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EFFECT OF
SEAWATER ENVIRONMENTAL EXPOSURE
ON FATIGUE PROPERTIES OF
POLYETHYLENE PIPE

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SOLAR ENERGY

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October 1980

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EFFECT OF SEAWATER ENVIRONMENTAL EXPOSURE
ON FATIGUE PROPERTIES OF POLYETHYLENE PIPE

D. G. Tipton

EXECUTIVE SUMMARY

High density polyethylene Sclairpipe™, from the OTEC-1 cold water pipe, was evaluated for resistance to corrosion fatigue in natural seawater. Fatigue tests, mechanical properties tests, physical properties tests, and fractography showed no evidence of environmental degradation of high density polyethylene in seawater.

ABSTRACT

One laboratory study at NIT was reported to show an unexpected decrease in crystallinity for a polyethylene material exposed to fatigue loading in a synthetic seawater solution. High density polyethylene Sclairpipe™, from the OTEC-1 cold water pipe, was evaluated for resistance to corrosion fatigue in natural seawater. Intermediate crystallinity measurements (via bulk density) showed no effect of corrosion fatigue exposure. Heat of fusion (a relative indicator of crystallinity) also showed no effect of the exposure. Seawater exposure produced no significant change in tensile strength. One failure was observed during the corrosion fatigue tests and was attributed to porosity observed by fractography.

These data suggest that high density polyethylene is not significantly sensitive to degradation of fatigue strength in natural seawater.

INTRODUCTION

One proposed design for the cold water intake pipe for a 100 MWe OTEC plant calls for the use of very large (up to 9 meter diameter) polyethylene pipe suspended vertically to a depth of up to 600 meters. A structure of this size will certainly be subjected to some spectrum of fatigue loading depending upon such variables as plantship velocity, wind direction and velocity, ocean current direction and velocity, ocean current gradient with depth, and surface wave sea state.

OTEC-1, a 1 MWe experimental plant, currently being deployed, is utilizing three 1.2 m diameter polyethylene pipes (Sclairpipe™ by DuPont, Canada). The design fatigue loading spectra has been studied at some length. The present work is intended to expose samples from the OTEC-1 cold water pipe material to fatigue loading in seawater at stresses associated with the most adverse conditions of waves, wind, current and ship heading to determine if corrosion fatigue in seawater is of realistic concern with polyethylene.

A laboratory study by Donnelly, et al. at MIT, has shown an unexpected decrease in crystallinity after fatigue loading in a synthetic seawater solution.¹ Since the degree of crystallinity indicates such properties as the degree of stiffness, hardness, and environmental stress-crack resistance in polyethylene, any adverse effects of fatigue loading and/or marine exposure on crystallinity could have serious implications regarding the OTEC cold water pipe.²

MATERIALS

High density polyethylene test stock was obtained through Argonne National Laboratory (ANL) from the OTEC-1 cold water pipe material. The section of pipe and the orientation of fabricated specimens is shown in Figure 1. The pipe section was produced by DuPont of Canada Limited, Burnaby, B.C., Canada and labeled "48 Series 74 Sclairpipe PE3510".

EXPERIMENTAL

Figure 2 shows the test matrix for the corrosion fatigue and mechanical (tensile) tests. The study consisted of five efforts:

- a) corrosion fatigue tests
- b) crystallinity measurements
- c) mechanical properties
- d) differential scanning calorimetry
- e) fractography

Corrosion Fatigue Tests

The corrosion fatigue exposures utilized the ASTM Proposed Method of Test for Flexural Fatigue of Plastics by Constant-Amplitude-of-Deflection. This method utilizes a modified Krause-type fatigue testing machine of the fixed-cantilever, repeated constant deflection type (Appendix I). This loading geometry allows fatigue testing with a superimposed static stress. Using data from OTEC cold water pipe stress analyses by Global Marine Development, Inc., Department of Energy, and MGA, it was decided, for the purpose of conservative screening, to perform all fatigue tests at a frequency of 1.33 Hz with a cyclic bending stress of ± 2100 psi and a superimposed static stress of $+ 150$ psi.³ Even though the bending load cycle was under deflection control, stresses were not computed on the basis of deflection and elastic or dynamic moduli (a potential source of significant error in polymers due to time and strain dependency of elastic constants). All stresses were computed from the bending moments measured by a load cell on each fatigue machine. The outer fiber stress at the area of maximum bending stress was calculated by using the following cantilever beam formula:

$$\sigma = \frac{6 PL}{bt^2}$$

where σ is outer fiber stress, P is applied load from load cell response, L is distance from load point to failure point, b is specimen width, and t is specimen thickness. The loading frequency was measured by an oscilloscope trace of the load cell response versus time.

All fatigue specimens were modified ASTM D638 Type 1 tension test specimens (shown in Figure 3) as described in Appendix I.

As indicated in the test design in Figure 2, four specimens were exposed to fatigue loading. Three specimens were exposed to flowing natural seawater (once-through) at ambient conditions during the fatigue exposures. A transparent cell of thin, flexible plastic was used to contain the specimen to allow continuous immersion in the flowing seawater. One specimen was exposed to fatigue loading in air. Dry air conditions were maintained by mounting the specimen in a cell similar to the seawater cells but with inlet and outlet sealed.

All fatigue tests were conducted to failure or 10^7 cycles (~ 2100 hours). Intermediate removals were made at 10^5 cycles (~ 21 hours) and 10^6 cycles (~ 210 hours). During these intermediate removals, measurements were made indicating any change in crystallinity due to the corrosion fatigue exposure. After each intermediate removal, the specimens were remounted in the containment cell and the fatigue load readjusted to ± 150 ± 2100 psi.

Crystallinity Measurements

Of the potential detrimental effects of corrosion fatigue on polyethylene a serious effect on an OTEC cold water pipe might be a loss in mechanical properties caused by a loss in crystallinity. Density in polyethylene is

directly proportional to crystallinity (although other factors such as porosity and homogeneity also influence density), such that density could be taken as an indirect indication of relative crystallinity. Since intermediate removals were to be taken and changes in crystallinity of each independent specimen were of interest, it was decided to use density measurements according to ASTM D792-66 Method A-1 instead of more exacting, but tedious, measurement techniques for crystallinity (e.g. x-ray diffraction and calorimetry). Thus, density was used as an indirect indication of crystallinity.

Mechanical Properties

As shown in Figure 2, mechanical tensile tests were performed on specimens which were exposed to seawater but no fatigue. Tensile tests were conducted according to ASTM D638 on specimens shown in Figure 3. Specimens were exposed to seawater for periods of time corresponding to the intermediate fatigue removals at 10^5 , 10^6 , and 10^7 cycles.

After seawater exposure, the specimens were pulled to maximum load on an MTS servohydraulic universal testing machine. A high elongation extensometer was used to detail the yielding behavior. A typical load versus strain trace is shown in Figure 4. Tensile strength was computed from the maximum load. Specimens receiving no seawater exposure were tested as a control.

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC), giving relative heat of fusion measurements, gives another indirect indication of relative crystallinity similar to density. Unlike density, DSC uses a very small (<10 mg) specimen and can thus give an indication of crystallinity at essentially a point. Also unlike density, DSC is not affected by porosity--a non-homogeneity which may be found in large sections of commercial polyethylene as a result of thermal processing.

A number of DSC measurements were made at Inco Research and Development Center (IRDC), Sterling Forest, New York using a duPont 910 Differential Scanning Calorimeter. Figure 5 shows a typical DSC melting curve.

Fractography

One specimen suffered complete fracture during the fatigue testing. The fracture surface was submitted to fractographic analysis at IRDC on a Cambridge Stereoscan 180 scanning electron microscope (SEM). The fracture surface was prepared by sputter coating with carbon.

