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Technical Report on Low Cycle Fatigue Properties
Ferrous and Non-Ferrous Materials

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1. **Scope**—Information that provides design guidance in avoiding fatigue failures is outlined in this SAE Information Report. Of necessity, this report is brief, but it does provide a basis for approaching complex fatigue problems. Information presented here can be used in preliminary design estimates of fatigue life, the selection of materials and the analysis of service load and/or strain data. The data presented are for the “low cycle” or strain-controlled methods for predicting fatigue behavior. Note that these methods may not be appropriate for materials with internal defects, such as cast irons, which exhibit different tension and compression stress-strain behavior.

2. References

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated, the latest revision of SAE publications shall apply.

1. Mitchell, M. R., *Fundamentals of Modern Fatigue Analysis for Design*, ASM, Vol. 19, Fatigue and Fracture, 1997.
2. Annual Book of ASTM Standards, Metals—Mechanical Testing: Elevated and Low Temperature Tests; Metallography, Standard E 606-80, "Constant-Amplitude Low-Cycle Fatigue Testing," Vol. 3.01, American Society for Testing and Materials, West Conshohocken, PA, 1996.
3. Dowling, N.E., *Mechanical Behavior of Materials; Engineering Methods for Deformation, Fracture, and Fatigue*, Prentice-Hall, 1993.
4. Chernenkoff, R.A., Editor, *Fatigue Research and Applications*, SP-1009, Society of Automotive Engineers, Warrendale, PA, 1993.
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7. Wetzel, R. M., Editor, *Fatigue Under Complex Loadings: Analysis and Experiments*, AE-6, Society of Automotive Engineers, Warrendale, PA, 1977.
8. Bannantine, J., Comer, J., and Handrock, J., *Fundamentals of Metal Fatigue Analysis*, Prentice-Hall, 1989.
9. *Multiaxial Fatigue; Analysis and Experiments*, AE-14, Society of Automotive Engineers, Warrendale, PA, 1989.
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14. Gallagher, J. P., "What the Designer Should Know About Fracture Mechanics Fundamentals," Paper 710151 presented at SAE Automotive Engineering Congress, Detroit, January 1971.
15. Sinclair, G. M., "What the Designer Should Know About Fracture Mechanics Testing," Paper 710152 presented at SAE Automotive Engineering Congress, January 1971.
16. Ripling, E. J., "How Fracture Mechanics Can Help the Designer," Paper 710153 presented at SAE Automotive Engineering Congress, Detroit, January 1971.
17. Campbell, J. E., Berry, W. E., and Feddersen, C. E., "Damage Tolerant Design Handbook," MCIC HB-01, Metal and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, OH.
18. Jaske, C. E., Feddersen, C. E., Davies, K. B., Rice, R. C., "Analysis of Fatigue, Fatigue Crack Propagation and Fracture Data," NASA CR-132332, Battelle Columbus Laboratories, Columbus, OH, November 1973.
19. Moore, T. D., "Structural Alloys Handbook," Mechanical Properties Data Center, BelFour Stulen, Inc., Traverse City, MI.
20. Wolf, J., Brown, W. F., Jr., "Aerospace Structural Metals Handbook," Vol. 1-4, Mechanical Properties Data Center, BelFour Stulen, Inc., Traverse City, MI.
21. Raske, D. T., "Review of Methods for Relating the Fatigue Notch Factor to the Theoretical Stress Concentration Factor, Simulation of the Fatigue Behavior of the Notch Root in Spectrum Loaded Notched Members," Chapter II, TAM Report No. 333--Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, January 1970.
22. Topper, T. H., Wetzel, R. M. and Morrow, JoDean, "Neuber's Rule Applied to Fatigue of Notched Specimens," *Journal of Materials*, ASTM, Vol. 4, No. 1, March 1969, pp. 200-209.

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25. Morrow, JoDean, "Cyclic Plastic Strain Energy and Fatigue of Metals," Internal Friction, Damping, and Cyclic Plasticity, ASTM STP 378, American Society for Testing and Materials, 1965, pp 45-87.
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27. Annual Book of ASTM Standards, Metals—Mechanical Testing; Elevated and Low Temperature Tests; Metallography, Standard E 739-91, "Statistical Analysis of Linear or Linearized Stress-Life and Strain-Life Fatigue Data," Vol. 3.01, American Society for Testing and Materials, West Conshohocken, PA, 1995.

