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Fatigue and Static Strength of Notched and Unnotched Aluminum-alloy and Steel Specimens

Principal objective of paper is to present data on some commonly used aircraft materials in a form so that variations in the fatigue strength with elastic stress-concentration factor can be shown

by Richard E. Whaley

ABSTRACT—This paper describes a method of presentation of fatigue data on three commonly used aircraft materials, 2024-T3 and 7075-T6 aluminum alloys and normalized SAE 4130 steel, such that variations in fatigue strength with stress-concentration factor can be shown. Comparisons of the fatigue strengths of 2024-T3 and 7075-T6 aluminum are made for the most useful range of stress-concentration factors.

Static-strength results of notched and unnotched specimens of the three materials are presented to show how the strength varies with some parameters of the stress concentration. Comparison of the data with one theory for the strength of cracked specimens was made.

Symbols

- A = Neuber material constant, in.
- K_f = fatigue-strength-reduction factor
- K_n = Neuber "practical" stress-concentration factor
- K_t = elastic stress-concentration factor
- K_u = theoretical stress-concentration factor for ultimate tensile strength
- r = notch-root radius, in.
- S_{max} = maximum load divided by initial net sectional area, ksi
- S_0 = ultimate tensile strength of unnotched specimen, ksi
- S_u = ultimate tensile strength of notched specimens, ksi
- NSR = S_u/S_0 = notch strength ratio
- q = notch sensitivity
- γ = relative stress gradient, in.$^{-1}$

Introduction

When aircraft structures are designed, or when fatigue failures occur, comparisons are usually made with data from simple specimens. It is often difficult to compare the data, because comprehensive data on simple specimens is not usually found for the elastic stress-concentration factor desired. One of the objectives of this paper is to present data on some commonly used aircraft materials in a form so that variations in the fatigue strength with elastic stress-concentration factor can be shown.

It is generally assumed that the static strength of materials is little affected by stress concentrations such as notches, holes and fillets. Another objective of this paper is to show the relationship of the static strength with some parameters of the stress concentrations.

Description of Specimens

The specimens used to obtain the notch tensile-strength results are shown in Figs. 1 and 2. Specimens were designed to obtain the widest range of notch-root radii that was practical for each value of stress-concentration factor. The specimens were all machined from the same sheet of 0.091-in. thick 2024-T3 aluminum alloy. The static-strength properties are given in Table 1.

