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

Foreword—Designing a component to avoid fatigue failure is one of the more important, yet difficult, tasks an engineer faces. Many factors are involved and the relationships between these factors are developed largely through empiricism. Fatigue failure is caused by repeated loading with the number of loading cycles to failure being dependent upon the load range.

Designing to avoid fatigue failure requires knowledge of the following:

a. The expected load-time history (the local strain-time and stress-time history at the most critical locations).
b. The geometry of the component and areas of stress concentration (geometrical, metallurgical, surface finish, manufacturing variability, etc.)
c. The nature of the environment in which the component is operated (wet, dry, corrosive, temperature, etc.)
d. The properties of the material as it exists in the finished component at the most critically stressed locations (“inherent” fatigue properties, residual stress effects, surface effects, sensitivity to corrosion, “cleanliness,” variability, etc.)

Variability in fatigue life is another aspect of fatigue life evaluation and prediction that must be considered. This often calls for statistical analysis. Circumstances dictate the degree of sophistication required in all aspects of an evaluation or prediction.

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.

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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.

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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.
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15. Sinclair, G. M., "What the Designer Should Know About Fracture Mechanics Testing," Paper 710152 presented at SAE Automotive Engineering Congress, January 1971.
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19. Moore, T. D., "Structural Alloys Handbook," Mechanical Properties Data Center, BelFour Stulen, Inc., Traverse City, MI.
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21. Raske, D. T., "Review of Methods for Relating the Fatigue Notch Factor to the Theoretical Stresss 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.
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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.

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

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.

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

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

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

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 σ versus log ε_p plot as shown in Figure 2.

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

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.

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

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.

$$\Delta\varepsilon_p/2 = \Delta\varepsilon/2 - \Delta\varepsilon_e/2 \quad \text{(Eq. 8)}$$

According to Hooke's law,

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

where:

E = modulus of elasticity

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

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 $\Delta\varepsilon_p/2$ plot, where $\Delta\sigma/2$ and $\Delta\varepsilon_p/2$ are measured from cyclically stable hysteresis loops.

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

where:

$\Delta\varepsilon_p/2$ = "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.

$$\Delta\varepsilon/2 = \Delta\sigma/2E + \Delta\varepsilon_p/2 \qquad \text{(Eq. 12)}$$

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

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

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.

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

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 ($\Delta\varepsilon_p/2$) 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 ($\Delta\varepsilon_p/2$) 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.

$$\Delta\varepsilon/2 = (\Delta\varepsilon_e/2) + (\Delta\varepsilon_p/2) \quad \text{(Eq. 15)}$$

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

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

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).

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

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.

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

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 in 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

TABLE 2A—STEEL—MONOTONIC PROPERTIES

Material	Material Condition	Test Condition	BHN	Yield—0.2% (MPa)	UTS (MPa)	RA %	K (MPa)	n	E (GPa)
1004	HR,CC	As-rec.		287	378				
1004	HR,CC			472	490				
1005	HR,IC	As-rec.		226	321				
1005	HR,IC	As-rec.		234	356				
1005	HR,IC	As-rec.		245	323				
1005	HR,IC	As-rec.		267	359				
1008	HR,CC	As-rec.		252	363				
1008	HR,CC	As-rec.		273	399				
1008	HR,CC			381	392				
1008	HR,CC			424	433				
1008	HR,SH	As-rec.	86	234	331	77.5		0.190	207
1008	HR,SH	As-rec.	90	255	365	77.9		0.184	203
1010	HR,SH	As-rec.		200	331	80.4	534	0.185	203
1010	HR,SH	As-rec.							203
1010	HR,SH								203
1015	HR,SH	Norm.	80	228	414	68			207
1020	HR,SH	As-rec.	109	262	441	61.8	738	0.190	203
1020	CR,SH	As-rec.	108	255	393	64	400	0.072	186
1025	HR,SH	As-rec.		306	547	62.6	1142	0.281	207
1035	HR,Bar	As-rec.		443	641				
1035	HR,Bar	As-rec.		448	623				
1040	CD,Bar	As-rec.		637	759				
10V40	HR,Bar	As-rec.		572	802				
1045	CD	Annealed	225	517	752	44			
1045		Q&T	500	1689	1827	51		0.047	207
1045	HR,Bar	Q&T	595	1862	2241	41		0.071	207
1045	HR,Bar	Norm.	192	424	718	48			
1045	HR,Bar	HT	277	620	942	39			
1045	HR,Bar	HT	336	787	1322	21			
1045	HR,Bar	HT	410	865	1516	6			
1045	HR,Bar	HT	563	1636	2297	18			
1045	HR,Bar	HT	500	1729	1956	38.3	2352	0.041	207
1045	HR,Bar	HT	390	1275	1344	59		0.044	207
10B21		HT	318	999	1048	67.6	1295	0.054	197
10B21		HT	255	806	834				203
10B22		HT	255	806	834				203
15B27		HT	250	772	847	69		0.075	203

