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# Conditions of Failure in Fatigue Cracked 4340 Steel

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## ABSTRACT

For a fatigue-cracked tension specimen, the conditions of plastic failure, i.e., the stress conditions under which the section under the notch becomes plastic, have been developed by Hill. The analysis assumes the material to be ideally plastic, but, nonetheless, should be adequately approximate for heat-treated 4340 steel. Tension tests have been completed, and the results have been used to predict the notch strength for 4340 steel heat-treated to strength levels characteristic for this steel. The calculated notch-strengths have been compared with the notch strengths which were earlier measured and reported. For limited conditions the calculated and measured values are found to be in adequate agreement. Differences in the calculated and measured values in the plastic failure interval can be attributed to the strain-hardening to which the 4340 steel is subject.

At values for the notch strength greater than the yield strength, ultimate failure by fracturing in the fatigue-cracked specimens takes place by crack development from the notch base, which development is greater the more the notch strength exceeds the yield strength. Following development of this crack, separation of the section is cataclysmic. Because of this, it is possible to establish both a nominal notch strength and a fracture notch strength. The nominal notch strength can be determined readily. The fracture notch strength is more difficult to determine, but the limit of this quantity can be estimated. This limit is set at about 500,000 psi for the most crack resistant materials.

The conventional tensile properties of 4340 steel at the several strength levels examined agree with the data in the literature except that the ductility is reduced. The true-stress natural-strain data indicate a transition in the strain-hardening exponent ($n$) from high to low values as the tensile strength increases from the minimum to the maximum values measured.

## PROBLEM STATUS

This report completes one phase of the problem; work on other phases of the problem is continuing.

## AUTHORIZATION

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## DEFINITIONS

$\sigma_1, \sigma_2, \sigma_3$ - Principal normal stresses in usual order

$\delta_1, \delta_2, \delta_3$ - Principal natural strains; $\delta_1 + \delta_2 + \delta_3 = 0$

$k$ - Flow stress measured in shear. It is related to true tensile stress by $\sqrt{3}k = \sigma$. For a perfectly plastic body $k$ is invariant and equals the yield strength. For a strain hardening material, i.e., the present steel, $k$ is a variable and takes on all values available corresponding to real values of $\sigma$.

$\sigma$ - True stress, $\sigma = L_i / A_i$

$L_i$ - Instantaneous load

$A_i$ - Instantaneous area

$\sigma_{YS}$ - Tension yield strength

$\sigma_N$ - Notch strength, $\sigma_N = P/A_N$

$P$ - Nominal load

$A_N$ - Area under the notch

$\delta$ - Natural strain, $\delta = \ln A_0/A_i$

$A_0$ - Initial area

$\delta_{ML}$ - Natural strain at maximum load

$\sigma_0$ - Strength coefficient

$n$ - Strain hardening exponent

($\sigma_0$ and $n$ are determined from the relation $\sigma = \sigma_0 \delta^n$.)

CONDITION OF FAILURE IN FATIGUE CRACKED 4340 STEEL

## INTRODUCTION

Yielding under combined stresses in metals is generally accepted as described by Tresca (1) with

$$\sigma_1 - \sigma_3 = \text{constant} \qquad (1)$$

or, where the intermediate stress is deemed important, as described by von Mises (2):

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 6k^2. \qquad (2)$$

These yield criteria (for two dimensions) are illustrated in Fig. 1, where it can be seen the two values differ by at most about 15%. The quantity $k$ is frequently described as the yield strength* in pure shear, and according to the von Mises yield condition $\sqrt{3}k = \sigma_{YS}$ for the customary tension test measurement of the yield strength.

By use of the von Mises yield condition, Hill (3) has developed analytically the conditions for yielding of a number of geometric forms among which are punch indented strips and circumferentially notched bars. Under certain conditions either of these two geometric forms yields in a compression stress field of the same value as the value of the tension stress field in which it yields (3,4). For the notched tension specimen configuration in Fig. 2 this value is called the notch strength and is given by

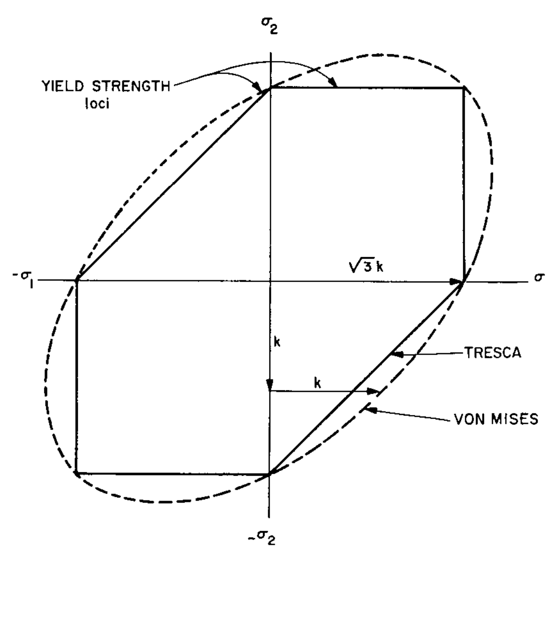



Fig. 1 - The yield strength loci under combined stresses according to Tresca and von Mises as indicated

*This follows in straightforward manner for a perfectly plastic body, but for strain hardening materials a strain-hardening law must be taken into consideration. This indicated adjustment may be difficult to make.

