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THE EFFECT OF A FATIGUE CRACK ON THE NOTCH STRENGTH AND FRACTURE DEVELOPMENT IN CYLINDRICAL SPECIMENS OF HEAT-TREATED 4340 STEEL

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ABSTRACT

As the notch root radius in the notch-tension specimen is reduced, a limit is reached beyond which sharper machined notches are not feasible. Sharper notches, potentially, can be formed by fatigue action. The fatigue notches have a flank angle of effectively zero, while the notch root radius is from two to three orders of magnitude less than that for the machined notches. It is important to know the effect of a fatigue notch on the notch strength of a steel, which in the present work was a 4340 steel heat-treated to characteristic strength levels.

Fatigue-cracked specimens for the various heat-treated conditions were tested in static tension at temperatures from 75° to -323°F to establish notch-strength transitions. The notch strengths measured with the fatigue-cracked specimens demonstrate that the notch formed in fatigue is more severe than the sharpest machined notches. The ductile-brittle transition measured with 0.5-inch cylindrical fatigue-cracked specimens occurs at higher temperatures than that for comparable 1.5-inch cylindrical specimens with the sharpest machined notches. Fracture appearance transitions were also established from examination of the fracture facets, and the data obtained have been compared with the NDT temperature measurements for a similarly heat-treated steel which was reported by Puzak. The fatigue-notch tension data yield fracture indices of brittle behavior which parallel but which are not equal to the NDT index measured in the drop-weight tests reported by Puzak.

PROBLEM STATUS

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

AUTHORIZATION

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THE EFFECT OF A FATIGUE CRACK ON THE NOTCH STRENGTH AND FRACTURE DEVELOPMENT IN CYLINDRICAL SPECIMENS OF HEAT-TREATED 4340 STEEL

INTRODUCTION

The notch properties of heat-treated 4340 steel as determined for a mechanically notched cylindrical specimen have been reported by Klier and Weiss (1) to vary with specimen size. The machined-notch root radius of 0.001 inch for these specimens is effectively as sharp as can be machined. However, limited evidence suggests that a more severe effective notch may be formed either by hydrogen embrittlement (2) or by fatigue action (3-5), and the specimen size effect reported by Klier and Weiss consequently may not be unique. There is need for more systematic data obtained with the more severe notches, and such data are here reported for a fatigue notch.

Cylindrical specimens 1/2 inch in diameter were tested at temperatures from 75^0 to -323^{0}F. Notch strength and fracture data are presented and compared with the data earlier taken.

EXPERIMENTAL PROCEDURE

Materials

The 4340 steel of composition 0.41 C, 0.79 Mn, 0.013 P, 0.016 S, 0.31 Si, 1.83 Ni, 0.77 Cr, 0.23 Mo is the same steel as that investigated by Klier, Muvdi, and Sachs (6).

Test Specimen

The 1-1/2-inch-diameter bar stock was forged to slightly over 1/2 inch in diameter. Blanks were heat treated by quenching in oil from 1550^{0}F followed by tempering 2 + 2 hours at selected temperatures. A second smaller set of specimens was austenitized at 1550^{0}F, cooled to 1350^{0}F, and oil quenched, followed by tempering 2 + 2 hours at selected temperatures. These heat-treated blanks were ground and machine-notched about the circumference after which a fatigue crack was formed at the base of the notch. The combination notch was approximately a 50% notch; i.e., the final cross-sectional area equaled 50% of the initial area. The specimen ends were next threaded, and then the specimen was pulled in tension.

A photograph of the fatigue machine setup is given in Fig. 1. A drawing of the fatigue-cracked specimen is given in Fig. 2, and photographs of the machined notch and fatigue notch sections are presented in Fig. 3. The fatigue crack clearly forms a sharper notch than does the machined notch and due to the flank angle of near zero degrees imposes higher elastic-plastic constraint than does the machined notch.

Notch Tension Test Procedure

Specimens were pulled at 75^{0}F in air, at -100^{0}F in dry ice and a mixture of 1 part carbon tetrachloride to 1 part chloroform, at -150^{0}F in Freon 12, and at -200^0 and -323^{0}F in fixtures cooled by liquid nitrogen.

