Standard Practice for Strain-Controlled Fatigue Testing[1]

This standard is issued under the fixed designation E 606; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

ϵ^1 NOTE—Section 10 was editorially revised in July 2005.

1. Scope

1.1 This practice covers the determination of fatigue properties of nominally homogeneous materials by the use of test specimens subjected to uniaxial forces. It is intended as a guide for fatigue testing performed in support of such activities as materials research and development, mechanical design, process and quality control, product performance, and failure analysis. While this practice is intended primarily for strain-controlled fatigue testing, some sections may provide useful information for force-controlled or stress-controlled testing.

1.2 The use of this practice is limited to specimens and does not cover testing of full-scale components, structures, or consumer products.

1.3 This practice is applicable to temperatures and strain rates for which the magnitudes of time-dependent inelastic strains are on the same order or less than the magnitudes of time-independent inelastic strains. No restrictions are placed on environmental factors such as temperature, pressure, humidity, medium, and others, provided they are controlled throughout the test, do not cause loss of or change in dimension with time, and are detailed in the data report.

NOTE 1—The term *inelastic* is used herein to refer to all nonelastic strains. The term *plastic* is used herein to refer only to the time-independent (that is, noncreep) component of inelastic strain. To truly determine a time-independent strain the force would have to be applied instantaneously, which is not possible. A useful engineering estimate of time-independent strain can be obtained when the strain rate exceeds some value. For example, a strain rate of 1×10^{-3} sec^{-1} is often used for this purpose. This value should increase with increasing test temperature.

1.4 This practice is restricted to the testing of uniform gage section test specimens subjected to axial forces as shown in Fig. 1(a). Testing is limited to strain-controlled cycling. The practice may be applied to hourglass specimens, see Fig. 1(b), but the user is cautioned about uncertainties in data analysis and interpretation. Testing is done primarily under constant amplitude cycling and may contain interspersed hold times at repeated intervals. The practice may be adapted to guide testing for more general cases where strain or temperature may vary according to application specific histories. Data analysis may not follow this practice in such cases.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products
E 3 Practice for Preparation of Metallographic Specimens
E 4 Practices for Force Verification of Testing Machines
E 8 Test Methods for Tension Testing of Metallic Materials
E 9 Test Methods of Compression Testing of Metallic Materials at Room Temperature
E 83 Practice for Verification and Classification of Extensometer System
E 111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E 112 Test Methods for Determining Average Grain Size
E 132 Test Method for Poisson's Ratio at Room Temperature
E 157 Practice for Assigning Crystallographic Phase Designations in Metallic Systems[3]
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E 209 Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
E 337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E 384 Test Method for Microindentation Hardness of Materials
E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials
E 466 Practice for Conducting Force Controlled Constant

[1] This practice is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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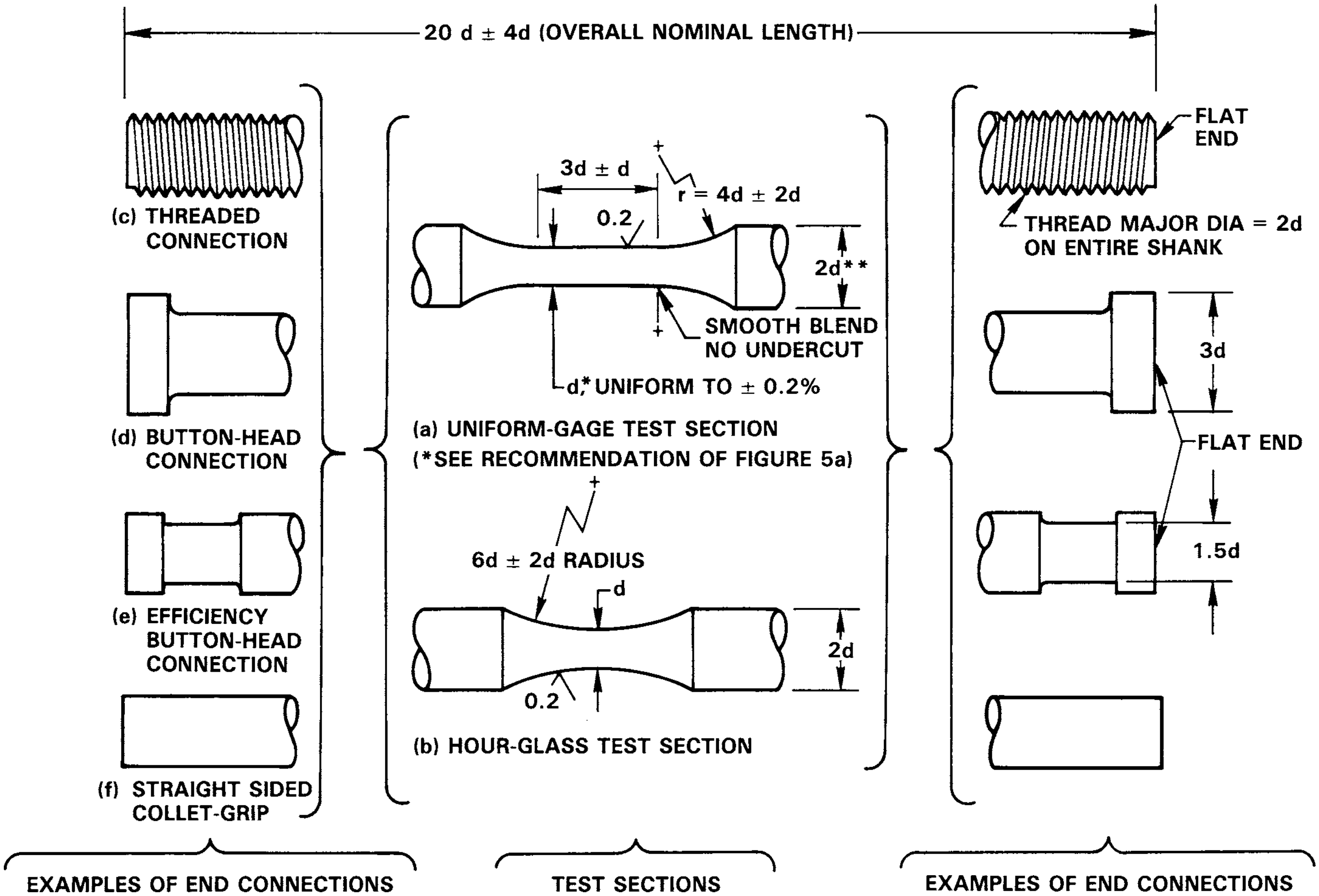
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Withdrawn.



NOTE 1—* Dimension d is recommended to be 6.35 mm (0.25 in.). See 7.1. Centers permissible. ** This diameter may be made greater or less than 2d depending on material hardness. In typically ductile materials diameters less than 2d are often employed and in typically brittle materials diameters greater than 2d may be found desirable.

FIG. 1 Recommended Low-Cycle Fatigue Specimens

Amplitude Axial Fatigue Tests of Metallic Materials
E 467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
E 468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E 739 Practice for Statistical Analysis of Linear or Linearized Stress-Life (*S-N*) and Strain-Life (ϵ-*N*) Fatigue Data
E 1012 Practice for Verification of Specimen Alignment Under Tensile Loading
E 1049 Practices for Cycle Counting in Fatigue Analysis
E 1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 The definitions in this practice are in accordance with Terminology E 1823.

3.2 Additional definitions associated with time-dependent deformation behavior observed in tests at elevated homologous temperatures are as follows:

3.2.1 *hold period*, τ_h—the time interval within a cycle during which the stress or strain is held constant.

3.2.2 *inelastic strain*, ϵ_{in}—the strain that is not elastic. For isothermal conditions, ϵ_{in} is calculated by subtracting the elastic strain from the total strain.

3.2.3 *total cycle period*, τ_t—the time for the completion of one cycle. The parameter τ_t can be separated into hold and nonhold components:

$$\tau_t = \Sigma\tau_h + \Sigma\tau_{nh} \quad (1)$$

where:
$\Sigma\tau_h$ = sum of all the hold portions of the cycle and
$\Sigma\tau_{nh}$ = sum of all the nonhold portions of the cycle.

τ_t also is equal to the reciprocal of the overall frequency when the frequency is held constant.

3.2.4 The following equations are often used to define the instantaneous stress and strain relationships for many metals and alloys:

$$\epsilon = \epsilon_{in} + \epsilon_e \quad (2)$$

$$\epsilon_e = \frac{\sigma}{E^*} \text{ (see Note 2)}$$

and the change in strain from any point (1) to any other point (3), as illustrated in Fig. 2, can be calculated as follows:

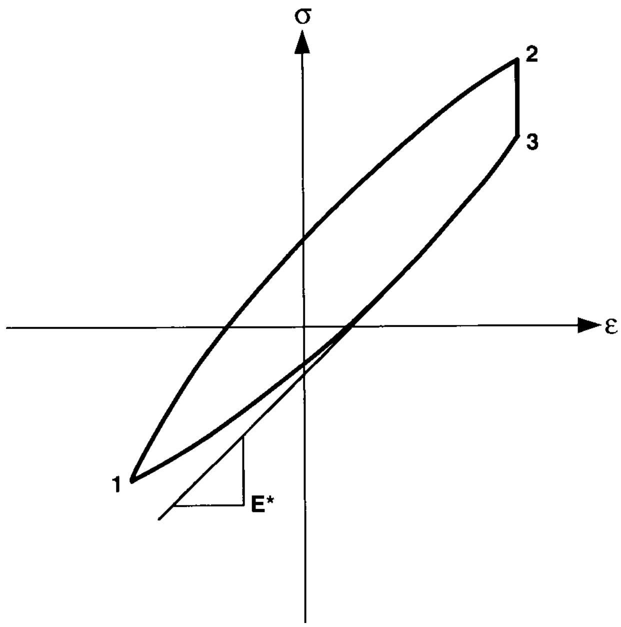


FIG. 2 Analyses of a Total Strain versus Stress Hystersis Loop Containing a Hold Period

$$\epsilon_3 - \epsilon_1 = \left(\epsilon_{3in} + \frac{\sigma_3}{E^*}\right) - \left(\epsilon_{1in} + \frac{\sigma_1}{E^*}\right) \quad (3)$$

All strain points to the right of and all stress points above the origin are positive. The equation would then show an increase in inelastic strain from 1 to 3 or:

$$\epsilon_{3in} - \epsilon_{1in} = \epsilon_3 - \epsilon_1 + \frac{\sigma_1}{E^*} - \frac{\sigma_3}{E^*} \quad (4)$$

Similarly, during the strain hold period, the change in the inelastic strain will be equal to the change in the stress divided by E^*, or:

$$\epsilon_{3in} - \epsilon_{2in} = \frac{\sigma_2 - \sigma_3}{E^*} \quad (5)$$

NOTE 2—E^* represents a material parameter that may be a function of environment and test conditions. It also may vary during a test as a result of metallurgical or physical changes in the specimen. In many instances, however, E^* is practically a constant quantity and is used rather extensively in isothermal, constant-rate testing, in the analysis of hysteresis loops. In such cases, a value for E^* can best be determined by cycling the specimen prior to the test at stress or strain levels below the elastic limit. E^* is NOT the monotonic Young's modulus.

