SSC-137

LOW-CYCLE FATIGUE OF METALS—LITERATURE REVIEW

by

J. T. P. Yao

and

W. H. Munse

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

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October 31, 1961

Dear Sir:

Structural experience both with ships and other structures has indicated that fatigue-type failures, particularly low-cycle fatigue, are an important structural problem. In order to evaluate the influence of a few load cycles at high stress levels upon the mechanical properties of ship steels, a project on "Low-Cycle Fatigue" was initiated at the University of Illinois. Herewith is a copy of the first progress report, SSC-137, Low-Cycle Fatigue of Metals--Literature Review by J. T. P. Yao and W. H. Munse.

This project is being conducted under the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

This report is being distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely yours,

J. A. Alger, Jr.
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-137

First Progress Report
of
Project SR-149

to the

SHIP STRUCTURE COMMITTEE

on

LOW-CYCLE FATIGUE OF METALS--LITERATURE REVIEW

by

J. T. P. Yao and W. H. Munse

University of Illinois
Urbana, Illinois

under

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October 31, 1961

ABSTRACT

An evaluation of the data on low-cycle fatigue of metals based on type of test, cyclic rate, stress concentration, crack propagation, material property change and method of analysis indicates that (a) there is presently no general analysis applicable to all low-cycle fatigue test conditions; (b) the shape of the load-time curve is an important factor in analyzing low-cycle fatigue tests; (c) the extent of the time effect on low-cycle fatigue behavior, particularly with respect to creep and crack propagation, still remains to be explored; (d) the use of strain rather than stress is more desirable in low-cycle fatigue studies of coupon-type specimens because of the plastic deformation that takes place during such tests; and (e) the fatigue hypotheses based on strain, although developed from limited data, exhibit good agreement with the test results and show promise of providing a good indication of low-cycle fatigue behavior for selected loading conditions.

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INTRODUCTION

Low-cycle fatigue tests subject specimens to repeated stress or strain until failure occurs at a relatively small number of cycles. The upper limit in low-cycle life has generally been selected arbitrarily by individual investigators to lie in the range of 10^4 to 10^5 cycles. On the other hand, the lower limit of life is the static test which has been represented by various investigators as 1/4, 1/2, 3/4 or one cycle.

Investigations in low-cycle fatigue have been conducted either (a) to provide information concerning a particular problem or (b) to obtain fundamental information.

It is the purpose of this review to summarize and to discuss the information available on the low-cycle fatigue behavior of metals. Separate sections are presented on type of test, cyclic rate, stress concentration, crack propagation, material property change, method of analysis and miscellaneous items. An appendix referring to essential information of each experimental investigation is also included.

Type of Test

Fatigue tests may be performed by subjecting members to repeated axial loads, bending moments or torques. When the resulting applied stresses are low and within the elastic range of the material, the stress is directly proportional to the strain and there is little or no difference between tests based on controlled strain or stress limits. In the case of low-cycle fatigue tests however, the applied stresses are generally high enough to cause plastic deformation and a corresponding hysteresis in the stress-strain behavior. If, in such tests, the load limits are maintained constant, the limits of deformation or strain will vary through at least some part of the life and vice versa. Therefore, low-cycle fatigue tests need to be further identified as constant-stress, constant-load or constant-deformation tests. A limited number of exploratory tests controlling limits of "true" stress have been conducted by Lin and Kirsch.[38] In spite of the fact that extreme care was exercised in monitoring these "true" stress limits, large scatter occurred in the test results because of the difficulty of controlling the "true" stress in low-cycle fatigue tests. All other constant-stress and constant-strain tests reviewed here were performed by controlling respectively the limits of engineering stress (representing load) and limits of engineering or "true" strain (representing deformations over a given gage length or at a given test section). In addition, there are some low-cycle fatigue tests reported in which the specimens were subjected to repeated applications of high temperature. Tests in which cyclic heat was used to introduce constant deformation ranges to the specimen have been included in this report as constant-deformation type tests.

<u>Constant-Load Tests</u>. A number of constant-load tests are reported in the technical notes of the National Advisory Committee for Aeronautics.[24,26,27,31] In 1942, Hartmann and Strickley[28] tested six 17S-T aluminum alloy specimens in the life range of 1/2 to 10^5 cycles under zero-to-tension load cycles. Three specimens were tested in a manually operated static testing machine; the remaining three were "preloaded" in a static machine and then tested in a fatigue machine. The test results showed that the S-N (stress versus number of cycles) curve is rather flat in the region of 1/2 to 10^4 cycles. Grover et al[24] compiled, for two aluminum alloys, axial-load test data from four laboratories. Since some of the S-N curves for these two alloys extend to very short lives, it has been possible to compare these low-cycle data with those of other low-cycle tests for similar materials in which failures were obtained at lives on the order of 10^2 cycles. Hardrath et al[26] present results of axial-load zero-to-tension fatigue tests on plain and notched sheet specimens of 61 S-T6 aluminum alloy, 347 and 403 stainless steels. In these tests a phenomenon that has been called the "minimum life at high stresses" was observed. It was found that if a specimen had survived the first load cycle, it would not fail until a certain "minimum life" was exceeded. For the three materials tested, the "minimum lives" were approximately 10^4, 10^3 and 10^2 cycles for specimens with theoretical stress

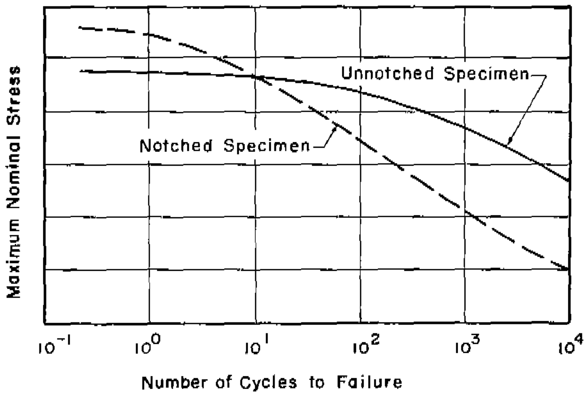

FIG. I TYPICAL S-N CURVES FOR CONSTANT-LOAD TESTS

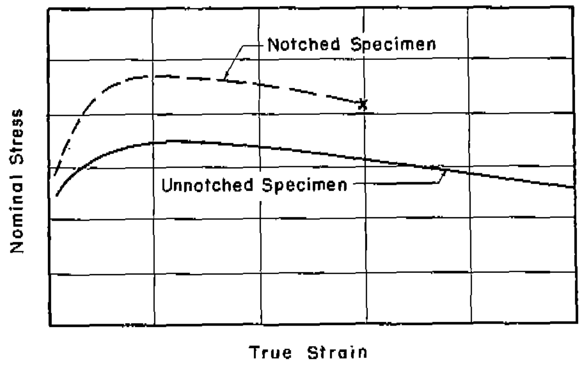

FIG. 2 TYPICAL STRESS-STRAIN CURVES

concentration factors (defined as the ratio of the maximum stress to the nominal stress in a member) of 1.0, 2.0 and 4.0 respectively. Hardrath and Illg[27] conducted reversed-load axial fatigue tests on two aluminum alloys with specimens having a theoretical stress concentration factor of 4.0. They found that the S-N curve in this case was initially concave downward and at about 10 cycles of loading reversed itself and became concave upward for the remainder of the curve. Later, Illg[30] also found evidence of "minimum life" in axial-load fatigue tests (at constant mean stress) of 2024-T3, 7075-T6 aluminum alloy, and normalized and heat-treated 4130 steel specimens with theoretical concentration factors of 1.0, 2.0 and 4.0. The mean stresses employed were 0, 20 and 50 ksi and the "minimum life" was found to range from 2 to 58 cycles. In 1961, Dubuc[15] presented the results of a number of full-reversal tests on specimens of eight materials and reported that the S-N curves for these materials were nearly flat up to a life of about 10 cycles, i.e., the "minimum life" was approximately 10 cycles.