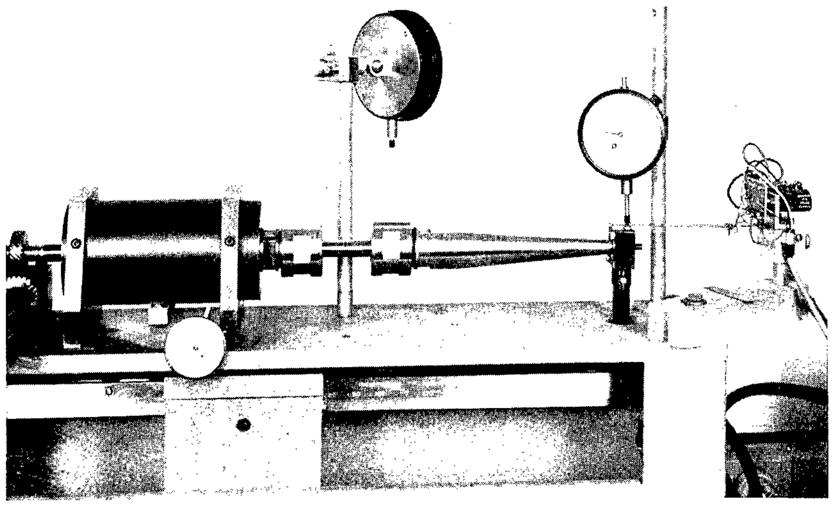

Fig. 1 - The fatigue machine used for the preparation of the fatigue-notch tension specimens

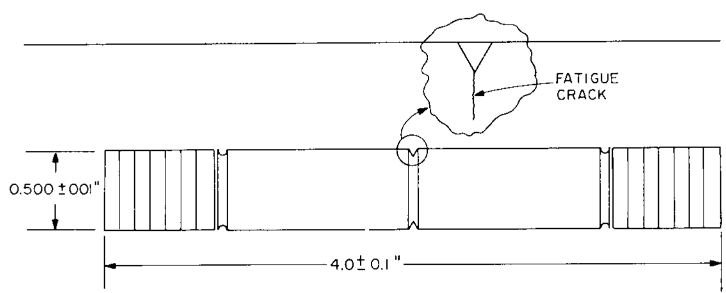

Fig. 2 - The notch-fatigue specimen in the final form for tension testing

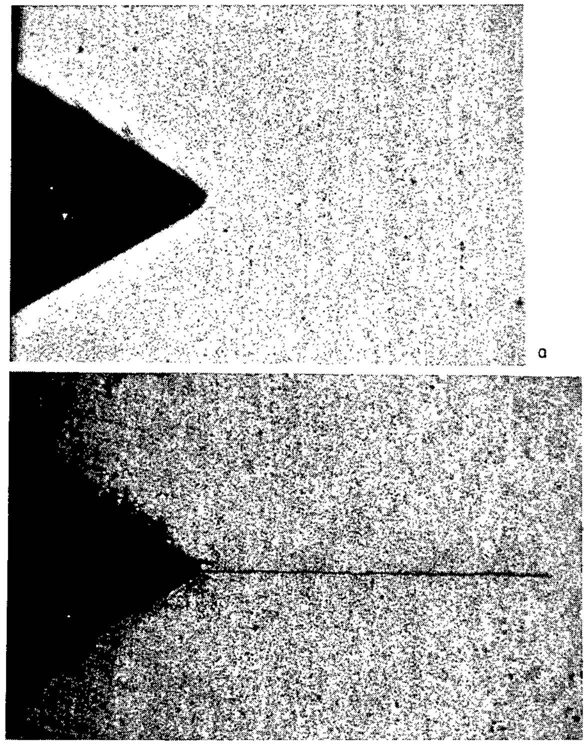

Fig. 3 - The notch configuration in the notch-tension specimen (a) before, and (b) after fatigue crack development

The notch strength was calculated with reference to the fatigue-notch diameter. The ratios of notch strength to tensile strength were also calculated by reference to the tension test data of Sachs, Weiss, and Klier (7) for 4340 steel similarly heat-treated and tension-tested.

Representation of the Test Data

The numerical test data are reported graphically. Characteristic fractures are represented graphically and by means of photographs.

EXPERIMENTAL RESULTS

Notch Tension Properties

Notch tension and comparative tension data as function of testing temperature with tempering temperature as parameter are presented in Fig. 4. To repeat, the tension data are taken from Sachs et al. (7). The notch strength data tend to minimize at the testing temperature of -323°F, and become equal to or less than the tensile strength. For the lowest tensile strength material, Fig. 4a, the notch strength rapidly rises with increase in testing temperature from -323°F, forms a flat maximum, and then falls with further increases in testing temperature. This behavior establishes a transition which is shown by Fig. 4 to occur at higher temperatures the higher the strength level of the steel condition. A transition temperature, therefore, can be defined. This transition temperature