4. Significance and Use

4.1 Strain-controlled fatigue is a phenomenon that is influenced by the same variables that influence force-controlled fatigue. The nature of strain-controlled fatigue imposes distinctive requirements on fatigue testing methods. In particular, cyclic total strain should be measured and cyclic plastic strain should be determined. Furthermore, either of these strains typically is used to establish cyclic limits; total strain usually is controlled throughout the cycle. The uniqueness of this practice and the results it yields are the determination of cyclic stresses and strains at any time during the tests. Differences in strain histories other than constant-amplitude alter fatigue life as compared with the constant amplitude results (for example, periodic overstrains and block or spectrum histories). Likewise, the presence of nonzero mean strains and varying environmental conditions may alter fatigue life as compared with the constant-amplitude, fully reversed fatigue tests. Care must be exercised in analyzing and interpreting data for such cases. In the case of variable amplitude or spectrum strain histories, cycle counting can be performed with Practice E 1049 .

4.2 Strain-controlled fatigue can be an important consideration in the design of industrial products. It is important for situations in which components or portions of components undergo either mechanically or thermally induced cyclic plastic strains that cause failure within relatively few (that is, approximately $<10^5$) cycles. Information obtained from strain-controlled fatigue testing may be an important element in the establishment of design criteria to protect against component failure by fatigue.

4.3 Strain-controlled fatigue test results are useful in the areas of mechanical design as well as materials research and development, process and quality control, product performance, and failure analysis. Results of a strain-controlled fatigue test program may be used in the formulation of empirical relationships between the cyclic variables of stress, total strain, plastic strain, and fatigue life. They are commonly used in data correlations such as curves of cyclic stress or strain versus life and cyclic stress versus cyclic plastic strain obtained from hysteresis loops at some fraction (often half) of material life. Examination of the cyclic stress–strain curve and its comparison with monotonic stress–strain curves gives useful information regarding the cyclic stability of a material, for example, whether the values of hardness, yield strength, ultimate strength, strain-hardening exponent, and strength coefficient will increase, decrease, or remain unchanged (that is, whether a material will harden, soften, or be stable) because of cyclic plastic straining (**1**).[4] The presence of time-dependent inelastic strains during elevated temperature testing provides the opportunity to study the effects of these strains on fatigue life and on the cyclic stress-strain response of the material. Information about strain rate effects, relaxation behavior, and creep also may be available from these tests. Results of the uniaxial tests on specimens of simple geometry can be applied to the design of components with notches or other complex shapes, provided that the strains can be determined and multiaxial states of stress or strain and their gradients are correctly correlated with the uniaxial strain data.

5. Functional Relationships

5.1 Empirical relationships that have been commonly used for description of strain-controlled fatigue data are given in Appendix X1. These relationships may not be valid when large time-dependent inelastic strains occur. For this reason original data should be reported to the greatest extent possible. Data reduction methods should be detailed along with assumptions. Sufficient information should be developed and reported to permit analysis, interpretation, and comparison with results for other materials analyzed using currently popular methods.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

5.2 If use is made of hourglass geometries, original data should be reported along with results analyzed using the relationships in Appendix X2.

6. Methodology

6.1 *Testing Machine*—Testing should be conducted with a tension-compression fatigue testing machine that has been verified in accordance with Practices E 4 and E 467, unless more stringent requirements are called for in this specification. The testing machine, together with any fixtures used in the test program, must meet the bending strain criteria in 6.3.1. The machine should be one in which specific measures have been taken to minimize backlash in the loading train.

NOTE 3—Force measuring capability of 45 kN (approximately 10 kips) or greater would be sufficient for the recommended specimens (Section 7) and most test materials. The machine force capacity used for these specimens would not be required to exceed 110 kN (approximately 25 kips); however, large-capacity fatigue machines may be beneficial because of increased axial stiffness and decreased lateral deflection of these systems. Achieving a change in axial concentricity of less than or equal to 0.05 mm (0.002 in.) TIR (total indicator reading), as measured between the top and bottom specimen fixture under cyclic force, is a measure of success with respect to minimizing lateral deflection of the loading train.

6.2 *Strain Control*—Testing machine controls should permit cycling between constant strain limits. If material behavior permits (for example, aging effects do not hinder), control stability should be such that the strain maximum and minimum limits are repeatable over the test duration to within 1 % of the range between maximum and minimum control limits.

NOTE 4—See 6.4.1 and 6.5 on use of force and strain transducers in relation to repeatability requirements.

NOTE 5—For strain control under long-life conditions it is sometimes advantageous to run a pseudostrain control test under force control. The test could be started in strain control and switched to force control after cyclic stabilization of the stress response occurs. In these cases strain should be monitored (directly or indirectly) and adjustments made in force control to maintain strain limits within 1 % of the range between maximum and minimum limits. Practice E 466 provides additional details on force controlled axial fatigue testing.

6.3 *Fixtures*:

6.3.1 To minimize bending strains, specimen fixtures should be aligned such that the major axis of the specimen closely coincides with the force axis throughout each cycle. It is important that the accuracy of alignment be kept consistent from specimen to specimen. Alignment should be checked by means of a trial test specimen with longitudinal strain gages placed at four equidistant locations around the minimum diameter. The trial test specimen should be turned about its axis, installed, and checked for each of four orientations within the fixtures. The maximum bending strains so determined should not exceed 5 % of the minimum axial strain range imposed during any test program. For specimens having a uniform gage length, it is advisable to place a similar set of gages at two or three axial positions within the gage section. One set of strain gages should be placed at the center of the gage length to detect misalignment that causes relative rotation of the specimen ends about axes perpendicular to the specimen axis. An additional set of gages should be placed away from the gage-length center to detect relative lateral displacement of the specimen ends. The lower the bending strain, the more repeatable the test results will be from specimen to specimen. This is especially important for materials with low ductility where much better alignment may be needed (that is, bending strains should not exceed 5 % of the minimum strain amplitude).

NOTE 6—This section refers to Practice E 1012 Type A tests.

NOTE 7—Four strain measurements, 90° opposed to each other, are required to ensure that bending strains are not large. Utilization of a single extensometer with dual axial outputs will allow for only two specimen loadings to gather the required four strain readings, without the necessity of strain gaging specimens.

6.3.2 Several commonly used fixturing techniques are shown schematically in Fig. 3. The selection of any one fixturing technique depends primarily upon the user's specimen design. Fixtures should be constructed of hardened steel for high strength and abrasion resistance. The collet type grip shown, or other fixturing techniques that provide high precision lateral stiffness to hold precise alignment are acceptable. Fixtures not capable of high alignment may be coupled with the Woods metal pot **(2, 3)** of Fig. 4 or a similar device. Such a device may help to compensate for misalignment in the loading train that would induce bending strains in the specimen during fixturing. Placement of the fixtures within die-set or flex bars reduces relative lateral motion of specimen ends and increases lateral stiffness that is important in machines that do not provide adequate safeguards against compressive buckling of the test specimen.

6.3.3 For elevated-temperature testing it is usually necessary to provide some means for cooling the fixtures to prevent damage to other loading-train components such as force tranducers. One method commonly used employs water-cooling coils attached to the fixtures or to other appropriate locations in the loading train. Care must be taken to avoid affecting the force tranducer calibration or the loading-train alignment by the addition of cooling coils.