RESULTS AND DISCUSSION

Corrosion Fatigue Tests and Density Measurement

Table I gives the results of intermediate density measurements after exposure to air fatigue and natural seawater with and without fatigue loading after 0 cycles/0 hours, 10^5 cycles/21 hours, 10^6 cycles/210 hours, and 10^7 cycles/2100 hours. These data are shown graphically in Figure 6. Typical density values for polyethylene are also given.⁴ It can be seen that, through the course of the fatigue exposures, the density for a given specimen decreased by no more than 0.3%. Interestingly, the specimen which showed the maximum change in density during the course of the fatigue exposures was the specimen tested in air. This could be attributed to effects of internal friction and heating even at this low loading frequency (1.33 Hz) in the air environment-- whereas the specimens tested in seawater were subject to cooling by the seawater flow ($\sim 100 \text{ mL/min}$).

Another interesting point from these data is that the density variation for the specimen which failed at $\sim 5.58 \times 10^6$ cycles was less than 0.1%. Also, the failed specimen had a somewhat lower density than the remaining four specimens. The significance of this lower density will be discussed later.

To assess the homogeneity of density across the pipe wall, which could vary due to thermal processing, a density profile was measured. One specimen each was taken from location 1) near the surface at the outside diameter, 2) from mid wall, and 3) near the surface at the inside diameter. Table II gives the results of this density profile. The density of the failed fatigue specimen is near the density of the OD location, while the density of the other fatigue specimens is near the density of the ID and midwall locations.

It should be noted that the load magnitudes used in these tests represent a very severe fatigue environment from a purely mechanical standpoint. The maximum stress (2250 psi) is approximately 80% of the measured tensile strength (2574 to 2850 psi, from Table III) of the polyethylene test stock.

In summary, deleterious effects of corrosion fatigue exposure of polyethylene (e.g., work by Donnelly et al. at MIT in low density polyethylene¹) were not found in these corrosion fatigue/density data.

Mechanical Properties

Table III gives the results of the mechanical tensile tests of polyethylene after exposure to seawater with no fatigue loading. Figure 7 shows these data graphically. Clearly, seawater exposure produced no significant change in tensile strength.

Differential Scanning Calorimetry

Table IV gives the results of the DSC tests. Here the relative heat of fusion is given for material from 1) failed and unfailed fatigue specimens near the area of maximum bending and 2) from the unstressed end and from two locations from the untested pipe sample stock. None of the heat of fusion

measurements (indicative of crystallinity) showed significant differences. These results are in good agreement with the density measurements described earlier. Neither seawater exposure or seawater corrosion fatigue exposure produced a significant difference in DSC results -- indicating no significant change in crystallinity.

Fractography

Figure 8 shows low magnification photomicrographs of the fracture surface from the failed fatigue specimen. The surface of the cantilever beam subjected to the maximum bending is on the left. The crack propagated left to right, with probable initiation at the upper left of Figure 8a. Note the stepwise early propagation of the crack--typical of fatigue crack growth. The "flat" feature on the right side of Figure 8a and 8b is the last-to-fail area of ductile rupture.

Figure 9 is a closeup of the area of probable fracture initiation. The striations in the upper right are marks on the original outer surface from the specimen fabrication by machining and by abrasive paper preparation. Note the apparent porosity on the fracture surface. This suggests that porosity could have been a factor in the failure of this specimen.

Figure 10 shows a closeup of the smooth area on the fracture surface. This area shows little evidence of ductile rupture and is suggestive of brittle fast fracture.

In summary, the fractography showed features associated with mechanical failure with no obvious effects of the seawater exposure. Indeed, the apparent fracture initiation site showed a possible contribution by material porosity to the fatigue failure.

CONCLUSIONS

1. Bulk density (a relative indicator of crystallinity) showed no significant effect from corrosion fatigue exposure in natural seawater.
2. Heat of fusion (a relative indicator of crystallinity) showed no significant effect from corrosion fatigue exposure in natural seawater.
3. The single fatigue failure was not due to environmental deterioration in seawater, since porosity was suggested by density measurements and fractography as a probable cause of crack initiation.
4. The failure was apparently purely mechanical in nature (maximum stress was approximately 80% of tensile strength).
5. These data suggest that high density polyethylene is not significantly sensitive to degradation of fatigue strength in natural seawater, even at very high fatigue loads.