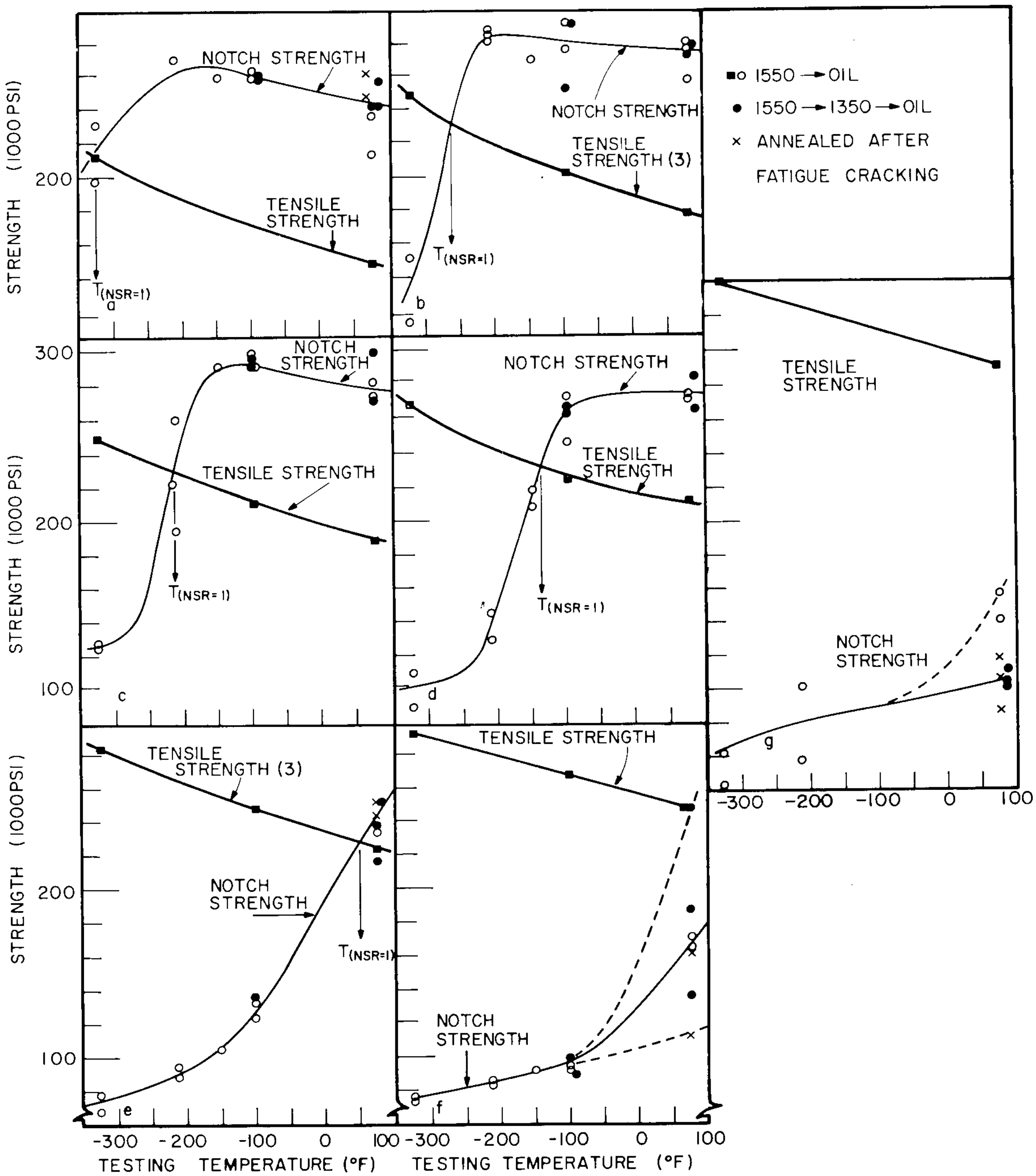

Fig. 4 - Tension and notch-tension data as a function of testing temperature with the tempering temperature as a parameter for 4340 steel (tensile strength from Ref. 7): (a) tempered at 1200°F 2 + 2 hours; (b) tempered at 1000°F 2 + 2 hours; (c) tempered at 900°F 2 + 2 hours; (d) tempered at 800°F 2 + 2 hours; (e) tempered at 700°F 2 + 2 hours; (f) tempered at 600°F 2 + 2 hours; (g) tempered at 400°F 2 + 2 hours

may be measured as low as -323°F or at temperatures well above 75°F for the different heat treated conditions. The transition temperatures that correspond to NSR = 1 are indicated in the figures (NSR = notch strength ratio, the ratio of notch strength to tensile strength).