In the above mentioned references, it may be seen also that the initial portion of an S-N curve is generally rather flat and that this flat portion is shorter for notched than for plain specimens. Typical S-N curves of this type are shown in Fig. 1. The difference or apparent reversal in initial behavior is thought to be related to the stress-strain properties of the members (typical stress-strain curves are shown in Fig. 2). It is evident that the slope of the stress-strain curve in the vicinity of the ultimate load is smaller for the unnotched specimen than for the notched specimen. Consequently, the life expectancy for the unnotched specimens tested under repeated loads near the ultimate strength of the material can be expected to vary greatly depending upon the maximum strain in the first application of load. However, because of the steeper slope of the stress-strain curve and the reduced deformation capacity of the notched specimens, the flat portion in the S-N diagram is shorter for these specimens. Yao and Mosborg,[69] in a preliminary investigation of the low-cycle fatigue behavior of ABS-Class C normalized steel, report strain values for the application of the first tensile load in constant-load tests and show that, for specimen lives of less than 1000 cycles, strain is a more sensitive measurement of life than the nominal stress.

Few low-cycle fatigue tests have been conducted in the compression range only. Newmark, Mosborg, Munse and Elling[52] obtained low-cycle fatigue failures in cast iron specimens with zero-to-compression loadings. In the same study, however, compressive fatigue failures could not be obtained for aluminum alloy and steel specimens except at very long lives.

Constant-Deformation Tests: In 1912, Kommers[33] reported a series of tests in which a cantilever specimen was subjected to cyclic bending. He concluded that the magnitude of the deflection is a very important factor in low-cycle fatigue. In more recent investigations, however, strains calculated from deformation or deflection measurements have been used in presenting the test data.

Evans[16] has conducted fatigue tests in which he has applied repeated constant increments of longitudinal tensile strains to mild steel specimens. Although the author was primarily interested in determining the elongation of the specimen to failure, he also obtained information concerning the number of cycles to fracture. In Fig. 3, strain increments in percent versus number of cycles to failure are plotted on a log-log scale for a mild steel and a copper wire. It appears that, in the low-cycle range, straight line relationships exist for both materials.

Low[40,41] conducted bending fatigue tests by applying preset angular movements to both ends of a rectangular plate specimen. A spherometer was

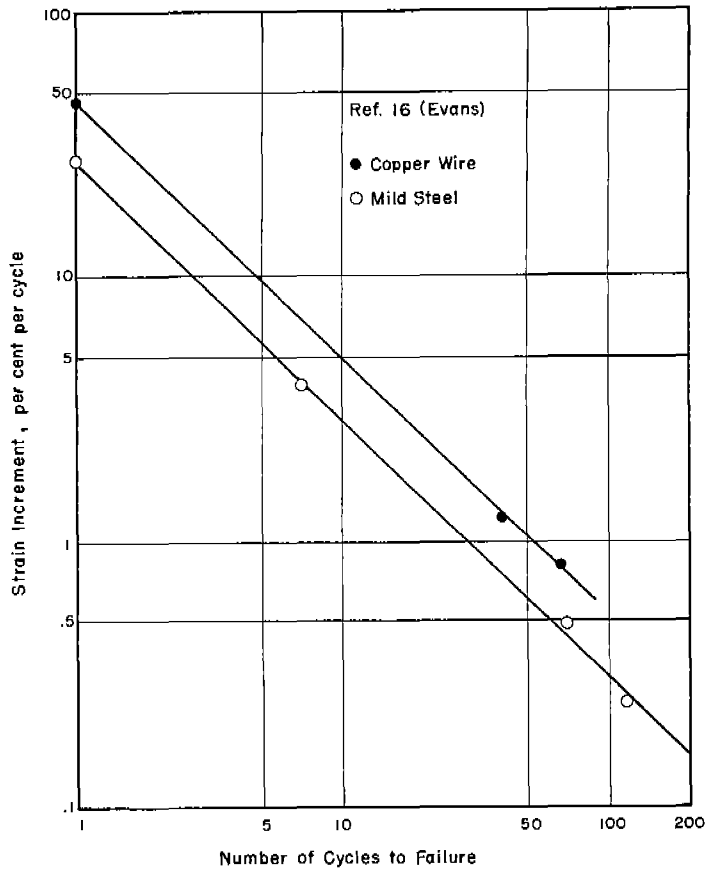

FIG. 3 CONSTANT STRAIN-INCREMENT TEST DATA

used to measure the curvature at the test section to determine the maximum strain. During each test the maximum strain was found to remain substantially constant until localized yielding or cracking took place in the test section. Altogether, two types of aluminum alloy and three types of steel were investigated. For these materials, it was observed that (a) the initiation of cracks appeared at approximately 2/3 of the total specimen life and (b) the number of visible cracks increased with increasing strain range. The test data show also that the fatigue life of these unnotched plate specimens in reversed bending may best be related to strain for strain ranges greater than $\pm$ 0.4%. In the elastic range the fatigue life may be related readily to either stress or strain.

Johansson[32] conducted cyclic bending tests on three steels at various temperatures and found that a linear relationship with a slope of -1/2 exists between log ϵ and log N (strain and cycles to failure respectively) for test tem-

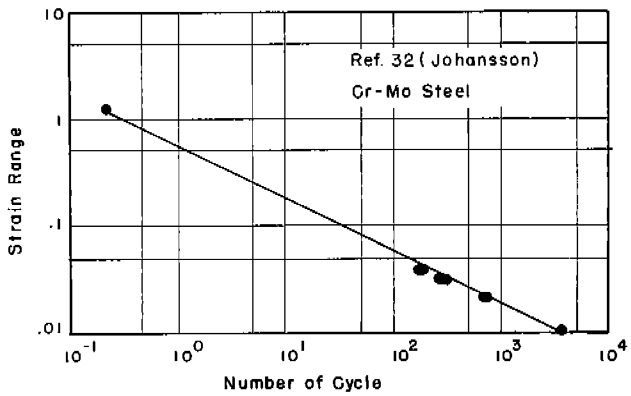

FIG. 4 STRAIN RANGE VS. LIFE ON LOG-LOG PLOT

peratures ranging from 20 to 500 C.

In recent years there has been an increase in the use of "true" strains in low-cycle fatigue investigations; however, in 1944 MacGregor[42,43] suggested the possibility of using true stress-strain relationships in fatigue tests.

