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Current Activities in Standardization of High-Temperature, Low-Cycle-Fatigue Testing Techniques in the United States

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CURRENT ACTIVITIES IN STANDARDIZATION OF HIGH-TEMPERATURE, LOW-CYCLE-FATIGUE TESTING TECHNIQUES IN THE UNITED STATES

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SUMMARY

American Society for Testing and Materials (ASTM) Standard E606-80 is the most often used recommended testing standard for low-cycle-fatigue (LCF) testing in the United States. The standard was first adopted in 1977 for LCF testing at room temperature and was modified in 1980 to include high-temperature testing practices. Current activity within ASTM is aimed at extending the E606-80 recommended practices to LCF under thermomechanical conditions, LCF in high-pressure hydrogen, and LCF of metal-matrix composite materials. This paper discusses interlaboratory testing programs conducted to generate a technical base for modifying E606-80 for the aforementioned LCF test types.

E-5891

INTRODUCTION

American Society for Testing and Materials (ASTM) Standard E606-80 (ref. 1) is a recommended testing standard for strain-controlled, low-cycle-fatigue (LCF) testing of uniaxially loaded metallic test specimens. This standard was first adopted in 1977 for room-temperature LCF and was modified in 1980 to include high-temperature LCF. ASTM Committee E09, which oversees ASTM fatigue activities, is currently extending the recommended practices of E606-80 to other types of fatigue loading of metallic specimens. These include thermomechanical fatigue (TMF), multiaxial fatigue, and fatigue in high-pressure hydrogen environments. In addition, standardization of room-temperature and elevated-temperature fatigue testing of metal-matrix and ceramic-matrix composite materials is being examined in conjunction with ASTM Committee D30 on High Modulus Fibers and Their Composites.

In the process of standardizing testing practices, problems unique to each of the fatigue test types mentioned above must be addressed. Difficulties unique to thermomechanical fatigue testing include phasing of the thermal and mechanical components of loading, careful control of the dynamic temperature gradients in the specimen gage section, and accurate assessment and application of thermal expansion strains during strain-controlled tests (ref. 2). Standardization of high-temperature LCF test methods for metal-matrix composites requires an assessment of the effect on fatigue behavior of various test parameters such as specimen design and preparation, specimen heating method, and test control mode (ref. 3). Strain-controlled LCF testing in high-pressure hydrogen requires specially designed test facilities and specimens (ref. 4). Test parameters that can affect the LCF behavior of metallic specimens in high-pressure hydrogen environments include the purity of the hydrogen environment, the hydrogen pressure, and the test temperature (ref. 5).

Interlaboratory test programs have been traditionally used to evaluate ASTM standards and to gather information on the precision and bias of data generated using these standards. This paper summarizes all past, present, and future interlaboratory test programs in the area of low-cycle fatigue under the auspices of ASTM Committee E09. These test programs have been, are being, and will be performed to evaluate ASTM Standard E606 and to adopt or modify these testing practices for test types other than room-temperature uniaxially loaded, strain-controlled testing.

PAST AND PRESENT INTERLABORATORY FATIGUE TEST PROGRAMS

Round-Robin Fatigue Test Program on RQC-100 Steel

Background. - The interlaboratory round-robin fatigue test program on RQC-100 steel was organized by ASTM Subcommittee E09.08 in 1974. The principal program objective was to verify the recommended practices in the recently adopted standard E606 and, in particular, to examine specific aspects of the standard such as maximum allowable bending, alignment accuracy, specimen design, requirement for constancy of test temperature, and the required accuracy of extensometers, load transducers, and recording systems. The 20 laboratories that participated in this program are listed here in alphabetical order.

(1) Babcock and Wilcox Company, Alliance, Ohio
(2) Beckman Instruments, Inc., Palo Alto, California
(3) Bethlehem Steel Corporation, Bethlehem, Pennsylvania
(4) Deere & Company, Moline, Illinois
(5) Dominion Foundaries and Steel Ltd., Hamilton, Ontario, Canada
(6) Ford Scientific Research, Dearborn, Michigan
(7) General Atomic Corporation, San Diego, California
(8) General Electric Company, Materials and Properties Laboratory, Schenectady, New York
(9) General Electric Company, Corporation Research and Development, Schenectady, New York
(10) Inland Steel Company, East Chicago, Indiana
(11) Instron Corporation, Canton, Massachusetts
(12) Ishikawajima-Harima Heavy Industries, Tokyo, Japan
(13) MTS Systems Corporation, Minneapolis, Minnesota
(14) NASA Lewis Research Center, Cleveland, Ohio*
(15) Steel Company of Canada, Ltd., Burlington, Ontario, Canada
(16) Union College, Schenectady, New York
(17) Unversity of Illinois, Urbana, Illinois
(18) Westinghouse Research, Pittsburgh, Pennsylvania
(19) Westinghouse Materials Testing and Evaluation Laboratory, Pittsburgh, Pennsylvania

Material and specimens. - Bethlehem Steel Corporation provided a 152- by 366- by 2.5-cm plate of a carbon steel designated RQC-100. This is a water-quenched and tempered structural steel with a specified minimum yield strength of 690 MPa (100 ksi). Each participating laboratory was provided a 30- by 33- by 2.5-cm plate from which 12 specimens were to be manufactured. Instructions on how to cut specimen blanks from the plate and how to label them according to position in the plate were

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*NASA Lewis performed two series of fatigue tests and therefore is counted as two participants.

provided. Specimen design, machining, and surface preparation procedures specified by the organizers were those contained in standard E606.

Test procedures. - Two tension tests and eight strain-controlled LCF tests at room temperature were required. Each participant conducted two fatigue tests at each of these strain ranges: 4.0, 2.0, 0.9, and 0.6 percent. Specimens machined from the supplied plates were randomly selected for each test. The cycle frequency employed was 0.2 Hz. No specific failure criterion was provided. The strain-time waveform was not specified. Data to be reported were those recommended in standard E606.

