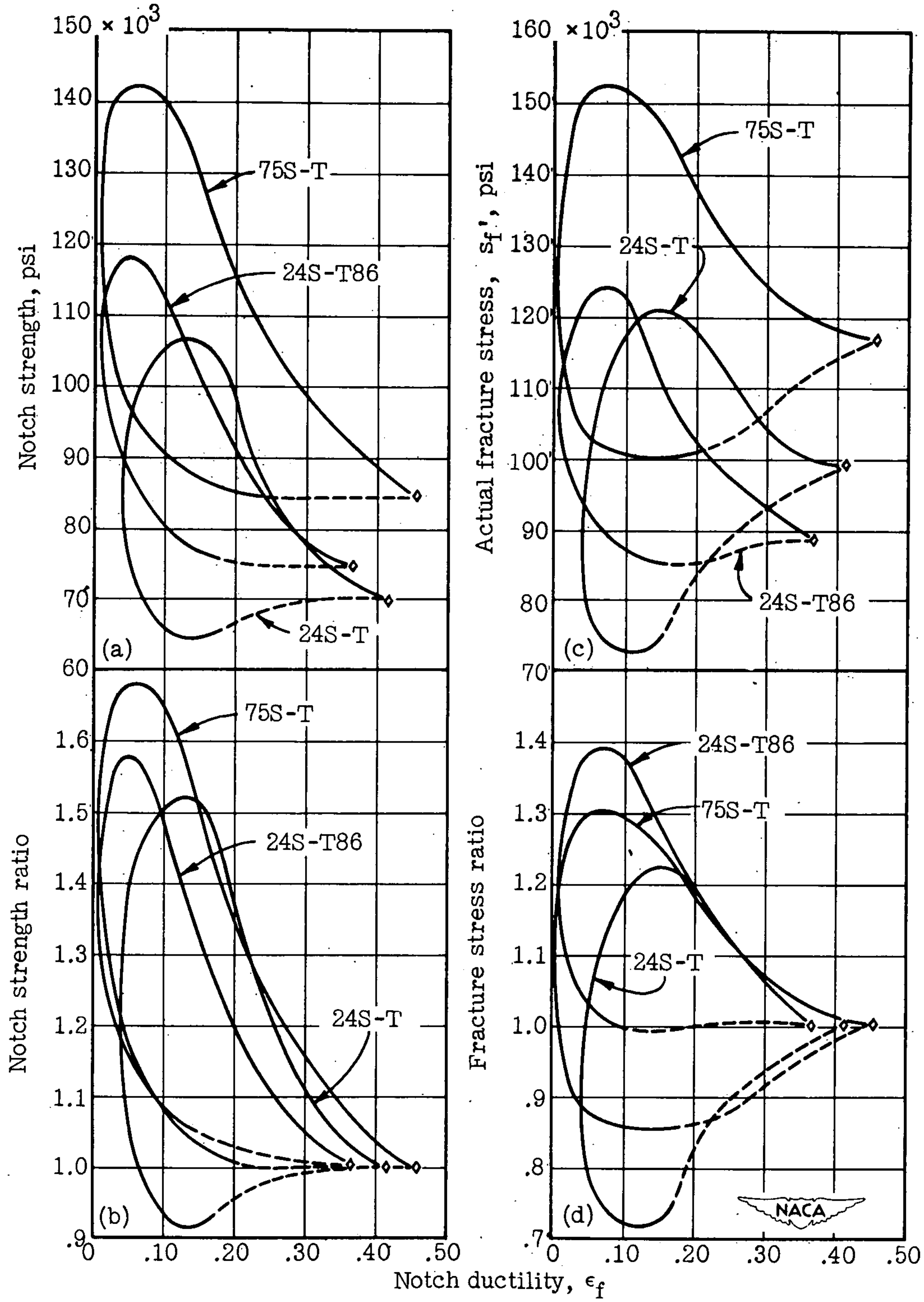
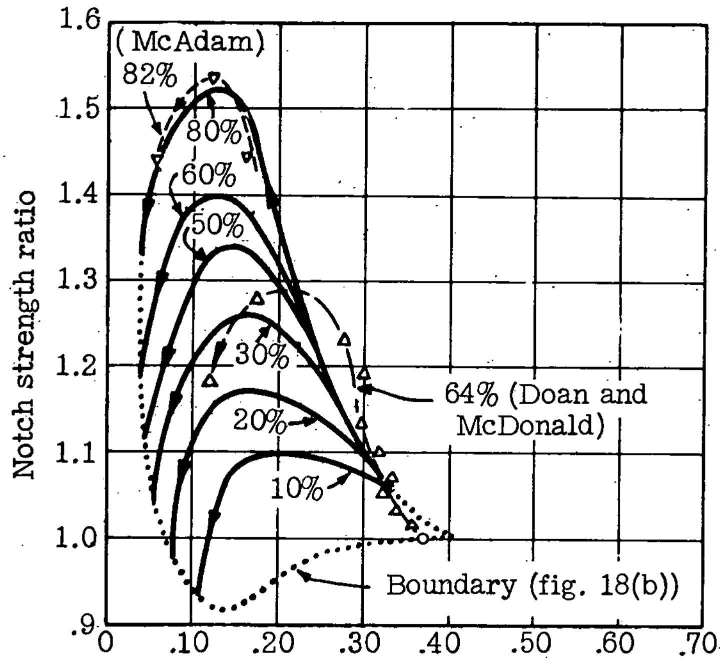
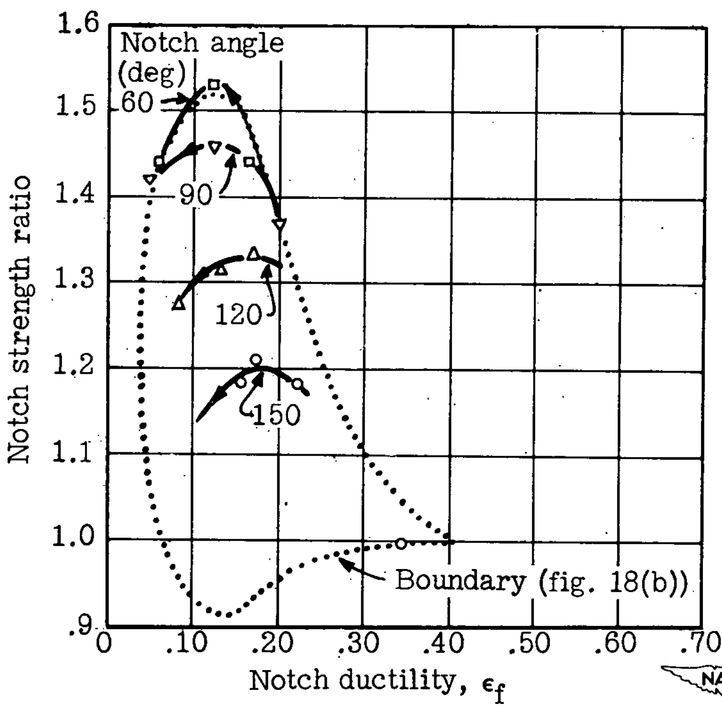