In 1948, Liu, et al[39] conducted complete reversal, axial-load low-cycle fatigue tests on 24 S-T aluminum alloy with controlled limits of true strains. The maximum life span attained was seven cycles. Pian and D'Amato[56] performed low-cycle fatigue tests on the same material but with variations in strain ratio (i.e., ratio of minimum strain to maximum strain) and obtained lives ranging from 1 to 200 cycles. Later, D'Amato[13] carried the same type of test up to 10^4 cycles. These results show that, on a log-log basis, a straight line relationship exists between either the maximum strain or the strain range and the specimen life. However, the slope of the lines was reported to depend upon the value of mean strain. Sachs et al[57,58] conducted both axial and bending low-cycle fatigue tests on specimens of A-302 steel, 5454-0 aluminum, and 2024-T4 aluminum alloy. They report that the effect of mean strain becomes insignificant when the specimen lives are greater than 10^4 cycles.

Coffin and his associates[2,5-10,12,63] have conducted extensive experimental studies on the problem of low-cycle fatigue under thermal and mechanical strain-cycling. In their earlier works, engineering strains were used as a basis of conducting the tests. Recently, they have placed emphasis on the true strain measurements both in testing and in the analysis of the test results. In the strain tests, they too show that there is a straight line relationship between the logarithmic values of either the maximum strain or the range of strain and the lives of the members. A typical diagram of strain versus life on a log-log plot is shown in Fig. 4.

Cyclic Rate

Smith et al[61] tested bare and Alclad 24 S-T3 aluminum alloy sheet specimens in axial-load fatigue tests at cyclic rates of 12 and 1000 cpm. From these tests it was concluded that the fatigue strength at the lower speed was less than that at the higher speed. The same general conclusion has been reached at other speeds and by other investigators in (a) reversed-bending fatigue tests of two steels,[23] (b) axial strain-cycling tests of Inconel, Hastelloy B and beryllium at high temperatures,[14] and (c) rotating bending tests of hydrogen-embrittled steels.[60] It appears that, at frequencies of less than 1000 cpm, the fatigue strength generally decreases with a decrease in cyclic rate. In Ref. 3, Benham recommended the use of a cyclic rate of between 50 and 100 cpm for low-cycle fatigue tests to (a) avoid the generation of excessive heat in the specimens, (b) keep test time within a reasonable length, and (c) reduce to a minimum the speed effect.

The shape of the load-time curve of the load cycle is found to be an important factor in low-cycle fatigue. Johansson[32] suggests that the time factor may become more and more important with increasing mean stress and Benham[3] suggests that the shape of the load-cycle curve may influence the fatigue behavior with respect to creep and crack propagation.

Coffin[5] conducted a series of tests in which the specimens were subjected to repeated thermal strains at four different cyclic rates but with the heating or cooling time maintained constant for all tests. Therefore, the "hold time," defined as the length of time at which the specimen was held at the high or low temperature in each cycle, was the only variable. Hold times of 6, 18, 60 and 180 seconds for cyclic rates of 2.5, 1.25, 0.45 and 0.16 cpm, respectively were used. Again it was found that, at the lower frequencies of cycling, i.e., longer hold times, the number of cycles required for failure decreased.

Stress Concentration

A stress concentration is formed wherever there is a discontinuity in the geometry, structure, or temperature in a material;[7] although the term "stress concentration" generally refers to the stress increase resulting from a notch in a member. Based on the theory of elasticity, a theoretical stress concentration factor, previously defined as the ratio of the maximum stress to the nominal stress in the member, can be computed for most types of notches. Another stress factor which is used in fatigue studies is the "effective stress concentration factor," defined as the ratio of the fatigue strength of an unnotched specimen to that of a notched specimen at a certain life. At the present time, the effective stress concentration factor can only be obtained by experimental means.

A great amount of effort has been devoted to studies of the effects of stress concentrations in fatigue. However, most investigators have been interested primarily in correlating the theoretical and the effective stress concentration factors for a particular type of member. Consequently, the use of these correlations is limited only to those cases that have been studied.

It is generally found that the material in the region near a stress concentration deforms plastically in most fatigue tests. This is especially true in low-cycle fatigue tests where the applied stresses are high. This yielding affects the stress concentration in the following ways: (a) The ratio of the maximum stress to the average stress is no longer a constant; and (b) The geometry of the notch, which is the basis for the calculation of the theoretical stress concentration, changes. In addition, work hardening is generally introduced in the vicinity of the tip of the notch, and a new complication results from the non-uniformity of the material. Consequently, the theoretical stress concentration factor for a notched specimen becomes a fictitious quantity when yielding of the material occurs at the notch. However, since it is desirable to use numerical values in representing the severity of various

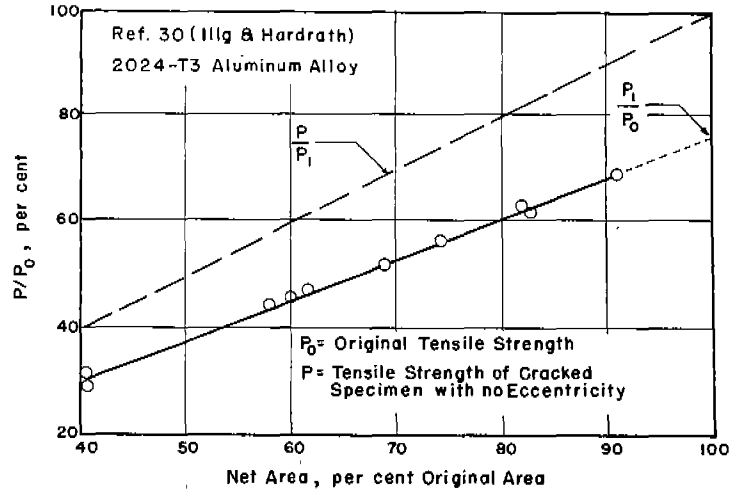

FIG. 5 STRENGTH OF SPECIMENS WITH FATIGUE CRACKS

notches, the theoretical stress concentration factor is often useful for purposes of comparison.

Hardrath and Ohman[25] derived a formula for a stress concentration factor in the plastic range. In Ref. 26, Hardrath et al compare K_f and K_p, the effective and the plastic stress concentration factors respectively, and show that the corresponding values for these two factors, although generally different, converge at high stresses.

Illg and Hardrath[30] conducted static tension tests of aluminum alloy sheet specimens with fatigue cracks of various lengths. Most of these fatigue cracks, previously developed in long-life zero-to-tension tests, occurred on one side of the specimens only. Therefore, a modification was made in the specimen geometry to minimize the eccentricity in the tension tests. The test results were presented in terms of P/P_o versus A/A_o plots (see Fig. 5), where P and P_o are the tensile strengths of the cracked and virgin specimens, A and A_o are the remaining and original cross-sectional areas, respectively. In Fig. 5, the ratio P/P_o is extrapolated and found to be 76% at A/A_o = 100%. Assuming P_1 = .76 P_o is the tensile strength of a specimen with an infinitesimal crack length, the dashed-line shows the relationship between P/P_1 and A/A_o. It is interesting to note that the tensile strength of a cracked specimen is a constant regardless of the initial crack length. From these data the investigators concluded that, for static loading, the effective stress concentration factor for the fatigue cracks was approximately 1.3.