A wide range of load-train fixtures and testing procedures were employed by the participating laboratories. Fourteen laboratories used liquid-metal grips, five used mechanical grips, and one employed hydraulic grips. Nine laboratories checked load-train alignment. Ten laboratories employed restraints against lateral movement of the actuator. Fourteen laboratories calibrated their load cells before the program. Sixteen laboratories conducted tests under axial strain control. Thirteen of these tested cylindrical specimens and the other three tested rectangular-cross-section specimens. Three laboratories tested solid hourglass-shaped specimens under diametral strain control, and a single laboratory controlled diametral strain on tubular hourglass-shaped specimens. Extensometers were calibrated before each fatigue test in six laboratories and before initiation of the program in the remaining laboratories. Eight participants maintained a constant strain rate during the tests; 12 maintained a constant cycle frequency regardless of strain amplitude. Fifteen laboratories employed a triangular waveform and the other five used a sine wave. Two of the 20 participants controlled displacement instead of strain. The failure criterion employed by 9 laboratories was separation of the specimen into two pieces, 10 used a percentage of tensile load drop or load range drop, and one terminated each test upon detection of a crack with a 4X glass.

Results. - Several variations in the method of reducing and reporting data were employed. Seven laboratories graphically obtained and 12 calculated plastic strain amplitude; one did not separate the total strain amplitude into its elastic and plastic components. Five laboratories measured the elastic modulus in each fatigue test, eight used modulus values measured in companion tension tests, and five used modulus values from supplied tensile data for data reduction purposes. Some laboratories reported true stresses and strains; others reported engineering values. Specimen failure location was reported by only some of the participants.

The fatigue data generated by all the participating laboratories are given in table I. The stresses and strains reported were determined from hysteresis loops recorded at half the fatigue life. The first two digits of the specimen numbers identify the laboratory that generated that data. The strain-life data were examined by using the analysis of covariance. The analysis of covariance will detect significant differences among data generated at different laboratories if they exist (ref. 6). In this analysis the regression of log(strain amplitude) versus log(life) was assumed to be linear.

The composite data, when plotted in the form of total strain amplitude versus reversals to failure, show a tenfold variability in life (fig. 1). The total strain data are stratified according to specimen type (fig. 2). Lives of the diametral strain-controlled, hourglass-shaped specimens approached the upper bound on the lives of the axial strain-controlled cylindrical specimens in the long-life regime. The hourglass-shaped specimens had longer lives in the short-life regime. The lives of the rectangular-cross-section specimens approached the upper bounds of the lives of the cylindrical specimens. The lives of the tubular hourglass-shaped specimens tended toward the lower bound on the lives of the cylindrical specimens.

Analysis of the data generated by laboratories using axial extensometers on cylindrical specimens showed that the data could be separated into four groups ranked in order of average life (fig. 3). The laboratories whose data exhibited longer lives generally (1) used grips that permitted a greater degree of alignment accuracy, (2) checked the load-train alignment, and (3) restrained the actuator against lateral movement. These laboratories also graphically obtained both the plastic strain amplitude and the modulus and maintained a constant strain rate by using a triangular waveform. Laboratories whose data tended toward shorter lives generally did not check alignment or restrain the actuator against lateral movement. These laboratories were more likely to calculate the plastic strain amplitude, maintain constant frequency, and use a sine waveform.

One laboratory conducted the fatigue experiments on both solid and tubular hourglass-shaped specimens under diametral strain control. As shown in figure 4, the fatigue lives of tubular hourglass-shaped specimens were shorter than those of solid hourglass-shaped specimens. One factor that may have contributed to this difference was the observed poor internal surface finish of the tubular specimens.

Conclusions. - Because of the wide range of test parameters and data analysis techniques employed by the participating laboratories, it was difficult to define sources of the spread in fatigue life. In light of the tests performed in this study (e.g., LCF, large plastic strains), it appears that careful attention to load-train alignment and stiffness will result in longer life.

Interlaboratory Fatigue Test Program on Alloy 800H

Background. - The interlaboratory fatigue test program on alloy 800H was organized by General Atomic Corporation (GAC) in 1974. The program was completed in 1975, and the results were presented to ASTM Subcommittee E09.08 in the same year. The work was formally reported in the Journal of Testing and Evaluation in 1987 (ref. 7). The aim of the program was to generate definitive fatigue data for a particular heat of alloy 800H and to use these data to evaluate the experimental approach used at GAC. The test method in question was that described in detail in reference 7 and involved the use of electrohydraulic test systems, hourglass-shaped geometry specimens, diametral extensometers, and axial strain computers. Five laboratories participated in the program.

Material and specimens. - The specimens used in this study were obtained from a single heat of alloy 800H, Huntington Alloy's heat number HH5556a. The material was in 1.91-cm-diameter bar form and specimens were manufactured from material in the as-received, solution-annealed condition. All specimens used in the program were manufactured by a single machinist working to a single set of detailed instructions. All specimens had hourglass profiles, which were of identical design in the case of three laboratories and of similar design at the fourth. The fifth laboratory opted to use tubular specimens.

Test procedures. - Each participant was required to conduct a total of six strain-controlled fatigue tests. The temperatures selected for the program were 20, 593, and 760 °C. Strain ranges of 1 and 2 percent were specified for the room-temperature tests; strain ranges of 0.5 and 2 percent were specified for the elevated-temperature tests. It was requested that all raw data in the form of x-y plots and strip chart recordings be supplied to GAC so that the same approach to data reduction could be used throughout. The definition of failure used in the reduction process was a 5-percent drop in tensile stress amplitude N_5. This approach was preferred over corresponding drops in stress range, since compressive stresses had been found to vary erratically once cracks were initiated.

Each of the five participating laboratories used different test equipment and different test procedures. One laboratory used a two-post load frame, another used a four-post load frame, and the remaining laboratories use three-post load frames. Die sets were used by three of the participants to preserve specimen alignment during testing. Flat load cells were used at two laboratories to provide a high degree of structural rigidity. Liquid metal grips were used at two laboratories to minimize specimen bending resulting from installation. Four laboratories used a threaded specimen grip end; the fifth used a buttonhead design.

All five laboratories used diametral extensometers. The calibration of the extensometers was checked before individual tests at four laboratories and at the beginning and end of the program at the fifth. Values of axial strain computed by using analog strain computers (ref. 8) were used for test system control at four laboratories. The fifth participant opted to use diametral strain for control purposes. Specimen heating was by 2.5-kW radiofrequency induction heaters at four laboratories and by silicon carbide heating elements at the fifth.

Results. - The approach adopted for data reduction was straightforward in the case of four laboratories. It simply involved the identification of a stabilized hysteresis loop, plotted as stress versus axial strain and judged typical for the particular experiment. For consistency, the fully cyclically hardened condition was assumed to have been achieved at about one-half the cyclic life. In the case of the laboratory that chose to control diametral strain, these strains were converted to axial strains analytically and the corresponding hysteresis loops were plotted manually. In all cases the hysteresis loops reported represented average behavior. The raw data from all five laboratories exhibited varying degrees of noise, which was not shown for simplicity.

