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An Investigation of the Rotating-Beam Test for Low-Cycle Fatigue Crack Propagation Studies

E. A. Lange, T. W. Crooker, and R. E. Morey

Strength of Metals Branch
Metallurgy Division

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

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ABSTRACT

A method is described for investigating the low-cycle fatigue behavior of high-strength, notch-tough materials using standard rotating beam fatigue machines. The method includes the application of tensile tests on partially fatigued specimens to obtain notch tensile-strength and crack depth information. An analysis based on experimental data from HY-80 steel specimens of three sizes and three heat-treatments is presented. Crack depth and crack propagation rate are employed as parameters in the analysis.

It is shown that the test can detect differences in low-cycle fatigue performance resulting from specimen size and heat-treatment. Variations in performance are found to correlate well with corresponding variations in the Charpy V energy values and the notch tensile strength to yield strength ratios for the materials tested. The test appears promising as a laboratory means for comparing the low-cycle fatigue performance of various materials.

PROBLEM STATUS

This report completes this aspect of the problem; work is continuing on other aspects of the problem.

AUTHORIZATION

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AN INVESTIGATION OF THE ROTATING-BEAM TEST FOR LOW-CYCLE FATIGUE CRACK PROPAGATION STUDIES

INTRODUCTION

The term low-cycle fatigue refers to fatigue failures which occur in less than about 100,000 cycles of load application. Such rapid failures necessarily involve plastic strains and, thereby, do not readily lend themselves to analysis. However, the demands placed on modern structures require that a quantitative knowledge of the low-cycle fatigue characteristics of high-strength materials be made available to structural designers.

Failure from low-cycle fatigue involves two phases: crack initiation and crack propagation. Since manufacturing techniques frequently leave a new structure with ready-made cracks, the life of a structure will depend largely on its ability to survive such repeated loading while in a cracked condition. The ability of a material to resist the growth of fatigue cracks can often control the service life of a structure.

Low-cycle fatigue tests are generally conducted for one of two purposes: the evaluation of material performance or the evaluation of structure life. The lack of a suitable analysis between these two types of tests at the present time necessitates the evaluation of the latter, in the form of costly and elaborate model tests. The purpose of this study was to evaluate rotating-beam loading as a laboratory test procedure for determining the crack growth resistance of high-strength materials.

The constant-load rotating-beam fatigue test was selected for the initial study. The test features a steep stress gradient, resulting from the application of bending loads on test specimens of relatively small cross section and a symmetry of crack movement through the specimen. The steep stress gradient acts to localize plastic deformations and thereby minimize any influence which the applied cyclic loads may exert to alter the initial properties of the test material prior to the development of the stress field associated with the crack tip.

An analysis of crack propagation rates under these conditions offers the possibility of developing a ranking index for crack propagation in virgin materials and also for determining the effects of such factors as prior strain and environment on the growth rates of low-cycle fatigue cracks. In addition, the specimens can be used for the determination of notch tensile strength, under conditions of maximum notch sharpness and good cross-sectional symmetry.

EXPERIMENTAL TECHNIQUE

General Description

Deeply notched specimens were tested in rotating-beam fatigue machines employing cantilever loading. The applied loads were selected to produce failures within the low-cycle fatigue range—less than 100,000 cycles.

Test specimens were removed from the machines at various stages of crack penetration, before terminal failure occurred, and subsequently broken in tension to obtain crack depth and notch-strength data.

Materials

The materials used in this experiment consisted of HY-80 steel heat-treated to three specific strength levels. HY-80 is the current submarine hull material, and therefore, it is of particular interest as a basic, high-strength material. Its selection for submarine hull application is based on a moderately high yield strength (YS), good weldability, and excellent resistance to notches, as shown by its low NDT (nil-ductility-transition) and high Charpy V energy shelf values (Fig. 1). The chemical analysis (weight-percent) of the HY-80 steel was as follows:

C	Mn	Si	P	S	Ni	Cr	Mo	V	Cu
0.16	0.30	0.24	0.015	0.017	3.20	1.68	0.50	0.01	0.04

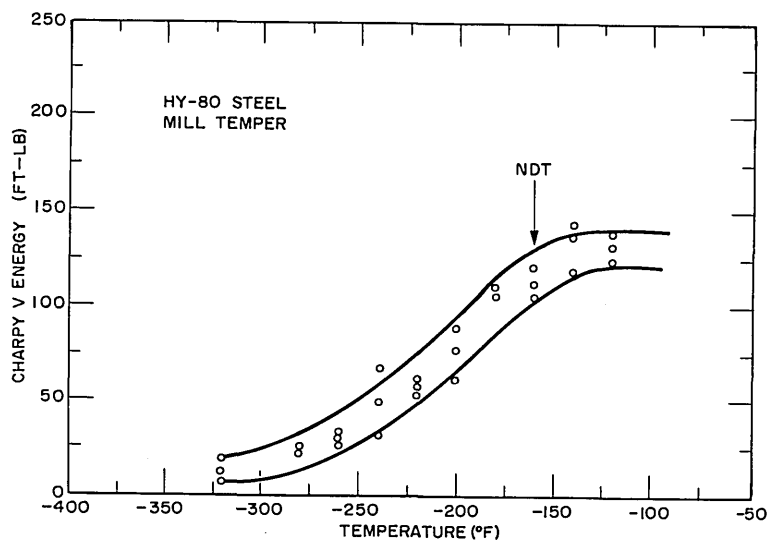


Fig. 1 - NDT temperature and Charpy V energy values for mill-temper HY-80 steel

One group of specimens was tested in the as-received, mill-temper condition, after having been stress-relieved for 1 hour at 1100°F followed by slow cooling. The remaining two groups received a heat-treatment of 1 hour at 1650°F and a water quench followed by 1 hour of tempering. Tempering temperatures of 400° and 600°F were chosen. The tensile properties of these three materials are listed in Tables 1 and 2; the NDT temperatures and Charpy V energy values are presented in Figs. 1-3.