The tension and notch-tension data are presented in Fig. 5 as function of tempering temperature with testing temperature as a parameter. The critical tempering temperatures thus established for a NSR = 1 would seem to be important primarily in developing a tensile strength of about 230,000 psi at the transition condition.

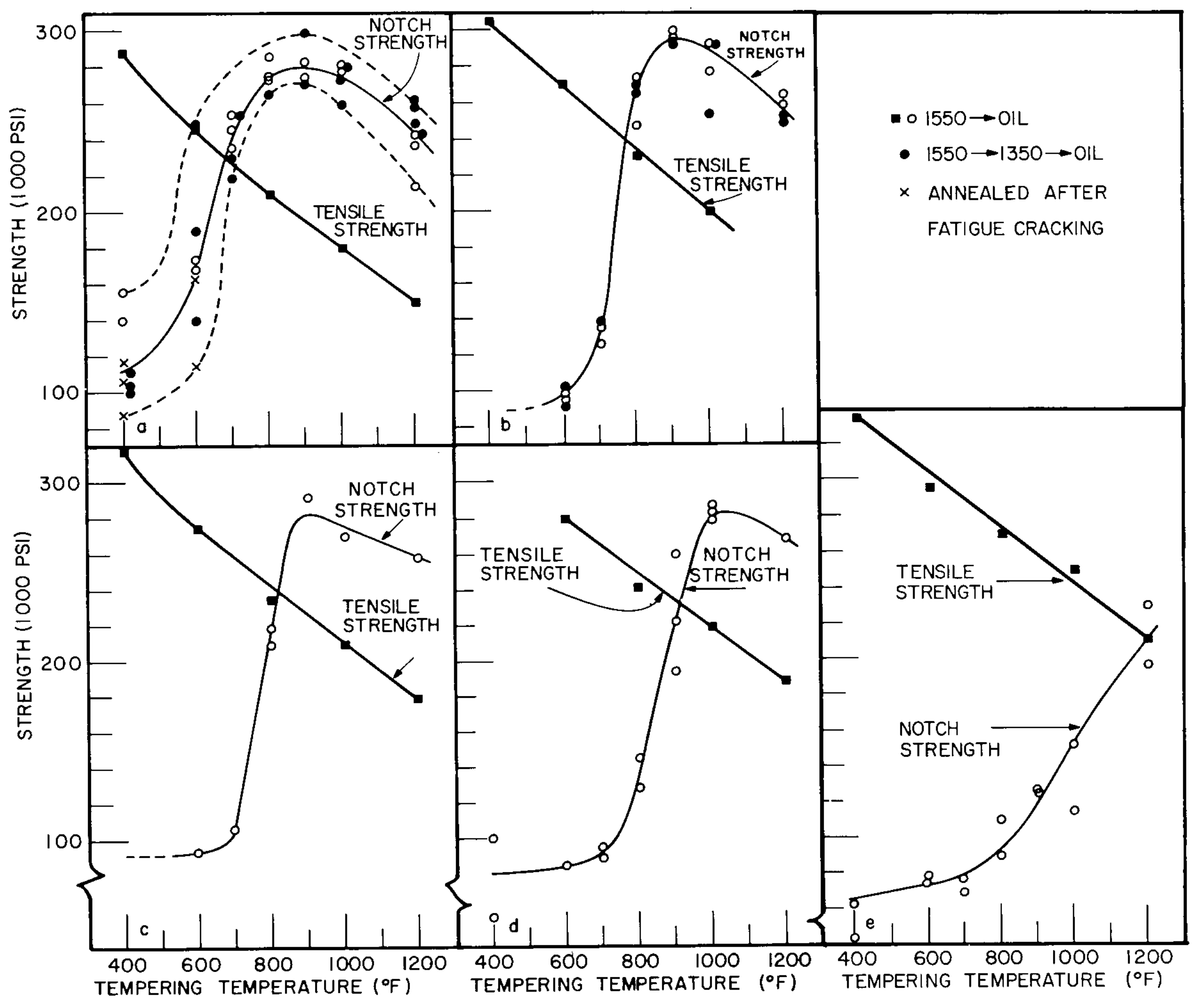

Fig. 5 - Tension and notch-tension data as a function of tempering temperature with the testing temperature as a parameter for 4340 steel (tensile strength from Ref. 7): (a) tested at 75°F; (b) tested at -100°F; (c) tested at -150°F; (d) tested at -200°F; (e) tested at -323°F