Determination of LCF data in the form of axial strain range versus cycles to failure was again straightforward. As previously noted, failure in these experiments was defined as the number of cycles corresponding to a 5-percent drop in tensile stress amplitude. The data reduction process in this case involved identifying this value on the strip chart recording of stress versus cycles. The corresponding value of axial strain range was obtained from the hysteresis loop judged typical for the experiment.

In analyzing the results it was noted that similar test equipment and procedures were used at laboratories 1 to 4. It followed that comparing data obtained at these laboratories was a logical first step in analyzing the data. Considering first the stabilized hysteresis loops (figs. 5 to 7), data generated using a strain range of 2 percent were in fairly good agreement for all temperatures. In contrast, hysteresis loops determined for lower strain ranges were not in such good agreement for temperatures of 20 and 760 °C and were in worse agreement for 593 °C. At the last temperature the difference between the maximum and minimum stress ranges was about 10 percent; the corresponding difference in the plastic component of strain was almost a factor of 2. As might be expected, similar trends carried over to the fatigue life data. It can be seen in figure 8 that cyclic lives determined at a strain range of 2 percent were in excellent agreement for all three temperatures. Cyclic lives determined for lower strain ranges exhibited significant scatter at 20 and 760 °C, the longest lives exceeding the shortest by a factor of about 5. This variability was even more pronounced at 593 °C, one laboratory producing a cyclic life of about 20 000 cycles and two producing runouts of lives greater than 300 000 cycles.

These trends reflected to a large extent the ease or difficulty of running tests on alloy 800H at the specified test condition. This material exhibited discontinuous yielding over a range of thermomechanical conditions, the effect being most pronounced in this program at 593 °C. As a result of this behavior difficulties were experienced at all five laboratories in maintaining test system control. This problem largely resulted from using computed values of axial strain for control purposes rather than measured values. Apparently the use of analog strain computers exacerbated stability problems when the material response was discontinuous. Measures taken at GAC to correct this problem included running tests under reduced hydraulic pressure and reduced test system gain; including stability circuits in the control system; and incorporating mechanical damping on the diametral extensometer. It was shown in a subsequent series of experiments at GAC that, although these measures might prove successful in maintaining test system stability, their use can result in distorted hysteresis loops and unreliable fatigue data (ref. 7).

One obvious feature of the fatigue data generated by the fifth laboratory was that cyclic lives fell short of average behavior by a factor of about 2. A possible reason for this difference is that the fifth laboratory used tubular specimens rather than solid specimens. A similar degradation was seen in the RQC-100 test program. As part of that program this laboratory conducted tests on both tubular specimens and solid specimens using the same test equipment and procedures with the result shown in figure 4. Several factors may have contributed to these lower cyclic lives, including problems with surface finish on the specimen bore; a larger surface area to volume ratio with the tubular specimens; and localized specimen buckling influencing failure. Post-test examination of the tubular specimens used in the RQC-100 program indicated that surface finish on the bore was less than ideal and likely was a factor in reducing cyclic life. However, the fact that the differences increased as strain range was increased suggests that other factors were also involved. One possibility was that localized specimen buckling also played a role in reducing cyclic life.

Conclusions. - The main conclusion drawn from this program was that use of hourglass-shaped specimens, diametral extensometers, and axial strain computers can lead to distorted hysteresis loops and unreliable fatigue data under certain limiting conditions. In the alloy 800H study problems were encountered when material response was discontinuous and when tests were conducted at low strain ranges. A second conclusion was that cyclic lives determined in the tests conducted on tubular specimens were a factor of about 2 shorter than those for solid specimens. This discrepancy warrants further study, since thin-wall tubes are the preferred specimen design in fatigue programs investigating the effects of multiaxial stress states and thermomechanical loadings.

Round-Robin Fatigue Test Program on Type 316 Stainless Steel

Background. - The round-robin fatigue test program on RQC-100 steel identified a number of issues concerning LCF testing methods that were addressed and incorporated in an updated draft version of ASTM Standard E606. For example, the use of an hourglass specimen configuration was de-emphasized, the importance of restraint against lateral actuator movement was emphasized, and data reporting requirements were expanded. A new round-robin on uniaxial LCF testing was organized in 1988 to evaluate the effect of these and other changes on the reproducibility of fatigue data. A working group was established to develop test procedures, to prepare specimens, and to analyze data. A questionnaire was sent to prospective participants that collected some information on testing capabilities. Twenty laboratories responded to the questionnaire. These included commercial testing laboratories, industrial laboratories, and universities. Of these laboratories about half agreed to perform both room-temperature and elevated-temperature tests. Four countries were represented. To date, 10 laboratories have reported their results. Two more are known to be working on the testing, and one has dropped out.

Material and specimens. - The material selected was 25-mm bar stock of a heat of type 316 stainless steel purchased to aerospace standards. The mechanical and physical properties of the heat were well characterized over a broad range of testing conditions. In fact, some round-robin and material exchange testing had been previously performed on the heat. Bars were selected at random and coupons were cut, identified, and re-solution treated in a batch. Postannealing hardness numbers were taken on each bar. Coupons were assigned randomly to the various laboratories. The specimen gage length, radius, and surface finish were specified. The gripping configuration varied with each laboratory's fixturing equipment. Each laboratory was responsible for machining specimens. The participants were requested to return two machined specimens to the task group for subsequent testing as deemed necessary by the round-robin working group. All the specimens returned to the task group were machined to a common geometry.

Test procedures. - All fatigue tests were to be conducted in strain control by using an axial extensometer with a gage length of 12.7 mm. The strain ratio (minimum/maximum) was -1, and a triangular wave with a ramp rate of 0.004 sec^{-1} was requested. Tests temperatures were 20 and 538 °C. Three tests for each condition were requested, at 0.7- and 1.5-percent strain range for each temperature, for a total of 12 tests. Measurement of room-temperature modulus was requested prior to testing for all tests, and measurement of modulus at 538 °C was requested for the high-temperature tests. Fatigue tests were started in tension and cycled until either complete specimen separation or a 50-percent decrease in tensile force occurred. Each participant was requested to furnish detailed information about the test methods and equipment employed, including (1) specimen design and machining source; (2) description of the test equipment, including details about load train, heating equipment, temperature measurement and control, extensometry, and data recording equipment; and (3) test environment. Test results to be provided by each laboratory included all tested specimens, strip chart recordings, x-y plots, computer printouts, and a table of reduced data. The summary table required 25 pieces of information about each test conducted, including specimen number, specimen measurements, room- and elevated-temperature modulus, strain range, stress amplitudes in the first cycle and at half life, inelastic strain range, cycles to 5- and 10-percent tensile load drop, cycles to failure, failure criteria used for that test, and failure location.