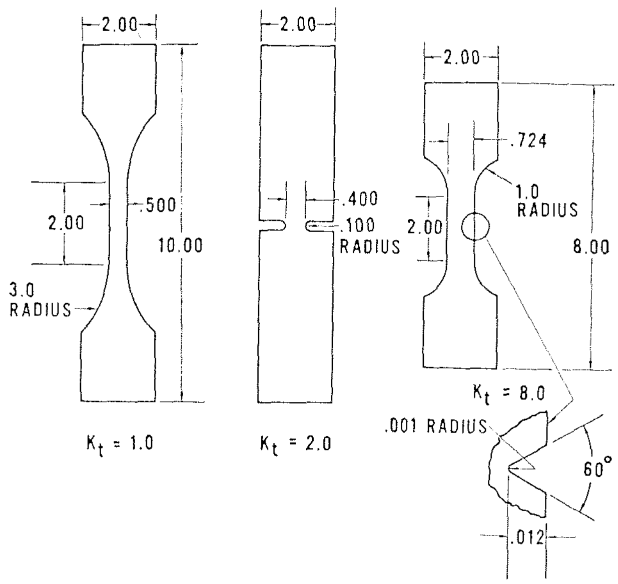

Fig. 1—Configuration of sheet specimens

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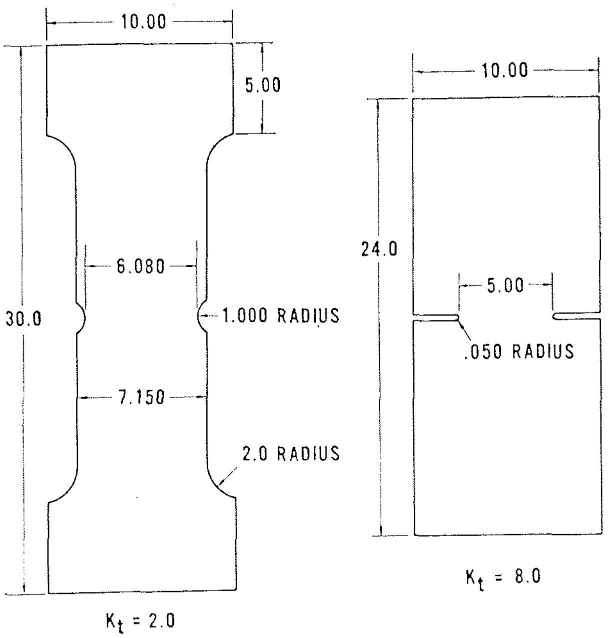

Fig. 2—Configuration of sheet specimens

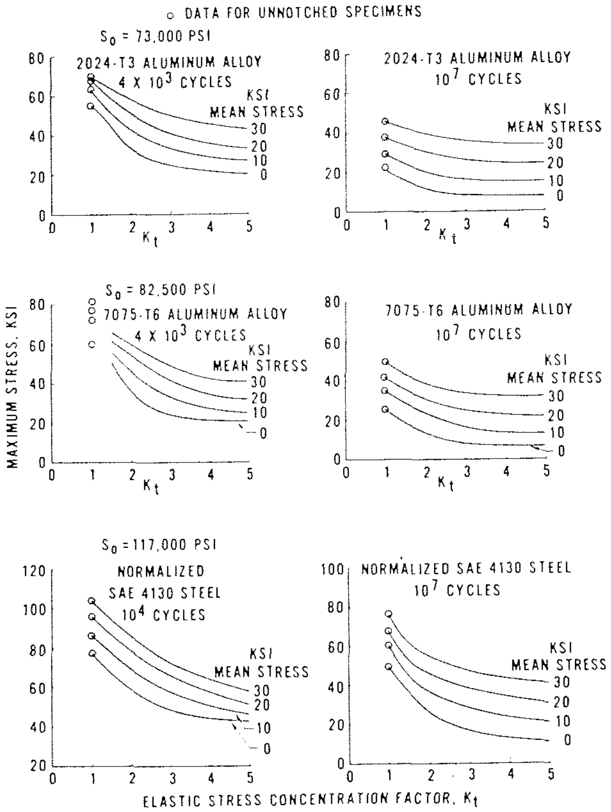

Fig. 3—Stress variation with stress-concentration factor for constant mean-stress curves

The specimens and material for most reference test results are described in Refs. 1 to 4. All specimens were of sheet material which was 0.091-in. thick for the aluminum specimens and 0.075-in. thick for the steel specimens. All material for the fatigue test

TABLE 1—STATIC TENSILE-STRENGTH PROPERTIES OF 2024-T3 ALUMINUM-ALLOY SHEET SPECIMENS

Type of specimen	Elongation in 2 in., %	Yield strength for 0.2% offset, psi	Ultimate strength, psi*
Unnotched	17.5	57,000	72,500
Notched ($K_t = 2.0$)			
r = 1.000	...	...	69,300
r = 0.100	...	...	73,300
Notched ($K_t = 8.0$)			
r = 0.050	...	...	59,800
r = 0.001	...	...	66,500

* Average results of three specimens.

results was selected from the same lot. Notched fatigue-test specimens had a net width of 1.5 in.

Procedure

The fatigue tests, as described in Refs. 1 to 4, were conducted on Krouse direct repeated-stress machines. Procedures and techniques were generally the same for all tests reported. All stress values indicated are nominal net area stresses.