3. Material Property Tables—Tables 2 to 4 list the monotonic and cyclic stress-strain properties and the fatigue properties for selected materials. These tables are preceded by a brief introduction, definitions, discussion, and Table 1 which lists the abbreviations used in this document.

The majority of the properties listed in the Tables have been contributed by members of the SAE Fatigue, Design, and Evaluation Committee and are the property of SAE International, Warrendale, PA, 15096. Researchers are encouraged to contribute their data and may do so by contacting the Fatigue Design and Evaluation Committee through the SAE.

For several materials commonly used in the as-received condition, there are numerous data sets available. These have been reported as a single value or a range and are identified as to which data were involved. As defined, these properties are from specimens tested in ambient environments and, therefore, do not include such influences as environmental effects (wet or corrosive conditions, elevated temperature, etc.), surface roughness effects, mean stress effects, notch effects, etc.

There are many procedures for using this information for design purposes. They are too lengthy to be included in this report; however, there are a number of publications which discuss these procedures. Several key references [1-27] that discuss fatigue properties, methods for determining fatigue properties, and illustrate the use of these data for making design decision are listed in Section 2.

4. Monotonic Stress-Strain Properties

4.1 Monotonic stress-strain properties are generally determined by testing a smooth polished specimen under axial loading. The load, diameter and/or strain on the uniform test section is measured during the test in order to determine the materials stress-strain response as illustrated in Figures 1 and 2. Properties, most of which are discrete points on the stress-strain curve, can be defined to describe the behavior of a material.

4.2 Ultimate Tensile Strength (Su)—The engineering stress at maximum load. In a ductile material, it occurs at the onset of necking in the specimen.

$$S_u = P_{\max} / A_o \quad (\text{Eq. 1})$$

where:

$P_{\max}$ = maximum load

A_o = original cross sectional area

4.3 True Fracture Strength (σ_f)—The “true” tensile stress required to cause fracture.

$$\sigma_f = P_f / A_f \quad (\text{Eq. 2})$$

where:

P_f = load at failure

A_f = minimum cross sectional area after failure

The value σ_f must be corrected for the effect of triaxial stress present due to necking. One such correction suggested by Bridgeman [11] is illustrated in Figure 3. In this figure, the ratio of the corrected value to the uncorrected value ($\sigma_f / (P_f / A_f)$) is plotted against true tensile strain.

4.4 Tensile Yield Strength (S_{ys} , σ_{ys})—The stress to cause a specified amount of inelastic strain, usually 0.2%. It is usually determined by constructing a line of slope E (modulus of elasticity) through 0.2% strain and zero stress. The stress where the constructed line intercepts the stress-strain curve is taken as the yield strength.

4.5 Percentage Reduction of Area (% RA)—The percentage of reduction in cross sectional area after fracture.

$$\%RA = 100(A_0 - A_f / A_0) \quad (\text{Eq. 3})$$

4.6 True Fracture Ductility (ϵ_f)—The “true” plastic strain after fracture.

$$\epsilon_f = \ln(A_0 / A_f) = \ln(100 / (100 - \%RA)) \quad (\text{Eq. 4})$$

4.7 Monotonic Strain Hardening Exponent (n)—The power to which the “true” plastic strain must be raised to be directly proportional to the “true” stress. It is generally taken as the slope of $\log \sigma$ versus $\log \epsilon_p$ plot as shown in Figure 2.

$$\sigma = K \epsilon_p^n \quad (\text{Eq. 5})$$

4.8 Monotonic Strength Coefficient (K)—The “true” stress at a “true” plastic strain of unity as shown in Figure 2. If the value of the true fracture ductility is less than 1.0, it is necessary to extrapolate. (see Equation 5).

4.8.1 Monotonic tension properties of a material can be classed into two groups, engineering stress-strain properties and “true” stress-strain properties. Engineering properties are associated with the original cross sectional area of the test specimen, and “true” values relate to actual area while the specimen is under load. The difference between “true” and engineering values is insignificant in the low strain region, less than or equal to 2% strain.

4.8.2 Until the test bar begins to locally neck, some simple relationships exist between engineering and “true” stress-strain values. Equation 6 gives the relationship between engineering and true strain.

$$\epsilon = \ln(1 + e) \quad (\text{Eq. 6})$$

where:

ϵ = “true” strain

e = engineering strain

Similarly, Equation 7 relates true stress to engineering stress.

$$\sigma = S(1 + e) \quad (\text{Eq. 7})$$

where:

σ = "true" stress

S = engineering stress

These relationships do not apply after onset of necking.