Results. - Each laboratory received a copy of the round-robin test summary record when their results were received by the working group. General dissemination of the results has been withheld pending completion of the round-robin. Data not directly bearing on fatigue life have been released, and some are provided here. Figure 9, for example, shows plots of the modulus at 20 and 538 °C against the record number for over 100 tests. These data reveal the general reproducibility of the modulus from laboratory to laboratory. In a few instances low moduli were reported. It was discovered from examination of the x-y charts that the investigators used a method different from that recommended in ASTM standard E606 to determine the modulus. Recalculation improved the agreement with the overall data base. In figure 10 the stress range of the fatigue data has been plotted versus total strain range. Substantial variation occurred in the first cycle data (fig. 10(a)), but a much smaller variation occurred in the stress range at half life (fig. 10(b)). Detailed data reduction will be performed once the statistical processing of the fatigue data has identified possible discrepancies. In the meantime some exploratory testing has been under way at Oak Ridge National Laboratory to examine factors that may have influenced test results such as machine stiffness, specimen bending, specimen end fixturing, and ratio of specimen gage length to extensometer gage length. These data will not be included in the round-robin testing statistics.

FUTURE INTERLABORATORY FATIGUE TEST PROGRAMS

Interlaboratory Thermomechanical Fatigue Test Program on Haynes 188

Background. - An interlaboratory thermomechanical fatigue test program is currently being organized by ASTM Committee E09.01 on Fatigue Research. The objectives of the program are to conduct preliminary in-phase and out-of-phase thermomechanical fatigue experiments on Haynes 188 and to identify possible variations in the stress-strain response as measured by different laboratories. The information generated will be used to formulate a more comprehensive interlaboratory program. Six laboratories will participate in this program.

Material and specimens. - The material selected for this program is Haynes 188, a cobalt-based superalloy. Specimen design followed recommendations in ASTM standard E606-80, but each laboratory will use its own design. All designs will have a parallel gage section sized to accommodate an extensometer of 12.7-mm gage length. Specimens will be machined by the organizers using a single machining source.

Test procedures. - Four strain-controlled, thermomechanical fatigue (TMF) experiments will be performed by each laboratory. A triangular waveform and a cycle period of 400 sec is to be used. Two in-phase and two out-of-phase tests will be conducted at a mechanical strain range of 1 percent. The temperature range of the TMF tests will be between 500 and 900 °C. Axial extensometry is to be used. Induction heating of the specimen and use of thermocouples for temperature measurement are preferred. Forced-air cooling of the specimen is not recommended because of the potential for excessive thermal gradients. The temperature gradient along the specimen gage length should be less than 10 °C during the thermal cycling.

Status. - Testing will begin in 1991.

Interlaboratory Tensile and Fatigue Test Program on a Metal-Matrix Composite

Background. - An interlaboratory tensile and fatigue test program on a metal-matrix composite is currently being organized under the auspices of ASTM Committee D-30 on High Modulus Fibers and Their Composites. The objective of the program is to define proper tensile and fatigue test procedures for metal-matrix composites. A limited supply of material restricted the number of participating laboratories to six.

Material and specimens. - The metal-matrix composite to be tested in this program is designated SCS-6/β-21S. The composite is composed of silicon carbide SCS-6 continuous fibers, 140 μm in diameter, in a β-titanium matrix. The fiber volume fraction is expected to be nominally 0.35. Testing will be conducted on composite plates of three layups: $(0°)_4$, $(0°/90°)_{2S}$, and $(0°/\pm45°/90°)_S$.

One issue of primary interest is that of specimen design for metal-matrix composites. Therefore, four designs are to be tested. One straight-sided specimen design and one reduced-gage-section specimen design are to be employed for testing the $(0°)_4$ and $(0°/90°)_{2S}$ layups. Straight-sided and reduced-gage-section specimen designs incorporating a greater width are to be used for the $(0°/\pm45°/90°)_S$ layup.

Test procedures. - Each participant will be required to perform 24 uniaxial tension tests and 30 fatigue tests. Test temperatures are room temperature and 480 °C. The tension tests are to be conducted under strain control at a strain rate of 1.67×10^{-4} sec^{-1} (0.010 min^{-1}). The fatigue tests are to be load controlled, employing a load ratio (minimum/maximum) of 0.1 and a cycle frequency of 3 Hz. LCF tests will be conducted at two stress levels, 55 and 80 percent of the tensile strength. Each participating laboratory will test straight-edge and reduced-gage-section specimens.

Status. - The composite material is scheduled to be delivered to the program organizers in late 1990. Testing will begin in 1991.

Interlaboratory Fatigue Test Program in a High-Pressure Hydrogen Environment

Background. - NASA Marshall Space Flight Center is sponsoring a program, called the Hydrogen Test Standardization Program, to standardize mechanical test methods for high-pressure gaseous hydrogen environments. High-temperature materials are used in high-pressure gaseous hydrogen environments in advanced high-pressure hydrogen/oxygen rocket engines such as the space shuttle main engine. Standardization of mechanical test techniques in hydrogen environments for tensile, low-cycle fatigue, high-cycle fatigue, and fatigue crack growth are included in the Hydrogen Test Standardization Program. Nine laboratories will participate in the low-cycle-fatigue testing portion.

Material and specimens. - The material to be used in this program is a nickel-base superalloy, Inconel 718. Participating laboratories will receive material in the form of 12.7-mm bar stock as well as several machined specimens. A single machine shop will fabricate one specimen geometry, a design that has shoulders for extensometer attachment. The program organizers will furnish a set of these specimens for each participant. Participating laboratories will machine a second set of specimens of the design normally used by that laboratory.

Test procedures. - Eighteen room-temperature, strain-controlled, low-cycle-fatigue tests are to be performed by each participant. A strain ratio of -1, a cycle frequency of 10 cpm, and a triangular waveform are to be used. Six tests at strain ranges of 1.5, 1.0, and 0.6 percent are to be performed. Half of these tests will be performed in gaseous hydrogen at a pressure of 6.9 MPa, and the other half at

34.5 MPa. The hydrogen test environment is to contain less than 1-ppm oxygen as determined by gas chromatography. A gas sample for analysis is to be taken at the end of the test program.