Results Discussion

Fatigue Test

The fatigue-strength information given in Refs. 1 to 4 is presented in Fig. 3 as maximum stress vs elastic stress-concentration factor for values of constant mean stress and constant lifetime. The data is presented for the three materials (2024-T3 and 7075-T6 aluminum alloy and normalized SAE 4130 steel) for unnotched specimens and specimens with edge-cut notches with constant over-all and net widths. The only geometrical variable, therefore, was the notch-root radius, r.

Examination of Fig. 3 reveals some interesting phenomena. The data points for unnotched specimens (K_t = 1) agree very well with the curves for the notched specimens extrapolated down to K_t = 1. Figure 3 shows that for the aluminum alloys with K_t greater than 4.0, there is not much change in the fatigue strength. For normalized SAE 4130 steel there is a continuing strength reduction up to a value of at least 5.0.

The largest change in fatigue strength, and thus the most critical fatigue-strength reduction for all materials tested, is in the very low values of K_t. This critical fatigue-strength reduction is shown by the steeper slopes of the curves of Fig. 3 at the low values of K_t.

The curves in Fig. 3 can be used for a comparison between the fatigue strength of 2024-T3 and 7075-T6 aluminum alloys. Typical curves have been reproduced in Fig. 4 at high and low mean stresses and high and low lifetimes. The curves indicate that the fatigue strengths of the two materials are very much alike, with 2024-T3 aluminum alloy being slightly better for the higher values of K_t for both