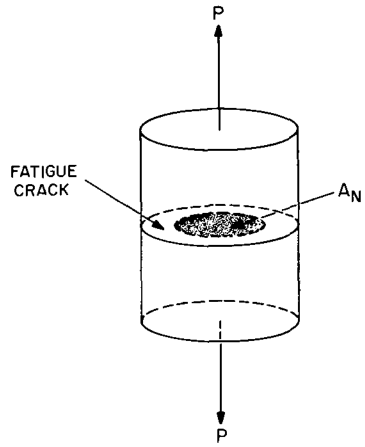



Fig. 2 - Schematic representation of the notched section in the fatigue-cracked tension specimen

$$\sigma_N = \frac{P}{A_N} = k\left(\frac{\pi}{2} + 1\right) = 2.57\ k\ . \tag{3}$$

This relation is derived for perfectly plastic materials and cannot be applied rigorously to structural steels. However, Orowan et al. (5) for tests on mild steel observed the relationship $\sigma_N = 2.6\ k$, although the mild steel in tension was observed to yield discontinuously. Further, Muvdi and Tong (6), for the related punch indentation problem, were able to obtain satisfactory agreement between theory and experiment for the yield conditions in a die steel under indentation.

The fatigue-cracked cylindrical specimens of 4340 steel which have been previously discussed (7,8) correspond to the specimen geometry in Fig. 2. The 4340 steel heat-treated to the several strength levels studied has a ratio of yield strength to tensile strength of about 0.9 and hence should not differ greatly from the requirements for a perfectly plastic material at the point of yielding. In the ductile-failure interval the yielding condition in the fatigue-notched specimens should be subject to Eq. (3).

To allow a more complete evaluation of the relations existing between tensile and notch strengths, the stress-strain relations in the 4340 steel previously studied have been determined. The results are presented herein.

## EXPERIMENTAL PROCEDURE

### Materials

The 4340 steel of composition 0.41 C, 0.79 Mn, 0.01 P, 0.016 S, 0.31 Si, 1.83 Ni, 0.77 Cr, and 0.23 Mo is the same steel used previously (7,8). This steel was austenitized at 1550°F. One set of specimens was oil-quenched, while a second set was first cooled to 1350°F and then oil-quenched. These two heat-treated conditions will be indicated on the graphs when significant.

### Tension Test Procedure

The small contoured tension specimen, Fig. 3, machined from broken 1/2-inch notch specimens (used for the work reported in Ref. 7) was pulled in tension with the load and minimum diameter being sensed to yield an autographic load-versus-diameter curve. The nominal-stress strain data were calculated, and, in addition, the true-stress natural-strain relationships were established. The $\sigma$-versus-$\delta$ data were not adjusted for the constraining effect of necking at loads beyond the maximum. Rather, the measurements were made in the relatively low strain interval 0.05 to 0.2.

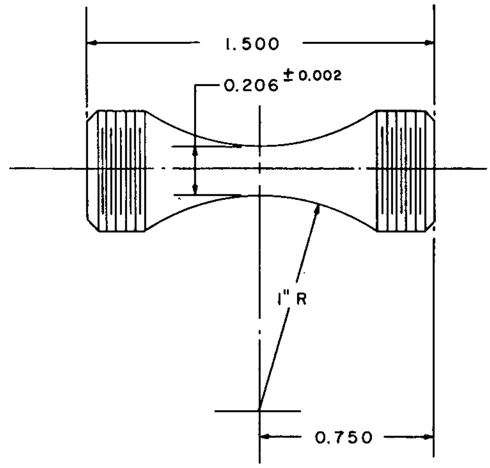



Fig. 3 - The tension specimen

## EXPERIMENTAL RESULTS

The numerical data are presented in Table 1.

### Tension Properties

A characteristic set of curves of nominal stress versus diameter change is presented in Fig. 4. The aggregate of maximum load strains is indicated on these curves and the envelope of the maximum load strain as a function of the tensile strength is entered in the figure. The maximum-load strain (diameter decrease) is a maximum for the minimum strength condition (the curve for the 1200°F tempering temperature). As the tensile strength increases to about 180,000 psi, the maximum load strain is relatively unchanged. With further tensile strength increase to about 220,000 psi, this quantity is continuously decreased to a value about one-half of the maximum observed and is stabilized at this value with further tensile strength increase. This transition in $\delta_{ML}$ indicated in Fig. 4 occurs in the same