ACKNOWLEDGEMENT

The author wishes to thank P. Bernstein and P. K. Sullivan at Inco Research and Development Center, Suffern, New York for their valuable advice and assistance in the analysis of these data.

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3. Memo W. M. Howerton to Sig Gronich, "Cold Water Pipe Stress Analysis", of July 25, 1979.
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TABLE I

Variation in Density of Linear Polyethylene
After Exposure to Air and Natural Seawater
With and Without Fatigue Loading*

Environment	Density (gm/cm ³)			
	No exposure	10 ⁵ cycles/21 hr	10 ⁶ cycles/210 hours	10 ⁷ cycles/2100 hours
Natural Seawater -- No fatigue	0.9568	0.9587	0.9579	0.9585
Natural Seawater -- Fatigue	0.9565	0.9583	0.9585	0.9581
Natural Seawater -- Fatigue	0.9578	0.9583	0.9581	0.9572
Natural Seawater -- Fatigue	0.9549	0.9559	0.9553	0.9552**
Air-fatigue	0.9564	0.9584	0.9576	0.9553

* Fatigue loading: mean stress - +150 psi
 alternating stress - +2100 psi

** At failure 5.58×10^6 cycles

TABLE II

Density Gradient Across Pipewall

<u>Location</u>	<u>Density (gm/cm³)</u>
Near OD Surface	0.953
Midwall	0.958
Near ID Surface	0.959

TABLE III

Variation in Ultimate Tensile Strength of Specimens
from Polyethylene Pipe After Exposure to Natural Seawater
(No Fatigue)

<u>Exposure to Seawater (hours)</u>	<u>Ultimate Tensile Strength* (psi)</u>
0	2670, 2574
21	2844, 2628
210	2755, 2708
2100	2677, 2850

* Duplicate specimens

TABLE IV

Relative Heat of Fusion Determined from
Differential Scanning Calorimetry Melting Curves

<u>Sample</u> <u>Material</u>	<u>Location</u>	<u>Relative</u> <u>Area Under</u> <u>Melting Curve</u>	<u>Wt. of</u> <u>Specimen (mg)</u>	<u>Relative Heat of Fusion*</u> <u>(Area under curve/wt specimen)</u>
Failed fatigue specimen	Unstressed End	63.6	4.9	13.0
Failed fatigue specimen	Near Max Bending	71.1	5.2	13.7
Unfailed fatigue specimen	Near Max Bending	91.8	6.4	14.3
Pipe Sample Stock	Near ID Surface	95.8	6.7	14.3
Pipe Sample Stock	Midway	108.6	7.4	14.7

* Dimensionless relative parameter indicative of percent crystallinity

Figure 1. Geometry of mechanical test specimens.

1. No Seawater Exposure
2. No Seawater Exposure
3. Seawater Exposure (No Fatigue)
4. " " " "
5. " " " "
6. " " " "
7. " " " "
8. " " " "

Mechanical (Tensile) Tests

1. Seawater Exposure (No Fatigue)
2. Seawater Fatigue Exposure
3. " " "
4. " " "
5. Air Fatigue Exposure

Density Measurements

Figure 2. Test Design

Figure 3. ASTM D635 Type I tension test specimen for plastics.

Blank

Figure 5. Typical DSC Curve

Figure 6. Effect of Fatigue Environment on Density

Figure 7. Effect of Seawater Exposure on Tensile Strength

a)

Negative No. 80129-1

b)

Negative No. 80130-4

Figure 8. SEM photomicrographs of fracture surface. Fracture probably initiated in upper left corner of a). The scale indicated is the distance between marks.

Negative No. 80130-1

Figure 9. Area of probable fracture initiation showing possible porosity.

Negative No. 80130-2

Figure 10. Area of smooth fracture surface.