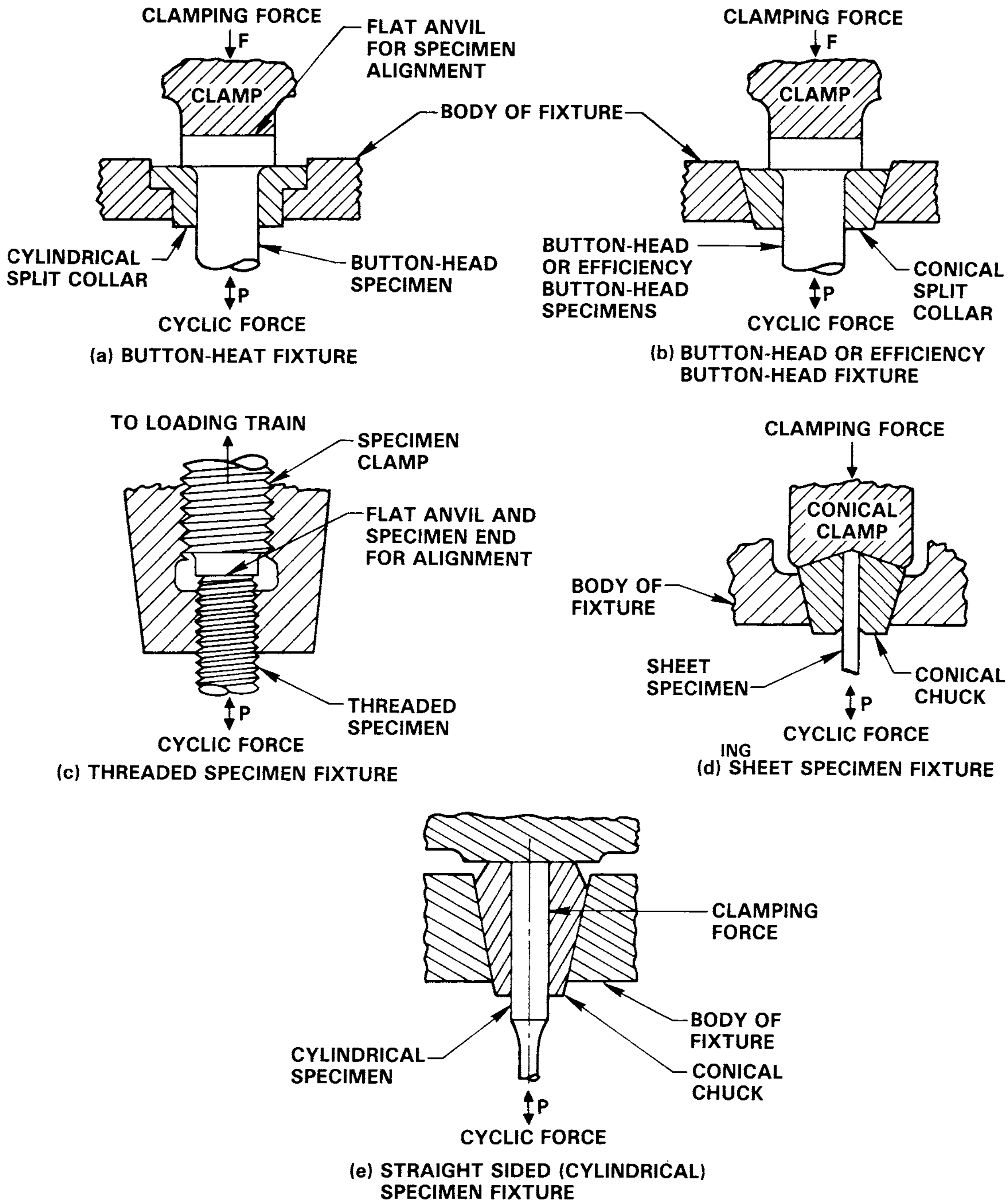
6.4 *Extensometers*—Extensometers should be employed for the purpose of measuring deformation in the gage section. They should be suitable for dynamic measurements over long periods of time.

6.4.1 The non-self contained extensometer may be of two major types: Contacting (for example, the more frequently used strain gage or LVDT type as shown in Fig. 5) or noncontacting (for example, optical types). The output of the extensometer or auxilary device of the extensometer system should be suitable for control purposes, readout, and recording. The extensometers should qualify as Class B-2 or better in accordance with Practice E 83.

NOTE 8—For best results, the extensometer system (mechanical and electrical) should have a maximum nonlinearity of 0.3 % of full-scale range. Thus, the extensometer design should minimize sources of mechanical hysteresis. The more effective designs have a low activation force that eliminates slippage of the contacts and a low mass to provide high natural frequency for improved dynamic response characteristics.

6.4.2 Extensometers should measure longitudinal deformation when a uniform-gage specimen, such as shown in Fig. 1(a), is tested. Generally, these extensometers are attached as shown in Fig. 5(a).

NOTE 9—Care should be exercised when installing the longitudinal

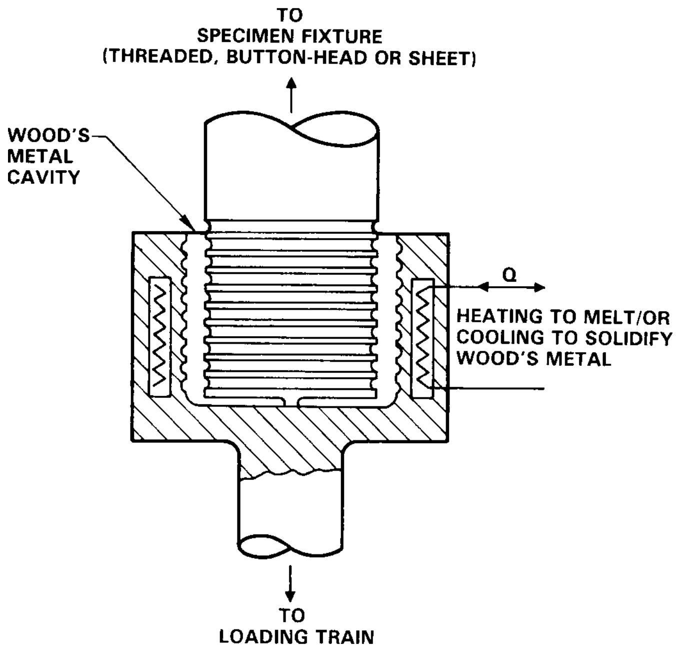


NOTE 1—The clamping force should be greater than the cyclic force to avoid backlash within the specimen fixture.

FIG. 3 Schematic Examples of Fixturing Techniques For Various Specimen Designs

extensometer so as to prevent damage to the specimen surface and consequential premature fatigue failure at the contact points. It is very important to ensure a secure attachment of the extensometer to the test specimen. Damaged or worn contacts or flexure in the attachment apparatus can induce significant hysteresis errors in the measurement. Often, small strips of transparent tape, copper bondable strain gage terminals, or other such protective tabs are adhered to the specimens uniform section at the locations where extensometer tips would contact the material. Use of the tape or tabs tends to "cushion" the attachment. Another alternative is the use of quick-drying epoxy. Light force springs or small rubber bands are often employed to hold the extensometer to the specimen. Dulling the tips for softer material is also commonly done. Extensometer slippage can be observed after the first several cycles from X-Y traces or strip chart recordings by observing the stress-strain response. Unusual shifts in mean values of stress in response to imposed strain ranges is an indication of such slippage.

6.4.3 Extensometers should measure diametral deformations when specimens having hourglass profiles are tested. A typical method of diametral displacement measurement is shown schematically in Fig. 5(b). Curved extensometer tips, convex in the longitudinal plane, can provide point contact during testing. Care should be exercised during installation of



NOTE 1—Wood's metal pot is used to provide initially zero stress in the specimen during fixturing. This pot may be within a die-set to combine zero fixturing stress with rigid alignment.

FIG. 4 Schematic of Wood's Metal Pot Showing Principle of Operation

the diametral extensometer to prevent damage to the test specimen surface. Extensometer tips should be adjusted properly to minimize the force they impose on the specimen. When installing the extensometer, gently move its tip longitudinally along the specimen while watching the gage readout to find the minimum diameter. Calibration of extensometers should be conducted before and after each test program.

NOTE 10—Care should be taken in the measurement of diametral strains for materials such as cast materials that possess large grains or a large degree of preferred orientation. These, as well as hexagonal close-packed materials, tend to be anisotropic and therefore may require special methods of strain measurement and interpretation because Poisson's ratio changes substantially with the orientation of the extensometer with respect to the crystallographic orientation of the specimen. Cyclic hardening or softening also might alter the apparent value of Poisson's ratio, thereby complicating data analyses and interpretation.

6.5 *Force Transducers*—A force transducer should be placed in series with the test specimen for the purpose of measuring magnitude and sense of the axial force transmitted through the specimen. Force transducer capacity should be selected to adequately cover the range of forces to be measured in the test being conducted, but not so large as to render larger errors (that is, greater than 1 % of the difference between maximum and minimum control limits). Force transducer calibration should be verified in accordance with Practices E 4 and E 467.

NOTE 11—The force transducer should be designed specifically for fatigue testing and possess the following characteristics: high resistance to bending; high axial stiffness; high linearity; accuracy and sensitivity; low hysteresis; high overturning moment stiffness; and high lateral stiffness. For best results, it is recommended that the maximum force transducer nonlinearity and hysteresis should not exceed 0.5 % and 0.3 % of full-scale range, respectively.

6.6 *Data Recording Systems*—Analog strip chart and X-Y recorders or their digital equivalent should be considered a minimum requirement for data collection.

NOTE 12—Accuracy of recording systems should be kept within 1 % of full scale. Analog/digital devices are available that include maximum and minimum limit detection, maximum-minimum memory, and underpeak detection.

NOTE 13—Data acquisition system characteristics such as sampling frequency and data skew between force and deformation (stress and strain) channels can affect hysteresis loop presentation on an X-Y recorder used in digital recording systems. It is recommended that these characteristics be taken into consideration along with the strain rate or frequency of cycling to determine that the hysteresis plots are within the required error limits.