Figure 18.- Relation between notch ductility and notch strength, notch strength ratio, average fracture stress, and fracture stress ratio for 24S-T86, 75S-T, and 24S-T aluminum alloys.

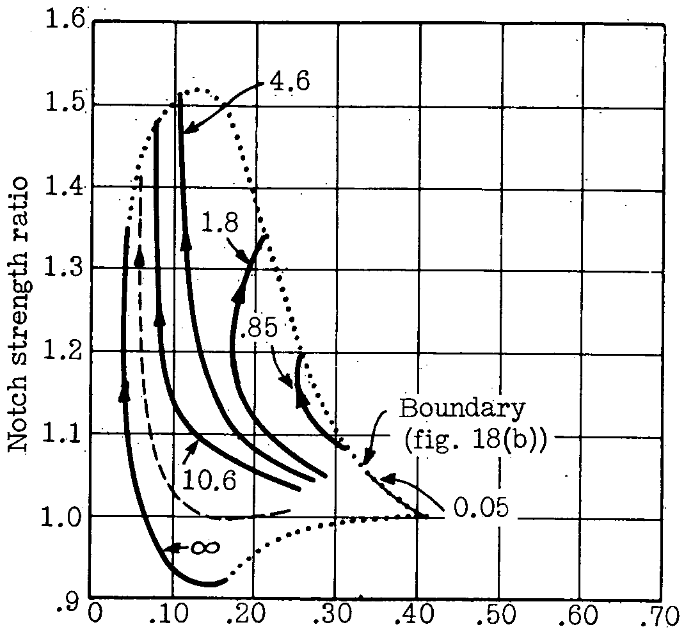


(a) 60°, V-type notches. Curve labels indicate percent notch depth.

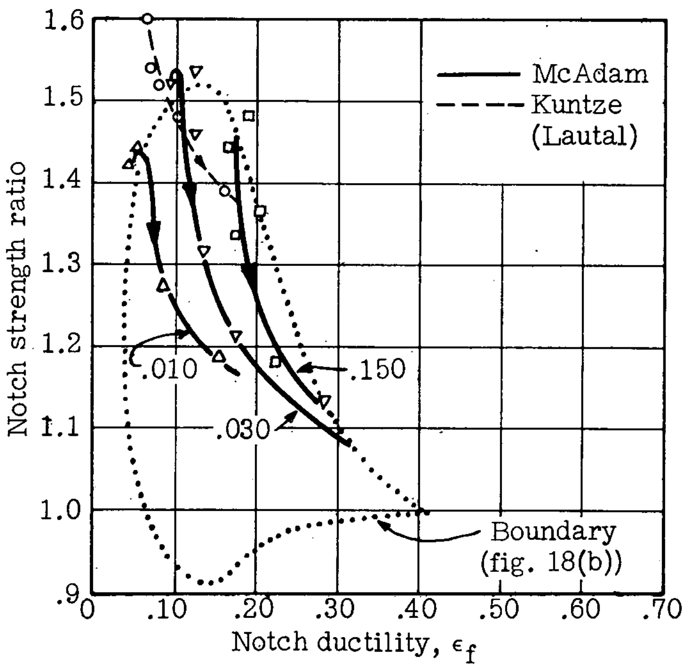


(b) Notch depth, 80 to 84 percent. V-type notches (McAdam).

Figure 19.- Composite representation showing trend curves for effect of notch sharpness on notch strength ratio for 24S-T aluminum alloy. Arrows on curves indicate increasing sharpness.



(a) Effect of notch depth. Arrows on curves indicate increasing depth. Curve labels indicate notch sharpness. 60°, V-type notches.



(b) Effect of flank angle. Arrows on curves indicate increasing flank angle. Curve labels indicate notch radius. V-type notches; notch depth, 80 to 84 percent.

Figure 20.- Composite representation showing trend curves for effects of notch depth and notch angle on notch strength ratio for 24S-T aluminum alloy.