In Ref. 31, Illg reports the results of axial constant-mean-stress fatigue tests on plain and notched sheet specimens of 2024-T3, 7075-T6 aluminum alloys and SAE 4130 steel. Semicircular notches with theoretical stress concentration factors of 2.0 and 4.0 were investigated for mean stresses of 0, 20 and 50 ksi. When the results were examined on the basis of effective stress concentration factor versus maximum nominal stress, it was found that the effective stress concentration factor decreased with increasing maximum nominal stress.

Pian and D'Amato[56] tested a series of notched plate specimens under zero-to-tension loading and with semi-circular notches which provided theoretical stress concentration factors of 2.0, 2.5 and 4.0. A sensitive extensometer with a 0.1-in. gage length was mounted at the root of the notch of the specimen being tested to determine the strain at the notch. It was found that the strain-range and the maximum strain at the edge of the notch did not begin to change until the specimen was about to fail. The test data also show that a linear relationship exists between the cyclic range of strains at the edge of the notch and the number of cycles to failure on a log-log plot.

Finch[18] conducted rotating bending fatigue tests of plain and notched specimens of three gun steels and reported that log S (based on strain measurements) versus log N curves for specimens with 45° and 90° V-notches were linear for specimen lives less than 10^5 cycles. The log S versus log N curves for plain and square-shouldered specimens were linear from 10^5 to about 10^3 cycles and then, at shorter lives, flatten out because of general yielding of the specimens. It is to be noted that all of these tests, including those with specimen lives as low as 20 cycles, were carried out at a cyclic rate of 600 cpm. With this high test speed, high temperatures would be generated in the high-stress low-cycle tests and have an effect on the behavior of the members.

Recently, Yukawa and McMullin[68] published test results on three types of notched specimens of a forged steel. All notches and a 45° angle had a root radius of 0.005 in. Although the three types of specimens were designed for different

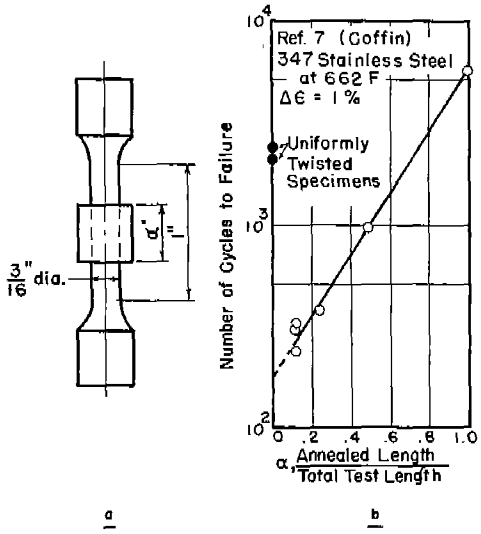

FIG. 6 COFFIN'S TEST DATA ON EFFECT OF NON-UNIFORM TEST MATERIAL

kinds of loadings, i.e., one for axial load, another for eccentric axial load, and the remaining one for bending load, zero-to-tension stress-cycles were used in all cases. It was found that for these specimens the nominal fatigue strength at 10^4 cycles was only about 50 per cent as great as the static strength. In the same reference, it is reported that some of the specimens during the tests were subjected to a single-cycle overstress resulting from a 10, 15, 20 or 40 per cent overload at various stages of their fatigue life. The test data show that while the lives of specimens subjected to 10 and 15 per cent overload increased, the lives of those that received a 20 or 40 per cent overload were not very different from the lives of specimens not subjected to an overload. A part of the reason for this may be that when an overload was applied, the root radius of the notch deformed enough to reduce the severity of the original stress concentration. Thus, the fatigue life of a moderately overloaded specimen was increased. However, cracks may have initiated at the critical section with a large overload and offset the benefits resulting from the increased root radius. As a result, tests with a 20 or 40 per cent overload had about the same life span as those without overload.

Coffin[7] tested annealed specimens for which a part of the test section had been cold-worked in the following manner. The specimen was machined in the shape as shown in Fig. 6a; torque was applied through the enlarged central portion to introduce plastic strain in the reduced section, and then the center portion was machined down to the same size as the adjacent test section. Specimens with different lengths of annealed center section were tested under repeated strains of one per cent and at a temperature of 350 C. The test data have been presented in terms of N and α as shown in Fig. 6b, where N is the number of cycles and α the ratio of annealed length to total length of the test section. It may be seen that, at $\alpha = 0$, the life of a uniformly twisted specimen was about ten times the life extrapolated from the test points. This discrepancy, as explained by Coffin, was due to a small region of inhomogeneity at the boundary between the annealed and cold-worked portions of the specimen. At any rate, the test results illustrate the significance of non-uniformity of the material in low-cycle fatigue investigations.

Crack Propagation

The PM (Philosophical Magazine) theory on crack propagation, originally developed for long-life fatigue tests, was expanded by Head[29] to include the low-cycle range of fatigue tests. The theory, based on an idealized material and consisting of elastic, elastic-shear and fully plastic elements, indicates that (a) cracks may initiate during rather early stages in fatigue tests, (b) the inverse square-root of the crack length is a linear function of the number of cycles, (c) the slope of the straight line (square root of the crack length versus number of cycles) is a function of the magnitude of the applied stresses. However, at present, there is little or no experimental evidence available to support this theory in the low-cycle field.

McClintock[49] presented a theoretical analysis along with some experimental results on crack propagation in bars subjected to fully plastic cycles of torsional stress. In his theoretical approach, a sand-heap analogy was used to help determine the strain distribution in a uniform bar of an idealized material in torsion. This idealized material was assumed to be fully plastic, non-work-hardening and to have a negligible Bauschinger effect. It was further assumed that the crack spreads when the maximum shear strain at radius ρ, a function of slip line spacing and grain size, from the tip of the crack reaches a critical strain value. McClintock[49] found that, at high strain amplitudes, (a) "Cracks always tend to grow toward the center of the remaining section: that is, the point most distant from the boundaries;" (b) the crack propagation depended upon the integrated absolute strain increments regardless of the number of cycles and cyclic strain increments, (c) cracks propagate faster in the larger of any two geometrically similar specimens under the same nominal strain amplitude, (d) the initial rate of crack propagation was independent of the notch angle. In the experimental study, specimens of aged 7075-T6 aluminum alloy were subjected to a selected number of cycles and then sectioned and examined for cracks. From the limited number of tests conducted, it appears that the theoretical hypotheses mentioned above are in general accord with the experimental data.

Scheven et al,[60] in their investigation of the effects of hydrogen on low-cycle rotating-beam fatigue tests of high strength steels, reported that (a) the cracks appeared after very few cycles and propagated at nearly a constant rate until about half of the specimen life was exhausted, and then the propagation proceeded at an increasing rate; (b) "the cracking rate of a 'hydrogen-loaded' material was found to be about three times as high as that of an unembrittled material."

Material Property Change

Benham[3] has indicated that the initial condition of the material is very important in any investigation of the property changes in low-cycle fatigue tests. He classified studies of this kind into (a) those in which a particular quantity (hardness, energy, strain, etc.) and its changes are measured at certain intervals of the test, and (b) those in which a static test to fracture is carried out after some cyclic loading to observe the effect caused by the latter.