Various methods have been used to establish the ductile-brittle transition phenomenon in steels. For the notch tension test a regularly employed method requires determination of the notch strength ratio. For specimens of the present configuration this is usually determined as the ratio of the notch strength to the tensile strength. When this value equals 1 or more, yielding in a structure may be expected to precede fracture. This results from the fact that the specimen configuration here used promotes a yield strength elevation corresponding to the combined stress system in the specimen. This value of yield strength is maximized for the 50% notched specimen and with change in the loading condition tends to be reduced. In a structure this would correspond to a local yielding condition which would not unload the notch, but which would not lead to a further increase in the load under the notch. If plastic deformation were possible under the notch (this corresponds to NSR > 1), actual unloading in this area could be achieved.

Selected notch strength ratios reduced with the available tension data (7) are presented in Fig. 6. This figure serves to emphasize that rapid embrittlement develops as the tensile strength rises above 230,000 psi. At this strength level an increase of the tensile strength by about 5% leads to a reduction in the fatigue crack strength by 50%. This is an interesting observation and suggests that a steel of the present kind could be reliably used in combined stress systems to a stress level of about 230,000 psi even in the presence of small cracks. At a slightly higher nominal yield-stress level, fracture would regularly be experienced if the small cracks were present. This strength level is in satisfactory accord with experimental observation of thin-walled pressure-bottle fractures (8,9).

The ductile-brittle transition measured for notch strength ratios of 1.0 and 1.5 in the notch tension test are compared in Fig. 7 with NDT (nil-ductility transition) measurements for a comparable steel as determined by Puzak (10). For the 1200°F tempered steel the NDT temperature falls between the two transition temperatures measured in

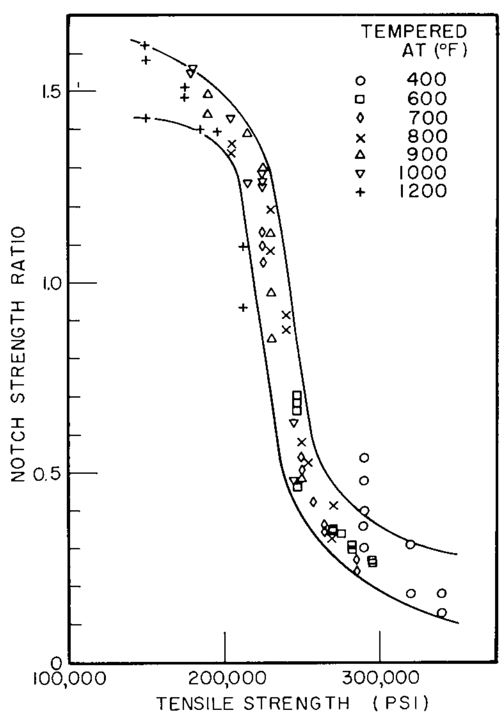

Fig. 6 - Notch strength ratio vs tensile strength for specimens tempered as indicated (tensile strengths from Ref. 7)

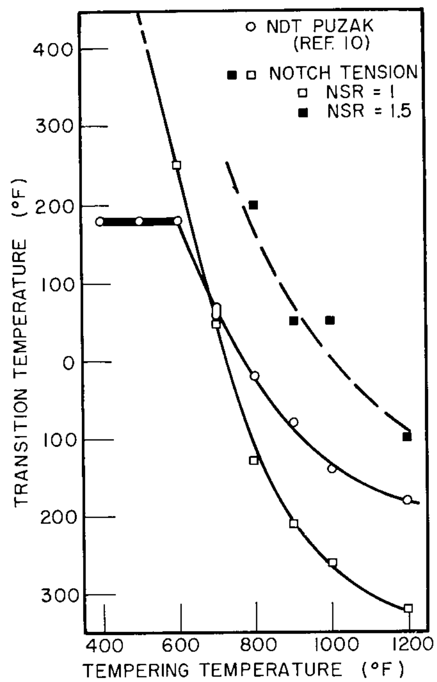

Fig. 7 - Transition temperatures for 4340 steel by the indicated notch-property criteria as a function of tempering temperature

the notch tension test. With reduction in tempering temperature, the NDT value relatively is lowered, and for the 700°F tempered condition the NDT coincides with the notch tension test transition measured for NSR = 1. For tempering temperatures lower than 700°F the NDT measurements fall below the notch tension test transition.