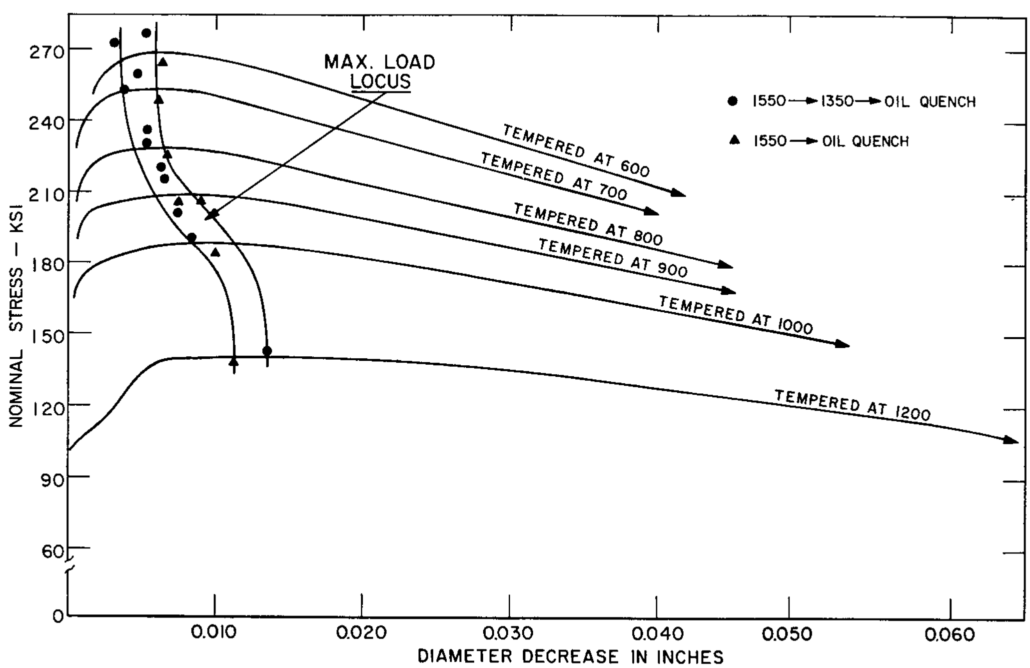



Fig. 4 - The load-versus-diameter curves for the indicated tempering temperatures for 4340 specimens tested at 75°F. The maximum-load points for all specimens tested and the envelopes of these points are indicated.

Table 1
The Tension Properties of 4340 Steel Tested at 75°F for the Indicated Tempered Conditions and the Calculated Notch Strengths ($\sigma_N = 2.57\ k$)

| Tempering Temperature (°F) | Specimen Number* | Tensile Strength (ksi) | Yield Strength (ksi) | Reduction of Area (%) | Strength Coefficient $\sigma_0$ (ksi) | Natural Strain at Max. Load $\delta_{ML}$ | Strain Hardening Exponent $n$ | Fracture Strain $\delta_F$ | $k = (1/\sqrt{3}) \times$ Yield Strength (ksi) | 2.57 $k$ (Yield Strength) (ksi) | $k = (1/\sqrt{3}) \times$ Tensile Strength (ksi) | 2.57 $k$ (Tensile Strength) (ksi) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 600 | KA-9 | 273 | 231.5 | 34 | 340 | 0.054 | 0.070 | 0.42 | 133.6 | 343.5 | 157.5 | 405 |
| | KA-11 | 267 | 231.5 | 22.7 | 330 | 0.054 | 0.060 | 0.39 | 133.6 | 343.5 | 154 | 398 |
| | K-18 | 265 | 202 | 38 | 340 | 0.069 | 0.080 | 0.48 | 116.6 | 299 | 153 | 393 |
| | Av. | 268.3 | 222 | 31.6 | 337 | 0.059 | 0.070 | 0.42 | 127.9 | 329 | 154.5 | 397 |
| 700 | KA-13 | 255 | 228.5 | 40 | 310 | 0.046 | 0.052 | 0.52 | 131.9 | 339 | 147 | 378 |
| | KA-14 | 248 | 214 | 40 | 295 | 0.042 | 0.052 | 0.45 | 123.6 | 318 | 143 | 367.5 |
| | K-32 | 249.5 | 220 | 36.5 | 320 | 0.069 | 0.080 | 0.46 | 127 | 326 | 144 | 370 |
| | Av. | 251 | 221 | 38.8 | 308 | 0.052 | 0.061 | 0.48 | 127.5 | 328 | 145 | 371.8 |
| 800 | KA-21 | 233 | 202 | 41 | 290 | 0.059 | 0.070 | 0.52 | 116.6 | 300 | 134.5 | 346 |
| | KA-24 | 225 | 205 | 41 | 290 | 0.092 | 0.070 | 0.55 | 118.4 | 304.5 | 130 | 334 |
| | K-41 | 225.5 | 202 | 39.5 | 290 | 0.077 | 0.083 | 0.50 | 116.6 | 299 | 130 | 334 |
| | Av. | 227.6 | 203 | 40.5 | 290 | 0.076 | 0.074 | 0.52 | 117.2 | 301 | 131.5 | 338 |
| 900 | KA-27 | 212.5 | 187 | 36 | 280 | 0.077 | 0.085 | 0.52 | 107.9 | 277.5 | 122.5 | 315 |
| | KA-30 | 216 | 188 | 40 | 280 | 0.092 | 0.085 | 0.52 | 108 | 277.8 | 125 | 321 |
| | K-51 | 207.5 | 196 | 44 | 277.5 | 0.10 | 0.090 | 0.57 | 113.1 | 290.25 | 119.5 | 307 |
| | K-55 | 206 | 184 | 42 | 277.5 | 0.10 | 0.109 | 0.54 | 106.1 | 272.5 | 119 | 306 |
| | Av. | 210.5 | 189 | 40.5 | 279 | 0.092 | 0.092 | 0.54 | 108.8 | 279.5 | 121.5 | 312 |
| 1000 | KA-33 | 188 | 163.3 | 46 | 260 | 0.092 | 0.109 | 0.58 | 94.25 | 242.5 | 108.5 | 279 |
| | KA-36 | 198.5 | 178 | 46 | 265 | 0.085 | 0.100 | 0.58 | 102.75 | 264 | 114.5 | 294 |
| | K-66 | 185.75 | 161.5 | 45.5 | 260 | 0.10 | 0.120 | 0.58 | 92.9 | 238.5 | 106.8 | 275 |
| | Av. | 191 | 167.6 | 46 | 262 | 0.092 | 0.110 | 0.58 | 97 | 248 | 109.9 | 283 |
| 1200 | KA-39 | 145 | 118.75 | 55.5 | 220 | 0.138 | 0.140 | 0.64 | 68.55 | 176.25 | 83.7 | 215 |
| | K-77 | 138.5 | 98 | 59 | 230 | 0.19 | 0.130 | 0.66 | 56.55 | 145.2 | 79.6 | 205 |
| | Av. | 142 | 108.5 | 58 | 225 | 0.164 | 0.135 | 0.65 | 62.6 | 162 | 81.6 | 210 |