An example of the first type of testing is the investigation conducted by Pian and D'Amato.[56] In their constant-load tests, the variation of the maximum true strain and the range of true strain was recorded with respect to the number of cycles. Similar studies were made in many strain-cycling tests, wherein the variation in the maximum load was recorded (with strain per cycle maintained constant) with respect to the number of cycles. It was found that, "for certain values of strain range, strain softening occurred at high values of mean strain, and while strain hardening occurred at low values of mean strain." Later, D'Amato[13] found that strain-hardening or strain-softening occurred when a selected specimen was subjected to mean strains respectively less or greater than a certain strain value; at this value neither hardening nor softening took place.

Coffin[12] applied cyclic plastic strains with superimposed mean stresses to various metals. It was observed that (a) "the superposition of cyclic strain on monotonic tensile deformation has the effect of substantially reducing the resistance of the material to deformation" (strain-softening), and (b) fracture ductility was increased with cyclic strain.

Liu et al[39] studied the true stress and strain values at static fracture of specimens at various stages of strain-cycling fatigue tests. From these tests it was concluded that (a) the true stress and true strain at fracture decrease with an increasing magnitude of cyclic strain and number of cycles, (b) the shape of the stress-strain curve changes greatly during the first few cycles and then only slightly as the cyclic loading continued, (c) the fatigue fracture is caused by progressive deterioration of the metal in the process of cyclic straining.

Method of Analysis

Pardue, Melchon and Good[55] tested rotating beam specimens with lives under 10^4 cycles. In these tests the variation in the dissipated energy was computed from measurements of the load and the lateral deformations for each specimen. It was observed that the total energy dissipated during the life of a specimen increased as the test load was decreased. Similarly, Martin and Brinn[48] conducted axial-load low-cycle fatigue tests of AISI type 347 stainless steel at a temperature of 1000 F and found that the total plastic work increased with decreasing test stress. However, it is to be noted that this "total energy" or "total plastic work" was calculated from the load and deformation experienced by the whole specimen. Whenever a crack or localized yielding occurs in a specimen, some kind of "energy sink" exists to absorb more energy than in the uncracked and unyielding portions. In other words, the distribution of the total work in the specimen is not uniform, particularly after the formation of a crack or cracks. Therefore, it is rather doubtful that the work thus computed represents the energy necessary to cause fracture at some particular location in the specimen.

Lazan and Wu[36] studied the effects on fatigue of damping energy, defined as the energy absorbed by 1 cu in. of metal during a complete cycle of vibration. Variables such as stress, cyclic rate and stress history were investigated. However, no low-cycle fatigue tests were reported.

Feltner and Morrow[17] postulated, as a hysteresis energy criterion, that the damaging energy to fracture in a fatigue test is constant and equal to the energy for fracture in the static tension test, i.e., the area under the true stress-strain curve in a tension test. The following equation was then derived to predict the S-N curves between 10^4 to 10^7 cycles.

$$\log \sigma_a = \log \left[\frac{U(1+n)}{2k} \right]^{\frac{n}{n+1}} - \frac{n}{1+n} \log N_f \qquad (1)$$

Where σ_a and N_f are corresponding stress amplitude and life, respectively, U is the area under the static true stress-strain curve, n is the slope of the line of true plastic strain versus the true stress on a log-log plot, $k = \epsilon_c / \sigma_c^{1/n}$, and σ_c and ϵ_c are any convenient corresponding values of true stress and true plastic strain taken in the region of the static stress-strain curve where plastic strain dominates. It is to be noted that the quantity σ_a was derived as a true stress. However, for the ordinary fatigue tests, i.e., for fatigue lives greater than 10^4 cycles, the values of true and nominal stress are probably very nearly equal.

In discussing the possibility of using an energy relationship for a fatigue theory, Tavernelli and Coffin[63] expressed doubts as to whether the total absorbed energy was a meaningful measure of fatigue failure since fatigue is a very localized phenomenon.

In the analysis of constant-strain tests, Orowan[54] made an assumption that the material fractures whenever a critical value of the total absolute plastic strain is reached. The following expression was derived from his analysis.

$$\epsilon \cdot N = \text{constant} \qquad (2)$$

Where ϵ is the constant plastic strain amplitude, and N is the number of cycles to failure. On the basis of test results, Manson,[45] as well as Gross and Stout,[23] empirically modified the equation to the following form,

$$\epsilon \cdot N^{m} = \text{constant} \tag{3}$$

Coffin[11] found the value of m to be 1/2 in most cases and consequently used the following form in his design recommendations.

$$\epsilon \cdot N^{1/2} = \text{constant} \tag{4}$$

In the case of a static tension test, $N = 1/4$, $\epsilon = \epsilon_f$, where ϵ_f is the true strain at fracture. Thus, in a static test, Eq. 4 becomes

$$\epsilon \cdot N^{1/2} = \frac{\epsilon_f}{2} \tag{5}$$

Equation 5 was considered to be accurate in most cases but conservative in others.

Recently Martin[47] used an energy criterion to obtain the following expression.

$$\epsilon \cdot N^{1/2} = \frac{\epsilon_f}{\sqrt{2}} \tag{6}$$

Comparisons of the constants from Eqs. 5 and 6 with existing test data show that (a) Eq. 6 gives a better prediction in the case of axial strain test at room temperature, and (b) Eq. 5 seems to give a better prediction in the case of flexural tests conducted at high temperatures.

Gerberich[20] obtained Eq. 7 by taking the effect of mean strain on low-cycle fatigue into consideration.

$$N = \left[\frac{\epsilon'_f - \epsilon_o}{\epsilon}\right]^2$$

$$\text{or} \qquad \epsilon \cdot N^{1/2} = \epsilon'_f - \epsilon_o \tag{7}$$

Where ϵ'_f is the apparent fracture ductility, and ϵ_o is the mean strain. In later reports on the same program, Sachs et al[57,58] substituted ϵ_{TR}, the total strain range for ϵ, the plastic strain range. Test results on 2024-T4 aluminum alloy specimens[20,57,58] show that Eq. 7 describes very effectively the behavior in low-cycle fatigue tests with various mean strains. However, it may be noted that (a) the apparent fracture ductility, ϵ_f' is a nominal value that can not be determined experimentally, and (b) this relationship applies only to tests with tensile mean strains.

Douglas and Swindeman[14] tested Hastelloy B, beryllium and Inconel at temperatures above 1300 F. The test data show that Eq. 3 was satisfactory in this instance. The values of m were 0.58, 0.81, and 0.76 for Hastelloy B, beryllium and Inconel, respectively. It was noted that since many metals exhibited a coefficient of 0.50 in low-temperature tests, the increase in the value at high temperatures indicates that the behavior depends on the temperature or deformation mechanism. In 1959 Majors,[44] in tests at high temperatures on titanium and nickel, found the constant m in Eq. 3 to vary from 0.48 to 0.51. More recently Dubuc[15] found that this constant was 0.53 for a low carbon steel and a brass in cyclic axial strain tests. These differences indicate that the exponential quantity m in Eq. 3 may be a variable and depend upon the various test conditions.