FRACTURES IN FATIGUE-CRACKED SPECIMENS

Characteristic fractures for specimens tempered at various temperatures and tested in the fatigue-cracked condition at 75° to -323°F are presented in Fig. 8a. Three groups of fractures are differentiated as ductile, brittle, and mixed, as illustrated in Fig. 8b. It is perhaps rather generally agreed that the fracture appearance satisfactorily corresponds with the velocity of crack propagation. Thus the brittle-faceted fracture developed not only at a low strain value but propagated rapidly across the section. The ductile fracture propagated with significant local plastic strain and relatively slowly. The mixed fractures developed and propagated with plastic strain and slowly; but final breaking was by fast fracture. Fracture transitions from low to high velocity, which parallel notch strength transitions, can be constructed with testing temperature or tempering temperature as parameters. Such transitions would correspond to the appropriate cuts through the fracture field representation in Fig. 8b. The correspondence between the fracture transition and notch strength can be illustrated by superimposing the notch strength ratio measurements on the fracture field representation. When this is done (Fig. 9) it is evident that the boundary between the brittle fracture field and the mixed fracture field nearly coincides with a notch strength ratio of 1.0. This corresponds to a condition of nonductile fracture propagation or to a condition of ductility exhaustion under the notch. A structural member designed to correspond to this condition would be strong only so long as local overloads did not develop. For reliable performance with a fatigue-notched structure the notch strength ratio should be somewhat greater than 1.

The ductile-brittle fracture transition for change in tempering temperature with test temperature as parameter is illustrated for two test temperatures in Fig. 10. The

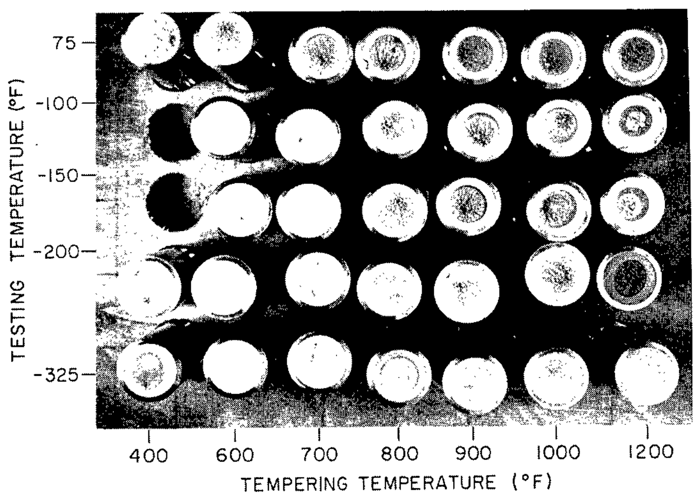

Fig. 8a - Characteristic fractures for fatigue-notch 4340 steel specimens as a function of tempering and testing temperatures

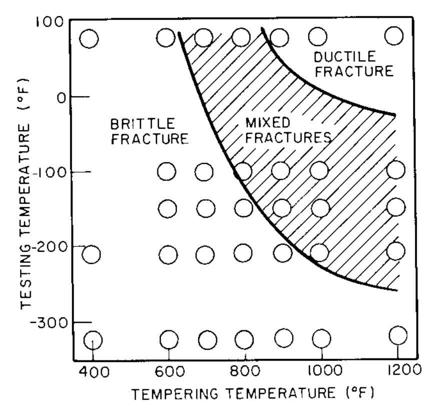

Fig. 8b - Suggested fracture transition behavior in 4340 steel as a function of tempering and testing temperatures

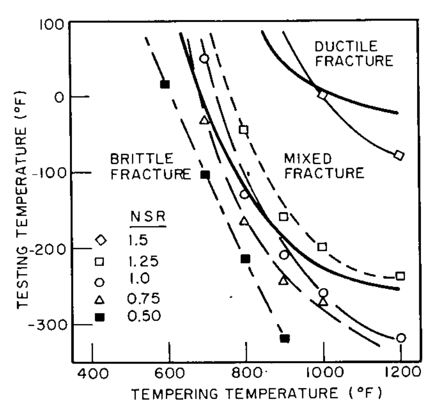

Fig. 9 - Contours of constant notch strength ratio superimposed on the fracture appearance field of Fig. 8b