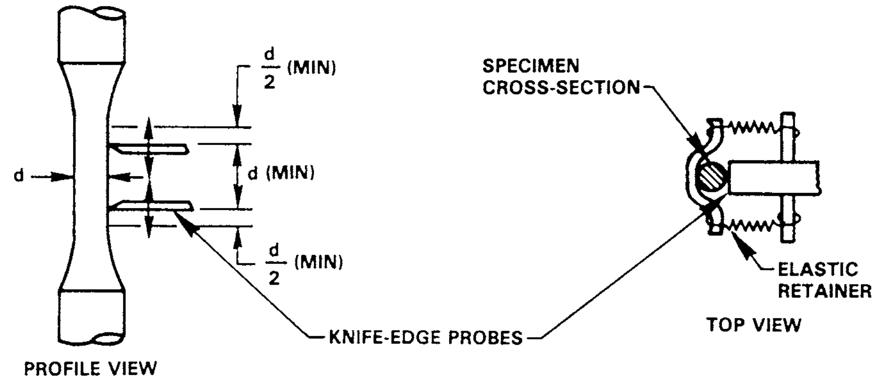
6.6.1 *X-Y Recording*—Some means of X-Y recording should be used for the purpose of recording hysteresis loops of force versus deformation or stress versus strain. A potentiometric X-Y recorder or an oscilloscope equipped with a camera are acceptable alternatives. The potentiometric X-Y recorder should be used only when the rate of cycling results in a pen velocity that is less than one-half of the recorder's slewing speed. At higher frequencies, the oscilloscope may be used. Alternative devices include: digital X-Y plotters for real time recording or to plot stored data and data logging devices that store data in a host computer system or transmit data to a printer.

6.6.2 If digital-type recording devices are used, it is recommended that a sufficient number of simultaneous data pairs (such as stress and strain) be taken for both the ascending segment and descending segment of the hysteresis loop to adequately determine the shape of the loop.

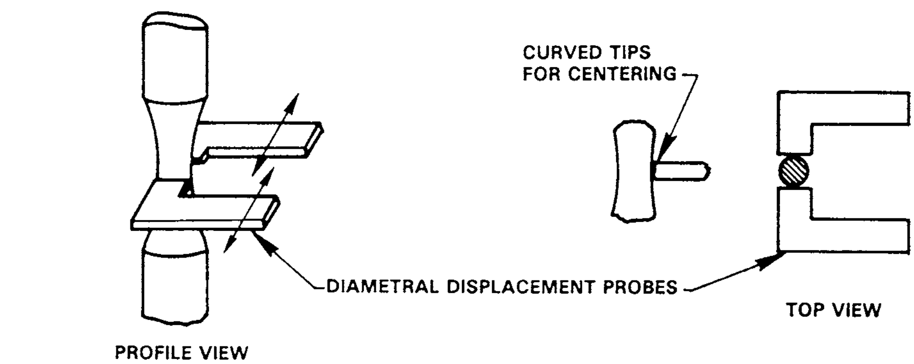
6.6.3 *Strip Chart Recording*—Strip chart recorders may be used to monitor force (or strain). If used, the frequency of the test should be such that the recording pen velocity never exceeds one-half of the recorder's slewing speed. It is recommended that these recorders be calibrated at the testing frequencies used. Storage oscilloscopes also may be used to record the force versus strain loops. Force or strain peaks also may be monitored by devices that detect, display, and retain maximums and minimums in memory or that reproduce these data at predetermined periods.

6.7 *Cycle Counter*—A cycle counter shall be used to indicate total accumulated cycles of loading or straining. An elapsed time indicator is a desirable adjunct to the cycle counter to provide an excellent check of both frequency and the current cycle count. Two types of counters are generally available, mechanical or electronic. A minimum requirement is that a counter have typically five or six digits and × 10, × 100, and × 1000 range multipliers. Digital counters with 1 count resolution with 1 count resolution (no multipliers) are available. Counters are often equipped with a "preset count" feature that may be used to stop a test for examination of the specimen, to command a recorder to take data, or to end a test after a specific number of cycles.

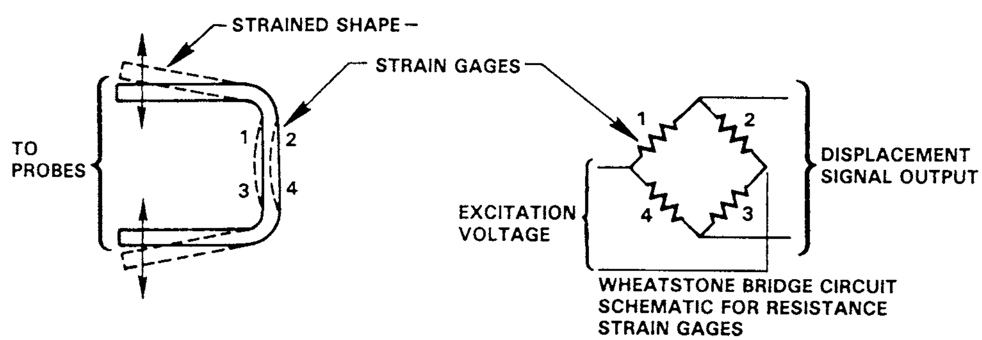
6.8 *Calibration*—The calibration interval of all electronic recording and transducer systems should be performed in



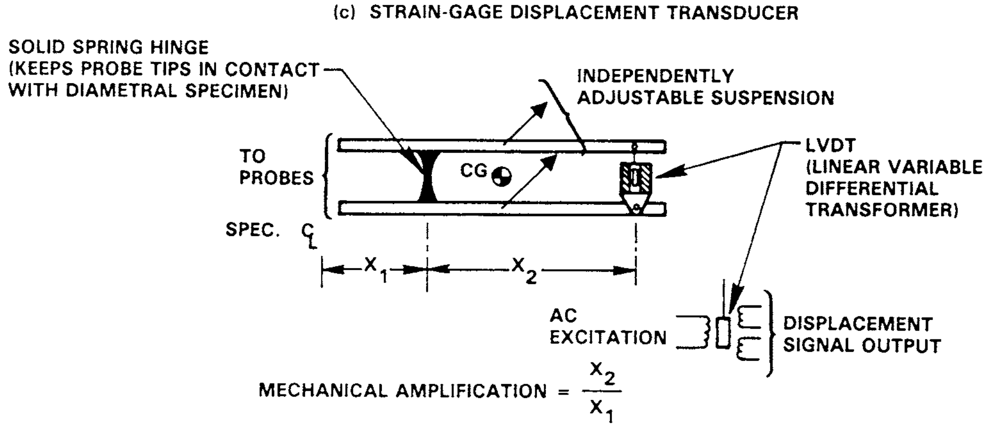
(a) LONGITUDINAL DISPLACEMENT MEASUREMENT FOR UNIFORM GAGE SPECIMEN OF FIGURE 1(a). (PROBES MAY BE ATTACHED TO EITHER TRANSDUCER 5(c) OR 5(d).)



(b) DIAMETRAL DISPLACEMENT MEASUREMENT FOR HOURGLASS SPECIMEN OF FIGURE 1(b). (PROBES MAY BE ATTACHED TO EITHER TRANSDUCER 5(c) OR 5(d).)



(c) STRAIN-GAGE DISPLACEMENT TRANSDUCER



(d) LVDT DISPLACEMENT TRANSDUCER

FIG. 5 Extensometer Schematic

accordance with the manufacturer's recommendations; in the absence of these, the interval should be no greater than six months and even more frequent if necessary to maintain required accuracy. Calibration should be checked whenever accuracy is in doubt. All calibrations should be traceable to the National Institute of Standards and Technology. When calibrating a transducer system, it is important that it be performed using the same setup and arrangement of components as used in the test. As an example, when calibrating a force transducer used on an automated system, it is necessary to calibrate the output from the computer, not from any intermediary electronics.

6.9 *Strain Computer*—An analog (or digital) computer is recommended for use in low-cycle fatigue tests of hourglass specimens whenever appreciable cyclic hardening and softening occurs during the test. Such a computer is useful when used in the real-time mode with servocontrolled testing machines and can be used for limit control of screw-driven machines. The computer should be designed to convert diametral strain and axial force signals into an axial strain signal. See Appendix X2 for conversion relations. In the case of servocontrolled machines, this axial strain signal may be used as a feedback signal for control purposes, thus simulating axial strain control. A block diagram for the analog (or digital) computer program is shown in Fig. 6.

7. Specimens

7.1 *Specimen Design*—Fig. 1 shows two basic specimen configurations. Fig. 1(a) shows a recommended uniform-gage specimen. When the choice of an hourglass configuration is deemed necessary, the profile recommended is as shown in Fig. 1(b). Use of Fig. 1(b) should follow careful consideration of problems of data interpretation, and anisotropy and buckling (see Note 10 and Note 14). Both of these recommended specimens possess a solid circular cross section and minimum diameters of 6.35 mm (0.25 in.) in the test section. Specific cross-sectional dimensions are listed here only because they have been dominant in the generation of the low-cycle fatigue database that exists in the open literature. Specimens possessing other diameters or tubular cross sections may be tested successfully within the scope of this practice; however, crack growth rate, specimen grain size, and other considerations might preclude direct comparison with test results from the recommended specimens (see Note 15). While design of specimen end connections is primarily dependent upon user preference (see Note 16), a number of commonly used configurations are shown in Fig. 1(c), 1(d), 1(e) and 1(f). Care must be exercised in the machining of uniform-gage specimens to blend the shoulder radius at the specimen ends with minimum diameter so as to avoid undercutting. So that stress concentrations are minimized, shoulder radius should be as large as possible, consistent with limitations on specimen length.