Miscellaneous

Wood[67] observed that when fatigue cycles imposed large plastic amplitudes of strain on a specimen, failure occurred in the same manner as in the case of static tests. In considering this same aspect, Evans[16] examined fractured specimens from both static tensile and low-cycle fatigue tests, and found that both showed identical fracturing modes. He also found that the true strains at fracture for both cyclically and statically tested specimens were about the same. Unlike the long-life fatigue tests where fractures of notched specimens exhibit little deformation, fractures resulting from low-cycle fatigue loadings may show deformations ranging from that of an ordinary long-life fatigue failure to that obtained in a static tensile failure. However, the mode of failure is apparently dependent upon many factors such as the type of test, the magnitude and nature of the applied stresses, the material, the geometry of the specimen, the test temperature, the cyclic rate, etc.

Baldwin, Sokol and Coffin[2] conducted tests on 347 stainless steel bars and plates of different grain sizes at constant limits of deformations and at a

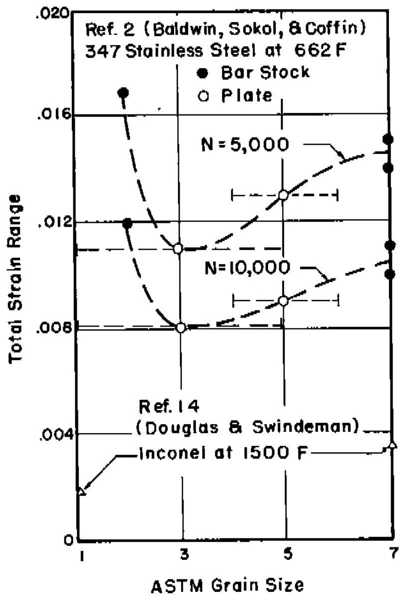

FIG. 7 EFFECT OF GRAIN SIZE

temperature of 350 C. Test results show that those specimens with larger grain size had a lower fatigue strength than those with small grain size for specimens made of bar stock materials. The reverse was found to be true for specimens fabricated from plate materials. However, if the approximate ASTM grain size for each type of specimen is plotted against the total strain range at certain lives, the relationships shown in Fig. 7 are obtained. Also shown in this figure are two points from the test data of Douglas and Swindeman[14] for Inconel tested at 1500 F.

Mehringer and Felgar[50] conducted thermal-strain-cycling tests on two high-temperature alloys. Because of the low-ductility possessed by both metals, plastic strain values could not be computed with the desired accuracy. Therefore, test results are presented in terms of stress range versus life. This experience indicates the inherent limitations on the usage of plastic strain range as a parameter in the case of low-ductility materials.

Baldwin et al[2] did some work on the problem of cumulative damage in low-cycle constant-deformation fatigue tests. It was found that the life under sequential loads varied from 72 to 163 per cent of the life in the simple tests. In this respect, Low[40,41] tested six specimens in the following manner. The specimen was cycled at some strain range $\pm \epsilon_a$ for 50 cycles, then cycled at $\pm$ 0.33% for 10^3 cycles, and finally cycled at $\pm \epsilon_a$ again until failure occurred. (Values of ϵ_a were varied from 1.54% to 2.27%). It was found that the life in five of the tests varied from 71 to 89 per cent of the life in simple tests, although the life of one specimen was 149 per cent of the life in simple tests. These data suggest that under variable cycle loadings the fatigue life of a specimen may vary considerably. In 1959 Gerberich[19] reported two series of cumulative damage tests on axially loaded specimens of 2024-T4 aluminum alloy.

In these tests the specimens were subjected to one magnitude of reversed strain for a selected number of cycles and then to another level of reversed strain until failure occurred. From these tests it was concluded that (a) "understraining will effect a decrease in the stress range after a sufficient number of cycles at the initial strain level. This causes a delayed increase in the cumulative damage ratio," and (b)" overstraining will effect a decrease in the stress range because of work-softening. This causes an initial increase in the cumulative damage ratio." However, D'Amato[13] in his tests on cumulative damage found that, when compared on the basis of equivalent strain range, the linear damage theory $[\Sigma(\frac{n}{N}) = 1.0]$ was applicable.

A difference in temperature causes changes in the mechanical properties of most materials. With this in mind, different results can be expected from tests conducted on the same material at different temperatures. In an investigation by Baldwin, Sokol and Coffin,[2] AISI 347 steel was tested in cyclic-strain tests at constant temperatures ranging from room temperature to 600 C. The test results indicated that the fatigue strength decreased with increasing test temperature. Coffin[9] also tested the same steel by alternately heating and cooling the specimens. It was found that metallurgical changes took place in the specimen when the test temperature exceeded 500 C. Coffin discussed the effect of temperature cycling on materials and concluded that, until the effects of externally applied and residual stresses and strains can be differentiated, it is difficult to interpret the behavior of complex alloys that are subjected to thermal cycling.

Summary

In low-cycle fatigue tests (generally less than 10^4 cycles) the magnitude and the range of the test load are usually sufficiently large to cause plastic deformation in the material and a corresponding hysteresis in its stress-strain behavior, which may change from one cycle to the next. Consequently, it is necessary to further identify low-cycle fatigue tests as constant-load or constant-deformation tests.

Experimental data from constant-load tests are often presented in the form of conventional S-N curves, where S and N are the maximum nominal stress and the corresponding life. The ultimate strength of the specimen is generally considered as the fatigue strength at the smallest possible number of cycles (1/4 to 1 cycle, depending upon the investigator's preference). The typical low-cycle S-N curve, starting from the ultimate strength, is initially concave downward and becomes concave upward at a point of inflection at some lower level of stress. The location of this point of inflection is not fixed but varies with material, geometry, cyclic rate, stress-cycle and temperature. At present, analytical evaluations of the constant-load tests are based upon an energy criterion and suggest that the fatigue failure occurs whenever the amount of energy absorbed by the specimen reaches a critical value. However, this criterion has often been questioned since the energy absorbed by the whole specimen may not be truly representative of the energy required for a very localized fatigue failure.

On the other hand, the results of constant-deformation tests, when presented in terms of the plastic strain range ϵ and the number of cycles N, are more consistent than those of constant-load tests. From the available test information, it may be concluded that the low-cycle log ϵ-log N curve is a straight line starting from the strain value at static fracture ($N = 1/4$ to 1 cycle) and has a slope of approximately $-1/2$. The strain value at static fracture may vary with material, geometry, cyclic rate, strain-cycle and temperature, while the slope of the log ϵ-log N lines seems to remain close to $-1/2$ for fully reversed strain tests.

Although the ultimate strength in a static test is usually incorporated into fatigue test results, there has been no attempt to make the loading rate of the static test comparable to that of the cyclic tests. In other words, a static fracture usually requires at least several minutes of loading while in most fatigue tests the loading process in each cycle takes a fraction of that time. At present, experimental data show that the fatigue strength decreases with decreasing test speed. However, the extent of the time effect on low-cycle fatigue behavior, particularly with respect to creep and crack propagation, still remains to be explored. In 1959, Lankford[35] listed "the time effects for cycling in the creep range" as one of seven subjects to be investigated in low-cycle fatigue.