Status. - The fatigue testing should begin in 1991.

SUMMARY OF RESULTS

Interlaboratory strain-controlled low-cycle-fatigue (LCF) test programs conducted in the United States in support of test technique standardization activities have been surveyed. Past, present, and future efforts were highlighted. Interlaboratory test programs conducted to date have concentrated on room- and elevated-temperature uniaxial LCF of engineering alloys. Some conclusions that can be drawn from the results of these programs are as follows:

1. When planning an interlaboratory LCF test program, all test parameters, including specimen design and machining, test control mode, cycle rate, cycle waveform, failure criteria, data analysis, and data to be reported, should be exactly specified in order to achieve the desired goals.

2. In light of the test results reported (e.g., LCF under large plastic strains), it appears that careful attention to load-train alignment and stiffness can result in longer lives.

3. The use of hourglass-shaped specimens, diametral extensometers, and axial strain computers can lead to unreliable fatigue data. This approach should be limited to generation of fatigue life data for applied strain ranges greater than about 2 percent.

Future efforts in LCF test methodology standardization are concentrating on nonisothermal fatigue, on fatigue of composite materials, and on fatigue in a high-pressure hydrogen environment.

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TABLE I. - SUMMARY OF LCF DATA ON RQC-100 STEEL AT 20 °C

[Stresses and strains determined at $2N_f/2$.]

Specimen number	Elastic modulus, ksi	Reversals to failure, $2N_f$	Total strain amplitude, $\Delta\epsilon_t/2$	Reported stress amplitude, $\Delta\sigma/2$, ksi	Calculated stress amplitude, $\epsilon_e E$, ksi	Reported plastic strain amplitude, $\Delta\epsilon_p/2$	Calculated plastic strain amplitude, $\epsilon_t - \sigma/E$
TT314	29 500	9 064	0.005	71.85	-----	0.0025	--------
TT414	↓	10 400	.005	71.8	-----	.0025	--------
TT214		1 820	.0099	82.7	-----	.007	--------
TT714		32 934	.0035	68.4	-----	.0012	--------
TT250		13 492	.005	72.45	-----	.00235	--------
TT821		1 940	.0099	82.9	-----	.0069	--------
TT721		24 974	.0035	74.05	-----	.001	--------
TT923		550	.0195	98.1	-----	.01635	--------
TT221		2 000	.0099	83.5	-----	.00695	--------
TT150		340	.0195	81.05	-----	.0161	--------
TT703		99 000	.0022	59.7	-----	.00015	--------
TT803		9 196	.005	72.85	-----	.0025	--------
TT901		25 866	.0035	67.0	-----	.00115	--------
TT103		204 620	.0022	61.5	-----	.00015	--------
TT903		340	.0195	92.95	-----	.01635	--------
TT203		75 820	.0022	60.25	-----	.00025	--------
TT948		92 400	.0022	61.65	-----	.0002	--------
2201	30 800	490	0.02	-----	96.1	0.0169	--------
2202	30 300	462	.02	-----	94.23	.0169	--------
2203	29 600	1 858	.01	-----	84.36	.00716	--------
2204	29 400	1 924	.01	-----	84.97	.00712	--------
2205	30 300	31 320	.00301	-----	68.78	.00074	--------
2206	31 300	15 608	.0045	-----	71.68	.00221	--------
2207	30 400	12 128	.0045	-----	74.78	.00204	--------
2208	30 500	36 092	.003	-----	68.93	.00074	--------

TABLE I. - Continued.

Specimen number	Elastic modulus, ksi	Reversals to failure, $2N_f$	Total strain amplitude, $\Delta\epsilon_t/2$	Reported stress amplitude, $\Delta\sigma/2$, ksi	Calculated stress amplitude, $\epsilon_e E$, ksi	Reported plastic strain amplitude, $\Delta\epsilon_p/2$	Calculated plastic strain amplitude, $\epsilon_t - \sigma/E$
2702	31 995	160	0.0199	91.65	-----	0.017	--------
2711		190	.0199	90.94	-----	.0171	--------
2703		700	.0099	83.88	-----	.0073	--------
2710		700	.0098	83.44	-----	.0072	--------
2704		6 760	.0044	74.10	-----	.0021	--------
2709		7 500	.0044	73.92	-----	.0022	--------
2706		32 400	.0029	70.55	-----	.0007	--------
2707		25 800	.0029	69.61	-----	.00072	--------
4901	29 500	46 796	0.00311	76.25	-----	0.000525	--------
4902		2 924	.00986	90.5	-----	.00679	--------
4904		612	.02035	105.45	-----	.0168	--------
4907		32 306	.00316	74.15	-----	.00065	--------
4909		666	.0206	105.25	-----	.01698	--------
4910		19 676	.00453	81.15	-----	.00178	--------
4911		15 892	.004475	78.05	-----	.00183	--------
4912		2 638	.0099	91.65	-----	.00681	--------
4302	25 300	336	0.02	92	-----	0.01636	--------
4311	22 700	400	.02	89	-----	.01609	--------
4303	25 000	2 000	.01	81	-----	.00675	--------
4310	26 100	2 360	.01	83	-----	.00682	--------
4305	27 400	9 460	.0045	74	-----	.00179	--------
4309	27 000	10 508	.0045	77	-----	.00165	--------
4312	25 400	16 070	.0045	70	-----	.0016	--------
4307	28 600	57 234	.003	70	-----	.00053	--------
4306	28 000	65 300	.003	69	-----	.00054	--------
3307	29 500	54 720	0.003	70.112	-----	0.00062	--------
3304		11 062	.0045	75.619	-----	.00194	--------
3310		1 234	.01	87.853	-----	.00702	--------
3309		12 028	.0045	75.845	-----	.00193	--------
3306		86 560	.003	70.148	-----	.00062	--------
3308		1 620	.01	84.459	-----	.00714	--------
3305		172 860	.0022	69.612	-----	0	--------
3403	29 500	1 126	0.01	83	-----	0.0069	--------
3411		306	.02	93	-----	.0164	--------
3407		35 100	.003	69	-----	.00054	--------
3410		1 388	.01	81	-----	.0069	--------
3406		40 660	.003	67	-----	.00058	--------
3409		7 020	.0045	73	-----	.00185	--------
3402		306	.02	92	-----	.0164	--------
3408		7 720	.0045	72	-----	.00175	--------
3405		120 700	.0022	64	-----	.00006	--------
3413		243 000	.0022	61	-----	.00006	--------
1802	29 500	750	0.02015	90.3	-----	--------	0.017089
1811		872	.02015	89.92	-----	--------	.017102
1803		3 430	.01005	68.89	-----	--------	.007715
1810		4 012	.01015	81.69	-----	--------	.007381
1804		27 572	.004475	71.97	-----	--------	.002035
1809		16 586	.004485	72.59	-----	--------	.002024
1808		22 732	.00443	71.99	-----	--------	.00199
1806		79 644	.00298	68.77	-----	--------	.000649
1807		64 634	.002925	68.95	-----	--------	.000588

TABLE I. - Continued.

