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THE EFFECT OF SPECIMEN SIZE ON THE FATIGUE CRACK STRENGTH OF CYLINDRICAL SPECIMENS OF HEAT-TREATED 4340 STEEL

E. P. Klier

Consultant
Metallurgy Division

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U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

Structures subject to severe service loads frequently fail by the development of free-running (brittle) cracks. Such cracks propagate at such very high velocities that they are difficult to observe, while at the same time their incidence may be difficult to control. This type of failure results from the fact that the high-strength properties now desired in structural materials tend to enhance embrittlement, while a number of factors influence the severity of the embrittlement experienced. Factors that are known in some measure to influence the toughness of high-strength steel in addition to strength level are (a) the testing temperature, (b) the specimen size, (c) the specimen geometry, and (d) the strain rate.

The present series of tests for a one-inch-diameter fatigue-notched specimen constitutes an extension of a previous series of tests for a one-half-inch-diameter specimen. The principal change introduced is the specimen size. This change in specimen size leads to minor variations in the fatigue-notch tensile-strength data, but for certain material conditions and specimen-size ranges the notch strength can be profoundly altered. The ductile-brittle transition indicated is critically dependent on tensile strength. During the course of the present tests load-elongation curves were taken, and these have allowed the examination of the ductile-brittle transition as established by stress, by strain, and by means of energy absorption. The experiments suggest that the stress-strain relations in certain fracture tests correspond to those measured for the notch tensile test.

PROBLEM STATUS

This is a final report on one phase of this problem; other phases of the problem are continuing.

AUTHORIZATION

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THE EFFECT OF SPECIMEN SIZE ON THE FATIGUE CRACK STRENGTH OF CYLINDRICAL SPECIMENS OF HEAT-TREATED 4340 STEEL

INTRODUCTION

The notch-strength properties of 4340 steel have been measured previously for a one-half-inch-diameter cylindrical specimen containing a fatigue notch (1). These data were compared with previous data (2,3) for similar specimens containing the sharpest possible machined notches. It was concluded that the fatigue notch leads to a significantly more severe notch condition than does the sharpest machined notch. It may be expected, then, that this notch configuration would be of importance in size-effect studies, and that the need for notch-strength-property measurements for different size fatigue-notched specimens is indicated. In the present work the notch properties for one-inch-diameter cylindrical fatigue-notched specimens of 4340 steel are reported.

The 4340 steel studied is the same as that used earlier (1,3), and the testing conditions are comparable with those used in the earlier work. In addition to the usual notch-specimen measurements, stress-strain curves for the notched specimens also were taken. These data allow comparisons of the notch-tension data with fracture-transition data obtained for a variety of test conditions.

EXPERIMENTAL PROCEDURE

Test Specimen

The 4340 steel composition was 0.41 C, 0.79 Mn, 0.013 P, 0.016 S, 0.31 Si, 1.83 Ni, 0.77 Cr, and 0.23 Mo. Available 1-1/2-in.-diameter bar stock was forged to slightly over one inch diameter. Suitable blanks were heat treated by quenching in oil from 1550°F, followed by tempering 2 + 2 hours at selected temperatures. The heat-treated blanks were ground and machine-notched, after which a fatigue crack was formed at the base of the notch. The specimen ends were next threaded, and the specimen was ready for testing. The specimen configuration at this point is indicated in Fig. 1.

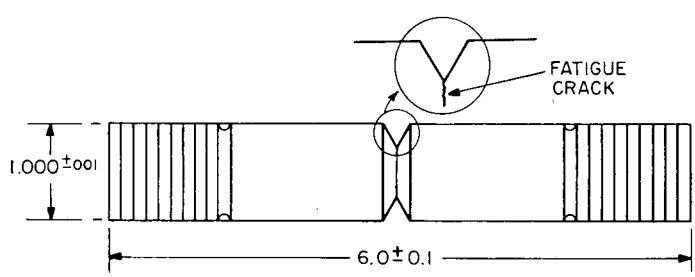


Fig. 1 - The notch-fatigue specimen ready for tension testing. Measurements are in inches.

Notch-Tension Test Procedure

The specimens were pulled at 75°F in air, at -110°F in dry ice and a mixture of one part carbon tetrachloride and one part chloroform, and at -323°F in liquid nitrogen. The stress-strain curve was autographically registered for each test. The notch strength was calculated with reference to the fatigue-notch diameter, and notch-strength ratios (notch strength/tension strength = notch-strength ratio = NSR) were calculated by reference to available comparative tension data (4).

EXPERIMENTAL RESULTS

The notch-strength data for the 1.0-inch-diameter specimens are presented in Fig. 2 for three testing temperatures in comparison with the notch-strength data taken for the 0.5-in.-diameter specimen. The transition from low to high notch strength is influenced by the change in specimen size, and for the larger specimen the transition is measured at a tensile-strength reduction of from 10,000 to 20,000 psi. This reduction, while here attributed to specimen size, may, however, be due to the modification in heat treatment that would arise because of the differences in heat-treated section size (3).