During a low-cycle fatigue test, changes take place continuously in the geometry and the material of the specimen, thereby making it difficult to evaluate the actual distribution of stresses and strains during the test. Consequently, most of the available test results are presented in terms of nominal stress or strain (based on the initial conditions of the test), and not on the basis of maximum absolute values. In other words, all numerical values thus obtained are relative in nature. For this reason, there is at present no general analysis applicable to all low-cycle fatigue test conditions.

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APPENDIX

TEST INFORMATION ON LOW-CYCLE FATIGUE TESTING

Ref. No.	Material	Ultimate Strength ksi	Type of Specimen	Test Temp.	Manner of Loading	Parameter Held Constant	Type of Cycle	Cyclic Rate cpm	Life Range
1	Steel A	86	Plain	Rm.	Bending	Strain	R = 0	34	$10^3 - 10^5$
"	Steel B	66	"	"	"	"	"	"	" "
2	AISI 347 Stainless Steel		"	Rm.-600C	Axial	"			$10^3 - 10^6$
4	X 200 - L		Cracked		"	Load, G	"		
"	Mellon M x P - 2	280	"		"	"	"		
"	Mellon M x P - 2 as-welded		"		"	"	"		
5	AISI 347 Stainless Steel (Annealed & Cold-Worked)		Plain	Variable	"	Temp.	$T_{m350\,C}$	Variable	$10^2 - 10^5$
7	AISI 347 Stainless Steel		"	"	"	"	"	4	$10^3 - 10^5$
"	(Annealed)		Notched	"	"	"	"	"	$10^2 - 10^4$
8	" " " "		Plain	"	"	"	"	2	$10^3 - 10^5$
13	2024-T4 Aluminum Alloy		(Plain & Notched)	Rm.	"	Local & Strain	ϵ_m = 0 to 27.5%	.3-10	$1 - 10^4$
14	Inconel (Annealed)		Plain	1500 F	"	Deform.	R = -1	1/2	$1 - 10^3$
"	Inconel Tube		"	(1300 F - 1600 F)	"	"	"	"	$1 - 10^4$
"	" "		"	"	"	"	"	1/30	$10 - 10^3$
"	Hastelloy B		"	1650 F	"	"	"	1/2	$1 - 10^3$
"	Beryllium		"	1250 F	"	"	"	"	$1 - 10^2$
15	24S-T4 Aluminum Alloy (Cold-Worked)	85	"	Rm.	"	Local & Strain	"	6(max)	$1 - 10^4$
"	24S-T4 Aluminum Alloy	85	"	"	"	Load	"	"	$10 - 10^3$
"	75S-T6 Aluminum Alloy (Cold-Worked)	99	"	"	"	"	"	"	$1 - 10^4$
"	75S-T6 Aluminum Alloy	100	"	"	"	"	"	"	$10 - 10^4$
"	Brass 69 (Hard Drawn)	83	"	"	"	Load & Strain	"	"	" "
"	Brass 69 (Annealed)	58	"	"	"	Load	"	"	" "
"	Duronze 609 (Hard Drawn)	79	"	"	"	"	"	"	" "
"	Duronze 609 (Annealed)	53	"	"	"	"	"	"	" "
"	SAE 1030 Steel (Annealed)	63	"	"	"	Load & Strain	"	"	" "
"	A-201 Steel	58	Plain & Welded	"	"	Load	"	"	" "
"	A-302 Steel	93	Plain & Welded	"	"	"	"	"	" "
"	Monel	108	Plain	"	"	"	"	"	" "
16	Mild Steel Bar	60	"	"	"	(Increment of Strain)	R = 0		
"	Mild Steel Strip		"	"	"	"	"		
"	.75 Carbon Steel		"	"	"	"	"		
"	70/30 α Brass		"	"	"	"	"		
"	Pure Aluminum		"	"	"	"	"		
"	Copper		"	"	"	"	"		
17	SAE 4340 Steel	139	"	"	"	Load	R = -1	1/2&1200	$10^3 - 10^6$
18	Steel No. 1 (.29% C)	140	(Plain & Notched)	"	Bending	Stress	"		$10 - 10^8$
"	Steel No. 2 (.32% C)	165	"	"	"	"	"		" "
"	Steel No. 3 (.36% C)	181	"	"	"	"	"		" "
19, 57, 58	2024-T4 Aluminum Alloy	68	Plain	"	Axial	Strain	R = -1 R = 0		$10\text{-}1 - 10^2$
21	A-201 As-Received	62	(Plain & Notched)	"	Bending	Strain	"		$10^3 - 10^6$
"	A-201 10% Pre-Strain	72	"	"	"	"	"		" "
"	A-201 with Bead Weld		With Welds	"	"	"	"		" "
"	A-201 Annealed	57	(Plain & Notched)	"	"	"	"		" "
"	A-201 Quenched	72	"	"	"	"	"		" "
"	A-212 As-rolled	79	"	"	"	"	"		" "
"	A-212 Quenched	105	"	"	"	"	"		" "
22	A-201 Steel	59	Plain	"	"	(Load & Deform.)	"	100	" "

TEST INFORMATION ON LOW-CYCLE FATIGUE TESTING (Continued)