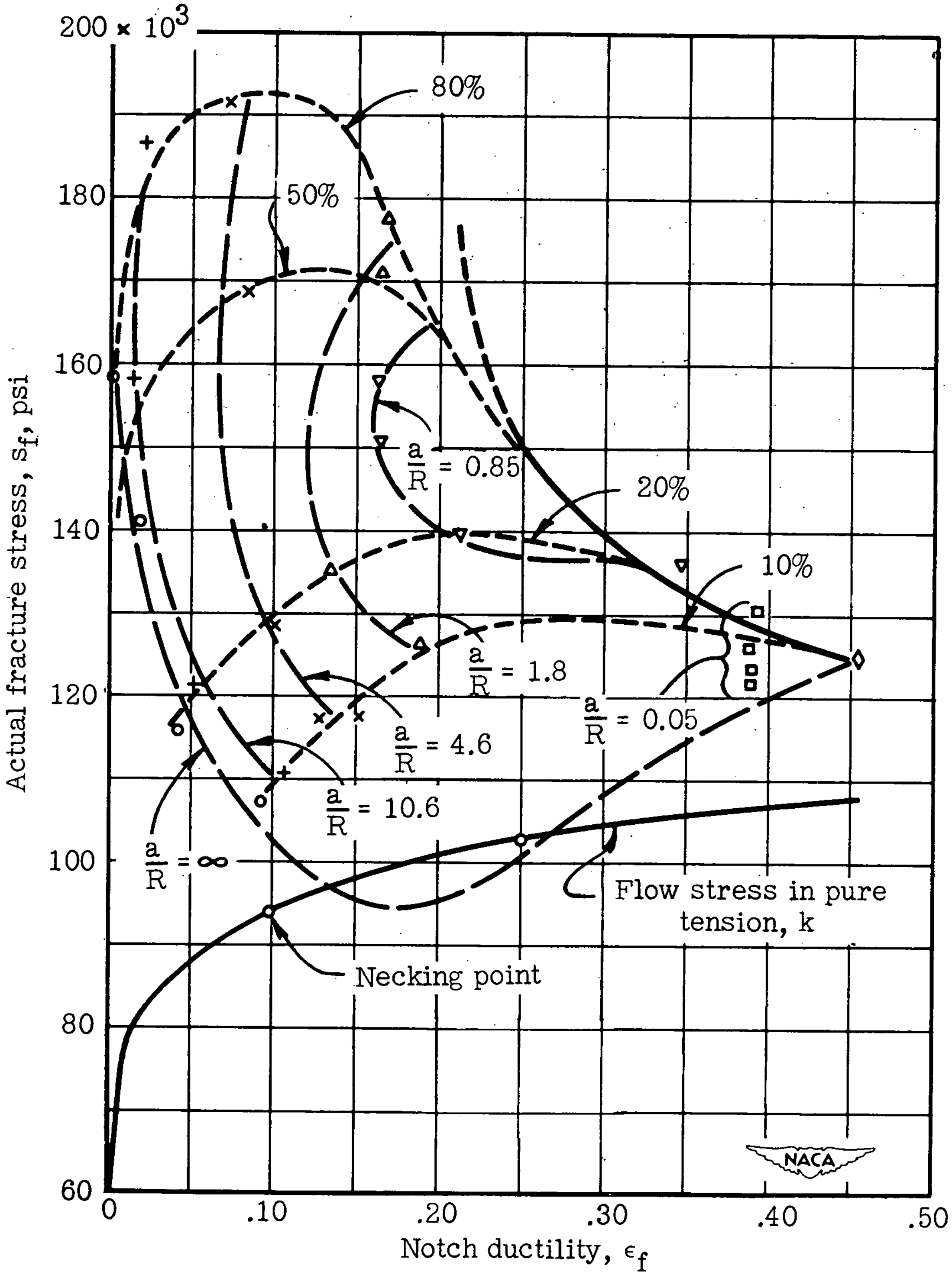


Figure 21.- Relation between actual fracture stress s_f and fracture strain ϵ_f for 75S-T rod re-solution-heat-treated. a = 0.106 inch. Percent values indicate notch depth.

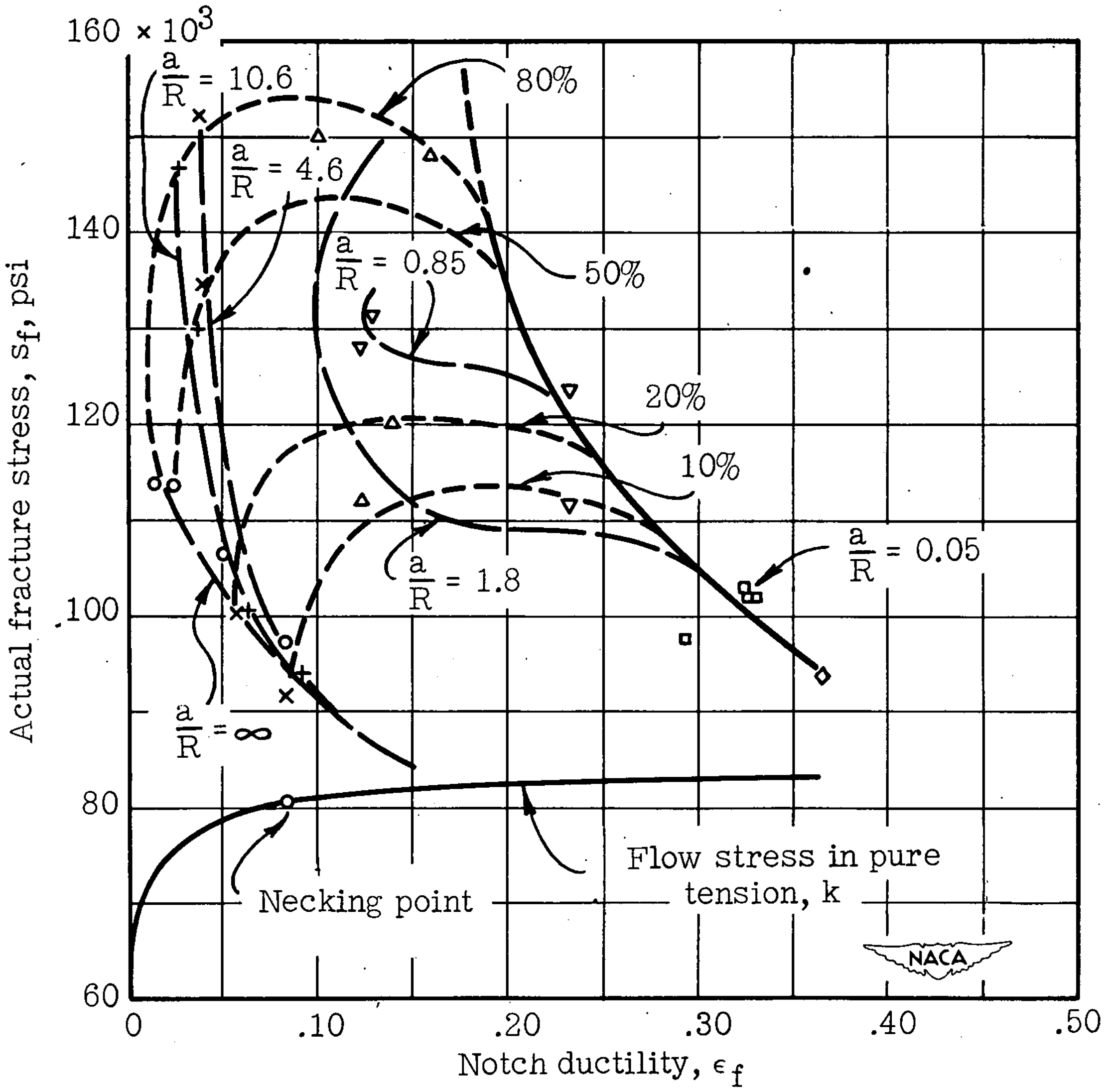


Figure 22.- Relation between actual fracture stress s_f and fracture strain ϵ_f for 24S-T86 rod re-solution-heat-treated. a = 0.106 inch. Percent values indicate notch depth.