4.8.2.1 A more detailed discussion and derivation of monotonic stress-strain properties can be found in ASTM STP 465 [12]. Figures 1 and 2 graphically illustrate a majority of these properties.

5. *Cyclic Stress-Strain Properties*

5.1 Cyclic stress-strain properties are determined by testing smooth polished specimens under axial cyclic strain control conditions. The cyclic stress-strain curve is defined as the locus of tips of stable "true" stress-strain hysteresis loops each obtained from a constant amplitude test specimen. A typical stable hysteresis loop is illustrated in Figure 4 and a set of stable loops with a cyclic stress-strain curve down through the loop tips is illustrated in Figure 5. As illustrated, the height of the loop from tip-to-tip is defined as the stress range. For completely reversed testing, one-half of the stress range is generally equal to the stress amplitude while one-half of the width from tip-to-tip is defined as the strain amplitude. Plastic strain amplitude is found by subtracting the elastic strain amplitude from the strain amplitude as indicated in Equations 8, 9, and 10.

$$\Delta\epsilon_p/2 = \Delta\epsilon/2 - \Delta\epsilon_e/2 \quad (\text{Eq. 8})$$

According to Hooke's law,

$$\Delta\epsilon_e/2 = \Delta\sigma/2E \quad (\text{Eq. 9})$$

where:

E = modulus of elasticity

$$\Delta\epsilon_p/2 = \Delta\epsilon/2 - \Delta\sigma/2E \quad (\text{Eq. 10})$$

5.2 A more complete discussion of the cyclic stress-strain curve and other methods of obtaining the curve are given in STP 465 [12] and [4].

5.3 **Cyclic Yield Strength (0.2% σ_{ys})**—The stress to cause 0.2% inelastic strain as measured on a cyclic stress-strain curve. It is usually determined by constructing a line parallel to the slope of the cyclic stress-strain curve at zero stress through 0.2% strain. The stress where the constructed line intercepts the cyclic stress-strain curve is taken as the 0.2% cyclic yield strength.

5.4 **Cyclic Strain Hardening Exponent (n')**—The power to which "true" plastic strain amplitude must be raised to be directly proportional to "true" stress amplitude. It is taken as the slope of the log $\Delta\sigma/2$ versus log $\Delta\epsilon_p/2$ plot, where $\Delta\sigma/2$ and $\Delta\epsilon_p/2$ are measured from cyclically stable hysteresis loops.

$$(\Delta\sigma)/2 = K'(\Delta\epsilon_p/2)^{n'} \quad (\text{Eq. 11})$$

where:

$\Delta\epsilon_p/2$ = "true" plastic strain amplitude

The line defined by this equation is illustrated in Figure 6.

5.5 Cyclic Strength Coefficient (K')—The “true” stress at a “true” plastic strain of unity in Equation 11. It may be necessary to extrapolate as indicated in Figure 6.

5.5.1 Stress-strain response of some materials can change significantly when subjected to inelastic strains such as can occur nominally or at notch roots due to cyclic loading. When fatigue failure occurs, particularly low cycle fatigue, such inelastic straining is present. Hence, the cyclic stress-strain curve best represents the materials stress-strain response rather than the monotonic stress-strain curve.

5.5.2 In many field test situations, it may be desirable to convert measured strains to stress in order to estimate fatigue life. The cyclic stress-strain curve can be described with an equation using the cyclic properties. Equation 10 can be rewritten by rearranging the terms as shown in Equation 12.

$$\Delta\epsilon/2 = \Delta\sigma/2E + \Delta\epsilon_p/2 \quad (\text{Eq. 12})$$

Rearranging the terms in Equation 11 indicates the relationship between plastic strain amplitude and stress amplitude.

$$\Delta\epsilon_p/2 = (\Delta\sigma/2K')^{1/n'} \quad (\text{Eq. 13})$$

Substituting Equation 13 into Equation 12 yields an equation relating cyclic strain amplitude to cyclic stress amplitude in terms of the previously defined properties and the modulus of elasticity.

$$\Delta\epsilon/2 = \Delta\sigma/2E + (\Delta\sigma/2K')^{1/n'} \quad (\text{Eq. 14})$$

5.5.3 For a more detailed discussion see STP 465 [12].

6. Fatigue Properties

6.1 Fatigue resistance of materials can be described in terms of the number of constant amplitude stress or strain reversals required to cause failure. The properties defined in this section are determined on smooth polished axial specimens tested under strain control. Stress amplitude, elastic and plastic strain amplitude and total strain amplitude can each be plotted against reversals to failure. The plot of log “true” plastic strain amplitude and log “true” stress amplitude versus log reversals to failure are typically straight lines as illustrated in Figures 7 and 8. The intercept at one reversal and the slope of these straight lines can be described as fatigue parameters.