Ref. No.	Material	Ultimate Strength ksi	Type of Specimen	Test Temp.	Manner of Loading	Parameter Held Constant	Type of Cycle	Cyclic Rate cpm	Life Range
22	A-302 Steel	87	Plain	Rm.	Bending	(Load & Deform.)	R = 1	100	$10^3 - 10^6$
"	New A-302 Annealed	73	"	"	"	"	"	"	" "
"	" " Stress Relieved	79	"	"	"	"	"	"	" "
"	" " with 10% prestrain	90	"	"	"	"	"	"	" "
"	" " Quenched & Temp. 400 F	196	"	"	"	"	"	"	" "
"	" " Quenched & Temp. 1300 F	93	"	"	"	"	"	"	" "
23	A-201 Steel	61	(Plain Notched & Welded)	Rm. & 650 F	"	Deform.	"	1.5 & 200	$10^2 - 10^5$
"	A-225 Steel	76	" "	"	"	"	"	200	" "
"	48_S 5 HT Steel	71	" "	"	"	"	"	"	" "
"	Fortiweld Steel	82	" "	"	"	"	"	"	" "
"	A-302 Steel	87	" "	"	"	"	"	1.5 & 200	" "
"	70 A Steel	95	" "	"	"	"		200	" "
"	70 B Steel	102	" "	"	"	"	"	"	" "
"	90 A Steel	130	" "	"	"	"	"	"	" "
"	90 B Steel	130	" "	"	"	"	"	"	" "
26	61S-T6 Aluminum Alloy	47	(Plain & Notched)	Rm.	Axial	Load	R = 0	2 & 180	$1 - 10^8$
"	347 Stainless Steel	92	"	"	"	"	"	"	" "
"	403 Stainless Steel	190	"	"	"	"	"	"	" "
27	24S-T3 Aluminum Alloy	69	Notched	"	"	"	R = -1	.4—1800	$1 - 10^7$
"	75S-T6 Aluminum Alloy	88	"	"	"	"	"	"	" "
28	17S-T Aluminum Alloy	61	Plain	"	"	"	R = 0		$10^{-1} - 10^{10}$
31	2024-T3 Aluminum Alloy	72	(Plain & Notched)	"	"	"	(S_m = 0, 20ksi)	12—1800	$1 - 10^8$
"	7075-T6 Aluminum Alloy	83	"	"	"	"	"	"	" "
"	4130 Steel Normalized	116	"	"	"	"	"	"	" "
"	4130 Steel Hardened	180	"	"	"	"	(S_m = 0, 50ksi)	"	" "
32	18-8 Cr-Ni Steel A	108	Plain	Variable	Bending	Strain	R = -1	0.5	$10^2 - 10^4$
"	18-8 Cr-Ni Steel B	102	"	"	"	"	"	"	" "
"	13% Cr Steel A	77	"	"	"	"	"	"	" "
"	Cr-Mo Steel A	112	"	"	"	"	"	"	" "
"	Cr-Mo Steel B	122	"	"	"	"	"	"	" "
33	Cold-rolled Steel(Annealed)	61	"	Rm.	"	Deform.	"	150—700	" "
37	17-7 PH Stainless Steel	205	Plain & Notched	"	Axial	Load	"		$1 - 10^8$
38	2024-T4 Aluminum Alloy	70	Plain	"	"	Load, True stress, true strain	R = 0, -1		$1 - 10^3$
39	24S-T Aluminum Alloy	72	"	"	"	Strain	R = -1		$1 - 10^1$
40, 41	Aluminum Alloy 5% Mg	48	"	"	Bending	"	"	(3 1/2 & 200—600)	$10 - 10^7$
41	" " DTD 546B	57	"	"	"	"	"	"	" "
"	Steel S 92	107	"	"	"	"	"	"	" "
"	Steel En 2	69	"	"	"	"	"	"	" "
"	Steel En 25	132	"	"	"	"	"	"	" "
44	Type A Nickel		"	525 F	Axial	Load	"	1	$10^4 - 10^5$
"	" " "		"	Variable	"	Temp.	T_m = 525 F	2	" "
"	Type Ti-75A Titanium		"	575 F	"	Load	R = -1	1	$10^3 - 10^4$
"	" " " "		"	Variable	"	Temp.	T_m = 575 F	2	" "
47	SAE 1018 Steel		"	Rm.	Torsion	Strain	R = -1		$10 - 10^2$
48	347 Stainless Steel		"	1000 F	Axial	Load	R = -1	140	$10^2 - 10^5$
49	Aluminum Alloy 7075-T6	84	Notched	Rm.	Torsion	Strain	"		$10 - 10^3$
50	Cast DCM Alloy(Hardness RC40)		Plain	Variable	Axial	Temp.	"		$1 - 10^5$
"	Cast Udimet 500 Alloy(Hardness RC36)		"	"	"	"	"		$10 - 10^5$
51	Tricent (Inco)		(Plain & Notched)	Rm.	"	Load	"		$10^2 - 10^6$
"	Cru. UHS-260		"	"	"	"	"		" "
"	Super TM-2		"	"	"	"	"		" "
52	Gray Cast Iron	(Comp)-95	Plain	"	"	"	R = ∞	290	$1 - 10^6$
53	SAE 2330 Steel	123	"	"	(Bending & Axial)	"	R = -1	90-3450	$10^3 - 10^8$
"	SAE 4340 Steel	175	"	"	"	"	"	"	
"	SAE 8630 Steel	126	"	"	"	"	"	"	
55	18-8 Stainless Steel		"	"	Bending	"	"	72	$10^2 - 10^5$
"	SAE 1020 Steel		"	"	"	"	"	"	" "

TEST INFORMATION ON LOW-CYCLE FATIGUE TESTING (Continued)

Ref. No.	Material	Ultimate Strength ksi	Type of Specimen	Test Temp.	Manner of Loading	Parameter Held Constant	Type of Cycle	Cyclic Rate cpm	Life Range
55	Commercial Copper		Plain	Rm.	Bending	Load	R = -1	72	$10^2 - 10^5$
"	2S Aluminum		"	"	"	"	"	"	" "
"	24 S-T Aluminum Alloy		"	"	"	"	"	"	" "
"	Mild Steel (hot rolled)		"	"	"	"	"	"	" "
"	Gray Cast Iron		"	"	"	"	"	"	" "
"	Copper (annealed)		"	"	"	"	"	"	" "
"	Mild Steel (annealed)		"	"	"	"	"	"	" "
56	2024-T3 Aluminum Alloy	69	(Plain & Notched)	"	Axial	"	R = 0	10(max.)	$1 - 10^4$
"	" " "	"	Plain	"	"	Strain	Variable (R=-1 to 0.75)		$1 - 10^3$
57, 58	2024-T4 Aluminum Alloy	68	"	"	Bending	"	R = -1 to 0.2		$10^1 - 10^4$
	5454-0 Aluminum	36	"	Rm. to 400 F	"	"	R = -1 to 0.88		$10^1 - 10^4$
	A-302 Steel	107	"	Rm. to 800 F	"	"	R = -1 to 0.88		$10^2 - 10^4$
59	SAE 4340 (Temp. at 400 - 800 F)	290 to 210	(Plain & Notched)	Rm.	"	Load	R = -1	10 & 250	$10^{-1} - 10^5$
"	" " " " " "	"	"	"	Axial	"	"	1800	" "
60	" " " " "	"	"	"	Bending	"	R = -1	$.3 - 10^4$	$1 - 10^5$
61	24S-T3 Aluminum Alloy	74	Plain	"	Axial	"	"	$12 \& 10^3$	$10^2 - 10^7$
"	Alclad 24S-T3 Al. Alloy	67	"	"	"	"	"	"	" "
62	2014-T3 Aluminum Alloy		Compressor Rotor	"	Spinning	Burst Speed	R = 0		$10^{-1} - 10^5$
63	2S Aluminum (annealed)		Plain	"	Axial	Strain	R = -1		$10^{-1} - 10^4$
"	" " (as-received)		"	"	"	"	"		" "
"	" " (Prestrained)		"	"	"	"	"		" "
"	OFHC Copper (annealed)		"	"	"	"	"		" "
"	" " (as-received)		"	"	"	"	"		" "
"	Low Carbon Steel (annealed)		"	"	"	"	"		" "
"	Nickel A (annealed)		"	"	"	"	"		" "
"	347 Stainless Steel		"	"	"	"	"		" "
"	24S-T Aluminum Alloy		"	"	"	"	"		" "
64	A-201 Steel	60	Welded	500 F & Rm	Bending	Load	"	100—400	$10^3 - 10^5$
"	A-285 Steel	58	"		"	"	"	"	" "
65	SAE 4340 Bar	216	Plain	Rm.	Axial	"	R = 0	50	$10^{-1} - 10^7$
"	SAE 4337 Sheet	211	"	"	Bending	"	"	35	" "
"	SAE 4140 Billet	194	"	"	Axial	"	"	50	" "
"	SAE 4140 Bar	195	"	"	"	"	"	"	" "
66	Forged Steel	99	Notched	"	Axial & Bending	"	"		$1 - 10^4$

$G = \frac{\sigma^2 b}{E} \tan\left(\frac{\pi a}{b}\right)$

(see Ref. 4)

$R = \frac{\text{Minimum Value of the Parameter}}{\text{Maximum Value of the Parameter}}$

ϵ_m = Mean Strain

T_m = Mean Temperature

S_m = Mean Stress

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