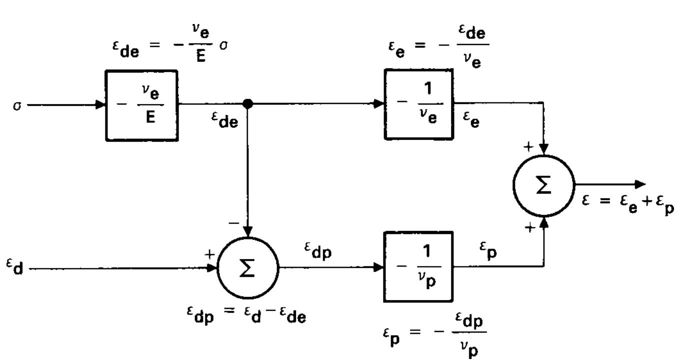


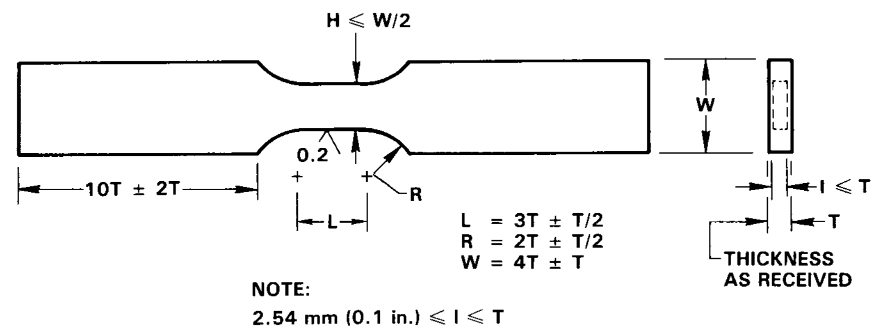
FIG. 6 Block Diagram of Strain Computer (See Appendix X2 for Discussion of Mathematical Relationship)

NOTE 14—Lives determined using tubular specimens are less than those for solid specimens, the extent of which depends on the failure criteria and specimen configuration. Differences in excess of a factor of two are not unusual for failure criteria based on separation, whereas for failure defined by crack lengths contained within the tube wall there will be much less difference.

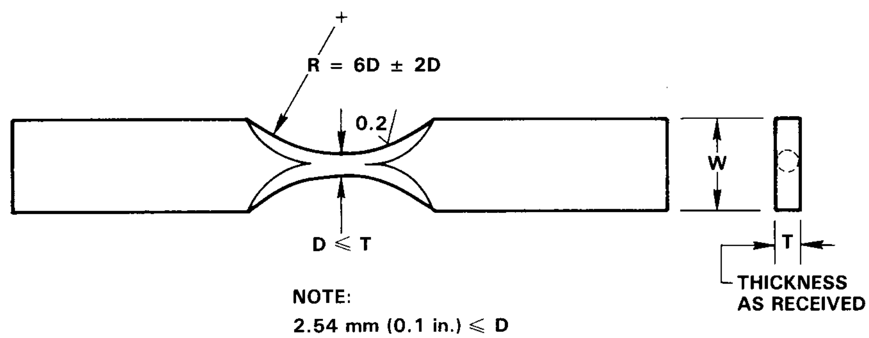
NOTE 15—Selection of either the uniform-gage section or hourglass profile is commonly based upon the magnitude of strain range to be imposed. The recommended uniform gage specimen is frequently suitable for strain ranges up to about 2 %. Above 2 % hourglass specimens may be necessary. Soft materials or elevated temperatures may dictate lower strain ranges. The maximum strain range may be increased by appropriate lateral restraints and through the use of short loading trains. Options to increase stiffness to avoid the use of hourglass specimens should be exhausted before adopting the configuration shown in Fig. 1(b). If these options fail, the recommended hourglass specimen possesses a profile ratio of 12:1 for radius-of-curvature to minimum radius-of-specimen. If the user wishes, different ratios between the limits of 8:1 and 16:1 may be employed. Lower limits will increase stress concentration and may affect fatigue life; higher ratios limit the specimen's buckling resistance. For some materials tested in the low-life range, hourglass specimens might give different results from similarly stressed uniform-gage specimens. It is very difficult to determine axial strains from measurements of diametral strain in hourglass specimens for many anisotropic as well as cast materials.

NOTE 16—Design of specimen end connections is dependent upon user preference, fixturing, or availability of material, or a combination of all three; it is constrained principally by proper considerations of axial alignment and backlash. Button-head end connections, such as those shown in Fig. 1(d) and 1(e), permit precise alignment with a specimen end clamping preload (to avoid backlash in the grip). The threaded connection, shown in Fig. 1(c), is useful where the available material is not thick enough to provide for the larger diameter button-head ends. The efficiency button-head connection, shown in Fig. 1(e), provides the button-head preloading feature without requiring larger diameter ends. The button-head design is useful at elevated temperatures, as it does not suffer the" oxidation-sticking" experienced with threaded ends, but it may produce some specimen failures in the fixture when used at room temperatures. The design shown in Fig. 1(f) is convenient for use in collet-type hydraulic grips. This configuration eliminates long life thread failures often associated with Fig. 1(c) type specimens.

7.1.1 *Alternative Specimen Design for Sheet Specimens*—Often, it is desirable to obtain test specimens from sheet material that is less than 6.0 mm (0.24 in.) thick. In general, the considerations discussed in other sections apply equally to sheet testing. However, special specimen geometries and gripping arrangements, as well as more sensitive force and strain transducers, are necessary. It is strongly recommended that torques introduced by actuator rod rotations be eliminated by use of rotational restraints or similar devices. Typical specimen designs that have been used successfully are shown in Fig. 7. The specimens in Fig. 7(a) have a rectangular cross section and are suitable up to strain amplitudes of at least 1 % applied to sheets as thin as 2.54 mm (0.10 in.). For higher strain amplitudes, antibuckling restraints can be adapted to the



(a) FLAT-SHEET FATIGUE SPECIMEN WITH RECTANGULAR CROSS SECTION



(b) FLAT-SHEET FATIGUE SPECIMEN WITH CIRCULAR CROSS SECTION

FIG. 7 Sheet Fatigue Specimens—Alternative to Fig. 1 Specimens

specific geometry and extensometer used. In using such restraints, care must be taken to avoid increased resistance to axial force influenced by the restraints. When restraints can not be adopted, it may be necessary to use the cylindrical cross section hourglass specimen in Fig. 7(b), see Ref (**4**) for other designs. The geometries that are adequate for resisting buckling and/or incremental bending collapse at short lives often will lead to grip failures at long lives. The investigator may find it convenient to employ two geometrically similar specimen designs for development of a strain-life curve.

7.2 *Specimen Preparation*—Specimens should be prepared by a specific set of procedures that is known to provide consistent test results. Agreement between the testing organization and the user of the test results concerning preparation procedures should be obtained. The following provides recommended guidelines.

7.2.1 *Specimen Coupons and Materials*—Coupons from which specimens are machined should either be nominally homogeneous or sampled from the source material, or both, so as to be representative of the properties sought in the application of the material to its end use. Thus, when material requirements allow, specimens should be removed from the same material and product form that will be used in the fabricated component of interest. Any material orientations, such as rolling direction or casting direction, should be identified with respect to the orientation of the specimen axes. Orientation notation used in accordance with Test Method E 399 is acceptable such as L, T, S, LT, TL, ST, and the like.

7.2.2 *Specimen Surface Preparation*—Specimens prepared from coupons will possess a "surface preparation history" as a consequence of machining operations, heat treatments, and the effects of environment during the storage period prior to testing. Unless the purpose of testing is to determine the influence of specific surface conditions on fatigue life, it is recommended that specimen surface preparation be performed in a manner that will have a minimum influence upon the variability in fatigue lives exhibited by the specimen group tested. Ordinarily, this would be accomplished by:

7.2.2.1 consistently machining specimens to be as smooth and uniform in surface finish (in the gage region) as feasible for the subject material and the machining techniques available, and by employing as a final operation a machining or other "finishing" procedure that would introduce minimal surface metal distortion (see Note 17), and by

7.2.2.2 ensuring, through the use of protective atmospheres, that surface attack, such as oxidation and corrosion, does not occur, either during heat treatments or during specimen storage, for all specimens within a program.

NOTE 17—Appendix X3 presents an example of a machining procedure that has been employed on some metals to minimize variability of machining and heat treatment influences upon fatigue life.

The exact procedure of specimen preparation and handling should be *clearly* and *carefully* documented. It also would be prudent to determine and record the surface residual stresses and the residual stress profile of at least one exemplary specimen.

7.3 *Specimen Storage*—Test specimens that may be susceptible to corrosion in moist room-temperature air should be protected immediately after preparation and stored until they are tested. Specimens may be stored in a suitable protective environment, such as dry inert gas (as might be conveniently employed in a laboratory desiccator) or a vacuum. The method of storage should be clearly and carefully documented.

7.4 *Materials Description*—A complete material description is desirable. It is recommended that the following microstructural and mechanical properties be obtained.

7.4.1 *Microstructural Characteristics*—Composition, grain size (see Test Methods E 112), crystallographic structure, preferred orientation if present, general shape of grains (that is, equiaxed or elongated), second-phase particles (see Practice E 157), heat treatment (whether at the mill, during fabrication, in the laboratory, or a combination of all three), position in ingot or sheet roll, and specification designation (ASTM, ASME, AISI, Military, SAE, etc.).

7.4.2 *Mechanical Properties*—For purposes of performing the test and calculating results it is desirable to have available the following representative mechanical properties, obtained at the appropriate temperature and measured in accordance with the applicable standards such as Test Methods E 8, E 9, E 111, E 132 and Practice E 209; tensile or compressive yield strength or yield point, or both; ultimate tensile strength; percent elongation; percent reduction of area; Poisson's ratio; and Young's modulus. The following true stress-strain properties also may be desirable: true fracture strength, true fracture ductility, strain hardening exponent, and strength coefficient. Hardness also may be determined in accordance with Test Methods A 370 or E 384, or both.

8. Procedure

8.1 *Test Environment*:

8.1.1 *Temperature*:

8.1.1.1 For materials that are fatigue tested at temperatures other than ambient, all temperatures throughout the gage section (for uniform gage specimens this is the region with constant cross-sectional area) shall be:

$$T_n \pm \Delta T \tag{6}$$

where:

T_n = nominal test temperature in °C and
ΔT = 2°C or 1 %, whichever is greater.

NOTE 18—The temperature variability in the gage section can become a critical issue, particularly if material properties (for example, major alterations of strength, modulus of elasticity, ductility, etc.) or metallurgical stability (for example, microstructure, crystal structure, etc.) are affected significantly. For these reasons as well as others, the temperature variability within the gage section should be maintained as small as possible. Because temperature effects can be significant, the actual temperature variability should be reported with the test results, as should the heating method (induction heating, resistance heating, infrared lamp, etc.).