The 400° and 600°F temper conditions are similar and both possess high strength. However, a considerable difference exists in their respective NDT temperatures.

Table 1
Mechanical Properties of HY-80 Steel

Tempering Temperature (°F-One Hr.)	Tensile Strength (ksi)	Yield Strength (ksi)	Percent Elongation	Percent Reduction in Area	Hardness No.
Mill Temper	109	92	25	74	239(BHN)
600	187	160	14	57	40(R_c)
400	197	163	14	56	42(R_c)

Table 2
Notch Tensile Strength of HY-80 Steel

Tempering Temperature (°F)	Major Diameter (in.)	Net Diameter (in.)	Notch Tensile Strength (ksi)
Mill Temper	0.750	0.280	213
Mill Temper	0.750	0.292	208
Mill Temper	0.750	0.315	202
600	0.500	0.304	253
600	0.500	0.312	246
600	0.500	0.315	242
600	0.500	0.317	248
600	0.500	0.317	242
600	0.500	0.325	247
400	0.500	0.261	243
400	0.500	0.318	232
400	0.500	0.326	219
400	0.500	0.331	217
400	0.500	0.331	233
400	0.500	0.333	220
400	0.500	0.333	233

Test Specimens

Figure 4 shows the rotating-beam fatigue specimens used. The specimen was designed so that the ratio of the initial net area to the total area approximates the ratio of the notch tensile strength to the yield strength for the materials tested. The notch radius is critical and was held to 0.001 in.

A deeply notched specimen was required to cause the initiation of the fatigue crack to occur in less than 1000 cycles. Early initiation of the fatigue crack concentrates the plastic strain at the root of the notch and thus precludes the formation of plastic strain at sites away from the notch. The sharpness of the mechanical notch facilitated uniform crack initiation. If the fatigue crack does not initiate uniformly around the circumference of the specimen, the net area soon becomes egg-shaped and the specimen is lost.

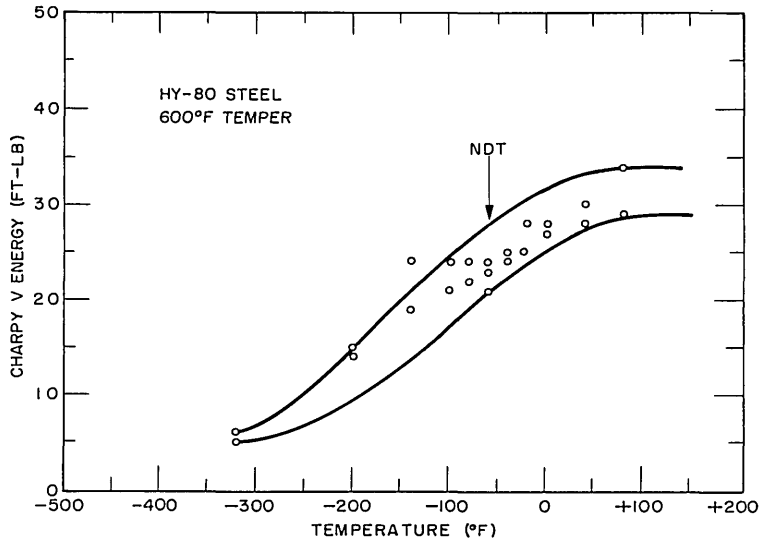


Fig. 2 - NDT temperature and Charpy V energy values for 600°F-temper HY-80 steel

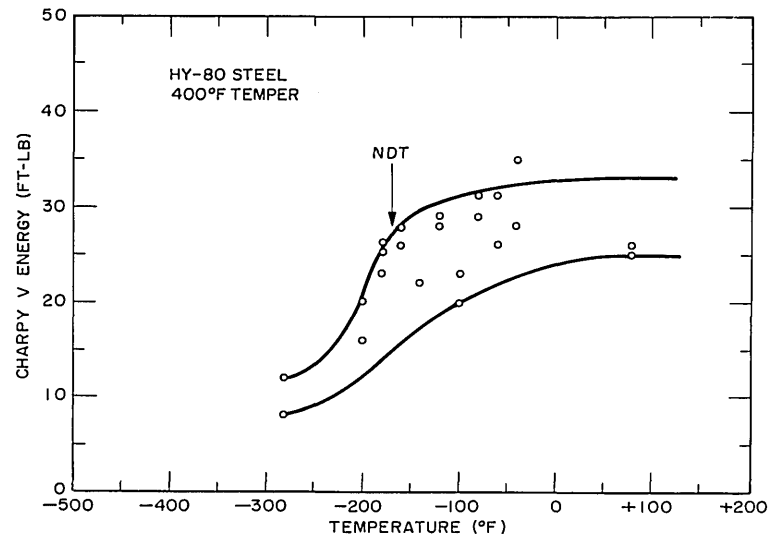
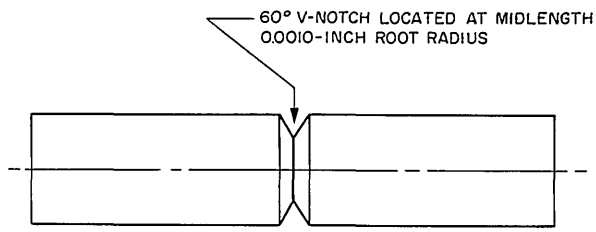


Fig. 3 - NDT temperature and Charpy V energy values for 400°F-temper HY-80 steel



SCHEDULE

MAJOR DIAMETER (IN.)	NOTCH DIAMETER (IN.)	LENGTH (IN.)
0.500	0.420	4.0
0.750	0.420	6.0
1.125	0.650	6.0

Fig. 4 - Rotating-beam fatigue specimens

Fatigue and Tension Tests

The notched specimens were loaded as a rotating cantilever beam in fatigue machines with special instrumentation (Fig. 5). Values of beam deflection and cycles were monitored and recorded at regular intervals. All tests were conducted at room temperature. A rotational speed of 250 rpm was found to be slow enough to prevent damage due to heating and yet fast enough to make the tests of short duration. Several tests were conducted at 60 rpm; however, no variation in the crack growth rate caused by a speed effect could be detected. The machines were deadweight calibrated for accurate loading. Beam deflection was followed by dial indicators and recorded to ± 0.0001 in. The specimens were loaded to a nominal stress level of 50,000 psi. This high level of nominal stress plus the sharpness of notches in the specimens resulted in a crack initiation period which was less than 5 percent of the life of each specimen.