Proposed Method of Test for FLEXURAL FATIGUE OF PLASTICS BY CONSTANT-AMPLITUDE-OF-DEFLECTION¹

This proposed method has no status as an ASTM standard and is published on behalf of the sponsoring Committee for information only for a maximum of two years. Comments are solicited and should be addressed to the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

1. Scope

1.1 This method² covers the determination of the effect of repetitions of the same magnitude of flexural strain on rigid plastics by fixed-cantilever-type testing machines, designed to produce a constant-amplitude-of-deflection on the test specimen each cycle.

1.2 See ASTM Method D 671, Test for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force³ for sections on: Significance, Conditioning, Plotting and Interpreting Results, Report, Suggested Form of Data Sheet, and Definitions and Description of Terms.

2. Summary of Method

2.1 This method measures the ability of a material to resist deterioration from cyclic deformation. The test results provide data on the number of cycles of deflection to produce specimen failure by fracture, softening, or reduction in stiffness by thermal heating or cracking.

3. Apparatus

3.1 *Testing Machine*—A fatigue testing machine of the fixed-cantilever, repeated constant-deflection type. In this machine, the specimen is held as a cantilever beam in a vise at one end and bent by a concentrated load applied near the other end. The bending is accomplished by a connecting rod driven by a variable eccentric mounted on a shaft. The shaft is rotated by a variable speed drive. The vise may be set in the plane of the eccentric so that the beam will be deflected on either side of the neutral position (completely reversed stress) or the vise may be set so that the deflection is greater on one side than on the other (mean stress not zero). The machine shall be capable of continuously measuring

the load on the specimen without stopping the test.

3.2 *Counter*, geared to the shaft so as to record the number of cycles.

3.3 *Loading Yoke*, pivoted at each end of the test specimen, used to flex the specimen. The loading yoke has two parallel arms, one along each side of the specimen. These arms are pivoted at the bending point of the specimen but do not fix the point of flexure. The connecting rod is pinned to the loading yoke at a point beyond the free end of the specimen. A pair of rollers which may be adjusted for specimen thickness loads the cantilever beam specimen at its free end. This loading system does not require the specimen to serve as a structural member of the apparatus and the action of the device is independent of sample properties.

3.4 *Dynamometer*—The vise at the fixed end of the specimen includes a dynamometer for measuring the load on the specimen. The dynamometer is a reduced section of the clamping arm which is instrumented so that the cyclic load response of the specimen can

¹ This proposed method is under the jurisdiction of ASTM Committee D-20 on Plastics and is the direct responsibility of Subcommittee D20.10 on Mechanical Properties.

Published as information only, June 1972.

² This proposed method replaces Method A of ASTM Method D 671 - 63 Repeated Flexural Stress (Fatigue) of Plastics. D 671 - 63 Method A cannot be adequately performed with the equipment described in the method because of the occurrence of standing waves of uncontrolled bending caused by dynamic imbalance of the specimen holder. The proposed method was developed to overcome these limitations. However, since this method is currently being used in very few laboratories, it is published as a proposed method for those using the equipment and Method A of D 671 - 63 which was dropped from publication. When sufficient laboratories are capable of using this method to successfully complete round-robin testing, it is intended to incorporate this method into ASTM Method D 671, Test for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force.

³ Annual Book of ASTM Standards, Part 27.

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be continuously recorded during a test.

3.5 Thermometer—Use a suitable means of measuring the temperature of the specimen, such as a radiation thermometer. If desired, the signal from the thermometer may also be used to control the temperature of the specimen at a selected point for the duration of the test.

NOTE 1—Figure 1 in a schematic diagram of the fatigue apparatus.

NOTE 2—Figure 2 is a close-up of a loading yoke and dynamometer (load cell) arrangement.

4. Test Specimens

4.1 The test specimens may be prepared by molding or machining from flat sheets. The test specimens may be taken from one end of an ASTM D 638 Type I tension test specimen as illustrated in Fig. 3 or conform to one of the two types shown in Fig. 2 of Method D 671. There are discrete advantages for each specimen type.