8.1.1.2 For the duration of the test, the controlled temperature of the specimen should be $T_n \pm 2°C$.

NOTE 19—If the temperature cannot be maintained within limits mentioned above, then temperature deviations should be reported. If possible, the effect of temperature should be demonstrated throughout the range of test temperatures.

8.1.2 Elevated temperatures may be imposed by any of several methods: (1) high-frequency induction (Note 20), (2) resistance or radiant furnace, or (3) immersion in an inert heated gas or liquid. In (1) and (2) above, an enclosure is recommended to prevent air currents in the vicinity of the specimen from causing undesirable temperature gradients. Specimens tested at room temperature also should be in draft-free surroundings. Temperatures below room temperature may be imposed by placing the specimen and gripping apparatus in a refrigerated chamber that may be either of the liquid or gaseous type, depending on temperature requirements and other possible environmental considerations. Liquefied gases, such as liquid nitrogen, or solidified gases, such as dry ice placed in a liquid medium, provide possible means for low-temperature testing.

NOTE 20—When inductively heating magnetic materials (those materials having relative permeabilities significantly greater than unity), it should be recognized that a varying stress in the specimen can affect the distribution of eddy currents in the specimen and may change the temperature profile. This effect is influenced by the specimen material, design and heat transfer characteristics, the temperature magnitude, the stress magnitude and distribution, the cyclic waveform, and the testing frequency (strain rate). The most pronounced effect is generally produced when conducting tests at low frequencies or with tests containing hold periods. In any case the temperature profile of magnetic specimens should be evaluated throughout the straining cycle. When the effect is severe, it may be necessary to use a susceptor with the induction coil or to use an alternate heating method.

NOTE 21—Use of glass insulation may avoid difficulty with wires submerged in a cooling solvent.

8.1.3 If testing is performed in air, relative humidity may be measured in accordance with Test Method E 337, unless it has already been determined that moisture has little or no effect on fatigue life for the material under test. If an effect is present, relative humidity should be controlled; when uncontrolled it should be carefully monitored and reported.

8.2 *Measurement of Test Specimen Dimensions*—For the purpose of making an accurate determination of specimen cross-sectional area, measure the reduced section as follows:

8.2.1 Measure the diameter at the center of the gage section by means of an optical comparator or other optical means to an accuracy of 0.0125 mm (0.0005 in.) or better. A precision micrometer may be used in place of the optical comparator if its use does not damage the gage section surface in a way as to affect specimen performance. For uniform-gage specimens, check diameters for at least two other positions within the specimen gage length. The minimum cross-sectional areas should be used for computing the stresses in the specimen during the test. The area at temperature should be used in calculating stress. This area can be obtained by correcting the room-temperature result using the coefficient of thermal expansion.

8.3 *Test Machine Control*—It is necessary to control one (or more) variable(s) (for example, stress, strain, force, displacement, or other appropriate parameters) in a manner that is in keeping with the test objectives.

8.3.1 *Control Mode*—Total axial strain amplitude is the most commonly utilized control variable in a low-cycle fatigue test. Total axial strain is often controlled continuously throughout each fatigue cycle in a manner prescribed in 8.4. It also is acceptable to control only the limits of either total axial strain or plastic axial strain. In such cases, vary another variable, such as diametral strain, displacement, or force, between these limits in some cyclically consistent manner under either closed loop or other control means. For long-life fatigue tests that exhibit low levels of plastic strain, it is acceptable to control force while monitoring strain and making periodic adjustments of mean force and force range in order to maintain the desired strain limits. Similarly, tests may be initiated in strain control and switched to force control using the stabilized force peaks as limits. When time dependent effects are present, it may no longer be acceptable to control only the limits of the required strain. Continuous control of the parameter of interest may be necessary to obtain the desired intra-cycle response. For example, if the force is controlled between total axial strain limits in this regime, a quite different material response will be produced than if the total axial strain is continuously controlled.

8.3.2 *Closed Loop Method*—Fatigue testing machines of the closed loop servocontrolled type often are capable of continuously controlling specific test variables such as force or displacement through appropriate selection of feedback signals. Application of scale factors to these signals thereby permits continuous control of stress or strain. Axial stress may be scaled directly from the force transducer signal. Axial strain may be scaled directly from an axial extensometer signal when uniform-gage specimens are tested. When hourglass specimens are tested, an axial strain signal must be determined from a diametral extensometer signal and the force signal by means of a computer (see 6.9) if closed loop control of diametral strain changes during cycling hardening and softening. Additional precautions should be observed when hold times are employed and time-dependent inelastic strains are present. For example, a hold on diametral strain will permit the total axial strain to change during each cycle and will not produce correct relaxation information.

8.3.3 *Other Control Methods*—Fatigue testing machines that do not provide continuous closed loop control of either specimen force or specimen displacement generally have the capability to impose limits on the chosen test variable. However, they do not control that variable throughout the fatigue cycle. Limit control is a special case of closed loop control. Thus, force and displacement signals may be handled in a manner similar to that of 8.3.2 to determine strain limits. It is not necessary to use a computer for limit control of hourglass specimens if periodic adjustments are made to the diametral strain amplitude in such a manner as to maintain constant axial strain limits. These adjustments are necessary for materials that undergo significant cyclic hardening and softening because of attendant changes to the relationship between axial strain and induced diametral strain. The additional complications of complex waveforms and time-dependent inelastic strains severely curtail the acceptability of limit control techniques. If the technique of limit control is used, the intra-cycle and inter-cycle variation of the parameter of interest should be monitored, and if necessary, periodic adjustments should be made to the testing machine to produce the desired response. Such changes should be reported.

8.4 *Waveform*—The strain (or stress) versus time waveform should be identical throughout a test program unless test objectives are to determine waveform effects. In the absence of specific waveform requirements or equipment limitations, a triangular waveform for continuous cyclic tests and trapezoidal waveforms for hold period tests are preferred.

8.5 *Strain Rate and Frequency of Cycling*—Either strain rate or frequency of cycling should be held constant for the duration of each test as well as for the duration of a test program, unless the test objective is specifically to determine either strain rate or frequency effects, respectively.

NOTE 22—While constant strain rate testing is often preferred, constant frequency testing may be of greater practical significance to the fatigue analysis of certain machine components. On the other hand, constant strain rate testing may be experimentally more tractable than constant frequency testing since long-life, small-strain tests in the former mode may be completed in shorter periods of time than tests conducted in the latter mode.

8.5.1 If nontriangular waveforms preclude constant strain rate testing because of equipment limitations and time limitations preclude constant-frequency testing, other means of rate control are available. One accepted procedure is to maintain constant average strain rate (twice the product of strain range and frequency) throughout each test and for the duration of the test program. Another acceptable procedure, one that is most convenient when testing under plastic strain limit control, is to maintain constant average plastic strain rate.

8.5.2 The selected range of strain rates or frequencies should be sufficiently low as to preclude specimen heating in excess of 2°C (3.6°F). In using a servocontrolled testing machine, make a comparison of the program and feedback signals to ensure that the selected rates or frequencies are and remain within system capabilities and accuracy requirements. Frequency response of extensometers (depending upon their design) is often a limiting factor in the system.

NOTE 23—Notwithstanding the need for constancy of rate, the testing rate may be reduced briefly in order to permit periodic recording operations if doing so does not change specimen behavior. An altered stress-strain response can be expected if the testing rate is reduced when time-dependent strain is present. In addition, a possible effect of the periodic reduction of rate on specimen life should be considered.

8.6 *Test Commencement*:

8.6.1 Begin all tests in the same direction of initial straining, tensile or compressive, unless the purpose of testing is to study initial loading effects. For some materials, it is acceptable to increase strain amplitude gradually and continuously over a period no greater than approximately 20 cycles or 2 % of anticipated life (whichever is less). Care should be taken in selecting the target strain for the initial cycle to avoid overshooting while minimizing the number of cycles to obtain the desired strain limits. Depending on the material, temperature, strain range, loading range, and dynamic response of the test systems, the peak strain of the initial cycle may vary. If overshooting does occur, the control limits should not be adjusted downward.

8.6.2 In reverse cyclic testing of thin sheet specimens it may be advisable to always begin in tension, particularly with coil products of materials where natural out-of-flatness occurs. In other materials such as flat sheet products, either tension or compression going starts are appropriate.

8.7 *Number of Specimens*—It is suggested that a minimum of ten specimens be used to generate a fatigue strain-life curve. It also is suggested that the replication guidelines given in STP 588 (**5**) be followed, especially if subsequent statistical analysis is planned. Reference also is made to Practice E 739.

8.8 *Recording*—Unless computerized data retrieval systems are employed continuously and it is convenient to record in logarithmic increments of fatigue life (that is, 1, 2, 5, 10, 20, 50, ...), record the initial series of hysteresis loops of axial stress (or force) versus total or plastic axial strain (versus total or plastic diametral strain if an axial strain signal is not available). Record hysteresis loops thereafter at successively larger increments of a cycle count. For tests of 100 cycles or more, a minimum of ten additional hysteresis loops is desirable. When practical, continuously record the dependent variables (for example, axial stress and plastic axial strain in a total axial strain control test) as a function of time.

NOTE 24—When continuous recording is not practical either because of lengthy test durations or the limited availability of recorders, intermittent records or alternative sampling of the recorded variables is acceptable.

8.9 *Determination of Failure*—The definition of failure may vary with the ultimate use of the fatigue life information (see Note 25). Acceptable alternatives are as follows:

8.9.1 *Separation*—Total separation or fracture of the specimen into two parts at (1) some location within the uniform section of a uniform-gage specimen, or (2) the vicinity of the minimum diameter in an hourglass specimen. All failure locations should be recorded.