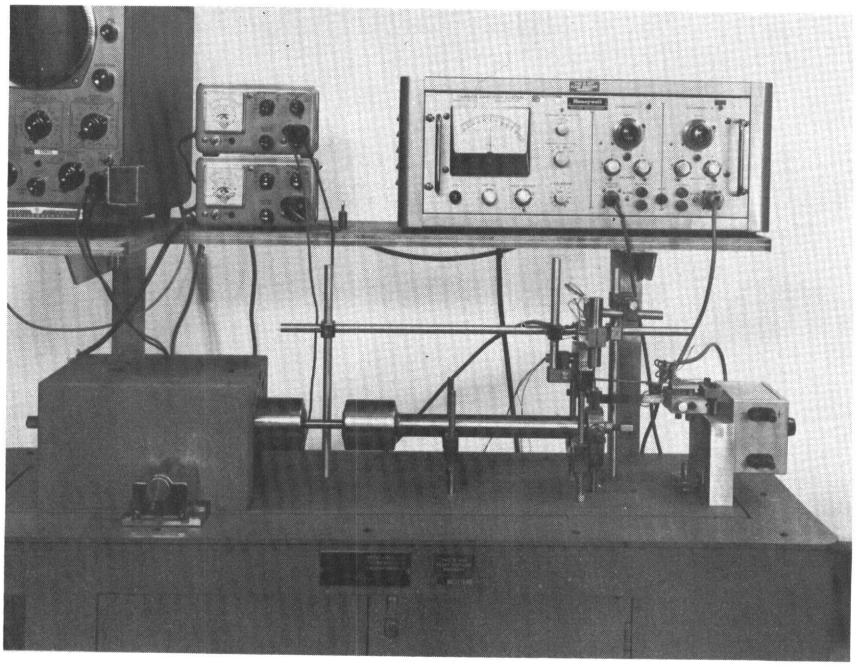


Fig. 5 - 1500-in.-lb fatigue machine used at 250 rpm for low-cycle fatigue tests

After fatigue cracks had been run into the specimens for a controlled distance, as determined by measured beam deflection, the specimens were removed from the fatigue machine and broken in tension. This procedure yielded notch tensile-strength data and data from which a calibration curve of crack depth vs beam deflection could be plotted for each material and specimen size. After a sufficient number of such tests had been conducted, the remaining specimens were cooled in liquid nitrogen and broken by impact to obtain additional crack depth data. Crack depths were determined by fracture appearance and were measured with an optical micrometer.

DISCUSSION OF RESULTS

Fatigue Tests

It was found that as the low-cycle fatigue crack penetrated the specimen, the beam of the fatigue machine deflected in proportion to the growth of the crack. The linear relationships between fatigue crack depth and beam deflection for the materials and specimens of this study are shown in Figs. 6-9. These simple relationships between crack depth and beam deflection greatly simplified the reduction of the data by permitting averaging of the crack growth rates using the beam deflection data.

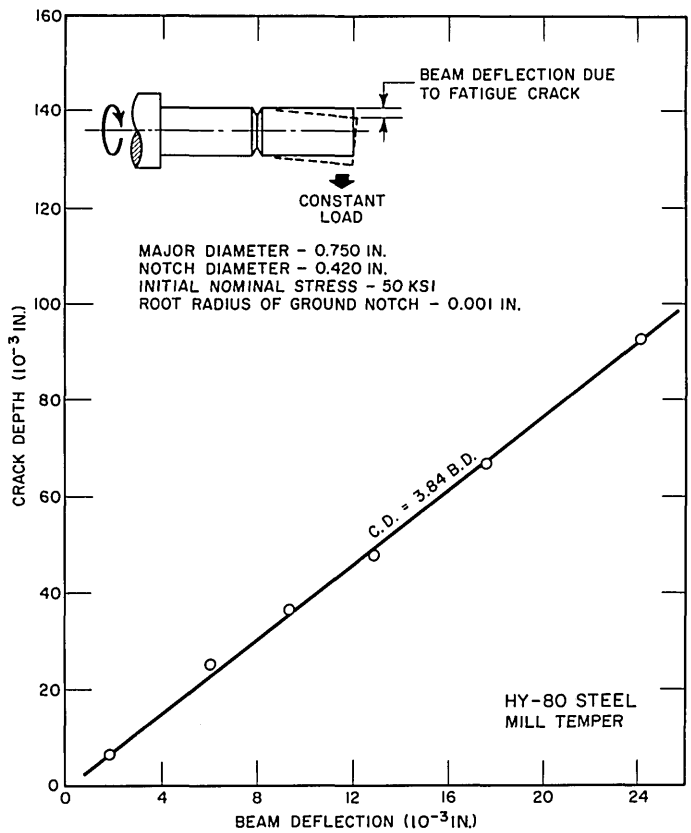


Fig. 6 - Relationship between depth of fatigue crack measured from root of notch and deflection of the fatigue-machine loading beam for mill-temper 3/4-in. specimens

It was previously mentioned that the crack initiation period was less than 5 percent of the life of the specimen. During this initial period, a plastic strain zone develops at the root of the notch and intermittent cracks form along the hardened plastic strain zone. In this manner, a continuous crack front is established. After this initial period, which requires a penetration of 0.005 to 0.015 in., the crack grows uniformly.