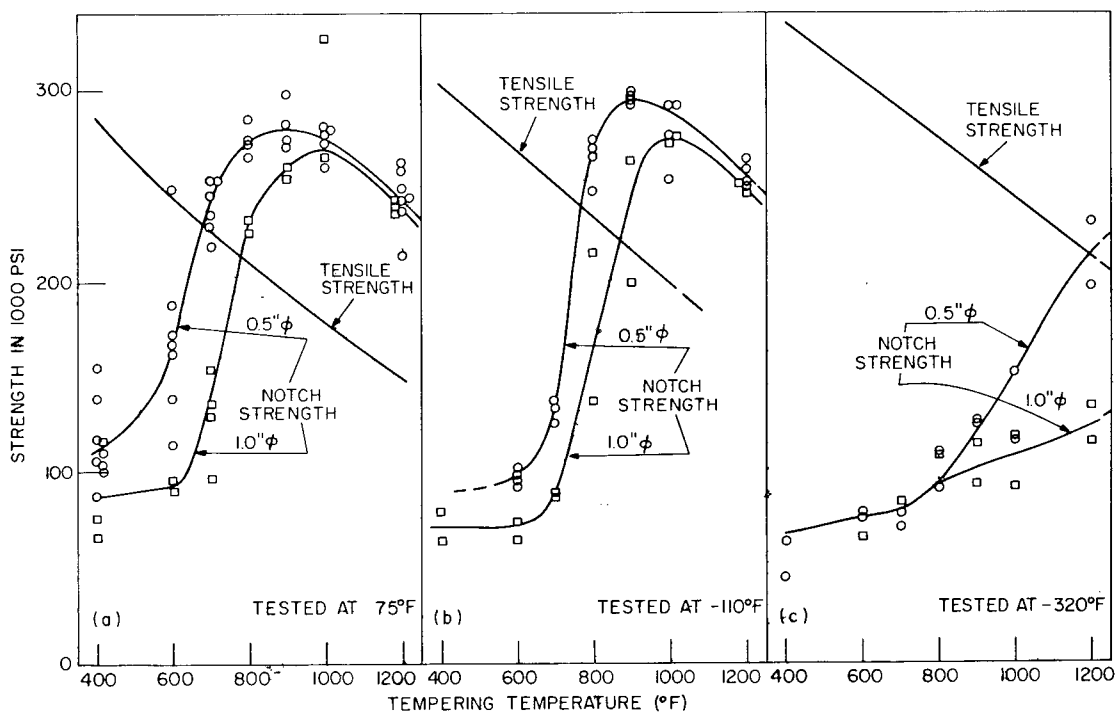


Fig. 2 - Tension and notch-tension strength data as functions of tempering temperature for the indicated test conditions

While the ductile-brittle-strength transition condition is somewhat adjusted for change in specimen size, the ductile-notch strength is in good agreement for comparative measurements at the two specimen diameters. The brittle strength for the lowest-temperature tests is in satisfactory agreement for the two specimen sizes. However, it is probable that the brittle-strength measurements are not as reliable as are the ductile-strength measurements (5).

The maximum ductile-notch strength is measured at a probable average value of 300,000 psi. The brittle-notch strength is assigned a probable value of 100,000 psi. These probable values will be discussed at greater length in a future report.

The notch-strength data as a function of testing temperature are presented in Fig. 3 for three specimen types. In the left-hand graph, the specimen is 0.3 in. diameter with a 50-percent notch of root radius 0.001 in. In the center graph, the specimen is 0.5 in. diameter with a fatigue crack, while in the right-hand graph, the specimen is 1.0 in. diameter with a fatigue crack. The small specimen yields notch-strength data that are significantly optimistic compared with those obtained with the fatigue-cracked specimens. The fatigue-cracked specimens yield notch-strength data that are in relatively good agreement, but the ductile-brittle transition temperatures for the comparative heat-treated conditions are measured at somewhat higher temperatures for the larger specimens.

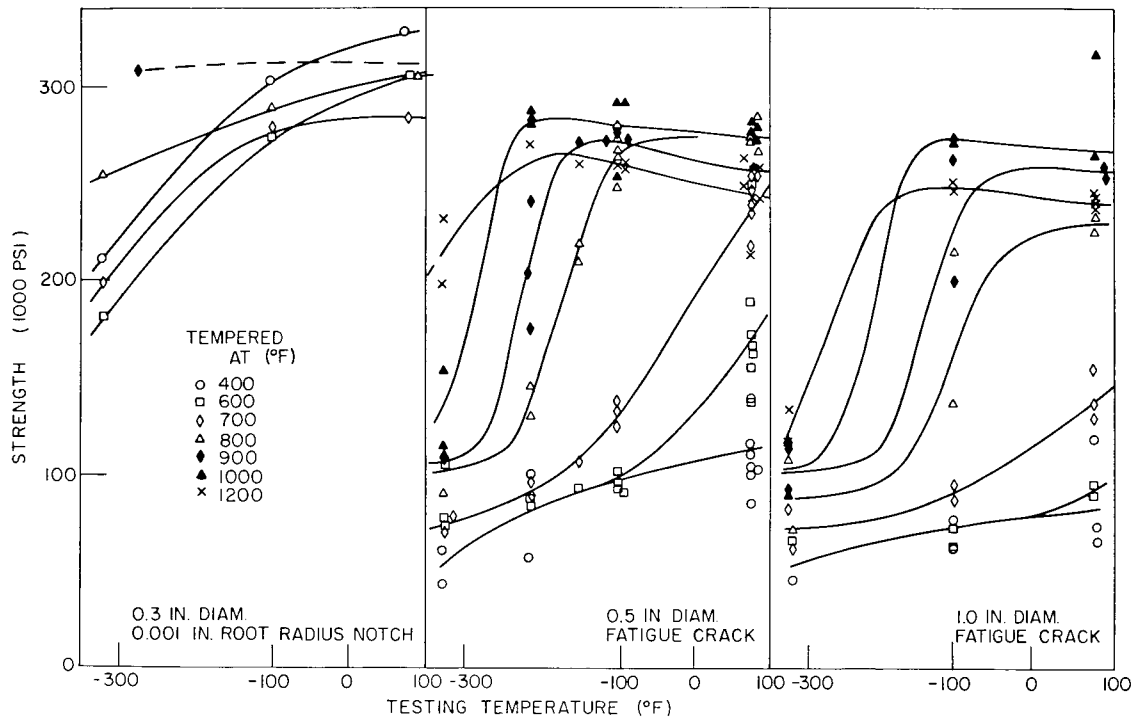


Fig. 3 - Tension and notch-tension strength data as functions of testing temperature for the indicated test conditions