Specimen number	Elastic modulus, ksi	Reversals to failure, $2N_f$	Total strain amplitude, $\Delta\epsilon_t/2$	Reported stress amplitude, $\Delta\sigma/2$, ksi	Calculated stress amplitude, $\epsilon_e E$, ksi	Reported plastic strain amplitude, $\Delta\epsilon_p/2$	Calculated plastic strain amplitude, $\epsilon_t - \sigma/E$
3810	30 000	1 356	0.01	81.25	-----	0.00729	--------
3809	↓	10 414	.0045	71.6	-----	.002115	--------
3806	↓	48 972	.003	68.6	-----	.000715	--------
3802	↓	3 796	.007	79.5	-----	.00435	--------
3807	↓	35 852	.003	70.1	-----	.000665	--------
3811	↓	17 800	.00375	71.5	-----	.001365	--------
3803	↓	1 824	.01	89	-----	.007035	--------
3804	↓	13 028	.0045	77.25	-----	.001925	--------
2610	29 350	2 800	0.00919	84	-----	0.00633	--------
2609	↓	24 000	.004145	82.5	-----	.001335	--------
2611	↓	800	.01935	97.05	-----	.01605	--------
2607	↓	72 000	.003005	69.75	-----	.00063	--------
2602	↓	600	.0193	97.25	-----	.016	--------
2606	↓	70 000	.00298	69	-----	.00063	--------
2603	↓	2 800	.009375	85.1	-----	.006475	--------
2604	↓	24 000	.004135	72.5	-----	.001665	--------
1901	29 500	708	0.0097	84.05	-----	0.00685	--------
1902	↓	1 182	.009615	83.7	-----	.006775	--------
1903	↓	284	.02125	96.6	-----	.018	--------
1904	↓	31 716	.00289	82.3	-----	.00057	--------
1908	↓	7 566	.00449	68.75	-----	.00216	--------
1910	↓	246	.02125	93.95	-----	.01805	--------
1911	↓	40 260	.0029	69	-----	.00056	--------
4402	29 500	312	0.0198	93.373	-----	0.0166	--------
4410	30 800	1 634	.00988	83.612	-----	.00705	--------
4403	31 900	1 622	.00988	82.706	-----	.00708	--------
4409	32 500	7 298	.00443	74.548	-----	.00190	--------
4404	31 800	8 560	.00445	74.040	-----	.00194	--------
4406	30 700	57 052	.00293	69.172	-----	.0062	--------
4407	30 900	52 308	.00295	69.023	-----	.0061	--------
4408	31 200	234 960	.00215	65.052	-----	0	--------
4405	31 400	142 860	.00215	67.142	-----	0	--------
4411	32 000	340	.0198	93.295	-----	.0166	--------
3002	29 500	216	0.02	97.35	-----	0.0167	--------
3007	↓	10 050	.003	64.9	-----	.0008	--------
3011	↓	226	.02	98.825	-----	.01665	--------
3006	↓	12 060	.003	76.11	-----	.00042	--------
3004	↓	5 668	.0045	76.11	-----	.00192	--------
3003	↓	860	.01	83.485	-----	.00717	--------
3009	↓	4 866	.0045	73.75	-----	.002	--------
3010	↓	868	.01	88.5	-----	.007	--------
3005	↓	57 000	.0022	59	-----	.0002	--------
3000	↓	76 000	.0022	61.95	-----	.0001	--------
3103	30 857	1 880	0.01	81.63	-----	0.0065	--------
3111	29 500	440	.02	94.9	-----	-------	0.0168
3110	29 500	2 168	.01	79.59	-----	-------	.0073
3102	30 000	498	.02	89.8	-----	.0156	--------

TABLE I. - Concluded.

Specimen number	Elastic modulus, ksi	Reversals to failure, $2N_f$	Total strain amplitude, $\Delta\epsilon_t/2$	Reported stress amplitude, $\Delta\sigma/2$, ksi	Calculated stress amplitude, $\epsilon_e E$, ksi	Reported plastic strain amplitude, $\Delta\epsilon_p/2$	Calculated plastic strain amplitude, $\epsilon_t - \sigma/E$
3909	30 450	250	0.020	91.0	-----	0.01575	--------
3908		236	.020	91.5	-----	.01575	--------
3904		1 664	.010	82.5	-----	.0071	--------
3902		1 260	.010	83.0	-----	.007	--------
3912		10 330	.0045	73.0	-----	.0015	--------
3906		10 432	.0045	72.5	-----	.0015	--------
3901		39 084	.0030	68.0	-----	.000595	--------
3903		43 572	.0030	68.0	-----	.000995	--------
4104	27 948	246	0.0167	94.25	-----	--------	0.013328
4109		8 664	.005	82.915	-----	--------	.002033
4110		7 114	.005	113.5	-----	--------	.000939
4111		446	.0167	99.25	-----	--------	.013149
4209	30 770	34 000	0.002875	66.31	-----	0.00056	--------
4211		36 900	.00281	71.62	-----	.000675	--------
4207		7 160	.00415	79.58	-----	.00175	--------
4206		6 640	.004375	73.39	-----	.0019	--------
4218		760	.00960	86.65	-----	.0067	--------
4205		1 340	.00960	88.42	-----	.0068	--------
4204		1 010	.00910	83.11	-----	.0065	--------
4219		820	.00970	88.42	-----	.0069	--------
4216		258	.01960	99.03	-----	.0162	--------
4217		172	.01945	96.55	-----	.0163	--------
2402	29 000	452	0.02025	91	-----	0.01695	--------
2411		456	.0202	92	-----	.01695	--------
2410		1 960	.00995	83	-----	.0071	--------
2409		2 160	.010	83.5	-----	.007	--------
2404		12 000	.0049	74	-----	.00225	--------
2401		11 800	.0045	73	-----	.0019	--------
2403		14 000	.0045	73.5	-----	.00195	--------
2406		58 000	.003	68	-----	.000645	--------
2407		31 000	.003	69	-----	.000625	--------
2408		196 800	.00235	66	-----	.000135	--------
2405		254 000	.00225	66	-----	.000055	--------
2910	30 100	1 480	0.00995	86.5	-----	0.0070	--------
2909	30 500	6 100	.0045	76.6	-----	.0020	--------
2902	32 200	210	.0198	95.7	-----	.0168	--------
2904	30 300	6 044	.0045	75.5	-----	.0020	--------
2903	29 700	1 400	.00995	86.1	-----	.0070	--------
2801	32 000	462	0.019	92.0	-----	0.0146	--------
2806	28 100	590	.020	91.5	-----	.0167	--------
2807	32 000	1 686	.010	86.0	-----	.0070	--------
2808	29 197	9 564	.0050	74.5	-----	.0023	--------
2810	28 800	1 790	.0101	83.1	-----	.0072	--------
2812	28 300	11 112	.0049	75.5	-----	.0022	--------
2815	28 093	558	.020	92.5	-----	.0167	--------
2820	29 158	13 768	.0045	74.5	-----	.0019	--------
2821	28 536	90 512	.0030	69.6	-----	.00057	--------
2824	28 820	2 722	.010	82.3	-----	.0071	--------