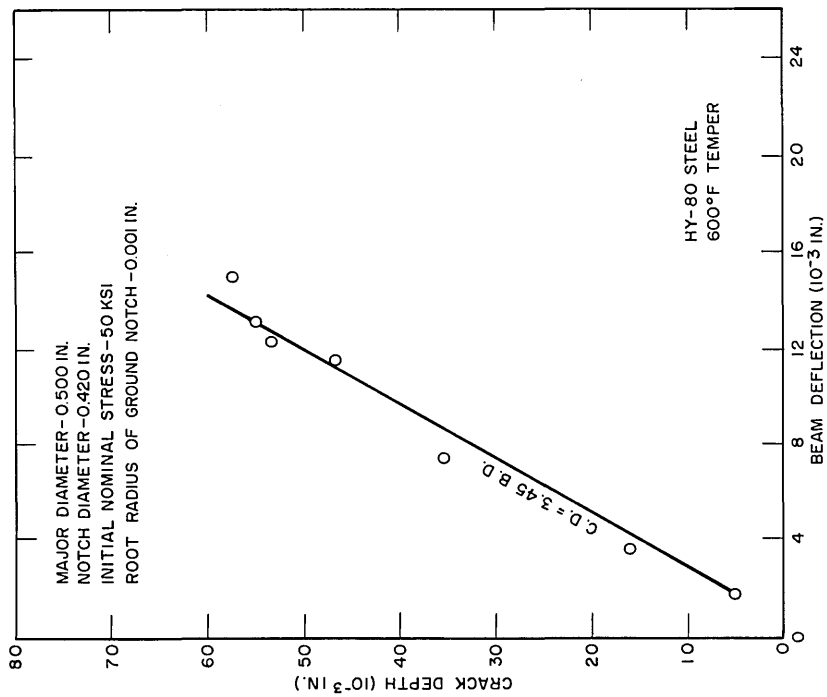


Fig. 8 - Relationship between depth of fatigue crack measured from root of notch and deflection of the fatigue-machine loading beam for 600°F-temper 1/2-in. specimens

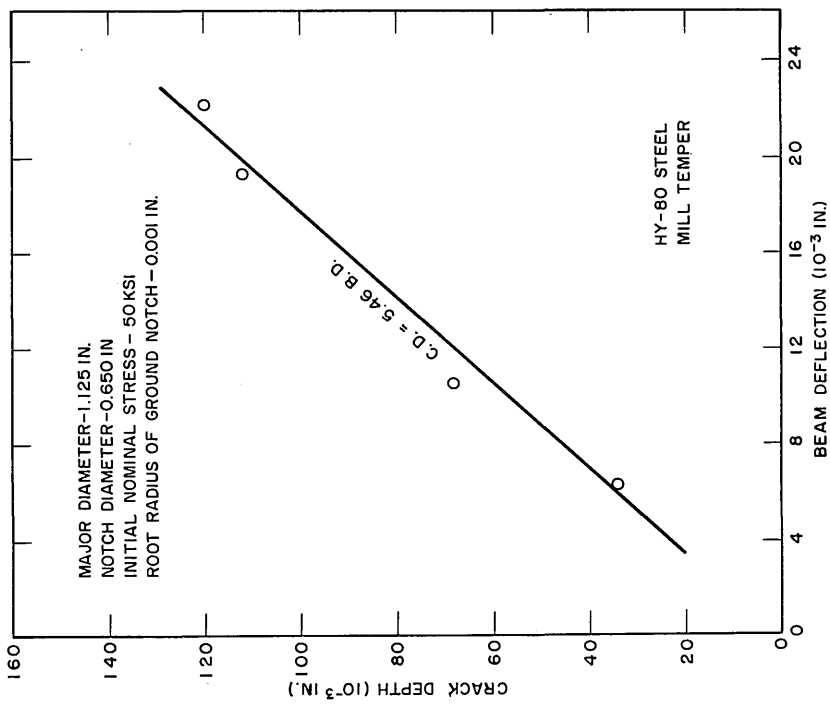


Fig. 7 - Relationship between depth of fatigue crack measured from root of notch and deflection of the fatigue-machine loading beam for mill-temper 1-1/8-in. specimens

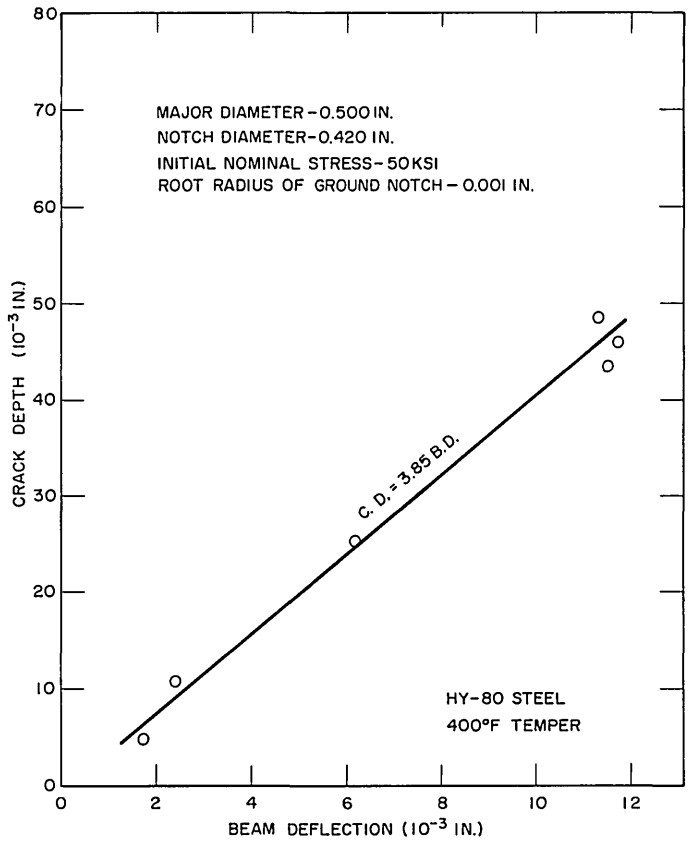


Fig. 9 - Relationship between depth of fatigue crack measured from root of notch and deflection of the fatigue-machine loading beam for 400°F-temper 1/2-in. specimens

It was observed that the crack growth rate is a function of crack depth, and a linear relationship was obtained on a semilogarithmic plot of beam deflection vs applied load cycles. These data for the three materials tested are presented in Figs. 10-13. The relationship between crack depth and load cycles can be expressed in an exponential equation as follows:

$$C.D. = e^{a+bN} + k$$

where

C.D. = fatigue crack depth

N = number of cycles

a, b, k = constants.