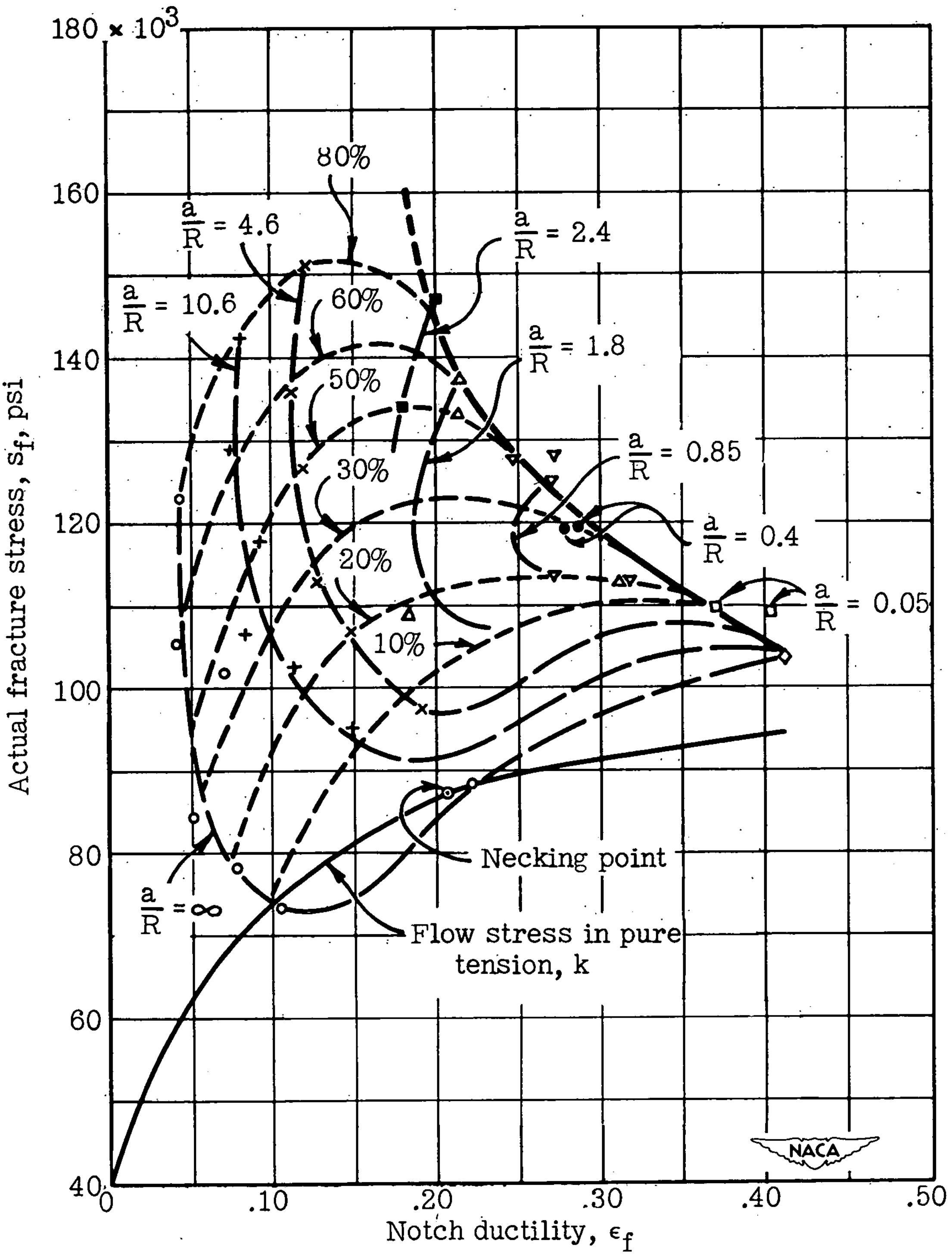


Figure 23.- Relation between actual fracture stress s_f and fracture strain ϵ_f for 24S-T rod re-solution-heat-treated. a = 0.106 inch. Percent values indicate notch depth.