*Specimens which were austenitized at 1550°F and oil-quenched are designated K specimens; those austenitized at 1550°F and cooled to 1350°F and oil-quenched are designated KA specimens.

strength interval in which the ductile-brittle transition is observed in the fatigue-cracked tension specimens (7,8).

With increase of the tensile strength (decreased tempering temperature), the reduction of area is gradually decreased (Fig. 5). Comparative data for 0.9-inch-diameter specimens (9) (dotted lines at lower left) suggest a possible ductile-brittle transition (tentatively indicated by drawing the hatched region with a down turn) for the small specimens (Fig. 3), which if it were verified would be atypical behavior for small specimens. Except for the reduction of area, the nominal tensile properties given in Fig. 5, are in satisfactory agreement with the tensile data that have been reported by a number of investigators for 4340 steel (9-11).

The true-stress natural-strain curves for a characteristic set of specimens are presented in Fig. 6 in ln-ln coordinates. Also reported are the maximum-load strains $\delta_{ML}$ and the envelope of these strains with variation in strength of the 4340 steel. The transition in the maximum load strain with increase in tensile strength is very evident in this frame of reference.

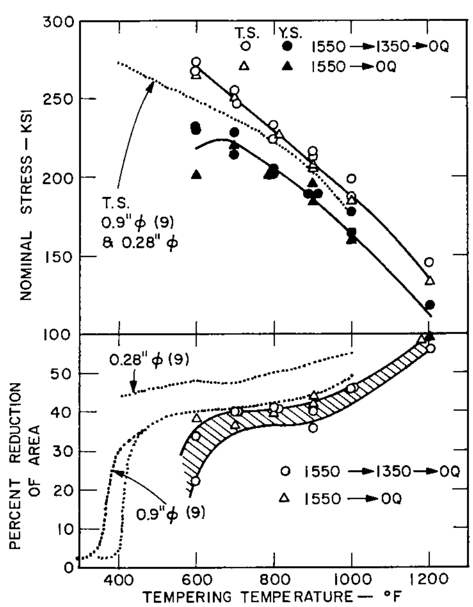



Fig. 5 - Summary of the nominal tensile properties of heat-treated 4340 steel versus tempering temperature. Comparative data for 0.28-inch and 0.9-inch specimens (9) are indicated.

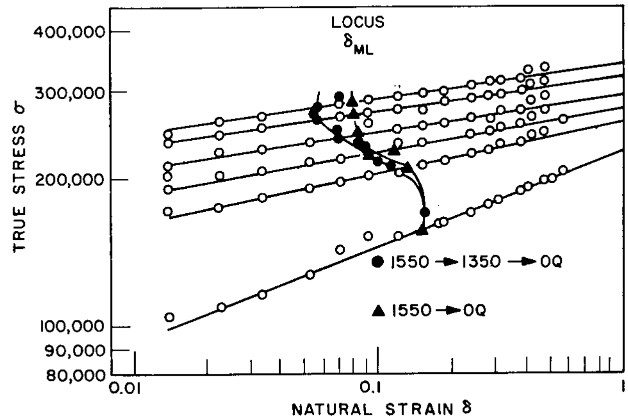



Fig. 6 - The true stress-natural strain curves in ln-ln coordinates for a characteristic set of 4340 steel specimens tested at 75°F

The strength coefficient $\sigma_0$ and strain hardening exponent $n$ which satisfy the expression

$$\sigma = \sigma_0 \delta^n \tag{4}$$

are plotted in Fig. 7, along with the fracture strain and the strain at maximum load, as functions of tempering temperature. These data are considered in agreement with the data of Larson and Nunes (12).