As will be demonstrated later in this report, the temperature at a notch-strength ratio equal to one in the notch-tension test corresponds to the NDT (nil ductility transition temperature) measured in the drop-weight test. The ductile-brittle transition data for NSR = 1 for the three notch-tension specimens, therefore, are presented in comparison with NDT measurements reported by Puzak (6), as shown in Fig. 4. The several curves are more or less parallel, suggesting that they are qualitatively related. It is evident, however, that ultimate quantitative agreement of the ductile-brittle-transition measurements obtained for the different tests must await the introduction and evaluation of factors in addition to those that have been studied in the present work.

In the earlier work with fatigue-cracked specimens, it was observed that failure of the specimen frequently was accompanied by readily observable plastic strain.

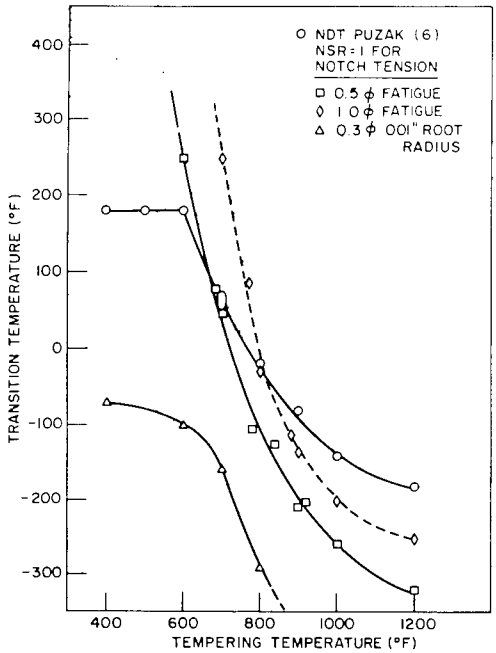
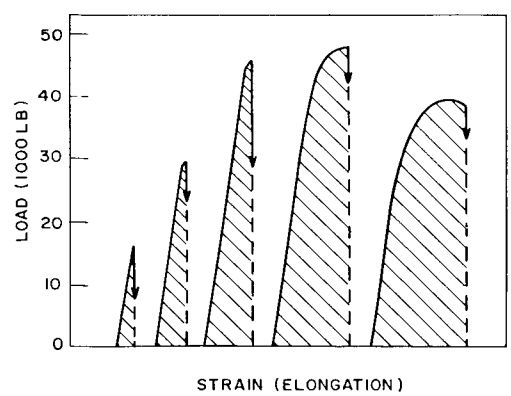


Fig. 4 - The notch properties transition temperatures for 4340 steel by the indicated criteria for comparative test conditions

Consequently, in the present work load-elongation curves were autographically taken for each test. Typical traces are presented in Fig. 5. For notch-sensitive material conditions, failure was unaccompanied by substantial plastic strain. With change in material condition, the load-elongation curve is progressively modified to indicate ductile-brittle transitions in both the ductility and load-bearing capabilities of the specimens. These ductile-brittle transitions are further illustrated in Fig. 6.

Fig. 5 - Load-elongation curves for selected notch-tension specimens



The notch-strength data are plotted in Fig. 6 as notch-strength ratio for three testing temperatures, and plastic strain is reported as plastic-strain units. The transitions from ductile to brittle for the two constructions are indicated. For notch-strength measurements, the ductile-brittle transition by definition is measured for NSR = 1. For the plastic-strain measurements the nil-ductility transition, or NDT, is by definition the condition of vanishing plastic strain. The two transition criteria for the fatigue-cracked specimens under study are identical. This is due to the high rate of change of notch strength with variation of any pertinent variable in the transition interval, so that an adequate approximation to the yield strength is probably given by the tensile-strength value.

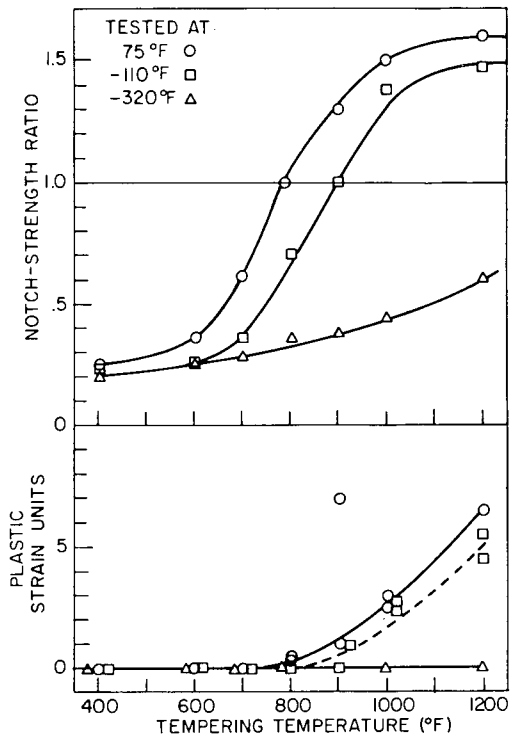


Fig. 6 - The notch-strength ratio and notch strain for 4340 steel specimens tested as indicated