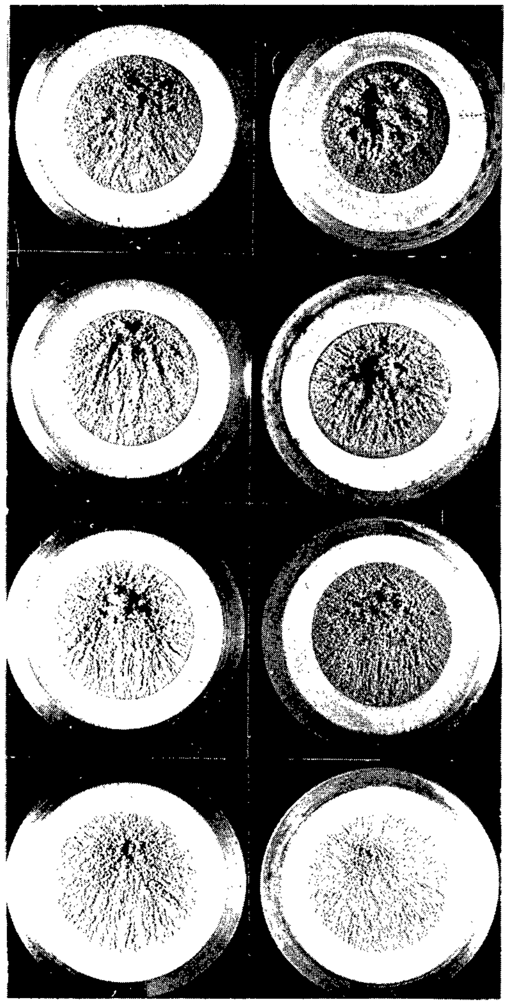

Fig. 10 - Fractographs illustrating the transition in fracture type with an increase in the strength level (~X5)

specimens on the left were tested at 75°F; those on the right were tested at -150°F. Those fractures on the left correspond to the fractures usually associated with fracture in a heat-treated steel. Here a cleavage type fracture is not evident and the fracture is perhaps best classified as a poorly developed star type. At the lower testing temperature, however, fracture facets readily identifiable as cleavage are evident. Fracture development in these specimens is believed to correspond to the sequence described by Klier and Weiss (1). The systematic change in fracture appearance through the fracture-transition zone results then from the extent of development of the respective fracture phases. For the ductile fracture, breaking is initiated at the notch base and propagates inward, while for the brittle fracture, breaking is (usually) initiated at an internal fracture nucleus and propagates to the notch base.

The above discussion presupposes that significant plastic strain accompanies crack development for ductile specimens, this plastic strain being progressively reduced as the steel is embrittled. That the plastic strain development does take place is illustrated in Fig. 11. This figure indicates the crack opening (cf. Fig. 3) observed for a ductile specimen loaded at 75°F. This opening is progressively reduced (and becomes nil) as the notch

Fig. 11 - Opening of the fatigue crack 4340 steel specimen tempered at 1200°F, tested at 75°F

strength maximizes. This behavior suggests that residual stress and elastic-plastic strain at the base of the fatigue notch may under some testing conditions influence the notch strength. Such an effect would be most critical in the lower transition range. To examine this question, briefly, several specimens were reannealed at the original tempering temperature and then tested at 75°F. For the 400°F tempered condition this annealing treatment led to a 30 to 35% reduction in notch strength (cf. Fig. 5). For the 600°F annealing temperature a reduction in notch strength was less consistently indicated, while for higher annealing temperatures no significant effect was detected. This behavior was as expected.

Klier and Weiss (1) reported the development of "shatter cracks" in certain of their broken specimens. An examination of the present series of specimens (Fig. 12) for such cracks indicates they are most common at intermediate tempered conditions. This corresponds to the condition for maximum notch strength, and simultaneously to maximum transverse loading due to the notch. For the present steel the notch strength in the transverse direction can be expected to be reduced (6), leading to early failure in this direction. The "shatter" cracks then more probably are longitudinal splits of the kind that were discussed by Holloman (11) and Klier (12). These longitudinal cracks probably developed before separation of the section in the normal direction.

Fatigue-Crack Strength as Modified by Step-Austenitizing

It has been proposed that the hardening response of 4340 steel can be modified by austenitizing at 1500° to 1550°F followed by cooling to 1350°F before oil quenching (13,14). More recently it has been demonstrated that the step treatment at 1350°F promotes the formation of bainite in the quenched section (15), while it has been shown that mechanical property variations result from this treatment (1,7,16). Limited specimens were tested mainly at 75° and -100°F to establish the effect of this heat treatment on the fatigue-notch properties of 4340 steel. The data are entered in Figs. 4 and 5. The notch strength data are in essential agreement with the data taken for the conventionally heat-treated specimens.