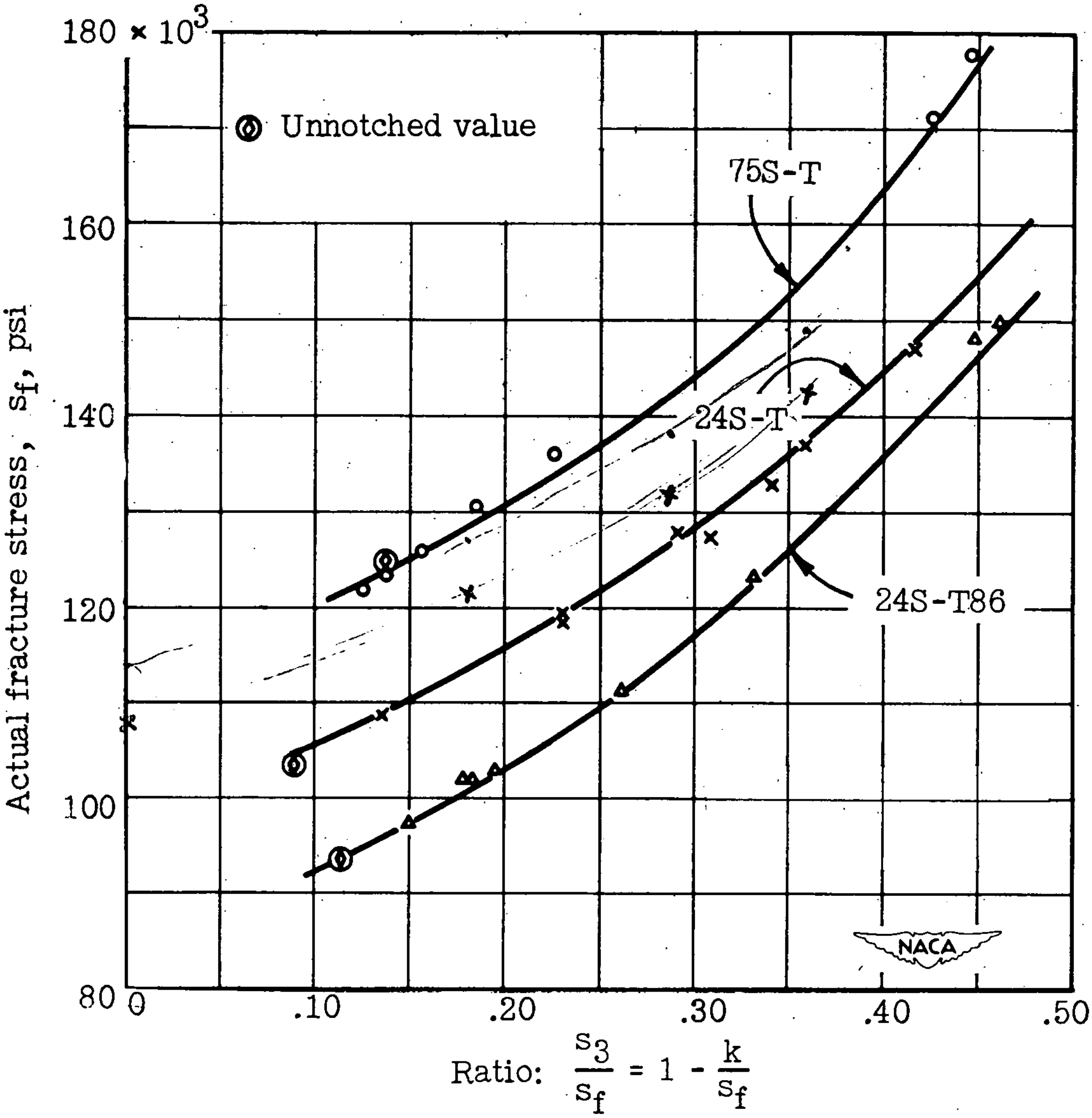


Figure 24.- Effect of triaxiality on actual fracture stress in mild notches for 75S-T, 24S-T86, and 24S-T alloys. 60°, V-type notches. a = 0.106 inch.

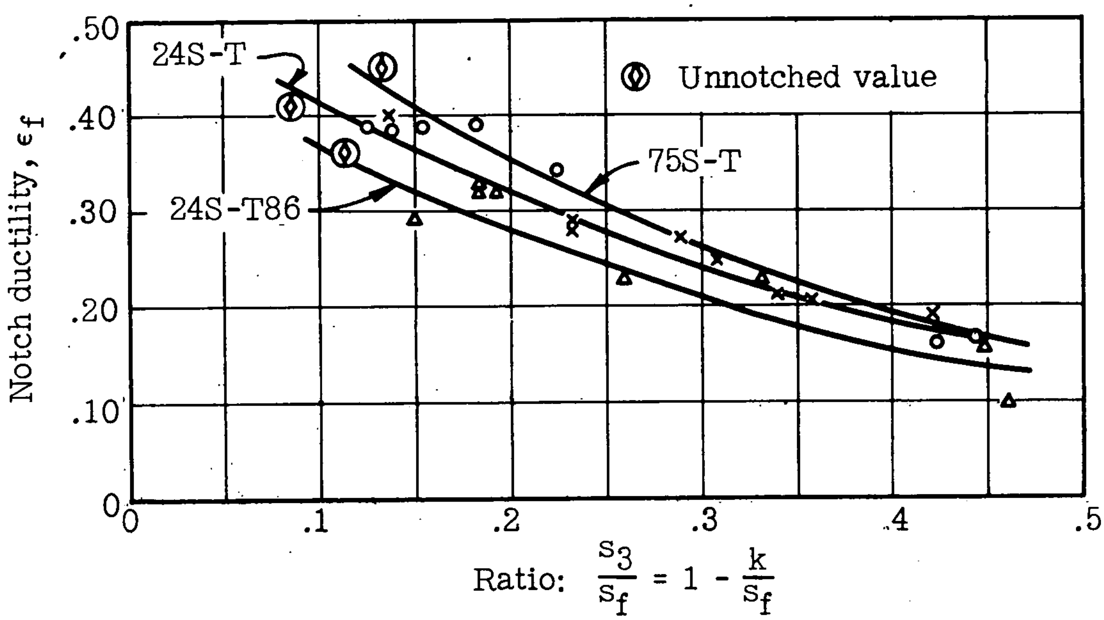


Figure 25.- Effect of triaxiality on notch ductility in mild notches for 75S-T, 24S-T86, and 24S-T alloys. 60°, V-type notches. a = 0.106 inch.

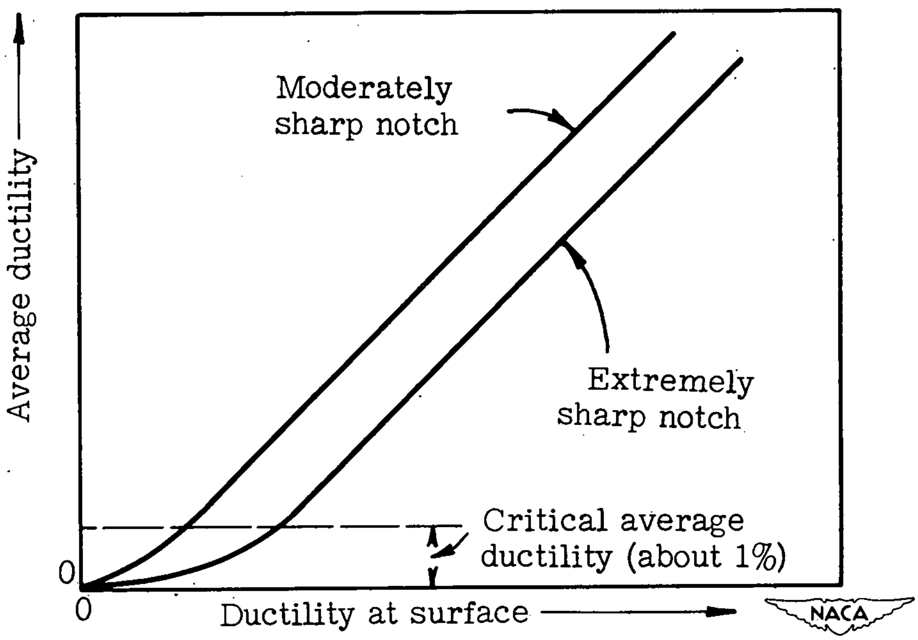


Figure 26.- Schematic representation of relation between actual and average ductilities for moderately and extremely sharp notches.