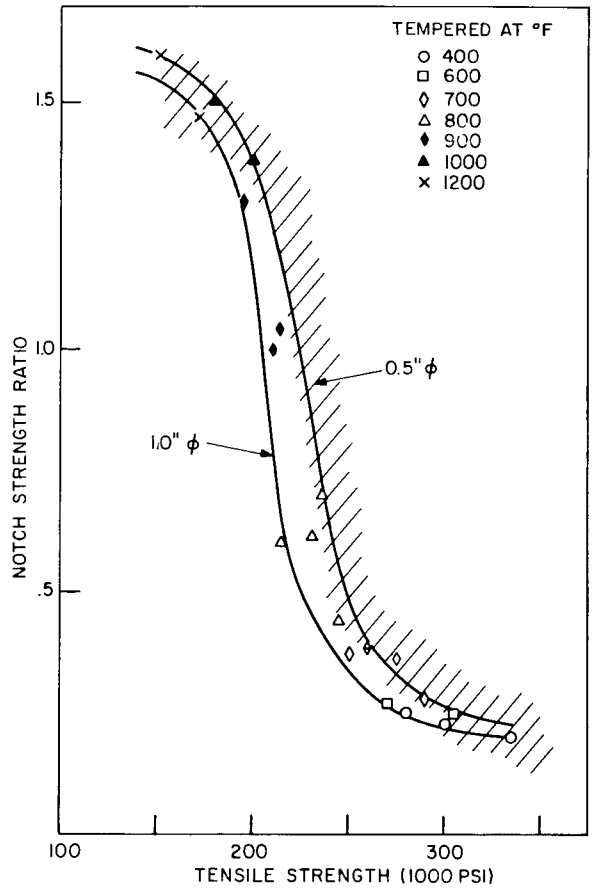


Fig. 7 - The notch-strength ratio versus tensile strength for 4340 steel tempered as indicated

The notch-strength ratio is plotted against tensile strength in Fig. 7. The data for the 0.5-in.-diameter specimens are indicated by the cross-hatching in the figure. The data for the 1.0-in.-diameter specimen are contained within the solid lines. At the maximum and minimum values of the NSR, the two sets of data are in agreement. In the transition interval the larger specimen gives the transition at the lower tensile strength. It is again noted that this slight displacement may be attributed to the change in size of the specimens, or there may be a heat-treating factor involved. The fractures of all specimens were observed and were found to correlate with the fractures obtained with the 0.5-in.-diameter specimens.

DISCUSSION

In the presence of a fatigue crack, a break in the heat-treated 4340 steel investigated can be considered in terms of the tensions required in the breaking section, the strains developed at the separating interface, and the interactions of these two quantities. The full description of the breaking process requires a detailed correlation of the local stresses and strains and the accelerations associated with crack propagation, and this correlation has not as yet been achieved. However, the data collected in the present work will allow limited discussion of these quantities. For example, the brittle and tough notch-strength conditions, generalized, allow the construction of ductile-brittle

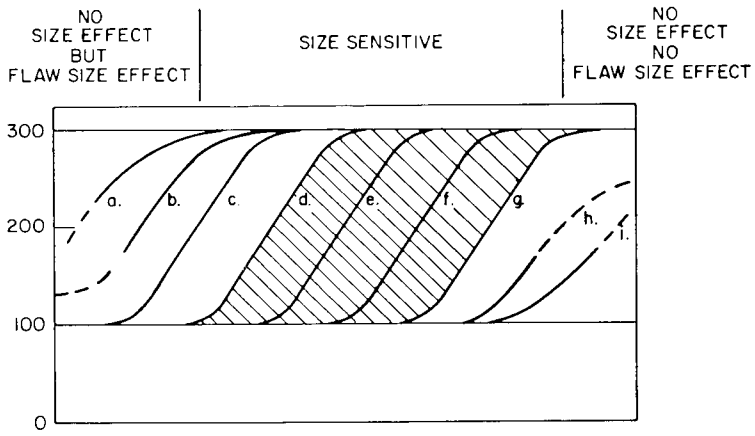


Fig. 8 - Idealized notch-strength transition curves, with selected variables as parameters. The transition curves are proposed to move from a toward i as: The notch-root radius is reduced, the testing temperature is reduced, the tensile strength is increased, the specimen size is increased, the strain rate is increased.

transition curves with indicated displacement for variations in pertinent variables (Fig. 8). In the lined interval, variations in the factor of concern for a specified parameter can lead to attainment of both idealized tough and brittle conditions. An ordinary type of ductile-brittle transition is effected. With displacement of the curve measured across the set of curves to the left, the fully brittle condition becomes increasingly difficult to achieve, while with displacement to the right a fully ductile condition becomes increasingly inaccessible. The notch-strength curves in these intervals have been drawn to conform to trends experimentally observed. The set of curves, consequently, is proposed to encompass all possible forms of ductile-brittle transitions that are based on notch-strength measurements. Notch strength for a given material is known to depend on notch-root radius, testing temperature, strength level, specimen size, and strain rate. The manner in which these factors potentially influence the notch strength is indicated in the legend to Fig. 8.