The above relationship is rather complex, and further reduction of the data in terms of fatigue crack growth rate resulted in a more simplified relationship from which a practical index of merit can be determined. The simplified relationship is based on the fact that the crack growth rate was found to be proportional to the crack depth. This linear relationship exists as soon as the initial fatigue crack is established and remains

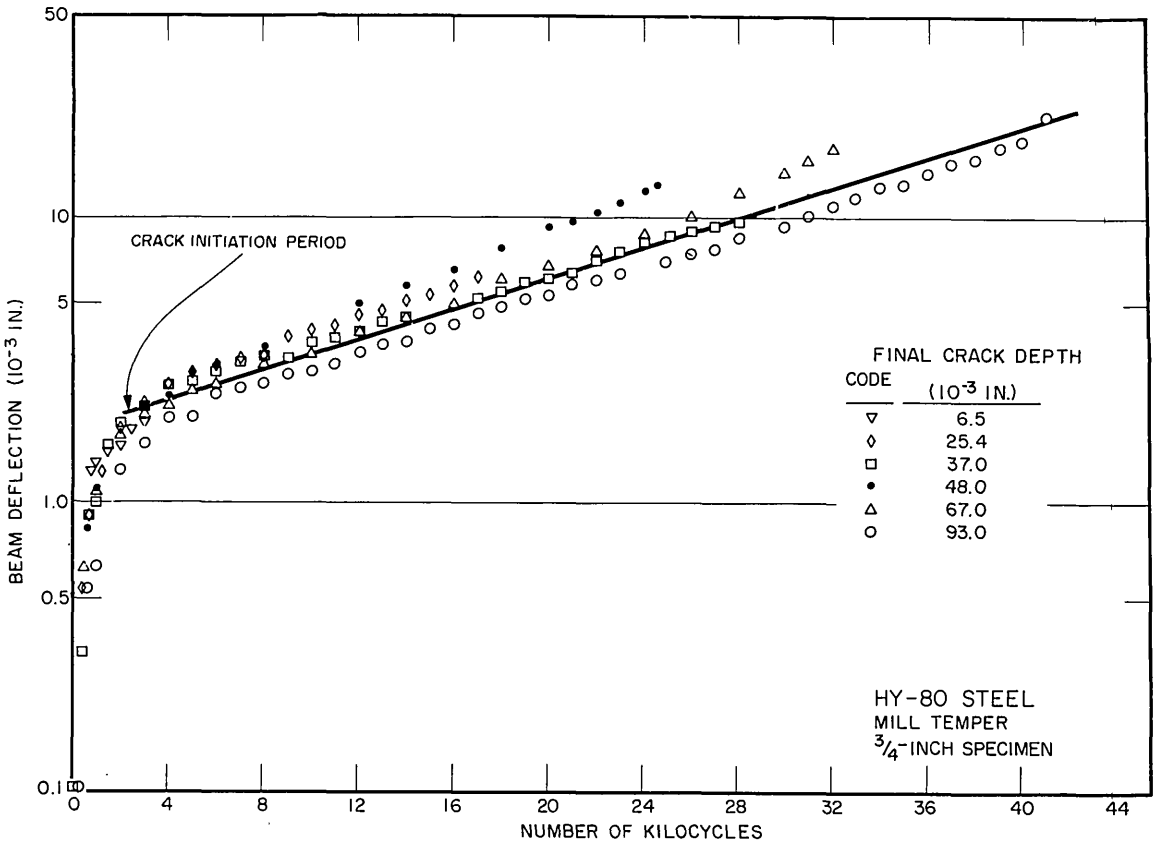


Fig. 10 - Beam deflection vs cycle data for six HY-80 3/4-in. mill-temper low-cycle fatigue specimens

valid until the net fiber stress approaches the notch tensile strength of the material. The relationship between crack growth rate and crack depth for the three materials is shown in Fig. 14.

The relative resistance of the various materials to the growth of fatigue cracks is indicated by the slope of the lines in Fig. 14. A low value for the slope indicates that the material is less sensitive to changes in stress level. A significant difference can be seen in the growth of fatigue cracks in the steel tempered to a YS of 90,000 psi (mill temper) and in the growth of fatigue cracks in the steel tempered to a YS of 160,000 psi (400°F temper). Although it was found that the material tempered at 400°F was more resistant to initiation of the fatigue crack than was the 600°F material, the growth of the fatigue crack in 400°F material was more rapid once initiation had been achieved, as indicated by the increased slope of the line for the 400°F material in Fig. 14.

It is apparent that the rotating-beam test results can be used to compare the low-cycle fatigue characteristics of various materials. However, crack growth rates for various materials must be compared with specimens of the same size and under the same loading conditions. This is apparent when the growth rates for the mill-temper material in the two specimen sizes, 3/4-in. and 1-1/8-in. O.D., are compared in Fig. 14. The data indicate that the crack rate is approximately proportional to the total area of the specimens, but additional experimentation is required to confirm the trend indicated from these limited tests.