NOTE 25—A post-mortem failure analysis should be performed to uncover any unusual causes of failure. Reporting the actual failure location is important. Inclusions, voids, defects, etc., that are not representative of the bulk material or its application may render fatigue life determination invalid (see 8.11.3). Also, consistent failures at one position may signal alignment problems or" knife-edge" failures caused by extensometer attachment.

8.9.2 *Modulus Method*—For any specified number of cycles, N, during the test, the modulus for unloading following a peak tensile stress is defined as E_{NT} and the modulus for loading following a peak compression stress is E_{NC}(see Fig. 8). Failure is defined when the ratio:

$$Q_N = E_{NT}/E_{NC} \tag{7}$$

reaches one-half the value of Q for the first cycle (see Fig. 8).

$$Q_{N_f} = 0.5\, Q_1 \tag{8}$$

The number of cycles where this occurs is designated as the number of cycles to failure, N_f. However, if total separation occurs first, as in 8.9.1, the life is N_f.

8.9.3 *Microcracking*—The existence of surface microcracks (for example, as observed optically or by replicas) that are larger than some preselected size consistent with test objectives.

8.9.4 *Force (Stress) Drop*—It is acceptable to define failure in a manner related to the ability to sustain a tensile force (stress). Failure is often defined as the point at which the maximum force (stress) or elastic modulus (as measured when

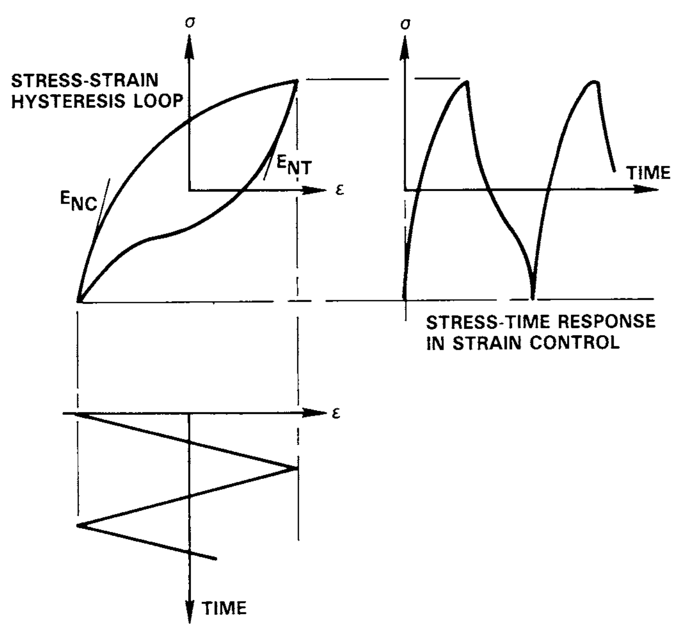


FIG. 8 Definitions of Tension and Compression Modulus for a Determination of Failure

unloading from a peak tensile stress) decreases by approximately 50 % because of a crack or cracks being present. The exact method and the percentage drop should be documented.

8.10 *Test Duration*—Conduct testing at least until failure and preferably until fracture when needs dictate and economics allow. Record total accumulated cycles to failure (and fracture) by means of a cycle counter and check against a measure of elapsed time.

8.11 *Analysis of Data*—While it is not the purpose of this practice to specify data analysis techniques, the following example represents a common procedure utilized when time dependent strains are insignificant.

8.11.1 *Determination of the Cyclic Stress-Strain Curve*—Generate a cyclic stress-strain curve from paired values of stress amplitude and strain amplitude typically at material half-life. When practical, assume a simplifying mathematical expression for the cyclic stress-strain relationship (**6**).

NOTE 26—See Appendix X1 for expressions.

8.11.2 *Determination of the Strain-Life Relationship*—Generate a strain-life curve from paired values of total strain versus life or plastic strain versus life and elastic strain versus life. When practical, assume a simplifying mathematical relationship. In a long fatigue life test program, if all the fatigue tests were started in strain control and switched to force control after cyclic stabilization of the stress response (Note 5), then Practice E 468 could be used to generate a fatigue life relationship.

8.11.3 *Post-Mortem Examinations*—Metallographic examination of the failed specimens is desirable for a variety of purposes depending in part on user interests. Of foremost importance is a fractographic examination of the two surfaces to determine any unusual causes of failure that might invalidate the test results. Dimensional instability of the specimen (unintentional changes in specimen geometry) may occur during the test as a result of time-dependent inelastic deformations. The post-mortem examination should include an evaluation of this occurrence.

8.11.3.1 Scanning electron microscopy and transmission electron microscopy of fracture replicas are two common methods used in such an investigation. Ref (**7**) provides a useful basis for fractographic analysis. The techniques of light metallography and transmission electron microscopy are frequently used when studying structural changes that occur during fatigue or the effects of metallurgical structure on fatigue behavior.

9. Report

9.1 The list of items of information that follows is suggested for inclusion in any report. When publishing results in the open literature, include as much information as possible, independent of the author's purpose. Routine laboratory reports need include only information pertinent to the end use of the test data. Minimum recommended requirements are indicated by an asterisk (*).

9.1.1 *Specific Objective of Testing*.

9.1.2 *Specimen Materials Description (including processing)* *.

9.1.2.1 All available mechanical properties including: yield strength or yield point, or both, ultimate tensile strength, percent elongation and gage length, percent reduction of area, Poisson's ratio, elastic modulus, true fracture strength, true fracture ductility, monotonic strain hardening exponent, monotonic strength coefficient, hardness number, and degree of cold work.

9.1.2.2 All available metallurgical characteristics: certified composition, grain size, crystallographic structure, preferred orientation with respect to specimen axis, general shape of grains (that is, equiaxed or elongated), second phase particles, and heat treatment. Include photomicrographs when possible to document the above properties.

9.1.3 *Specimen Description*:

9.1.3.1 Drawing of the specimen design, or reference to a geometry illustrated in this practice*.

9.1.3.2 Specimen fabrication and surface preparation procedures. If specimens were heat treated after fabrication, details must be provided*.

9.1.3.3 Deviations from recommended specimens configuration and specimen preparation procedures, if any.

9.1.4 *Description of Equipment*:

9.1.4.1 Specimen fixtures and the method used to maintain column rigidity during compression loading.

9.1.4.2 Testing machine.

9.1.4.3 Transducer system (that is, force transducer, deformation transducer).

9.1.4.4 Recorders and recording equipment.

9.1.5 *Description of Testing Environment*:

9.1.5.1 Gas, liquid, or vacuum; chemical composition of medium*.

9.1.5.2 Humidity of gaseous environment*.

9.1.5.3 Test temperature and temperature control method*.

9.1.5.4 Temperature sensing devices, location of temperature measurements, temperature variations in the gage section, any temperature variations in the cycle caused by adiabatic heating or magnetomechanical effects*.

9.1.6 *Testing Conditions and Procedures*:

9.1.6.1 Deviations from recommended procedures, if any.

9.1.6.2 Frequency of cycling (or cyclic strain rate) and description of waveform*.

9.1.6.3 Mode of control, that is, force or stress, continuous strain control, strain limit control, axial strain feedback, diametral strain feedback, etc*.

9.1.6.4 Ratio of axial strain limits (minimum and maximum) and total axial strain range*.

9.1.6.5 Procedure for maintaining constant axial strain limits.

9.1.6.6 Sign of strain at first quarter cycle, tensile or compressive.

9.1.7 *Test Results*—Tabulate the results for all test specimens. When used for purposes of structural analysis, the following three items are most important:

9.1.7.1 Initial, stabilized, or half-life values, or a combination of all three, of the dependent variables from the list of stress range, strain range, and inelastic strain range. Complete curves of these quantities throughout the specimen life. When complete curves are impractical, curves through intermittent values are acceptable*.

9.1.7.2 Relaxation or creep information also should be included for hold-time tests. This should include the values of the relaxed stress or of creep strain, the total amount of relaxation or creep, and the change in the amount of inelastic strain during the hold period. Periodic stress-time recordings obtained with an expanded time scale may be necessary to obtain the desired resolution and to fully characterize the relaxation or creep behavior*.

9.1.7.3 Total number of cycles to failure, N_f, and some additional life measure indicative of crack formation, including the definition used*.

9.1.8 *Results of Analysis for Cyclic Stress-Strain Properties*—If data analysis is performed by means of the relationships in Appendix X1, a tabulation of results should include the cyclic strain hardening exponent and the cyclic strength coefficient.

9.1.9 *Results of Analysis for Strain-Life Properties*—If data analysis is performed by means of the relationships in Appendix X1, a tabulation of results should include the fatigue strength exponent, the fatigue ductility exponent, the fatigue strength coefficient, and the fatigue ductility coefficient.

9.1.10 *Brief Description of the Fracture Characteristics*—Results of post-test metallography and scanning electron microscopy, identification of fracture mechanisms, and the relative degree of transgranular and intergranular cracking. Identify the mechanism or mode of cracking at the region of crack initiation, as well as in the region of crack growth, and note any differences.

10. Precision and Bias

10.1 *Interlaboratory Test Program* – An interlaboratory study of the variability in strain-controlled fatigue cycles to failure was performed during 1988 and 1989. The experimental program was conducted on uniform gage length specimens machined from 304 stainless steel rod material. Eight laboratories participated in the room temperature testing and five laboratories participated in the elevated temperature (538°C) testing. Each laboratory completed two to four tests on specimens at each condition, with three replicates being generated in the majority of cases. The design of experiments and the within- and between-laboratory analysis of variance of the fatigue life data were conducted in conformance with Practice E 691.

10.2 *Test Program Results*—The precision information given below, for strain-controlled fatigue cycles to failure, is stated as a percentage of the logarithm (base 10) of cycles to failure. Two strain ranges, 0.70% and 1.50%, were tested at both the room and elevated temperatures during the interlaboratory program. Fully reversed (R= -1.0) strain cycling conditions were used for all of the experiments. The repeatability and reproducibility of the method was similar at the two temperatures tested, so the results presented below were computed based on a weighted average of these results.