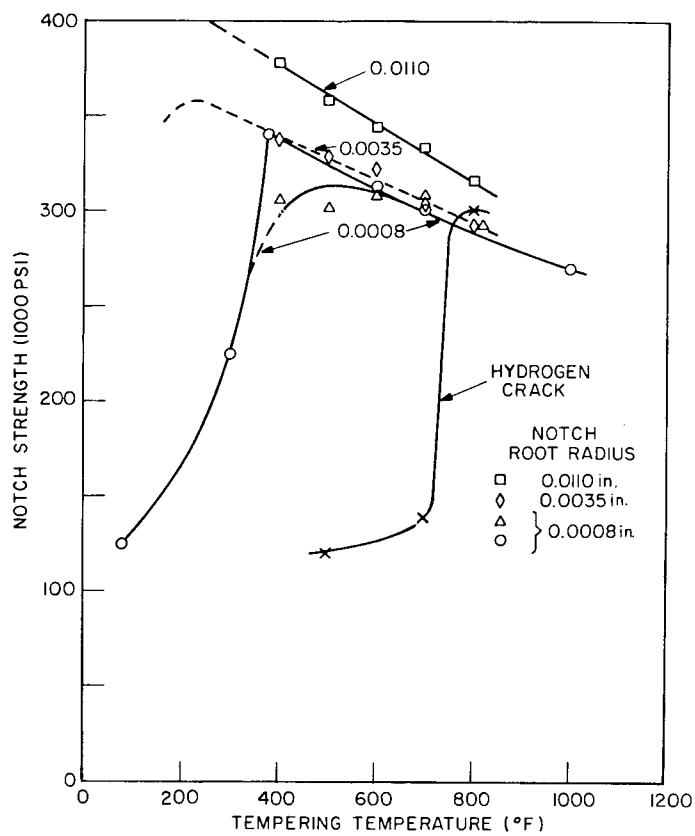
Since the present work is intimately concerned with the possible effect of specimen size on the notch strength of a given specimen configuration, it is also desirable to consider a second aspect of this phenomenon as it arises in practical test evaluation. For a given material condition, two factors must be considered: the gross specimen dimensions and the stress-raiser configuration. It is postulated that where the range of the parameter of concern leads to essentially brittle-strength evaluation, the problem may perhaps best be considered as one of flaw-size effect. When ductile strength only is being evaluated, the problem is not one of size effect or of flaw-size effect only, but is rather one amenable, in principle, to solution by plastic-stress analysis. In the intermediate ductile-brittle interval, neither analysis available for the ductile and brittle strength intervals can be expected to give quantitative answers. The results will depend on the dimensions and configuration of the specimens being tested and compared, without conformation to the laws of similitude that apply to the two extreme intervals. It is evident that quantitative analysis of fracturing in this last interval is, in principle, more complex than that arising in the brittle- and ductile-fracture intervals.

Factors Which Modify Notch-Strength Transitions

For the factors of importance in determining notch strength in Fig. 8, limited data to demonstrate the notch-strength transitions are available except for strain rate. The role

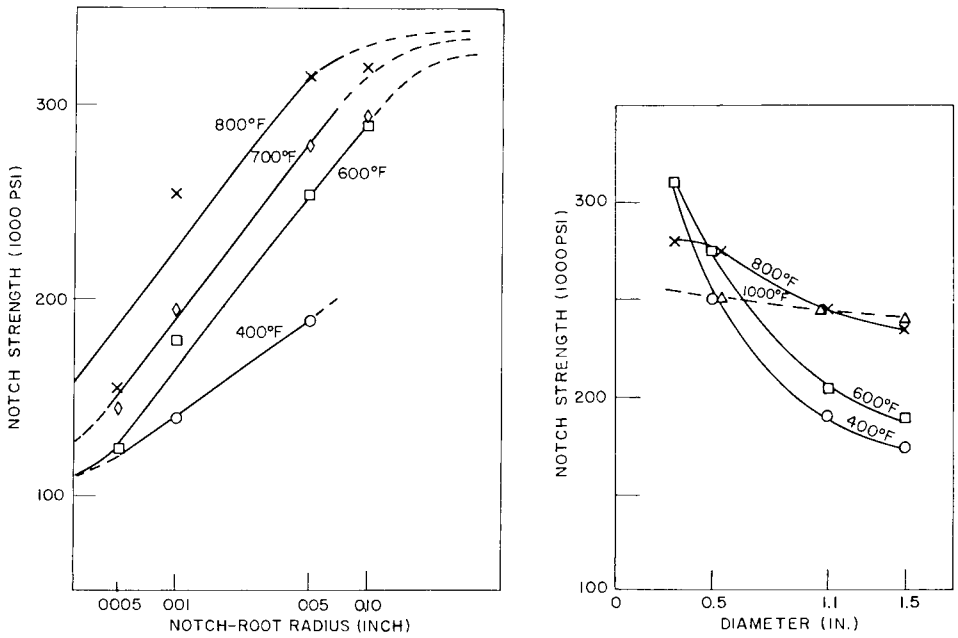
of strain rate in modifying the notch strength should probably be considered as unresolved at this time, although many strain-rate evaluations have been completed for smooth specimens (7-10).

The modification of the notch strength through modification in the notch-root radius is illustrated in Fig. 9a, where with notch-root radius as a parameter the notch strength is reported as a function of tempering temperature. As the notch-root radius is increased from that corresponding to a hydrogen crack, which is considered the limiting sharp notch and which gives the maximum displacement of the ductile-brittle transition to the right in Fig. 8, the ductile-brittle transition is lowered to tempering temperatures corresponding to higher strength conditions. The data plotted against notch-root radius with tempering temperature as a parameter are given in Fig. 9b. It may be seen that a given strength (tempered) condition becomes embrittled characteristically as the notch-root radius becomes increasingly smaller. There is then a ductile-brittle transition as a function of the notch dimensions. The notch strength versus specimen size with tempering temperature as a parameter and for constant notch-root radius is given in Fig. 9c. The embrittling effect of specimen-size increase for a sensitive material is readily evident in this figure. It may also be seen that the variation of notch strength with variation in specimen size is not a simple relationship. The variation of notch strength with change in testing temperature has been illustrated in Fig. 3.



a. Notch strength vs tempering temperature with notch-root radius as a parameter

Fig. 9 - Notch-strength data for 4340 steel tested at 75°F. The notch-root radius is 0.001 in.



b. Notch strength vs notch-root radius, with tempering temperature as a parameter

c. Notch strength vs specimen diameter, with tempering temperature as a parameter

Fig. 9 (continued) - Notch-strength data for 4340 steel tested at 75°F. The notch-root radius is 0.001 in.