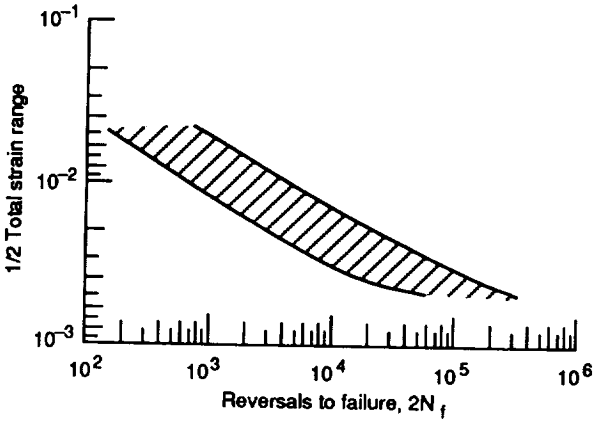


Figure 1.—Low-cycle-fatigue life data for RQC–100 at 20 °C for all round-robin participants.

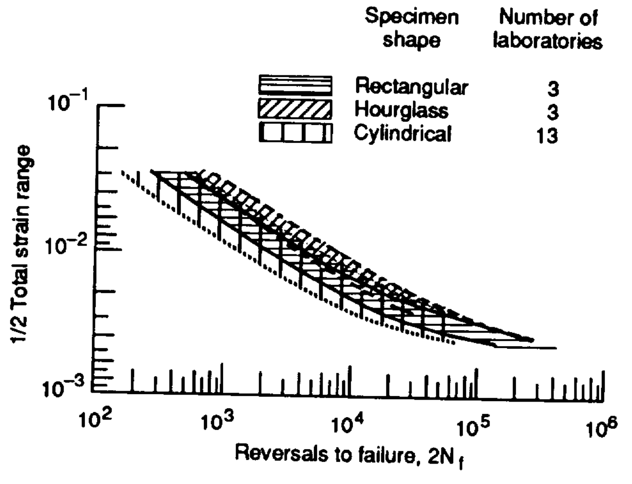


Figure 2.—Low-cycle-fatigue life data for RQC–100 at 20 °C separated according to specimen type.

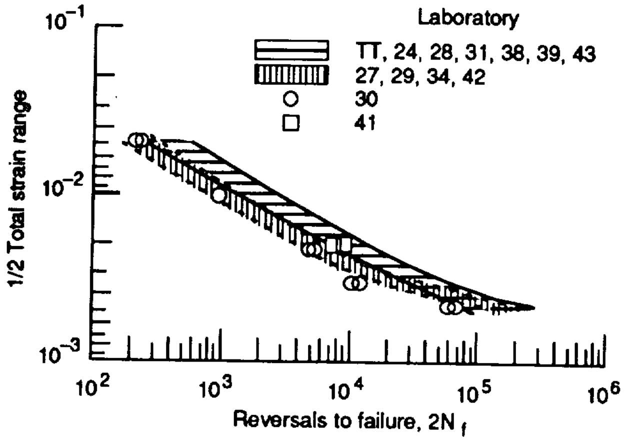


Figure 3.—Low-cycle-fatigue life data for RQC–100 at 20 °C for tests conducted on cylindrical specimens under axial strain control.

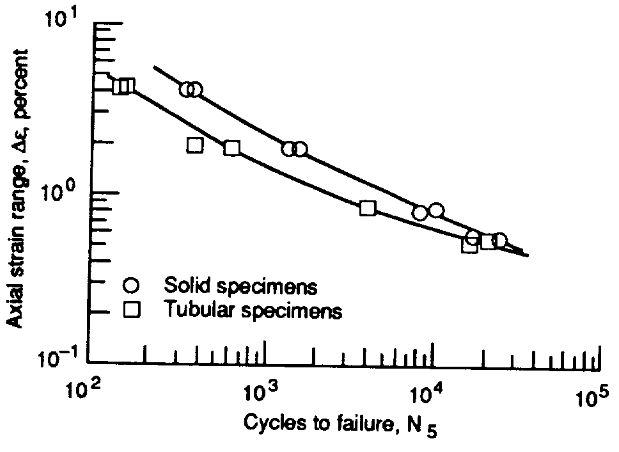
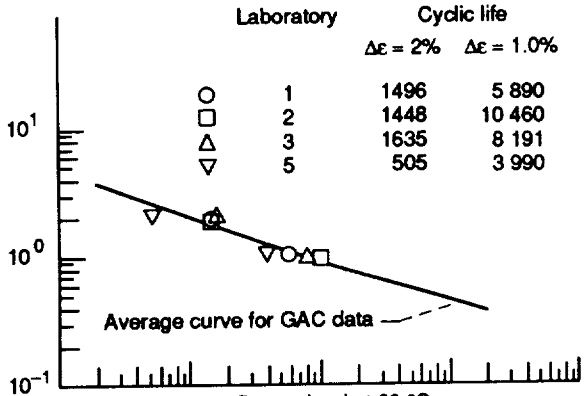
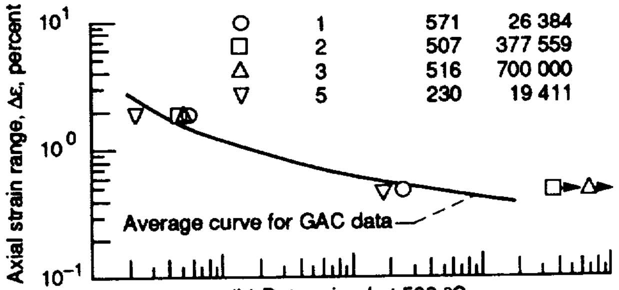