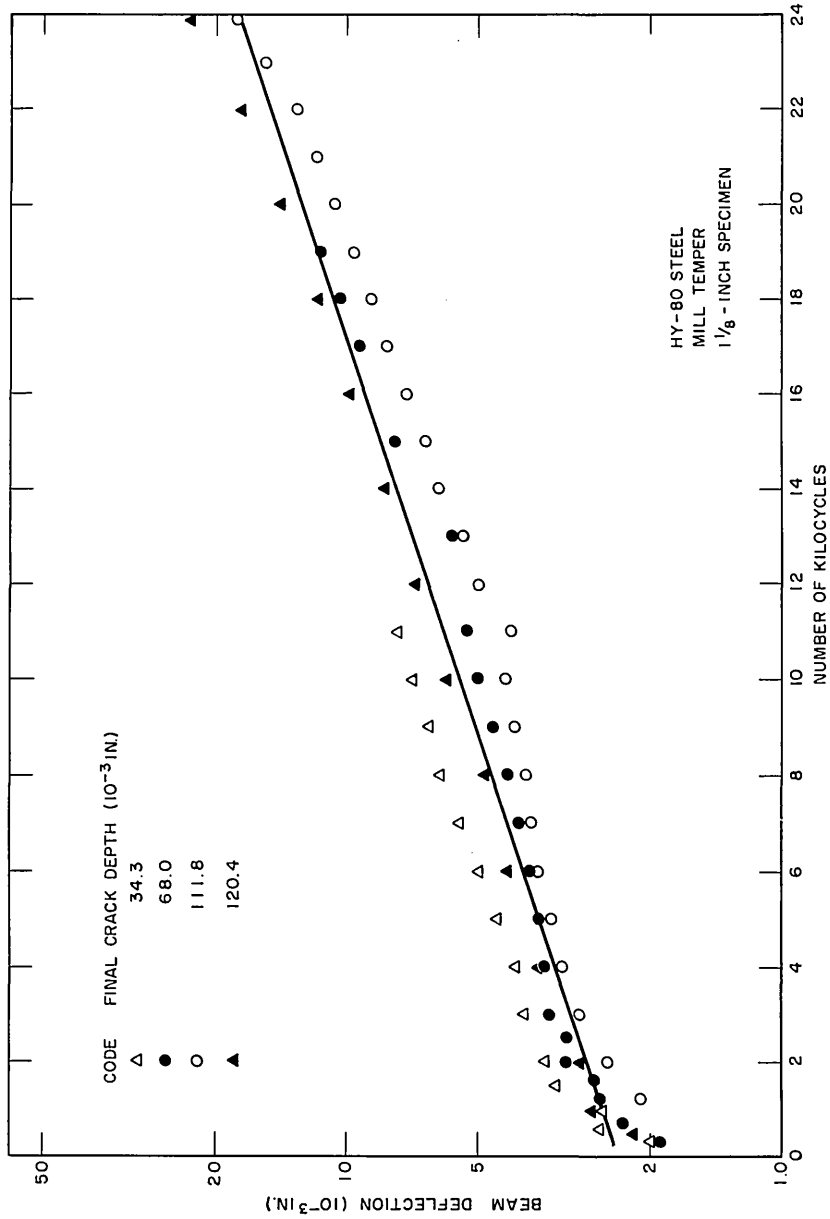


Fig. 11 - Beam deflection vs cycle data for four HY-80 1-1/8-in. mill-temper low-cycle fatigue specimens

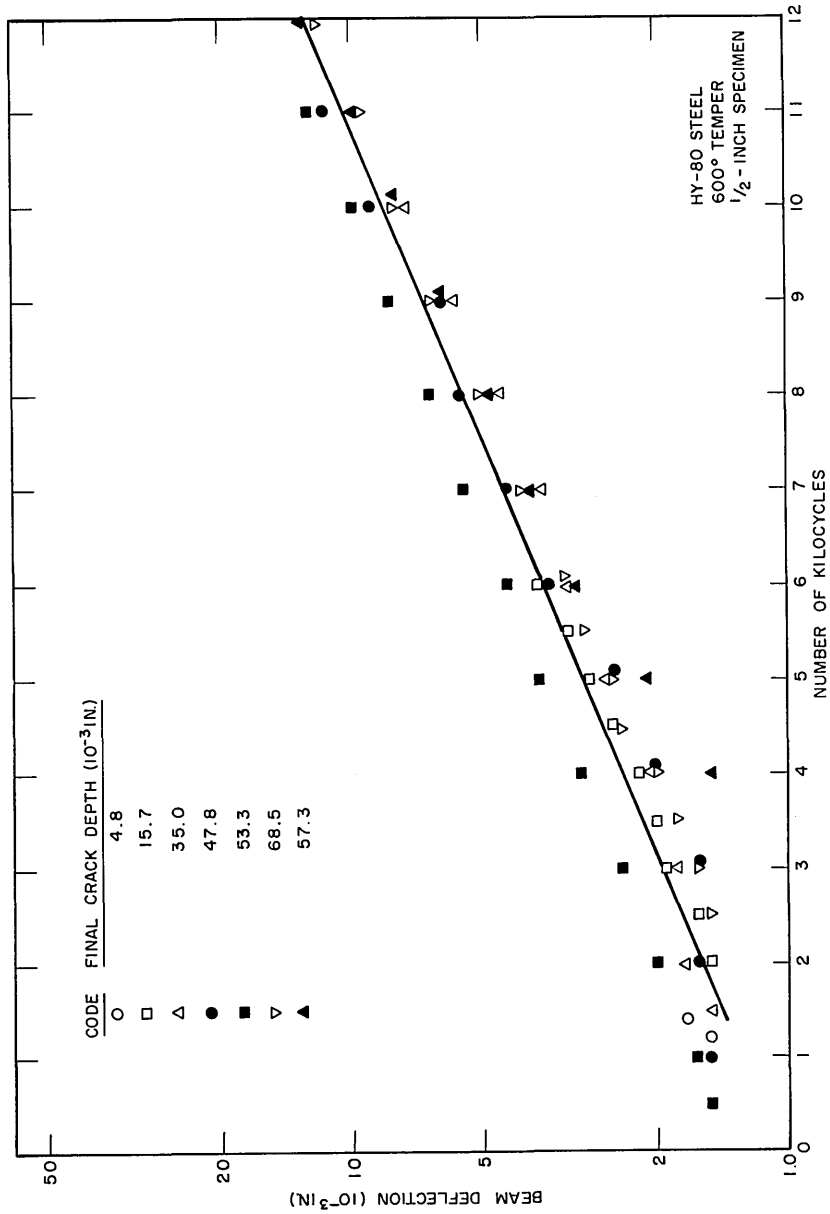


Fig. 12 - Beam deflection vs cycle data for seven HY-80 1/2-in. 600°F-temper low-cycle fatigue specimens