In each of the sets of transition curves, it is evident that the ductile-brittle transition occurs in such manner that it is not readily established by extrapolation. It is only when the material and testing conditions are already in the transition zone that extrapolation of properties is possible. The practical significance of this observation is that a test for material control should be designed to encompass the extreme conditions to be encountered in service if complete freedom from brittle failure is to be assured. However, from the data presented it is clear that the breaking phenomenon is influenced to the greatest extent by the notch configuration. If the notch is extremely sharp, as is the case for the fatigue-cracked specimens, property modification due to action of the other variables is minimized. The use of the fatigue-cracked specimen should lead to data which establish a reference in ductile-brittle-transition studies.

Notch-Strength Transitions in Fracture Tests

For tests in which the transition condition is established by the disappearance of ductility in the fracture process, relatively little effort in the past has been directed at measurement of the stress associated with crack initiation and propagation. Such investigations are difficult to execute and evaluate, due largely to uncertainty in the measurement of the stress at crack initiation. This stress evaluation is difficult, especially because of the plastic strain that is associated generally with crack initiation. This plastic strain leads to overloading, which influences the subsequent rate of crack acceleration once it has been initiated; again few data are available for consideration of these quantities. The correlated notch strength and strain measurements shown in Fig. 6 allow discussion of this point in qualitative terms, and the notch-strength data obtained in the present work are compared with the data obtained with the three test procedures now in use at NRL for the evaluation of fracture behavior. These tests are described as (a) the drop-weight bend test, (b) the drop-weight tear test, and (c) the explosion tear test.

For the purposes of the present discussion, the three tests possess the following important similarities and differences (11-14).

- In the drop-weight bend test, a notch is made in a brittle weld bead which is loaded in tension by the impacting weight. The specimen is bent sufficiently to allow the weld bead to break and is then brought to a stop by impacting on the bottom of the specimen support. The test evaluates the resistance of the specimen material to brittle crack propagation in the presence of a severe crack in a stress field equal to the bend yield strength of the specimen material.

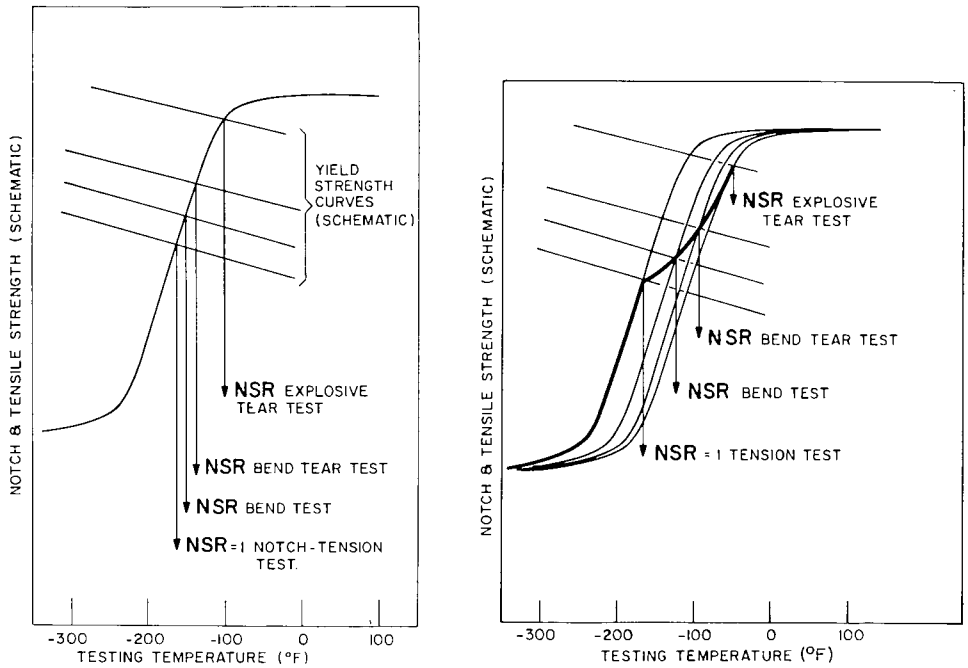
- The drop-weight tear test differs in two important details from the drop-weight bend test, although the two tests are executed in similar fashion. The section for the tear specimen is deep, and crack propagation is essentially in the direction of movement of the impacting load, while in the bend test crack propagation is essentially at right angles to the movement of the impacting load. In the tear test the brittle section – corresponding to the brittle weld bead in the bend specimen – may be increased to relatively large dimensions. For this latter condition the crack is initiated, accelerated to high velocity, and then at this velocity impacts on the material being evaluated. Three factors – the sharp crack, high impacting velocity, and modified stress gradient – now potentially influence crack propagation. The test then is of importance in measuring the crack-stopping characteristics of the material tested.

- In the explosive tear test, fracture is initiated in a centrally positioned brittle weld. Loading of the specimen is effected by a suitable explosive charge, which activates the crack starter. Depending on the material condition, the crack will run either as a ductile or brittle crack, but it will always run. This test may be considered as establishing an extreme upper limit to the severity of conditions in the loading of a structure. If the material survives this test with a ductile failure, it may be expected to perform in a structure as a ductile material.