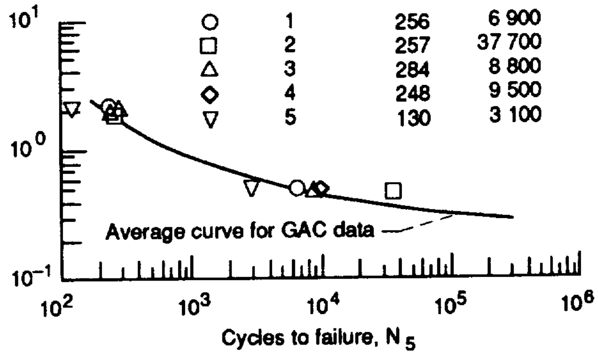
Figure 4.—Low-cycle-fatigue life data for RQC–100 at 20 °C for tests conducted at a single laboratory on solid and tubular hourglass-shaped specimens under diametral strain control.



(a) Determined at 20 °C.

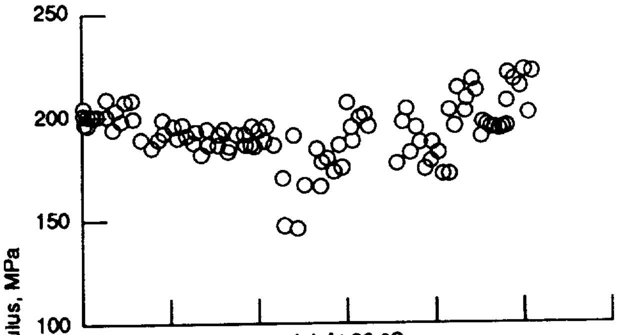


(b) Determined at 593 °C.

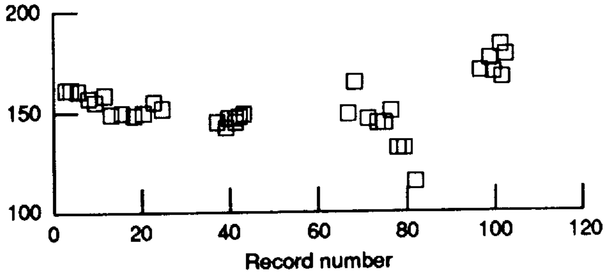


(c) Determined at 760 °C.

Figure 8.—Low-cycle-fatigue life data for alloy 800H. Strain rate, $\dot{\varepsilon} = 4\mathrm{x}10^{-3}\ \mathrm{sec}^{-1}$.

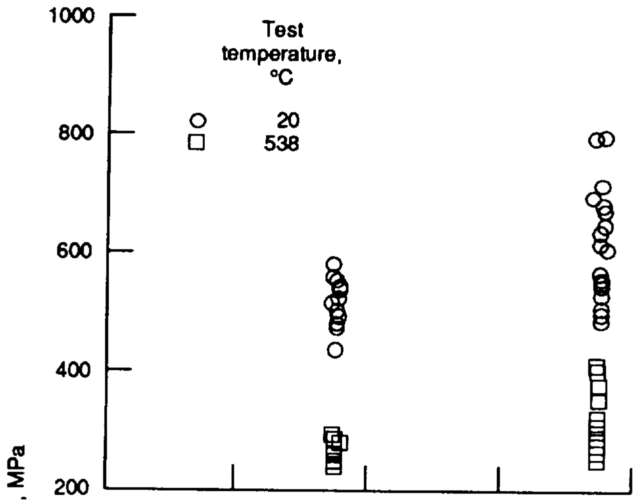


(a) At 20 °C

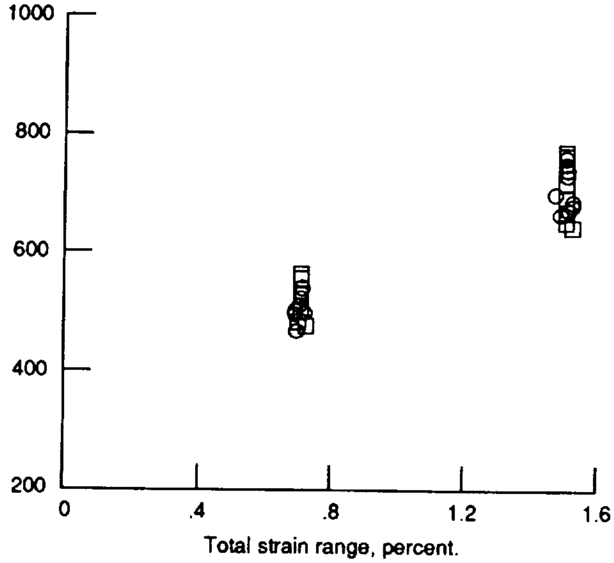


(b) At 538 °C

Figure 9.—Elastic modulus versus record number for type 316 stainless steel.



(a) Measured during first fatigue cycle.



(b) Measured at one-half fatigue life.

Figure 10.—Cyclic stress-strain behavior for type 316 stainless steel at 20 and 538 °C.

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16. Abstract

American Society for Testing and Materials (ASTM) standard E606-80 is the most often used recommended testing practice for low-cycle-fatigue (LCF) testing in the United States. The standard was first adopted in 1977 for LCF testing at room temperature and was modified in 1980 to include high-temperature testing practices. Current activity within ASTM is aimed at extending the E606-80 recommended practices to LCF under thermomechanical conditions, LCF in high-pressure hydrogen, and LCF of metal-matrix composite materials. This paper discusses interlaboratory testing programs conducted to generate a technical base for modifying E606-80 for the aforementioned LCF test types.

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