## Notch Tension Properties

The plastic-stress analysis for the fatigue-cracked specimens is expected to be most nearly correct for low levels of plastic deformation. At the same time it is necessary that the plastic deformation be accomplished without the development of a crack. For the specimens tested those that could acceptably be compared with these two restrictions were for the tempered conditions at 1000 and 1200°F (see Fig. 8). For the specimens tempered at 800°F and lower the notched section parted without becoming plasticized.

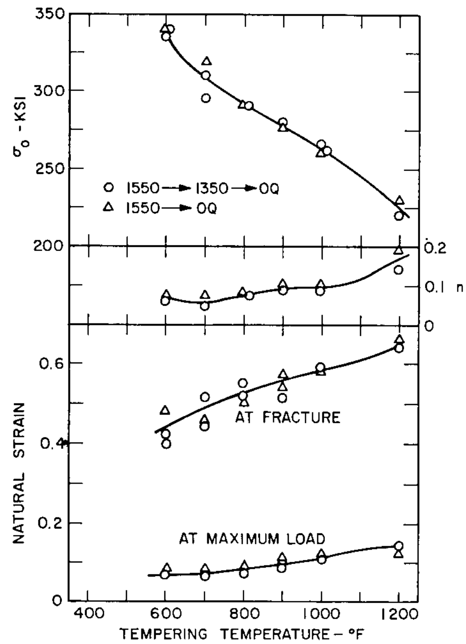



Fig. 7 - The strength coefficient $\sigma_0$, strain hardening exponent $n$, maximum load strain $\delta_{ML}$, and fracture strain $\delta_F$ versus tempering temperature for 4340 steel tested at 75°F

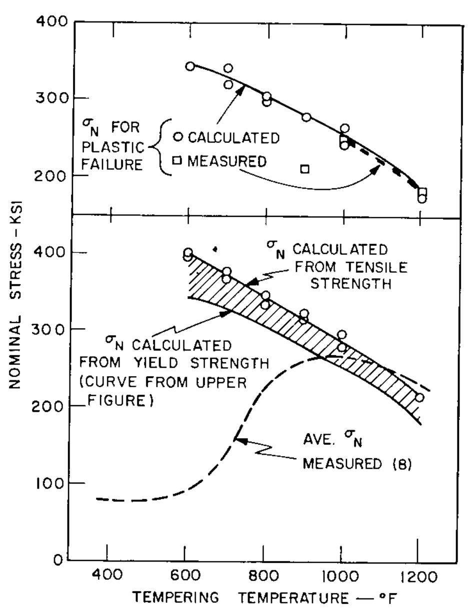



Fig. 9 - The calculated and measured values of notch strength versus tempering temperature for 4340 steel tested at 75°F

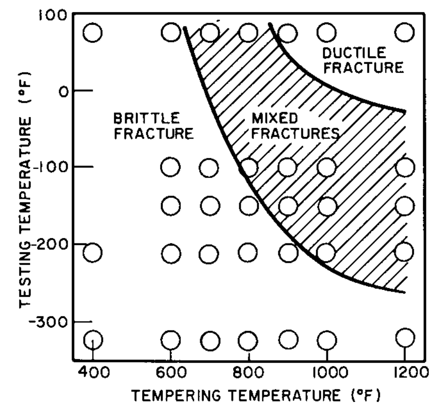



Fig. 8 - Failure mode as determined by fracture appearance in fatigue-cracked 4340 steel tension specimens for the indicated testing conditions

For specimens tempered at 800 and 900°F the notched section was, in part, plasticized, but the effects of crack development are believed to have intruded to modify the plastic failure load on the notched section.

For all tempered conditions that were tested in tension, a notch strength for plastic failure based on the yield strength can be calculated. Such values are given in Table 1 and are plotted in the upper part of Fig. 9. The notch strength calculated from yield strength measurements for the steel tempered at 1200°F is about 175,000 psi. This increases to about 250,000 psi for the 1000°F tempered structure. A maximum notch strength of nearly 350,000 psi is calculated for the steel tempered at 600°F. Comparative calculated and measured notch strength data are plotted in Fig. 9.