Comparative Notch-Strength Measurements

Notch strength measurements have been reported for variable notch root radius and specimen size for the present and comparable 4340 steels, and these data are summarized

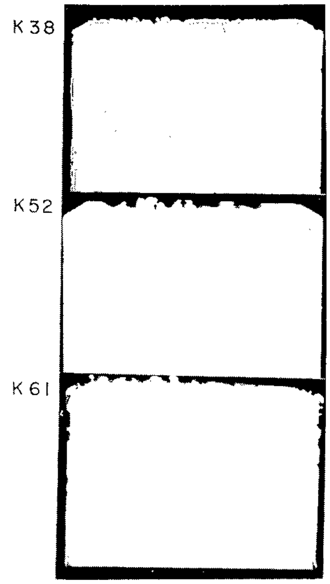

Fig. 12 - Photomacrographs illustrating crack development normal to the plane of the primary fracture (~X5): specimen K 38 tempered at 800°F, tested at 75°F; specimen K 52 tempered at 900°F, tested at 75°F; specimen K 61 tempered at 1000°F, tested at 75°F

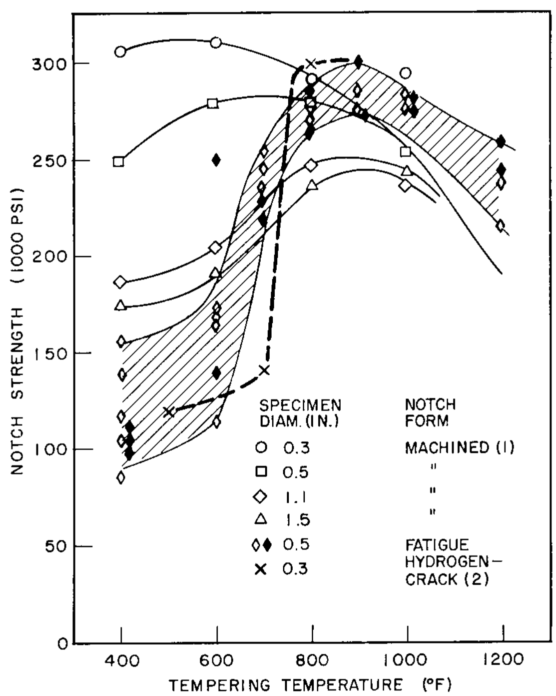

Fig. 13 - Comparative notch strength measurements as a function of tempering temperature for specimens of various sizes notched in the indicated ways

in Fig. 13. Only those data for the sharpest machined notch (approximately 0.001-inch root radius) are considered suitable for comparison with the fatigue-crack specimens at present under study, and this is true only because such specimens have been considered to be notched as sharply as possible.

It is readily evident that the notch strength is more severely evaluated in the fatigue-notched specimen than is true in the large machine-notched specimen. For the fatigue-notch specimens a reduction in notch strength is measured for the notch sensitive steel conditions, while an increased notch strength is measured for the notch tough steel conditions. Also entered in the figure are the notch data from Klier, Muvdi, and Sachs (2) obtained for hydrogen-embrittled 4340 steel. These comparative data suggest that the fatigue crack may be slightly less severe than the hydrogen-induced crack, but in order of magnitude the two crack forms are equal.

SUMMARY

The tensile strength of 4340 steel in the presence of a fatigue crack has been determined for a 1/2-inch cylindrical specimen. The steel was austenitized in the conventional and step manner and after oil quenching was tempered at selected temperatures in the interval 400° to 1200°F. The fatigue-notched specimens were broken in the temperature interval -323° to 75°F. The following conclusions have been reached.

1. A 4340 steel tempered at 1200°F is notch tough in the presence of a fatigue notch when tested at 75°F.

2. If either the tempering or testing temperature is lowered, the notch strength tends to increase, and maximizes at about 280,000 psi.

3. With continued reduction in tempering and/or testing temperature the notch strength is sharply reduced and becomes equal to the tensile strength of the steel at about 230,000 psi.

4. The notch strength is then further reduced and approaches a brittle-crack strength at about 100,000 psi.

5. The variation in the notch strength with tempering and testing temperature indicates that the fatigue notch used in the present tests is more severe than the machined notch employed by Klier and Weiss in a size effect study of 4340 steel.

6. Limited comparative data for a hydrogen-embrittled 4340 steel indicate the notches developed through fatigue and hydrogen embrittlement lead to about the same notch strength results.

7. However, there is evidence that fatigue action may develop elastic-plastic stress-strain conditions at the notch base that may prove important in notch strength measurements for brittle steels. This disturbance seemingly can be eliminated by annealing the fatigue specimen.

8. The fracture appearance data clearly show fracture facets that may best be considered as cleavage facets. The fracture appearance data agree fully with the notch tension strength trends.

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