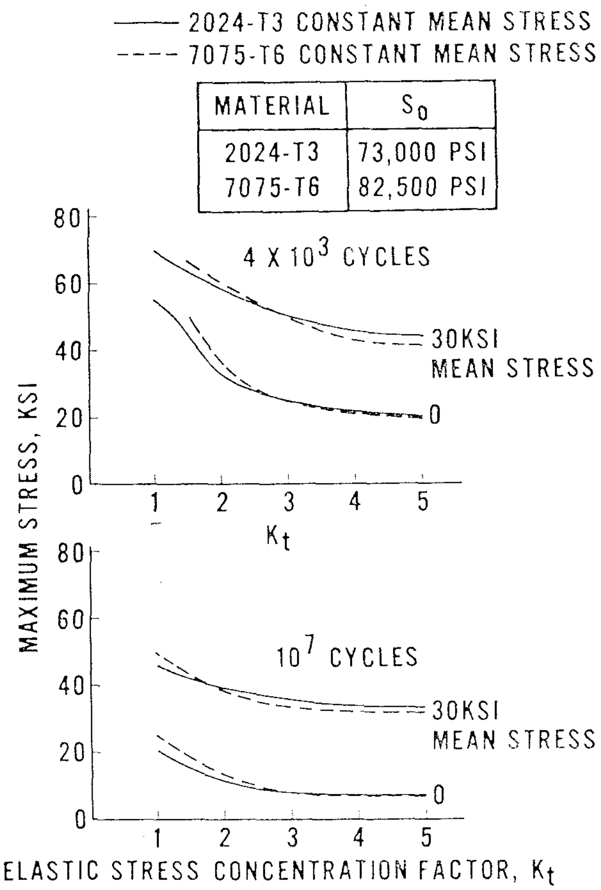

Fig. 4—Comparison of fatigue life of 2024-T3 and 7075-T6 aluminum alloys

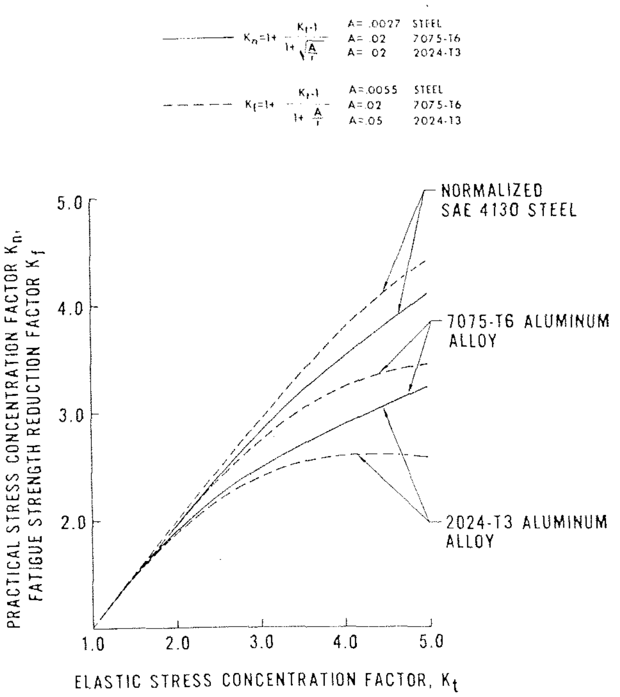

Fig. 5—Stress-concentration factors for edge notches

mean stresses and lifetimes. At fairly low values of K_t, the curves cross and diverge as K_t approaches unity. This higher fatigue strength of 7075-T6 aluminum alloy for both mean stresses and lifetimes might be expected because of the higher ultimate strength of 7075-T6 aluminum alloy over that of 2024-T3 aluminum alloy. The higher notch sensitivity of 7075-T6 aluminum alloy, however, lowers the fatigue strength to a value similar to that of 2024-T3 aluminum alloy at fairly low values of K_t. The largest differences in strength are so small that exceptions in these trends can be found. For example, Ref. 5 shows that the endurance limit of 2024-T3 aluminum alloy is slightly higher than that of 7075-T6 aluminum alloy for unnotched material.

Reference 6 shows a variation in the fatigue strength for different notch-root radii at the same values of K_t. The fatigue-strength-reduction factor, K_f, is a good representative of the fatigue strength of notched specimens and is defined as follows:

$$K_f = \frac{\text{Maximum stress for unnotched specimens}}{\text{Nominal maximum stress for notched specimens at the same load ratio and lifetime}} \qquad (1)$$

Reference 6 shows that for each value of K_t, K_f (and therefore the inverse of the fatigue strength) increases with increasing notch-root radius of an edge notch. For certain material constants, K_f is shown to be very nearly identical to the "practical" stress-concentration factor, K_n, developed by Neuber in Ref. 7. The expression for this factor, for notches with zero flank angle, in terms of the ideal factor K_t, notch-root radius r, and parameter A is as follows:

$$K_n = 1 + \frac{K_t - 1}{1 + \sqrt{A/r}} \qquad (2)$$

It is shown in Ref. 6 that in order to have K_n very nearly identical to K_f, the values of the parameter A are 0.02 in. for the aluminum alloys and 0.0027 in. for normalized SAE 4130 steel. In Ref. 8, slightly different results were obtained by using notch sensitivity which was defined as:

$$q = \frac{K_f - 1}{K_t - 1} \qquad (3)$$

Many fatigue-test results for zero mean stress were used in Ref. 8 for several different notch forms. The resulting value of notch sensitivity was:

$$q = \frac{1}{1 + (A/r)} \qquad (4)$$

The combination of eq (3) and (4) results in an equation slightly different from eq (2):

$$K_f = 1 + \frac{K_t - 1}{1 + (A/r)} \qquad (5)$$

The values of A in Ref. 8 are 0.05 in. for 2024-T3 aluminum-alloy sheet, 0.02 in. for 7075-T6 aluminum-alloy sheet, and 0.0055 in. for steel with an ultimate tensile strength equal to that of normalized SAE 4130 steel. The test results of Ref. 6 fall in with the scatter of the data of Ref. 8, so it appears reasonable to use eq (5) rather than eq (2) for the case of zero mean stress.