These notch strength data are presented in two forms, one of which is the customary notch strength value. However, it is emphasized, this value cannot, in general, be expected to agree with the value calculated for plastic failure. Thus a notch strength is measured for both brittle and ductile specimens, and, clearly, in the brittle fracture interval it is not a comparative measurement. In the ductile failure interval, due to strain hardening the notch strength is not fully compatible with a notch strength calculated from the yield strength. On the other hand, the desired comparative strength value can be obtained through inspection of the stress-strain diagram for the notched specimen and corresponds to the initial yield condition observed in this diagram. The notch strength values corresponding to this condition for tempering at 900, 1000, and 1200°F are given by the squares in the upper part of Fig. 9. These calculated and measured values of notch strength based on initial yield conditions for the two highest tempered structures are considered to be in good agreement.

The experimental notch strength data corresponding to yield strength measurements required for the above comparison are rarely taken, and it is desirable to obtain, if possible, a comparative set of calculated data for comparison with the customary notch strength measurements. Of possible interest is a calculated notch strength determined from $k$ measured at the tensile strength.* Notch strength values calculated for this stress condition are entered in Table 1 and are plotted in the lower part of Fig. 9.

The notch strength calculated from tensile strength is about equal to the experimental notch strength for the 1200°F tempered structure. As the tempering temperature is reduced, both notch strength values increase, but the experimental value increases at a lower rate with tempering temperature reduction than does the calculated value. The notch strength measured experimentally becomes equal to that calculated from the yield strength measurement at about the condition of vanishing ductility in the notched specimen.

## Fracture Development in Fatigue Cracked Specimens

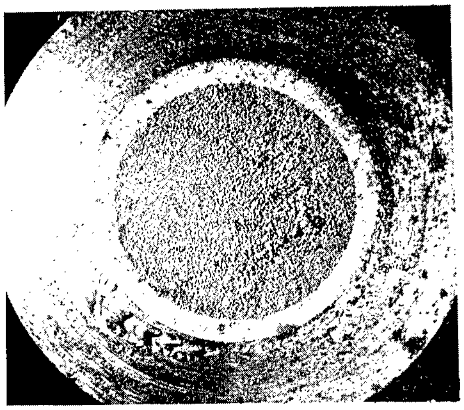
The fractures developed in the fatigue-cracked specimens have previously been discussed (7,8). Selected examples of these fractures are presented in Figs. 10 and 11. In Fig. 10a failure was initiated by the development of a crack from the notch base. This propagated toward the center of the section until about one-half of the section was parted and then the section fractured. The process is perhaps better illustrated in Fig. 10b, where the central portion of the specimen separated with a crystalline fracture. This suggests separation of the peripheral regions by relatively slow crack propagation and separation of the center of the specimen by fast crack propagation. For the fracture in Fig. 11, peripheral crack development did not take place in the sense described for the other two fractures, although there is evidence of oscillatory crack development from the notch base similar to that described for a titanium

a

b

Fig. 10 - The fracture surfaces developed in 1-inch-diameter fatigue-cracked 4340 steel specimens: (a) fully fibrous fracture and (b) 50% fibrous, 50% crystalline fracture

*Ideally this should be a true-stress measurement, but the true-stress measurement is not customarily taken. For the present steel conditions the true-stress values of $k$ would be about 10% greater than those measured from the tensile strength.



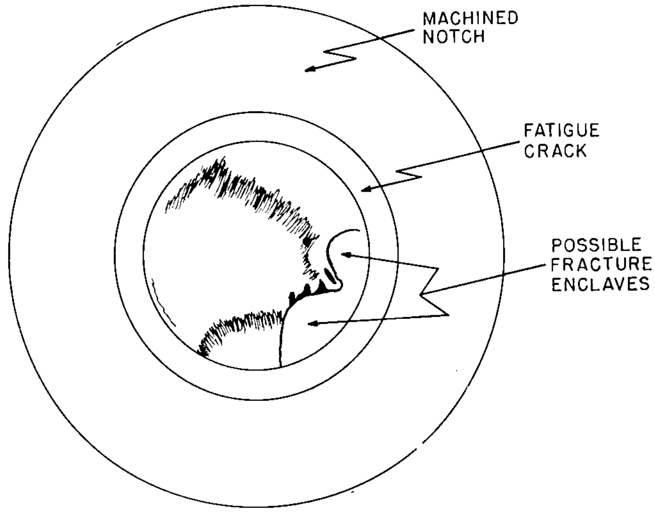



Fig. 11 - The brittle fracture for a fatigue-cracked 4340 steel specimen: (left) fully brittle fracture and (right) schematic representation of fracture details suggesting oscillatory crack development

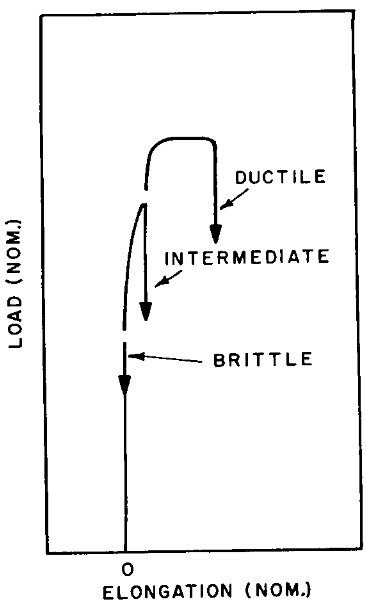



Fig. 12 - Typical load-elongation curves for 1-inch-diameter fatigue-cracked tensile specimens

specimen by Klier and Weiss (13). The fracture enclaves resulting from such possible oscillatory fracture development are indicated in the schematic representation in Fig. 11.