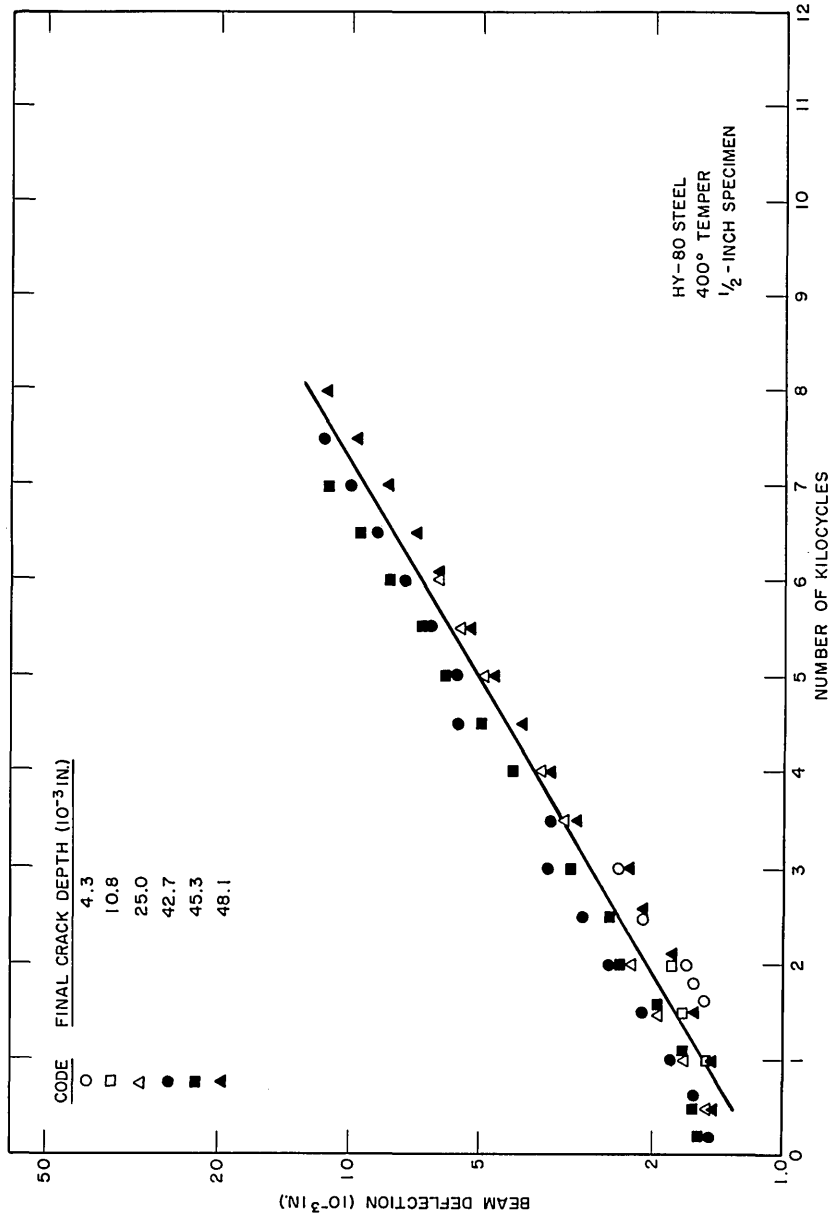


Fig. 13 - Beam deflection vs cycle data for six HY-80 1/2-in. 400°F-temper low-cycle fatigue specimens

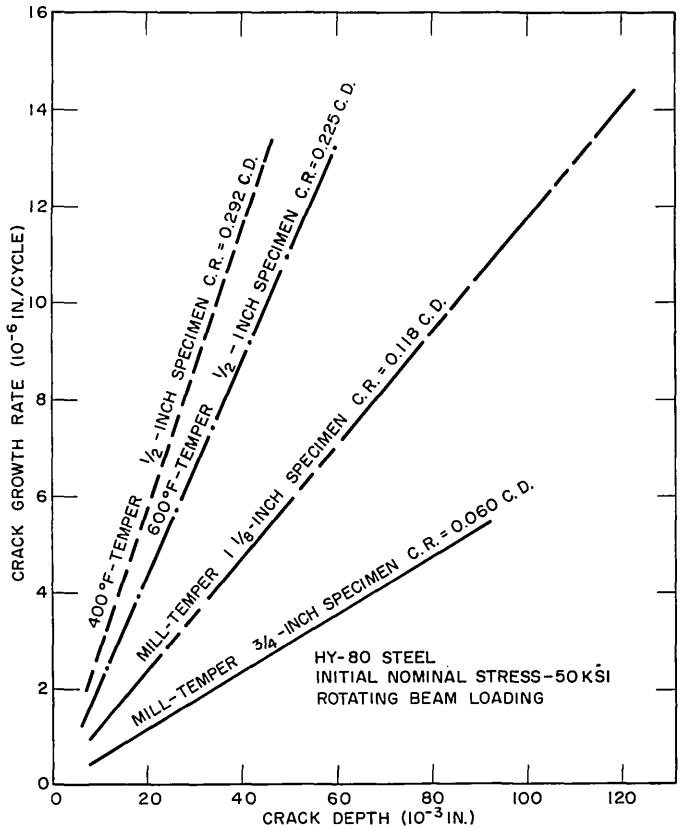


Fig. 14 - Relationship between crack growth rate and crack depth for HY-80 steels in a low-cycle rotating-beam fatigue test