NOTE 3—This one-ended D 638 tension-type specimen offers the following advantages:

(1) Because the maximum stress is localized this specimen is useful for monitoring heating effects at a predetermined failure area;

(2) It offers advantages for relative comparison with other data, such as tensile, creep, stress relaxation which were determined using this same type of specimen; and

(3) This type of specimen is usually readily available.

NOTE 4—The specimens shown in Fig. 2 of Method D 671 offer the following advantages:

(1) The triangular portion of these specimens provides for uniform stress distribution over the entire test span. Failure will occur at flaws within this volume.

(2) It is the same specimen used in the constant-force fatigue test (D 671), and

(3) The failure area can be identified by scanning the surface of the specimen with the temperature sensor and locating the "hot spots" associated with the flaw.

4.2 Figure 3 illustrates the portion of the tension specimen used and the location of the fixed clamp. The edge of the fixed clamp must be carefully aligned across the 19-mm ($\frac{3}{4}$ -in.) width and at the beginning of the 76.2-mm (3-in.) radius fillet. The location of the fixed clamp is critical because it affects the point at which failure occurs (see Note 5).

4.2.1 The recommended length of the specimen from the fixed-clamp edge to the loading point is 76.2 mm (3.0 in.). Other lengths may be used if necessary to induce stress levels not

attainable using the recommended length.

4.3 The constant-stress-type specimens illustrated in Fig. 2 of Method D 671 may be used.

4.4 Specimens may be molded to the dimensions specified, but care should be taken to relieve internal stress unless the effect of molded-in stress is to be measured.

4.5 Machining of each specimen should be accomplished with a very sharp cutting tool, using such combination of speed and feed as will give a good finish with a minimum of heating of the specimen. The test specimen should be polished with successively finer abrasive paper, finishing with No. 00 to remove all scratches and tool marks. The final polishing should be lengthwise of the specimen, since even small scratches transverse to the direction of tensile stress tend to lower the fatigue strength. In order to avoid heating, all polishing should be done either by hand or with light pressure on a slowly revolving sanding drum. Care should be taken to avoid rounding the edges of the specimen.

4.6 The type of specimen used must be reported with the data.

5. Calibration of the Dynamometer

5.1 Calibrate the dynamometer using a dummy steel specimen of the desired length (equal to the length of the test specimen). Calibration checks should be made at the beginning and end of each test.

5.2 Disconnect the connecting rod from the loading yoke and note where loading rollers contact the dummy specimen. Remove the loading yoke from the assembly. Hang known weights from the point where the loading rollers contacted the specimen and record the corresponding indication of the load-sensing system of the dynamometer (see Fig. 4, Schematic of Calibration Arrangement). Plot a calibration curve of dead-weight load against the dynamometer response. A straight-line diagram should result.

6. Calculation of Desired Initial Stress

6.1 Using one end of an ASTM Type I tension specimen as shown in Fig. 3, calculate the desired initial alternating stress in pounds-force per square inch (or megapascals), using the cantilever beam formula:

FLEXURAL FATIGUE BY CONSTANT-AMPLITUDE-OF-DEFLECTION

$$\text{Stress} = 6PL/bd^2$$

where:

- L = distance from load point to failure point, 67.9 mm (2.675 in.) (Note 5),
- b = specimen width at failure point, 13.5 mm (0.530 in.) (Note 5),
- d = specimen thickness at failure point, mm (or in.), and
- P = applied load obtained from the dynamometer response versus dead weight calibration curve, N (or lbf).

The dimensions of L and b may be verified by measurements taken after the specimen has failed. The values given for L and b locate the theoretical point of maximum nominal stress. These calculated values assume the specimen to be clamped within ± 0.75 mm (0.03 in.) of the location in Fig. 3.