Crack propagation such as takes place in leading to the fracture surfaces registered in Fig. 10 should be observable under certain conditions, and several specimens were broken to establish the course of fracture development. The objective of the tests was to measure the load as function of crack development, and characteristic load-extension curves are given in Fig. 12.

For the load-elongation curves in Fig. 12 no evidence of crack development was detected up to the point of separation of the section. For the ductile specimen this was established by measurement of the notch diameter in a comparator after the fatigue crack had been pulled open. The two segments of the fracture — the peripheral and central portions of the fracture — were developed at rates that could not be followed by visual inspection. Because of this there is some question concerning the magnitude of the stresses on the section as the fracture developed. However, it is possible to establish maximum and minimum nominal values for these stresses.

The minimum value is the notch strength as usually measured. The maximum value is that measured for the onset of fast fracture. Thus, for example, with slow development of the peripheral crack, the load supported by the separating section would be transferred to the unbroken section. The nominal notch stress in this unbroken section would consequently rise. This process of stress intensification would progress continuously to the point where the internal crack nucleation leading to separation of the central portion of the fracture takes place and complete fracture follows immediately. If it is assumed that complete transferal of the load borne by the peripheral cracked zone takes place, the nominal stresses on the core section can be computed. The fracture notch strengths so determined are reported in Figs. 13 and 14.

The fracture notch strength in a notch ductile specimen attains an indicated maximum value of about 500,000 psi. With decreasing tempering temperature, as the notch ductility decreases and becomes zero, the fracture notch strength tends to develop a typical transition curve and becomes equal to the notch strength as the notch strength passes to values less than the yield strength. There are certain variations in the trends of the data as the testing temperature is changed from 75°F to -100°F (cf. Figs. 13 and 14) but these variations appear to be influenced primarily by the variations in the ductile-brittle transitions observed at the two different testing temperatures.

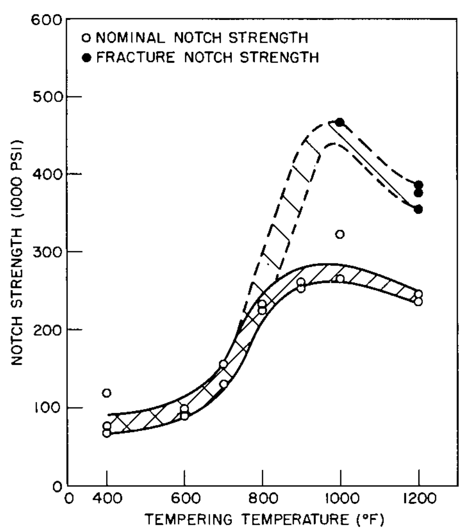



Fig. 13 - The notch strength curves versus tempering temperature for 1-inch-diameter fatigue-cracked tension specimens tested at 75°F

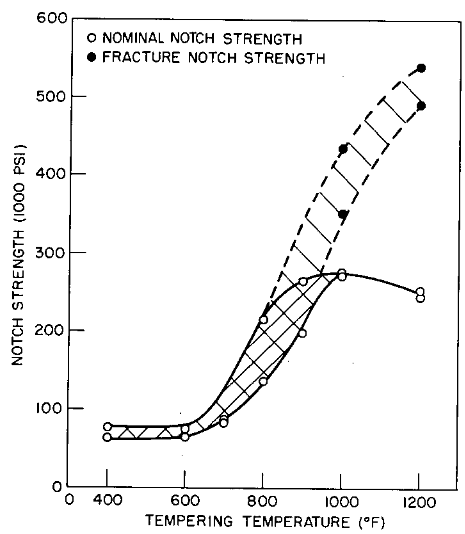



Fig. 14 - The notch strength curves versus tempering temperature for 1-inch-diameter fatigue-cracked tension specimens tested at -100°F

The trends in the fracture strength curves can conveniently be represented as functions of the hardness, with the hardness being measured as given in Fig. 15. These hardness values are considered in satisfactory agreement with those reported elsewhere (13). The notch strength data versus hardness are presented in Fig. 16. The trends in the notch strength and fracture notch strength curves versus hardness, in agreement with the tension results, indicate a ductile-brittle transition in the hardness range 40 to 50 $R_c$. The lower limit in this hardness interval depends on the criterion used, with the fracture notch strength being a more severe index of embrittlement than is the nominal notch strength.