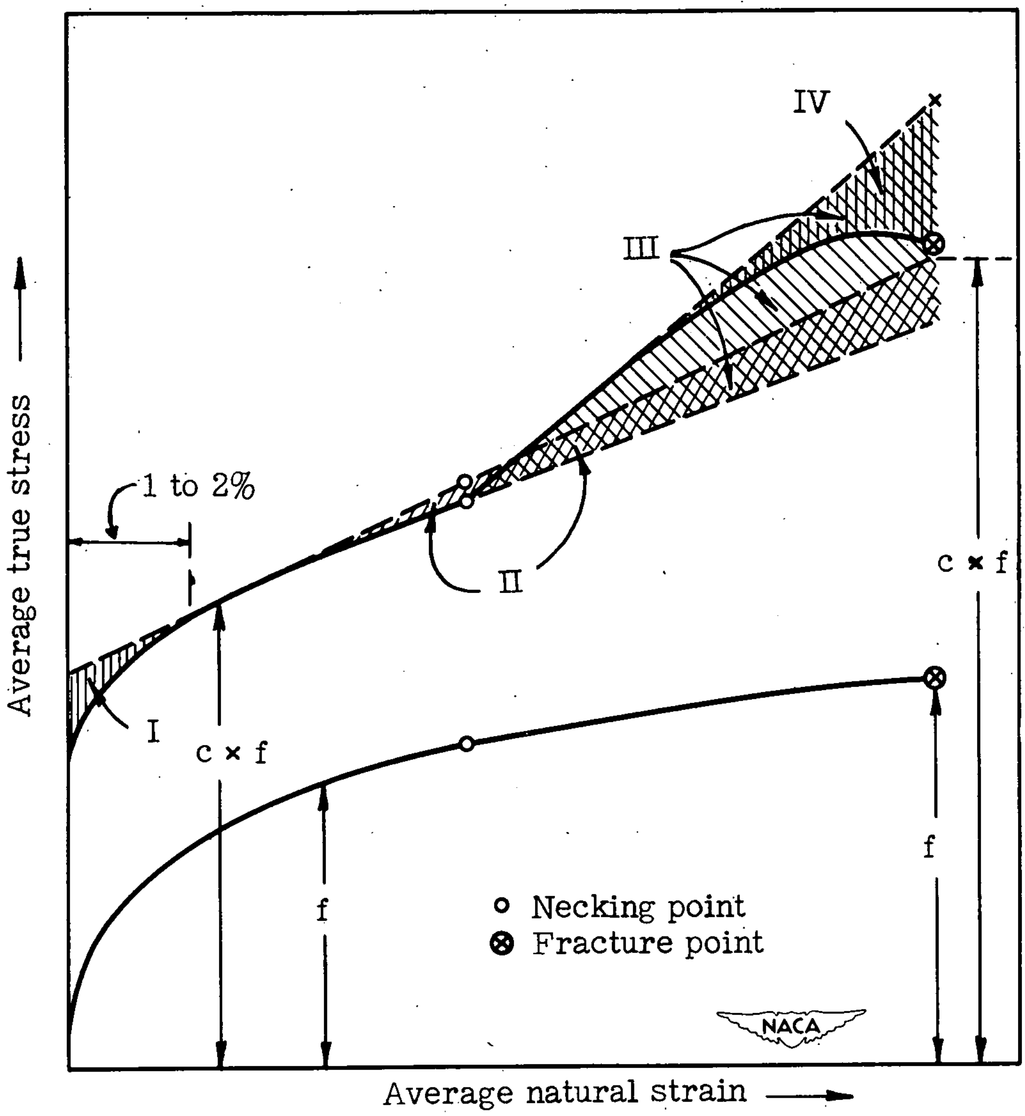


Figure 27.- Schematic representation of effects of notching on basic true stress-strain curve of a metal.

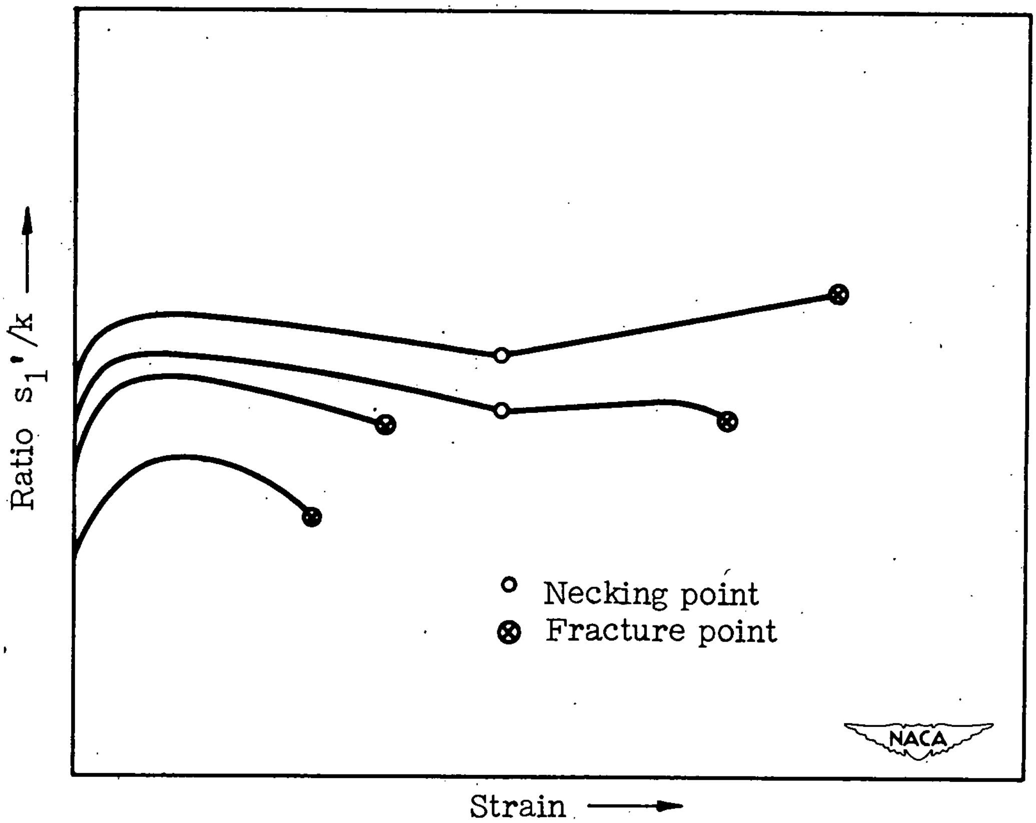


Figure 28.- Schematic representation of reduced stress-strain curves for a metal exhibiting various ductilities, depending on notch sharpness.