NOTE 5—These are calculated dimensions using the simple cantilever beam formula and the geometry of the specimen. The location of the failure area or point of maximum stress is a function of the loading moment length and the width of the specimen. Therefore, the location of the fixed clamp and the point of loading must be set accurately so that the region of maximum stress can be predicted by calculation. It has been demonstrated that moving the fixed clamp 12.7 mm ($\frac{1}{2}$ in.) away from the beginning of the 76.2-mm (3-in.) radius fillet towards the wide end of the specimen will cause failure to occur across the 19-mm ($\frac{3}{4}$ in.) width of the specimen. Changing the fillet radius from 76.2 mm (3 in.) to 6 mm ($\frac{1}{4}$ in.) does not significantly affect results. With the specimen clamped as illustrated in Fig. 3, the maximum stress does not occur exactly at the end of the minimum section but slightly further from the point of loading. Failure will develop in an area of maximum stress and for isotropic specimens repeatedly occurs at 67.9 mm (2.675 in.) from the loading point.

6.2 Using the constant-force fatigue specimens (see Fig. 2, of Method D 671) the desired initial alternating stress is calculated using the formula in 6.1. With this specimen the ratio of L/b is constant and L shall be the distance measured from the point of loading to the point along the principal axis through which the specimen width (b) is measured.

7. General Test Procedure

7.1 Select the length of the specimen and sample deflection or eccentric setting to produce the desired initial stress in the sample. This stress level for example could be chosen as some percent of the ultimate strength or from some other means.

7.2 Measure the sample thickness to the

nearest 0.03 mm (0.001 in.).

7.3 Position the clamping vise and loading yoke to accommodate the selected specimen length.

7.4 Secure the tensile-type specimen to the vise by bolting through the attachment hole in the specimen as shown in Fig. 3. When using the constant-force fatigue-type specimen, drill the attachment hole in the large end of the specimen along its center line. Locate this hole along the center line so that the leading edge of the clamp aligns across the inner edge of the large end of the specimen. Connect the sensing system of the dynamometer to the recorder and balance under no-load conditions.

7.5 Fit the free end of the specimen between the rollers which are adjustable for sample thickness. Adjust the load point rollers to contact the sample. The loading rollers contact line with the surface of the specimen shall be 4.8 mm (0.187 in.) from small end of the constant-force fatigue specimen.

7.6 Adjust the crank eccentric setting and secure it at the desired level of amplitude.

7.7 Rotate the eccentric by hand through several revolutions and observe the response of the dynamometer. Adjust the eccentric until the dynamometer indicates the load to produce the desired initial stress. If necessary, make a vertical adjustment of the clamping vise to achieve equal dynamometer response above and below the no-load or zero stress level.

7.8 Record the information as outlined in Appendix A2 of method D 671.

7.9 Focus the radiation thermometer on the failure area of the specimen. Temperature measurement should be over small areas such as 0.76 mm (0.030 in.) diameter, and scan the specimen, periodically, adjacent to the failure area to ensure that the area of maximum localized heating is being measured. Scan the surface of the constant-force specimen to locate "hot spots" due to flaws.

7.10 Conduct fatigue tests at frequency of interest. When frequency is not specified, conduct tests at 1800 ± 5 percent rpm.

7.11 *Readings*—Set the revolution counter at zero and also start the dynamometer recorder before starting a test. Continue the test until the sample fails or until the stress level has decayed to the predetermined value (see

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8.1.5 and 8.3).

7.12 Test three or more specimens at each of at least four different stress or strain amplitudes. Choose these amplitudes so as to yield a mean log of cycles to failure ($\log N$) of about 3, 4, 5, 6, and 7.

8. Plotting and Interpreting Results

8.1 When testing at constant-amplitude-of-deflection, the initial stress level will decay as the test continues. This decay is related to stress relaxation and increase in temperature due to flexing the specimen. The amount of stress decay is indicated by changes in the load sensing readout system of the dynamometer and can be determined and a stress decay curve plotted as follows:

8.1.1 Observe the readout system (recorder) that is recording the dynamometer output. Note the dynamometer response corresponding to the time or number of cycles of interest.