Acceptance of eq (5) does not rule out the use of

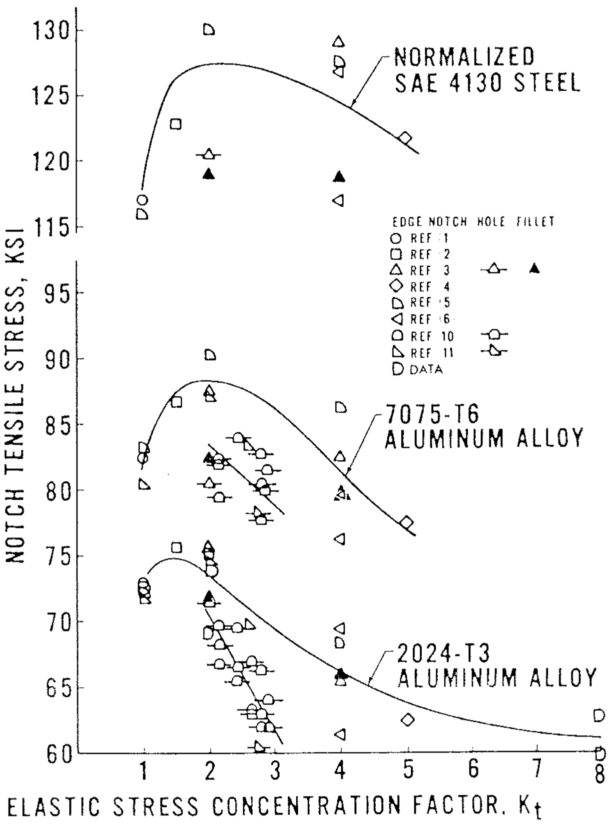

Fig. 6—Notch-tensile-strength variation with stress-concentration factors

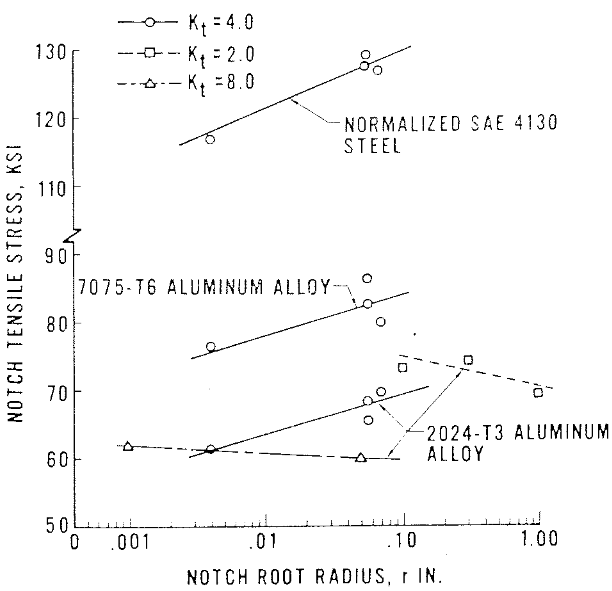

Fig. 7—Notch-tensile-strength variation with notch-root radius for constant elastic stress-concentration factor

eq (2). The differences between the two equations are small considering the scatter in fatigue data. The differences are shown in Fig. 5, where K_f and K_n are plotted against K_t for the edge-notched specimens of Refs. 1 to 4. The curves shown are for specimens with constant over-all and net widths. The use of eq (5) with constant-width specimens

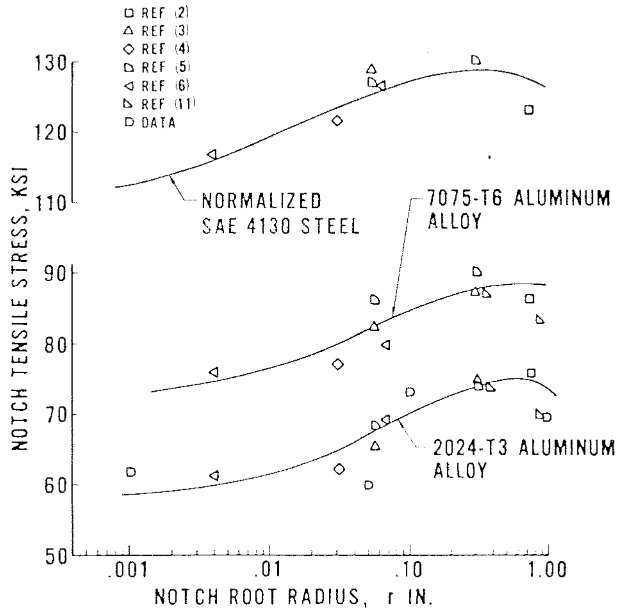

Fig. 8—Notch-tensile-strength vs. notch-root radius for all values of elastic stress-concentration factors