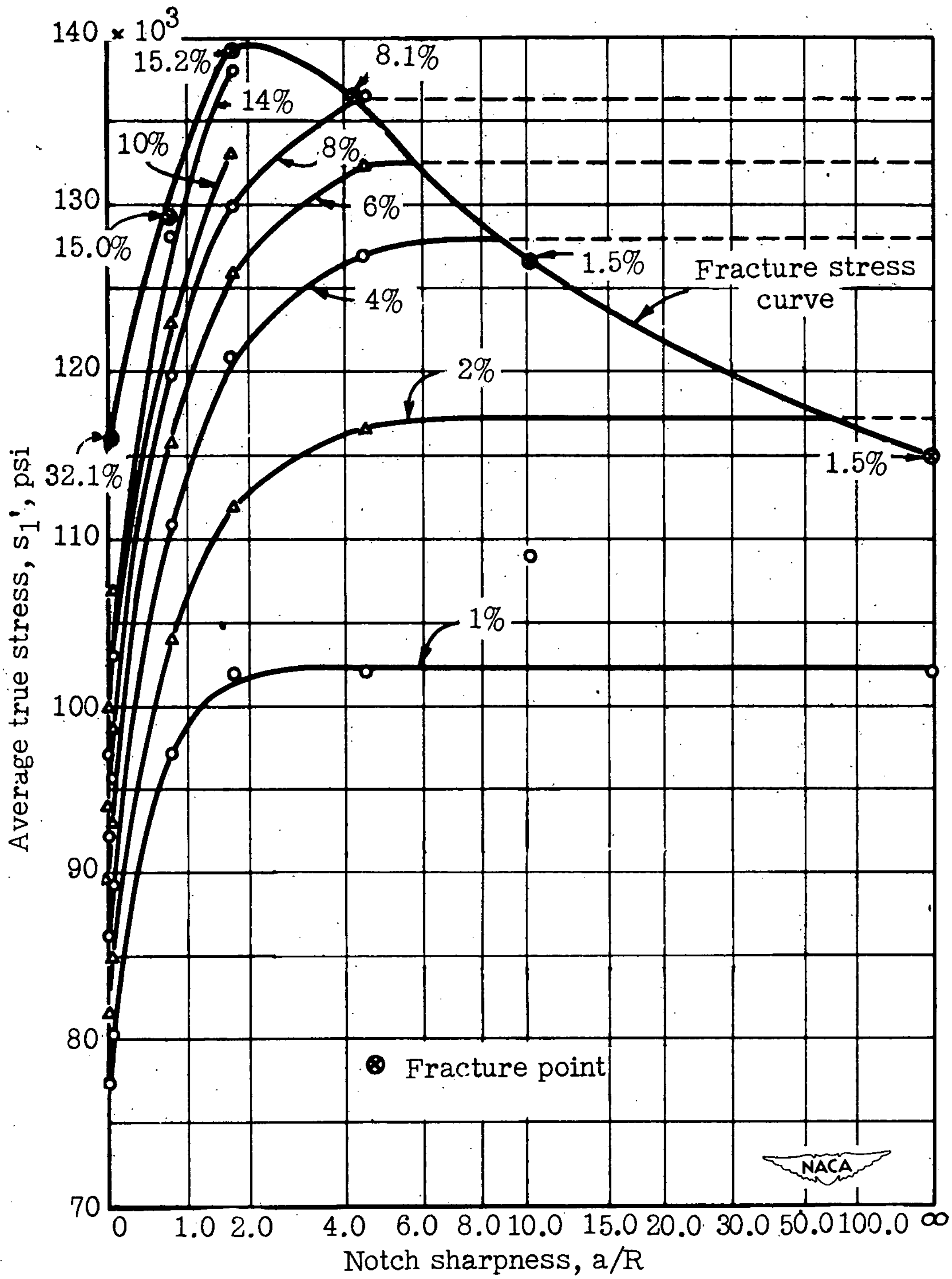


Figure 29.- Relation between average true stress and notch sharpness after various amounts of plastic flow for 75S-T aluminum-alloy rod. 50-percent, 60°, V-type notches. Curve labels indicate percent strain.