The fracture-stress conditions for the three tests, it is now proposed, are generated in the notch strength-yield strength frame of reference versus testing temperature analogous to that measured for the notch-tension test. As a first approximation, it is now assumed that the notch-strength curve is unaffected by strain rate. The yield-strength and tensile-strength curves, however, are known ordinarily to increase with increasing strain rate (7,8). Superposition of the notch strength-yield strength curves then gives the results in Fig. 10a. As the strain rate increases, there will be a gradual increase in the temperature of intersection of the tensile strength-notch strength curves due to the upward displacement of the yield-strength curve. If in addition the notch-strength transition is displaced to higher testing temperatures, there will be an added displacement of the point of intersection of the strength curves, and this will give the results presented in Fig. 10b.

The relationships advanced in Fig. 10 correspond to the rather unique conditions associated with reasonably available test procedures. These test procedures have without exception been designed to yield the most sharply notched test condition that is feasible. This has been done explicitly to establish the conditions under which a running crack may be stopped by a given material in a specified strength condition. With modification of the experimental conditions it is possible to displace the fracture-stress-curve transition to lower temperatures or in the direction of higher-strength conditions. The significance of Fig. 10, in which such temperature displacements have been illustrated, is that it establishes the interval in which brittle crack propagation may potentially be expected in service applications.

For example, in Fig. 11, curve a to the right corresponds to the limiting curve in Fig. 10. By modification of the notch configuration the fracture stress can be displaced to position b to the left. If now a crack is established in the structural member which



a. Velocity-insensitive notch-strength condition

b. Velocity-sensitive notch-strength condition

Fig. 10 - NSR conditions schematically represented for the indicated tests

initially gave curve b, crack propagation will take place, governed by the relationships in curve a. The temperature displacement of curve b to curve a can readily amount to 300°F to 400°F. Thus if curve b has been used to predict crack-propagation characteristics for the structural material, the likelihood of failure in service by brittle-crack propagation may be high. This projected behavior corresponds with experience, as the voluminous literature related to fracturing in high-strength metal structures attests.

Energy Absorption in the Notch-Tensile Test

The final procedure for evaluating the notch-tension-test results is to examine the interaction of the stress-strain terms at fracture. The proposed interactions lead to the statement of fracture-energy terms or their equivalents. These are usually energy-absorption terms, as measured in the impact test, or G_c (energy-release-rate) terms, as measured in fracture mechanics. Depending on circumstances, these energy terms may be measured relatively free from error, or they may be so erratic as to be practically useless for materials evaluation. Potential error in the test is related to reproducibility of the test, and this reproducibility has frequently proved difficult to achieve with certain tests. But it is perhaps useful to consider the fracture-strength and fracture-energy terms for a selected set of Charpy impact and notched tension specimens. Data trends for the comparison are entered in partial schematic form in Fig. 12.

The energy required to break a brittle 4340 steel impact specimen at about 75°F may be estimated at about 10 ft-lb. As the testing temperature is increased this value is slightly raised, but it is only for intermediate and low-strength conditions that a well-established ductile-brittle transition is obtained (15,16). The change of impact strength with change of structural condition, therefore, may more lucidly be examined for the

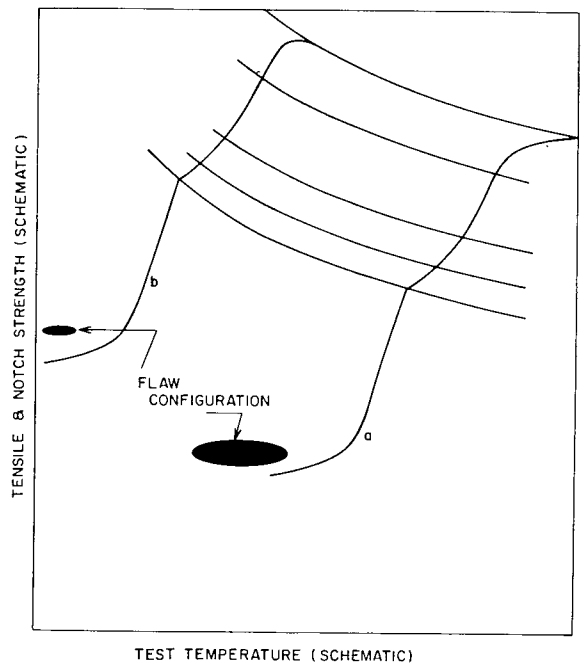


Fig. 11 - Displacement of the notch-strength curve by modification of flaw configuration (schematic) (a) notch-strength curve for a large flaw (b) notch-strength curve for a small flaw

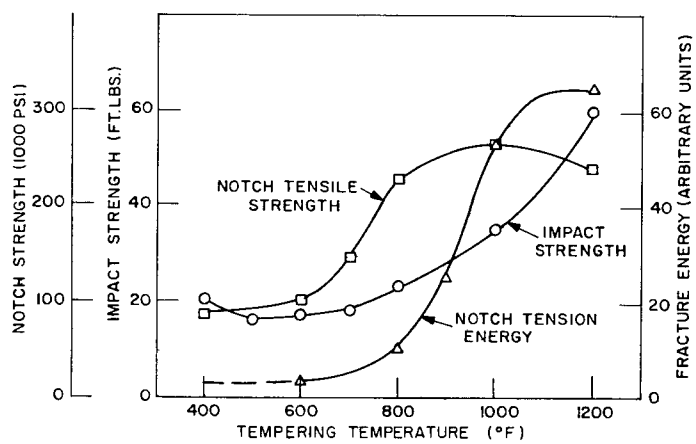


Fig. 12 - Ductile-brittle transition as measured for fatigue notch tension and Charpy V-notch specimen, tested at 75°F

ductile-brittle transition. Notch-strength and energy-absorption curves for the notch tension, and impact specimens as function of tempering temperature, as tested at 75°F, consequently are used for illustration in Fig. 12.