Notch Tensile Tests

After the growth rate of the fatigue cracks had been observed for various penetrations, the specimens were removed from the rotating-beam machine, threaded, and pulled to fracture in order to obtain notch tensile-strength values. Since notch tensile-strength data can be strongly influenced by small changes in notch acuity and since fatigue cracks are metallurgical cracks and thus notches with maximum acuity, the notch tensile-strength data obtained from fatigue-cracked specimens are more realistic than data obtained from specimens with mechanical notches. Due to the low NDT temperature and good fracture toughness of HY-80 steels, the notch tensile strengths of all three materials exceeded their yield strengths (Fig. 15). For the mill-temper HY-80 an effect of crack size on the notch tensile strength was noted. This was attributed to localized plastic deformation which reduced notch sharpness. However, the exceptionally high notch tensile strength to YS ratio of mill-temper HY-80 can be noted.

The resistance to the growth of low-cycle fatigue cracks can be considered an energy or fracture toughness problem. Figure 16 shows the crack growth characteristics of the HY-80 steels compared with their Charpy V energy values and also their notch tensile strength to YS ratios. Although a direct relationship between the two mechanical properties and the crack growth characteristics of the materials can be seen, a wider range of Charpy V energy values would enhance the usefulness of this relationship over that for the strength ratio. In fact the 45-degree slope indicates the crack rate to crack depth index to be inversely related to the Charpy V energy for these three steels.

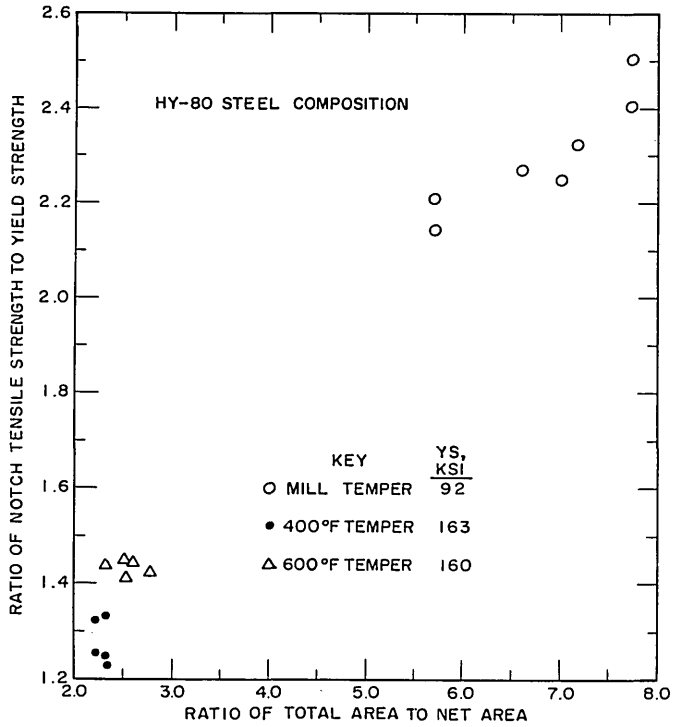


Fig. 15 - Notch tensile strength - yield strength ratio for HY-80 steels, and effect of notch depth on the notch tensile strength on mill-temper material

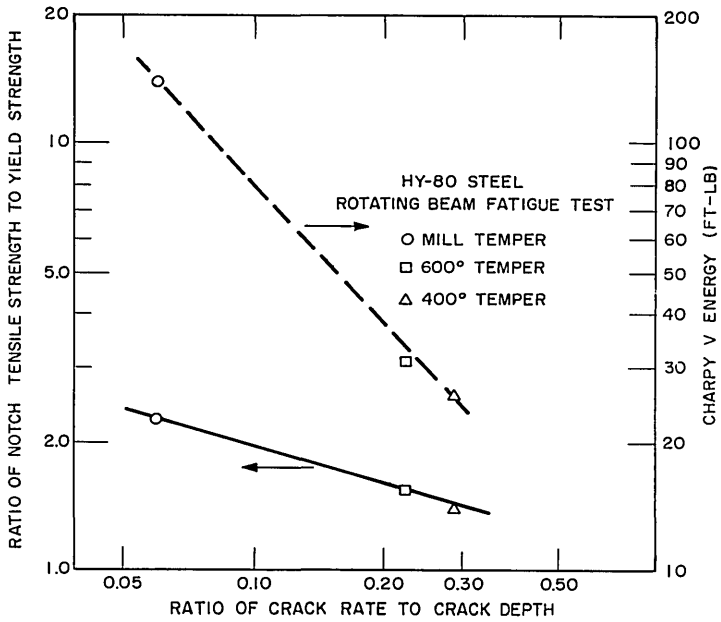


Fig. 16 - Relationship showing resistance to crack growth as a function of strength for HY-80 steels in a low-cycle rotating-beam fatigue test

The usefulness of this relationship is apparent, if verification with other steel compositions is obtained.

SUMMARY

The rotating-beam fatigue test, which is frequently regarded only as a reliable method for determining endurance limits, can be successfully adapted to low-cycle investigations. However, to achieve meaningful results with tough materials, proper care must be taken in designing the experimental procedure in order to obtain rapid crack initiation.

The performance of the rotating-beam fatigue specimens revealed a distinct "size effect," the larger specimens showing an increased rate of crack growth, as seen in Fig. 14. This was attributed to the reduced stress gradient in the larger specimens, which permitted more material to be affected by the strain zone associated with the crack tip. Consequently, more extensive cold working occurred ahead of the crack front, resulting in inferior resistance to fatigue crack propagation.

The greatest differences in performance were observed to occur with changes in heat treatment. As tempering temperature is reduced, low-cycle fatigue performance is also reduced. This variation correlates well with both the Charpy V energy values and the notch tensile strength to YS ratio (Fig. 16).

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