6.2 Fatigue Ductility Exponent (c)—The power to which the life in reversals, $2N_f$, is raised to be directly proportional to the “true” plastic strain amplitude. It is taken as the slope of the log ($\Delta\epsilon_p/2$) versus log ($2N_f$) plot.

6.3 Fatigue Ductility Coefficient (ϵ_f')—The “true” plastic strain required to cause failure in one reversal. It is taken as the intercept of the log ($\Delta\epsilon_p/2$) versus log ($2N_f$) plot at $2N_f = 1$.

6.4 Fatigue Strength Exponent (b)—The power to which life in reversals must be raised to be directly proportional to “true” stress amplitude. It is taken as the slope of the log ($\Delta\sigma/2$) versus log ($2N_f$) plot.

6.5 Fatigue Strength Coefficient (σ_f')—The “true” stress required to cause failure in one reversal. It is taken as the intercept of the log ($\Delta\sigma/2$) versus log ($2N_f$) plot at $2N_f = 1$.

6.6 Transition Fatigue Life ($2N_t$)—The life where elastic and plastic components of the total strain are equal. It is the life at which the plastic and elastic strain-life lines cross.

- 6.7** A materials resistance to strain cycling can be considered as the summation of the elastic and plastic resistance as indicated by Equation 15.

$$\Delta\epsilon/2 = (\Delta\epsilon_e/2) + (\Delta\epsilon_p/2) \quad (\text{Eq. 15})$$

An equation of the “true” plastic strain-life relationship can be written in terms of the previous fatigue properties (Figure 8).

$$\Delta\epsilon_p/2 = \epsilon_f'(2N_f)^c \quad (\text{Eq. 16})$$

where $2N_f$ is reversals to failure. The “true” elastic strain-life relationship is simply the stress-life relationship divided by the modulus of elasticity (Figure 7).

$$\Delta\epsilon_e/2 = (\sigma_f'/E)(2N_f)^b \quad (\text{Eq. 17})$$

Substituting Equations 16 and 17 into Equation 15 gives an equation between “true” strain amplitude and reversals to failure in terms of the fatigue parameters.

$$\Delta\epsilon/2 = (\sigma_f'/E)(2N_f)^b + \epsilon_f'(2N_f)^c \quad (\text{Eq. 18})$$

Equation 18 is illustrated in Figure 9.

Specimen failure may be defined several ways. Current definitions include complete separation, a change in hysteresis loop shape, and one of several percentage drop in stress. For several materials, the choice can effect the results. ASTM E 606 [2] should be consulted for current practice.

Sample geometry may have an effect on the fatigue results due to differences in surface residual stress, surface condition, gage length, and shape. Consult ASTM E 606 [2] for current practice.

A statistical treatment of these properties can be useful when making comparisons between materials or between many of the variables within a material grade. Numerous attempts have been made to describe these properties such that statistical lower limits for a specification could be determined. As yet, this has been somewhat less than successful. A more complete treatment of the procedures and sources of potential error may be found in ASTM E 739.

Estimating these fatigue properties, in the absence of test data, is not recommended: but, it is recognized that there will be times when the practitioner will require data and none will be available. As a first estimate, one might consider using data from a similar material in a similar condition at the same hardness or strength. A summary of estimating procedures and their use is included in Reference 6.

TABLE 1—ABBREVIATIONS

Abbreviation	Full-Term
HR	Hot-Rolled
CC	Continuous Casting
IC	Ingot Casting
SH	Sheet
CR	Cold Rolled
CD	Cold Drawn
MOD	Modified
BA	Batch Annealed
GA	Galvannealed
HT	Heat Treated
HDG	Hot-Dip Galvanized
ANN	Annealed
Norm.	Normalized
Q&T	Quenched & Tempered
As-rec.	As Received
UTS	Ultimate Tensile Strength
RA	% Reduction in Area
K	Strength Coefficient
n	Strain Hardening Exponent
E	Modulus of Elasticity
σ_f'	Fatigue Strength Coefficient
b	Fatigue Strength Exponent
ε_f'	Fatigue Ductility Coefficient
C	Fatigue Ductility Exponent
K	Cyclic Strength Coefficient
n	Cyclic Strain Hardening Exponent