results in a peak in K_f at some value of K_t beyond which K_f decreases. This peak is shown in the curve for 2024-T3 aluminum alloy. The peaks for 7075-T6 aluminum alloy and for the steel occur at higher values of K_t than shown in Fig. 5. Figure 5 indicates that, for 2024-T3 aluminum alloy, eq (2) would predict a decrease in fatigue strength and eq (5) would predict an increase in fatigue strength for the range of K_t greater than 5.0. Figure 3 shows that the fatigue strengths of both aluminum alloys tend to become constant for the range of K_t greater than 5.0. It thus appears that for the two aluminum alloys the $K_t = 5.0$ fatigue data can be used with little error for K_t values greater than 5.0. This conclusion is valid when the only geometrical variable is the notch-root radius, r.

In order to estimate the fatigue strength of notched material, K_f has to be clearly defined. Besides eq (1), K_f can be defined in several ways such as:

$$K_f = \frac{\text{Maximum stress for unnotched specimens}}{\text{Nominal maximum stress for unnotched specimens at the same mean stress and lifetime}} \quad (6)$$

$$K_f = \frac{\text{Alternating stress for unnotched specimens}}{\text{Nominal alternating stress for unnotched specimens at the same mean stress and lifetime}} \quad (7)$$

Reference 9 shows how K_f can vary over a large range, depending on eqs (1), (6) or (7). For most small-specimen tests, such as rotating-beam tests, the mean stress is zero and K_f for eqs (1), (6) and (7) are identical. In Ref. 8, only the case of zero mean stress was considered in establishing eq (4). In Ref. 6 several mean stresses were considered but K_f was defined as eq (1).

Unnotched-specimen data, along with either eq (2) or eq (5), could be used to estimate the fatigue strength of notched material, but care would have to be exercised in the use of the proper K_f definition.

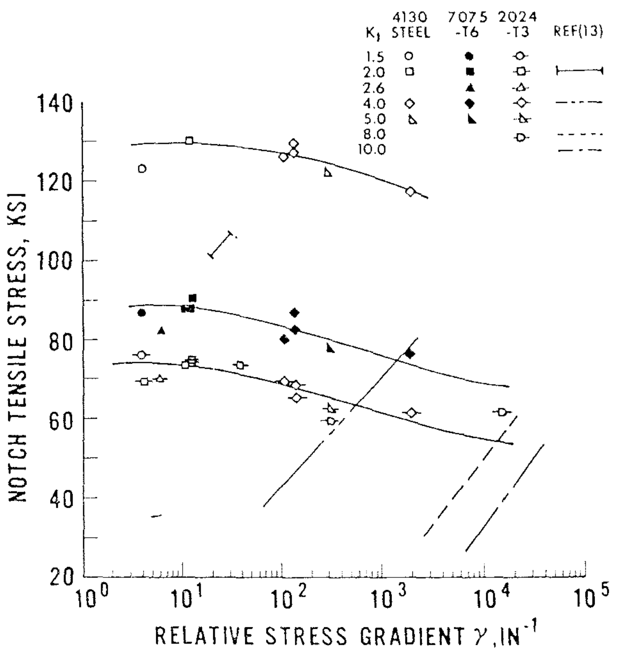

Fig. 9—Effect of relative stress gradient on the notch strength

Static Test

The results of static-strength tests, given in Table 1, and results from Refs. 1 to 6, 10 and 11, are plotted in Fig. 6 for 2024-T3 and 7075-T6 aluminum alloys, and normalized SAE 4130 steel. The data is presented in the form of notch-tensile strength vs. K_t. Most plotted points are the averages of several specimens. For the data from which no values of K_t were given, K_t was obtained by use of Ref. 12. There is a notch-strengthening effect for all three materials at low values of K_t. The curves in Fig. 6 are similar in form to the curves shown in Ref. 13. The curves in Ref. 13 were for a much higher ultimate strength and therefore less-ductile material than the material used to obtain Fig. 6. In Ref. 13, it was observed that for relatively ductile steel the curves would not show a decrease in strength in the range of $K_t = 2$ to $K_t = 13$. Figure 6, however, shows that for the aluminum alloys the strength decreases below the strength of unnotched material at a value of K_t less than 5.0.