## SUMMARY

The tension properties of heat-treated 4340 steels have been measured at 75°F, and from these data the fracture strengths for fatigue-cracked cylindrical specimens have been calculated by the analysis of Hill (3). The results are as follows:

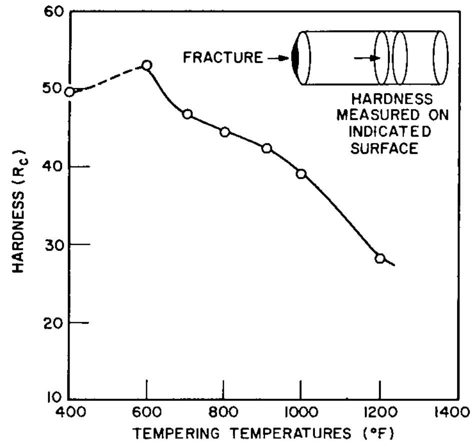



Fig. 15 - The hardness (Rockwell C) versus tempering temperature of 4340 steel measured as indicated in the insert figure at 75°F

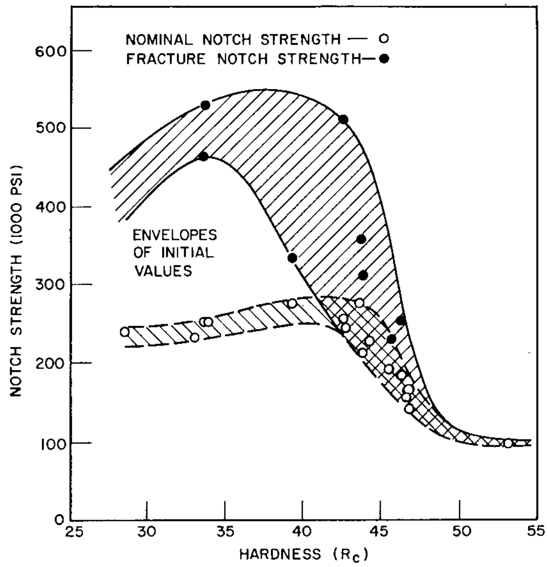



Fig. 16 - The notch strength curves versus hardness for 1-inch diameter reannealed fatigue-cracked tension specimens tested at 75°F

1. The tension properties observed for the 4340 steel studied, except for ductility, are in agreement with the data reported by other investigators.

2. With increase in tensile strength from about 190 ksi to 225 ksi, the maximum load strain $\delta_{ML}$ falls from a value of about 0.15 to about 0.075.

3. The value of the strain-hardening exponent $n$ changes in the same way as does $\delta_{ML}$.

4. The ductile-brittle transition in the fatigue-cracked tension specimen also occurs in this same properties-change interval.

5. The suggested ductile-brittle transition in reduction of area is not related to the transitions in $\delta_{ML}$, $n$, and $\sigma_N$.

6. The strength coefficient $\sigma_0$ does not undergo a transition.

7. For specimens tempered at 1000 and 1200°F and tested at 75°F the notch-strengths for plastic failure as measured and calculated are in good agreement. For specimens tempered at temperatures less than 1000°F the plastic-failure analysis is considered inapplicable.

8. In the tempered condition interval where the notch section becomes plasticized before fracturing, slow-crack and fast-crack development phases in fracturing are believed to exist. These fracture propagation phases suggest the existence of two characteristic fracture strengths associated with the crack development. The slow-crack phase corresponds to the conventional notch strength measurement. The nominal stress condition associated with fast-crack development at this time can be stated only as a limit which may or may not be realized. This stress condition designated the fracture notch strength may reach a value as high as 500,000 psi for a ductile specimen.

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13. ABSTRACT

For a fatigue-cracked tension specimen, the conditions of plastic failure, i.e., the stress conditions under which the section under the notch becomes plastic, have been developed by Hill. The analysis assumes the material to be ideally plastic, but, nonetheless, should be adequately approximate for heat-treated 4340 steel. Tension tests have been completed, and the results have been used to predict the notch strength for 4340 steel heat-treated to strength levels characteristic for this steel. The calculated notch-strengths have been compared with the notch strengths which were earlier measured and reported. For limited conditions the calculated and measured values are found to be in adequate agreement. Differences in the calculated and measured values in the plastic failure interval can be attributed to the strain-hardening to which the 4340 steel is subject.

At values for the notch strength greater than the yield strength, ultimate failure by fracturing in the fatigue-cracked specimens takes place by crack development from the notch base, which development is greater the more the notch strength exceeds the yield strength. Following development of this crack, separation of the section is cataclysmic. Because of this, it is possible to establish both a nominal notch strength and a fracture notch strength. The nominal notch strength can be determined readily. The fracture notch strength is more difficult to determine, but the limit of this quantity can be estimated. This limit is set at about 500,000 psi for the most crack resistant materials.

The conventional tensile properties of 4340 steel at the several strength levels examined agree with the data in the literature except that the ductility is reduced. The true-stress natural-strain data indicate a transition in the strain-hardening exponent ($n$) from high to low values as the tensile strength increases from the minimum to the maximum values measured.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Metallurgy<br>Steel<br>Fracture (mechanics)<br>Tensile properties<br>Tests<br>Experimental data<br>Heat treatment<br>Toughness<br>Hardness<br>Plasticity<br>Deformation | | | | | | |

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