10.3 Precision:

High Strain-Range Conditions (log Nf ~ 3.0 to 3.5)	
95% repeatability limit (within laboratory)	3.83%
95% reproducibility limit (between laboratories)	12.03%

Intermediate Strain-Range Conditions (log Nf ~ 4.0 to 4.5)	
95% repeatability limit (within laboratory)	2.41%
95% reproducibility limit (between laboratories)	6.32%

Example 1 – Given high strain-range conditions where average log Nf ~ 3.00
95% repeatability limits in log Nf ~ 3.00 * (1 ± 0.0383)
- within-lab variability in Nf ~ 770 to 1,300 cycles
95% reproducibility limits in log Nf ~ 3.00 * (1 ± 0.1203)
- between-lab variability in Nf = 435 to 2,300 cycles

Example 2 – Given intermediate strain-range conditions where average log Nf ~ 4.50
95% repeatability limits in log Nf ~ 4.50 * (1 ± 0.0241)
- within-lab variability in Nf ~ 24,600 to 40,600 cycles
95% reproducibility limits in log Nf ~ 4.50 * (1 ± 0.0632)
- between-lab variability in Nf = 16,400 to 60,900 cycles

The above terms (repeatability and reproducibility limits) are used as specified in Practice E 177. It is important to consider that the above results were obtained using only one specimen geometry and one heat of material. Substantially different repeatability and reproducibility results may have been found with other materials and testing conditions allowed by Practice E 606.

10.4 *Bias* —This method has no bias because strain-controlled fatigue properties of materials are defined in accordance with this method.

APPENDIXES

(Nonmandatory Information)

X1. FUNCTIONAL RELATIONSHIPS

X1.1 For many metals, the following empirical relationships (**8**) have been used for a convenient description of low-cycle fatigue data. Please note that the subscript used is that for“ plastic strain” rather than “inelastic strain.” They are used interchangeably in these fatigue equations.

X1.1.1 *Cyclic Stress-Strain Behavior:* The total strain amplitude for a completely reversed, strain-controlled test may be expressed as:

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E} + \frac{\Delta\epsilon_p}{2} \tag{X1.1}$$

Recognizing that:

$$\Delta\sigma/2 = K'(\Delta\epsilon_p/2)^{n'} \tag{X1.2}$$

we may express the cyclic stress-strain curve by the constitutive equation:

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \quad \text{(X1.3)}$$

X1.1.2 *Fatigue-Life Relationships:*

$$\Delta\sigma/2 = \sigma'_f(2N_f)^b \quad \text{(X1.4)}$$

$$\Delta\epsilon_p/2 = \epsilon'_f(2N_f)^c \quad \text{(X1.5)}$$

$$\Delta\epsilon/2 = [\sigma'_f/E](2N_f)^b + \epsilon'_f(2N_f)^c \quad \text{(X1.6)}$$

where the variables are:

$\Delta\sigma$ = true stress range,
$\Delta\epsilon$ = true strain range,
$\Delta\epsilon_p$ = true plastic strain range,
N_f = cycles to failure, and
$2N_f$ = reversals to failure;

and the constants are:

n' = cyclic strain hardening exponent,
b = fatigue strength exponent,
c = fatigue ductility exponent,
K' = cyclic strength coefficient,
σ'_f = fatigue strength coefficient,
ϵ'_f = fatigue ductility coefficient, and
E = Young's modulus (modulus of elasticity).

NOTE X1.1—The user is cautioned that the equations presented in these appendices are not readily amenable to direct use in conventional statistical analysis procedures. Care should be taken in transforming the variables to logarithmic base and in defining the dependent and independent variables.

X2. CONVERSION FROM DIAMETRAL STRAIN TO AXIAL STRAIN FOR ISOTROPIC MATERIALS AND UNIFORM STRAINS

X2.1 Conversion of diametral strain to axial strain requires first the separation of the elastic and plastic components from the total strain by:

$$\epsilon = \epsilon_e + \epsilon_p \quad \text{(X2.1)}$$

$$\epsilon_d = \epsilon_{de} + \epsilon_{dp} \quad \text{(X2.2)}$$

where:

e = elastic component,
p = plastic component,
d = diametral component, and
ϵ = total axial strain.

Axial and diametral components of strain are related through Poisson's ratio, ν, as:

$$\epsilon_e = -\epsilon_{de}/\nu_e \text{ and } \epsilon_p = -\epsilon_{dp}/\nu_p \quad \text{(X2.3)}$$

The above expressions may be rearranged to yield:

$$\epsilon_{dp} = (\epsilon_d - \epsilon_{de}) \quad \text{(X2.4)}$$

$$\epsilon = -\epsilon_{de}/\nu_e - (\epsilon_d - \epsilon_{de})/\nu_p \quad \text{(X2.5)}$$

The diametral elastic strain, ϵ_{de}, is related to axial stress by means of Poisson's ratio and Young's modulus,

$$\epsilon_{de} = -(\nu_e\sigma)/E \quad \text{(X2.6)}$$

Thus,

$$\epsilon = \sigma/E - \epsilon_d/\nu_p - (\nu_e\sigma)/(\nu_p)E \quad \text{(X2.7)}$$

Assuming that plastic deformation occurs under a constant volume condition:

$$\nu_p = 1/2 \quad \text{(X2.8)}$$

such that:

$$\epsilon = (\sigma/E)(1 - 2\nu_e) - 2\epsilon_d \quad \text{(X2.9)}$$

In an experiment using a diametral strain gage and an axial force transducer, analogs of σ and ϵ_d are continuously available. Young's modulus, E, can be determined in accordance with Test Method E 111. The elastic portion of stress, σ, versus diametral strain, ϵ_d, provides σ/ϵ_{de}, which permits ν_e to be calculated.

X3. EXAMPLE OF MACHINING PROCEDURE

X3.1 The following procedure was developed for machining high-strength materials and results in minimal surface damage and alteration. It can also be applied to lower strength materials. As a conservative general measure, this procedure is recommended unless: (*a*) the experimental objective is to evaluate another given surface condition, or (*b*) it is known that the material under evaluation is relatively insensitive to surface condition.

X3.2 *Procedure:*

X3.2.1 In the final stages of machining to within 0.025 mm (0.001 in.) of the final diameter, remove small amounts of material and reduce the gage diameter 0.125 mm (0.005 in.) by cylindrical grinding at a rate of no more than 0.005 mm (0.0002 in.)/pass.

NOTE X3.1—Some cast materials will not benefit from successive removal of material in small amounts, although this procedure is probably not to their detriment.

X3.2.2 Remove the final 0.025 mm (0.001 in.) by polishing (see Note X3.2) longitudinally to impart a maximum of 0.2-µm (8-µin.) surface roughness.

NOTE X3.2—Extreme caution should be exercised in polishing to ensure that material is being properly removed rather than merely smeared to produce a smooth surface. This is a particular danger in soft materials wherein material can be smeared over tool marks, thereby creating a potentially undesirable influence on crack initiation during testing.

X3.2.3 After polishing (see Note X3.2), all remaining grinding and polishing marks should be longitudinal. No circumferential machining should be evident when viewed at approximately 20× magnification under a light microscope.

X3.2.4 If specimen material is soft (for example, copper, aluminum, lead, etc.) at room temperature, final material removal can be performed by means of turning (rather than grinding) and subsequent polishing.

X3.2.5 Degrease the finished specimen. Caution should be exercised to assure that the degreasing agent does not alter material behavior (for example, methanol on titanium alloys).

X3.2.6 If heat treatment is necessary, conduct it before final machining or in such a manner as to avoid any surface damage; employ an inert protective atmosphere to eliminate surface oxidation.

X3.2.7 If surface observations are to be made, the test specimen may be electropolished in accordance with Methods E 3.

X3.2.8 Imprint specimen numbers on both ends of the test section in regions of low stress, away from grip contact surfaces.

REFERENCES

(1) Mitchell, M. R., "Fundamentals of Modern Fatigue Analysis for Design," *Fatigue and Microstructures*, ASM Handbook, Vol. 19, Fatigue and Fracture, ASM International, 1996, pp. 227–249.

(2) Raske, D. T. and Morrow, JoDean, "Mechanics of Materials in Low Cycle Fatigue Testing," Manual on Low Cycle Fatigue Testing, *ASTM STP 465*, ASTM, 1969, pp. 1–25.

(3) Feltner, C. E. and Mitchell, M. R., "Basic Research on the Cyclic Deformation and Fracture Behavior of Materials," iden, pp. 27–66.

(4) Marsh, G. M., Robb, A. D., and Topper, T. H., "Techniques and Equipment for Axial Fatigue Testing of Sheet Steel," SAE Paper No. 730578, May 1973.

(5) Little, R. E. and Jebe, E. H., *Manual on Statistical Planning and Analysis for Fatigue Experiments, ASTM STP 588*, ASTM, 1975. See also Little, R. E. and Jebe, E. H., *Statistical Design of Fatigue Experiments*, Applied Science Publishers, Ltd., London, 1975.

(6) Landgraf, R. W., Morrow, JoDean, and Endo, T., "Determination of the Cyclic Stress-Strain Curve," *Journal of Materials* (JMLSA), Vol 4, No. 1, March 1969, pp. 176–188.

(7) "Fractography and Atlas of Fractographs," *Metals Handbook*, Am. Soc. Metals, Vol 9, Eighth Edition, 1974.

(8) Ellis, J. R., "Results of an Interlaboratory Fatigue Testing Program Conducted on Alloy 800 at Room and Elevated Temperatures," *Journal of Testing and Evaluation* (JTEVA), Vol 15, No. 5, September 1987, pp. 249–250.