The notch strength of specimens with fillet notches and central circular holes is less than the notch strength of specimens with edge notches for the same values of K_t. The scatter and low range of K_t values, however, make it difficult to determine the trends for these other notch forms.

The notch-strength data for $K_t = 2.0$, 4.0 and 8.0 includes data for edge-notched specimens in which the notch-root radius was varied with constant K_t. The different notch-root radii data is replotted in Fig. 7 as notch strength vs. notch-root radii. These curves show that for the data at $K_t = 4$ there is a relationship of increasing strength with increasing notch-root radii for all three materials. The data at $K_t = 2$ and $K_t = 8$, which was obtained only for 2024-T3 aluminum alloy, shows a slight trend in the opposite direction. The reason for this difference has not been determined but it should be noted that the slopes for $K_t = 2$ and $K_t = 8$ are small. All of the data for edge-notched specimens is replotted in Fig. 8 in the same manner as plotted in Fig. 7. For each of the three materials, a single curve is drawn because of the differences in slope and the low slopes of the individual K_t curves of Fig. 7. A statistical treatment of the curves for 2024-T3 aluminum alloy, however, indicates that more scatter exists in the notch-root radii curve of Fig. 8 than in the K_t curve of Fig. 6. The notch strength of ductile material thus appears to be more a function of K_t than the notch-root radius.

In Ref. 13 the notch strength is shown to be a function of several parameters (such as notch depth, specimen width and stress gradient). The dominant factor, it was pointed out, is the relative stress gradient which was derived:

$$\gamma = \frac{2K}{r} \tag{8}$$

The notch strength for a relatively brittle alloy was shown to decrease with decreasing relative stress gradient for constant values of K_t. This decrease is, in effect, a function of the notch-root radius since K_t remained constant.

The data from Fig. 8 was replotted in Fig. 9, as a function of the relative stress gradient, along with the curves from Ref. 13 for a brittle titanium alloy. Here, again, if curves were drawn through the data for individual K_t values, there would be differences in slope between the data for $K_t = 4$ and the data for $K_t = 2$ and $K_t = 8$. More important, however, the slopes for all three ductile materials would be much less than the slopes for the brittle alloy. It thus appears that the notch strength of ductile material, as compared to a brittle material, is affected only slightly by the relative stress gradient for individual values of K_t. For this reason, a single curve is drawn through the data regardless of the values of K_t. A statistical treatment of the curves for 2024-T3 aluminum alloy, however, indicates that more scatter exists in the relative stress gradient curve of Fig. 9 than in the K_t curve of Fig. 6. The notch strength of ductile material thus appears to be more a function of K_t than any other parameter of the notch.

The theory presented in Ref. 11 for the static strength of cracked specimens was extended to the static strength of uncracked specimens and is shown in Fig. 10. The static-strength data has been calculated in terms of the reciprocal of the notch-strength ratio for comparison with the theory. The theoretical K_u was obtained from the Neuber formula, eq (2), and curves of K_u vs. K_u in Ref. 11, with the appropriate material constants for static-strength results also from Ref. 11. There is poor agreement between the data and the theory. One reason for poor agreement between theory and experimental data is due to the difference in the radius r. In the cracked-specimen case, r is a constant of small magnitude and, in the uncracked specimen case, r is a relatively large variable. The theory does not consider changes in strength due to notch-root radius even though the effect is small. Probably the predominant reason for poor agreement is due to the notch-strengthening effect which notched specimens exhibit at low values of K_t. The K_t values for cracked specimens, on the other hand, are large enough to preclude any such strengthening. The theory, therefore, does not consider notch strengthening. It ths appears that the static strength of notched uncracked specimens is a special case that requires a set of K_u vs. K_n curves, including the effects of notch strengthening, before the Neuber theory can be applied.