8.1.2 Use the calibration curve (Section 5) to obtain the applied load corresponding to this dynamometer response.

8.1.3 Calculate the stress using the cantilever beam formula as given in Section 6.

8.1.4 Plot the stress level versus the log of the number of flex cycles endured at the time the stress level was calculated. (Semilog paper is convenient for this plot.)

8.1.4.1 It is suggested that stress levels be calculated after $(1, 2, 5, 10) \times 10^2$ to 10^6 cycles. The initial stress level as obtained in 7.7 should also be included in this plot.

8.1.5 An example of a stress decay curve (specimen stiffness decay) is shown below. Point *A* represents the initial outer fiber stress applied at the start of the test. Point *B* is where the stress level has decayed to 70 percent of the initial value. When the stress level decays to the 70 percent value, the specimen

is considered to have failed. Point *C* represents complete failure of the specimen. Complete failure could also occur before the stress level had decayed to 70 percent of the initial value.

8.2 *S-N* or stress versus cycle-for-failure diagrams assume the applied stress to be constant throughout the entire duration of the test as in Method D 671. In constant-amplitude-of-deflection experiments the stress level does not remain constant. However, an *S-N* diagram may be constructed provided the stress axis shall be labeled as initial stress.

NOTE 6—*S-N* diagrams plotted by this concept are similar to those from constant amplitude of force tests but should not be considered equivalent. Usually a test specimen will fail in fewer cycles by constant amplitude of force test.

8.3 *Plotting Stress Results*—Plot an *S-N* (stress versus cycles-to-failure) diagram with the initial stress amplitude as the ordinate against the common logarithm of the number of cycles required for failure as the abscissa. Plot all test data and define the *S-N* diagram preferably using a regression analysis or by drawing the best-fit smooth curve as closely as possible through the points. The use of semilogarithmic paper will facilitate the plotting. Indicate on the diagram specimens that did not fracture by an arrow directed away from the plotted point in the direction of increasing cycles.

8.3.1 When sufficiently large number of samples are tested at a given stress level, probability plots of fatigue life at the given stress are useful to determine the F_{50} fatigue life at that stress. The F_{50} values at various stress levels may then be used to define the *S-N* diagram.

8.4 *Plotting Strain Results*—Plot an $\epsilon-N$ (strain versus cycles-to-failure) diagram with the alternating strain amplitude of the ordinate against the common logarithm of the number of cycles required for failure as the abscissa. Plot all test data and define the $\epsilon-N$ diagram preferably using a regression analysis or by drawing the best-fit smooth curve as closely as possible through the points. The use of semilogarithmic paper will facilitate the plotting. Indicate on the diagram specimens that did not fracture by an arrow directed away from the plotted point in the direction of increasing cycles.

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8.4.1 When sufficiently large number of samples are tested at a given strain level, probability plots of fatigue life at the given strain are useful to determine the F_{90} fatigue life at that strain. The F_{90} values at various strain levels are then used to define the ϵ - N diagram.

8.5 *Interpretation of Results*—When a material shows a knee in the S - N (stress-cycle diagram) or the ϵ - N (strain versus cycles-to-failure diagram) such that the curve gives clear indications that it becomes asymptotic to a horizontal line, it is sufficient to carry the number of cycles far enough beyond the knee

to indicate with a good degree of accuracy that the curve becomes asymptotic to a constant stress line. If the curve does not become asymptotic to a constant stress line, continue the test until the number of cycles reached is greater than the number of cycles that the material will be expected to withstand in its life. Report the value of the alternating initial stress or strain corresponding to this number of cycles as the "fatigue" strength at the maximum number of cycles for which the stress diagram has been well defined by the tests.

FIG. 1 Schematic Diagram of Flex Fatigue Testing Machine and Accessories.

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FIG. 2 Close-up of Loading Yoke and Dynamometer (Load Cell) Arrangement.

FIG. 3 Dimensions of Constant Deflection Flexural Fatigue Specimen Taken from ASTM D 638 Type 1 Tension Test Specimen Showing Location of Clamp.

FIG. 4. Schematic Diagram of Dynamometer Calibration Arrangement.

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