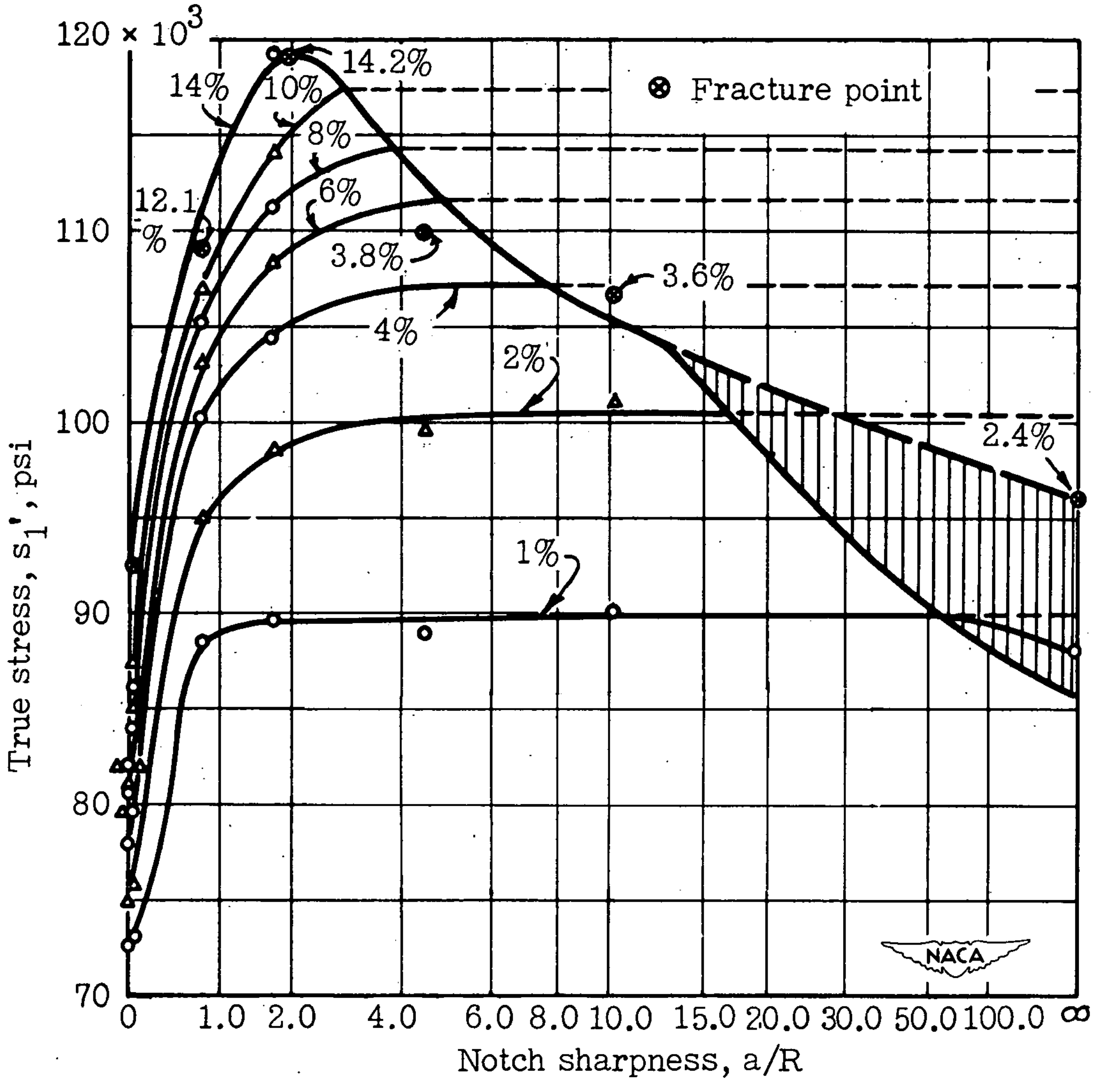


Figure 30.- Relation between average true stress and notch sharpness after various amounts of plastic flow for 24S-T86 aluminum alloy. 50-percent, 60°, V-type notches. Curve labels indicate percent strain.

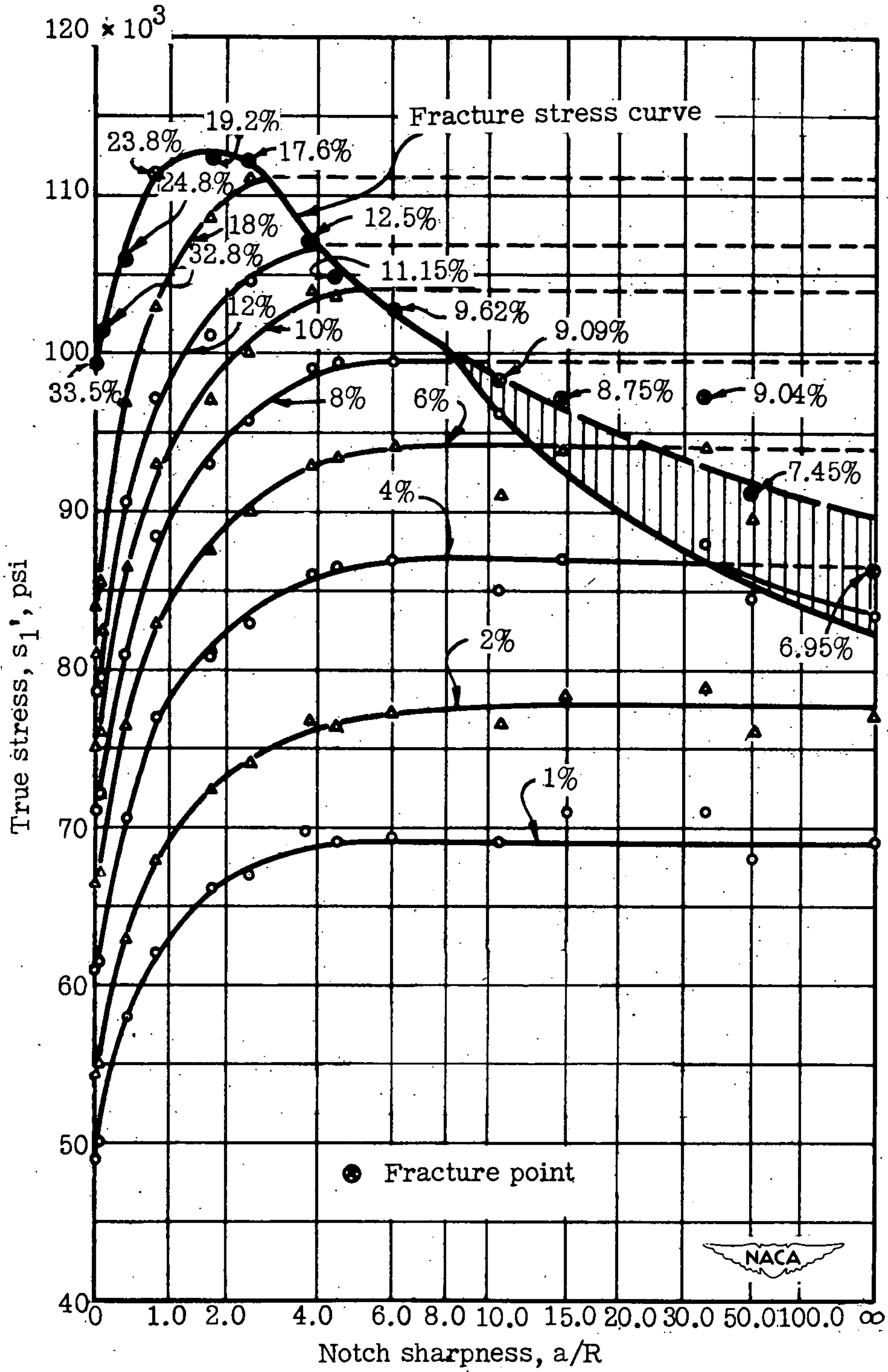


Figure 31.- Relation between average true stress and notch sharpness after various amounts of plastic flow for 24S-T aluminum-alloy rod. 50-percent, 60°, V-type notches. Curve labels indicate percent strain.