Conclusions

Fatigue and static-strength data from several sources was plotted in a manner so that the following conclusions were reached:

(*a*) The fatigue strengths of notched specimens of 2024-T3 and 7075-T6 aluminum alloys and normalized SAE 4130 steel exhibit a function of increasing strength with decreasing K_t to a value of unity. The unnotched-specimen data agrees with this function at a value of unity.

(*b*) There is little change in fatigue strength for specimens with K_t values greater than 4.0 for 2024-T3 and 7075-T6 aluminum alloys. There is a continuing strength reduction in normalized SAE 4130 steel up to a K_t value of at least 5.0. The largest change in fatigue strength, and thus the most critical fatigue-strength reduction, is in the lower values of K_t for 2024-T3 and 7075-T6 aluminum alloys and normalized SAE 4130 steel.

(*c*) A comparison of the fatigue lives of 2024-T3 and 7075-T6 aluminum alloys shows that, at low values of K_t, 7075-T6 aluminum alloy has a higher fatigue strength than 2024-T3 aluminum alloy. The higher notch sensitivity of 7075-T6 aluminum alloy at the low values of K_t lowers its fatigue strength to that of 2024-T3 aluminum alloy. The fatigue strengths of 2024-T3 and 7075-T6 aluminum alloys are very similar for most of the range of K_t, with 2024-T3 aluminum alloy slightly better.

(*d*) The fatigue strength for any edge notch can be calculated from unnotched specimen data on the basis of certain material constants and certain definitions of the fatigue-strength-reduction factor.

(*e*) The static strengths of notched specimens of 2024-T3 and 7075-T6 aluminum alloys and normalized SAE 4130 steel exhibit a notch-strengthening effect at low values of stress concentration. At higher stress concentration, the strength decreases with increasing stress-concentration factor.

(*f*) Specimens with edge notches show higher static strengths than specimens with either a fillet notch or a central circular hole for the same value of K_t.

(*g*) The strength of uncracked 2024-T3 and 7075-T6 aluminum alloy and normalized SAE 4130 steel specimens with edge notches is more a function of the elastic stress-concentration factor than any other parameter of the notch. The notch strength of ductile material is less affected by the relative stress gradient than brittle material.

(*h*) A theory for the strength of cracked specimens based on the Neuber theory would require the effects of notch strengthening before it could be extended to the strength of notched uncracked specimens.

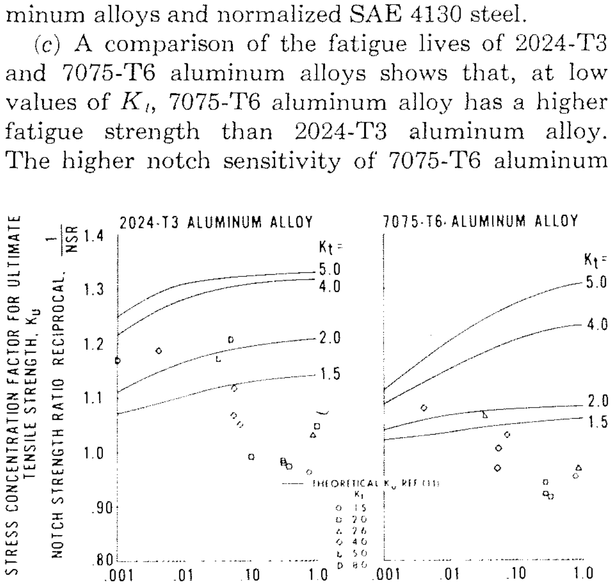

Fig. 10—Comparison of notch strength with theory based on cracked specimens

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