The impact-strength and notch-strength values, both of which generate ductile-brittle transitions, do not agree quantitatively. The fracture-energy curve for the notch-tension test is displaced to higher tempering temperature than is the notch strength, but again quantitative agreement in the sets of comparative data is not adequate. Since the

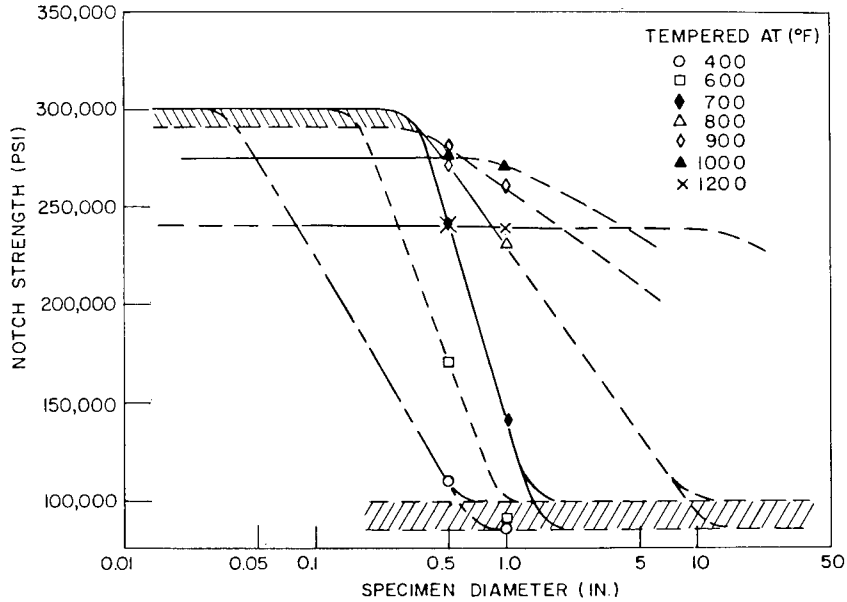


Fig. 13 - Notch strength vs log of specimen diameter for fatigue-cracked 4340 steel, tested at 75°F

notch configuration for the impact test is milder than that for the notch-tension test, this lack of quantitative correlation is attributed to the probable embrittling influence of strain rate in the impact test compared with the lack of this effect in the static notch-tension tests. The data presented are not at this time adequate for further discussion.

From the foregoing discussion it is evident that size-effect studies may be conducted in which the criterion of performance is based on strength measurements, ductility measurements, or again on the product of interaction of these two quantities. In general, an index of performance based on a ductile-brittle transition established by means of stress measurements will yield a more liberal evaluation of this transition than will one based on energy measurements. The data that have been collected pertain mainly to fracture-stress values, and size-effect phenomena are best considered for this quantity. Pertinent data are plotted in Fig. 13.

The notch-strength specimen-diameter curves illustrate the relatively mild variation of the notch strength for both the notch tough and fully brittle conditions. For intermediate materials, strong size-effect-dependent variations in notch strength are indicated. It will be noted that the fatigue-crack data do not agree fully with those data obtained for hydrogen-cracked specimens. This divergence in results cannot be resolved at this time, but it suggests that blunting of the sharp crack has taken place in the fatigue process.

For the fatigue-crack notched specimens, size-effect phenomena are observed. From Fig. 13, however, it is evident that this phenomenon is best considered as characteristic of material conditions that are transitional between full notch tough and notch brittle. For fully notch-tough and fully notch-brittle materials, the notch properties are measured as mildly size sensitive. The data, in the main, may as a consequence be taken as in support of the thesis developed by Klier and Weiss (2) that certain material conditions may best be considered as non-size sensitive in the treatment of fracture phenomena.

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CONCLUSIONS

The fatigue-notch strength of one-inch-round bars of heat-treated 4340 steel has been measured as a function of tempering and testing temperature. For the most part the data obtained are in qualitative agreement with comparative measurements obtained with one-half-inch-diameter fatigue-notched bars. In the present work, however, the test procedure has been adjusted to allow the taking of the load-elongation curve for each specimen. The following conclusions may be stated.

1. Data have been obtained from experiment, and in part extracted from the literature, to demonstrate the effect of changes in notch configuration, strength level, specimen size, and testing temperature on the notch strength of 4340 steel. Under suitable conditions each of these factors can promote a ductile-brittle transition.

2. It is suggested that strain rate is also a pertinent factor in fracture studies of high-strength steels, but definitive data are not available for the resolution of this question.

3. The condition of NSR = 1 corresponds to the point of vanishing macroscopic plastic strain in the notch-tension test.

4. By the assumption that the stress at breaking in fracture tests, in general, parallels that measured in the notch-tension test, it has been possible to discuss at length certain relations between the energy to fracture and the stress-strain conditions leading to fracture.

5. Ductile-brittle transition curves can be obtained in terms of notch strength and fracture energy for fatigue-notched high-strength steels. These transitions do not coincide, nor do they coincide with comparable impact-strength transitions measured in the impact test.

6. Type 4340 steel conditions exist for both high- and low-temperature tempering that are relatively non-size sensitive, as measured for fatigue-notched specimens. Since, however, the strength of a structural component is determined by the presence or absence of an embrittling stress raiser, the 4340 steel may regularly be used in such a manner that size effect would be experienced.

7. By use of the fatigue-notch data, the susceptibility of a material condition to size effect can probably be satisfactorily established.

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