TABLE 2A—STEEL—MONOTONIC PROPERTIES

Material	Material Condition	Test Condition	BHN	Yield—0.2% (MPa)	UTS (MPa)	RA %	K (MPa)	n	E (GPa)
15B27		HT	264	854	916	66.5		0.065	203
94B30		HT	285	799	896	63	1378	0.062	200
HF 50	HR	As-rec.		342	416				
HF 50	HR	As-rec.		359	442				
HF 50	HR	As-rec.		361	441				
HF 50	HR	As-rec.		375	461				
HF 50	HR	As-rec.		383	448				
HF 50	HR	As-rec.		385	448				
HF 50	HR	As-rec.		403	479				
HF 50	HR	As-rec.		417	492				
HF 50	HR	As-rec.		428	474				
HF 60	HR	As-rec.		416	481				
HF 60	HR	As-rec.		431	479				
HF 60	HR	As-rec.		434	525				
HF 60	HR	As-rec.		456	534				
HF 60	HR	As-rec.		459	533				
HF 60	HR	As-rec.		466	558				
HF 70	HR	As-rec.		505	570				
HF 70	HR	As-rec.		521	628				
HF 80	HR	As-rec.		557	617				
HF 80	HR	As-rec.		569	697				
HF 80	HR	As-rec.		579	756				
HF 80	HR	As-rec.		580	654				
HF 80	HR	As-rec.		581	645				
HF 80	HR	As-rec.		585	635				
HF 80	HR	As-rec.		596	657				
HF 80	HR	As-rec.		605	681				
HF 80	HR	As-rec.		642	719				
HF 80	HR			710	711				
DDQ+	CR,BA	As-rec.		152	306				
DQSK	CR,BA	As-rec.		171	307				
HF 40	CR,BA	As-rec.		279	370				
HF 50	CR,BA	As-rec.		357	490				
HF 50	CR,BA	As-rec.		439	496				
50Y60T	CR,CA	As-rec.		417	554				
80Y90T	CR,CA	As-rec.		603	747				
DDQ+	GA	As-rec.		140	292				
DDQ+	HDG	As-rec.		179	303				
DDQ	HA	As-rec.		150	279				
DQSK	HDG	As-rec.		185	321				

TABLE 2A—STEEL—MONOTONIC PROPERTIES

Material	Material Condition	Test Condition	BHN	Yield—0.2% (MPa)	UTS (MPa)	RA %	K (MPa)	n	E (GPa)
CQ	HDG	As-rec.		314	352				
HF 60	HDG	As-rec.		424	501				
4130	HT		366	1358	1427	54.7			200
4130	HT		259	778	896	67.3			221
4140	HT		293	848	938		1303	0.094	207
4140	HT		475	1895	2033	20.0			200
4142	HT		400	1447	1551	47.0		0.032	200
4142	HT		450	1860	1929	37.0		0.016	200
4142	HT		380	1378	1413	48.0		0.051	207
4142	HT		670	1619	2446	6.0		0.136	200
4142	HT		450	1584	1757	42.0		0.043	207
4142	HT		475	1722	1929	35.0		0.048	207
4340	HT		409	1371	1468	38.1			200
4340	HT		275	834	1048				190
4340	HR		243	634	827	43.4			193
4340	HT			1102	1171	56	1358	0.036	207
5160	HT		430	1488	1584	39.7	1941	0.0463	203
5160	MOD			1565	1755				
51V45				1871	2108				
52100	HT		519	1922	2912	11.2			207
	Cast Steel								
0030	Cast		137	303	496	46			207
0050A	Cast		192	415	787	19			209
	Cast		174	402	583	26			209
	Cast		206	542	702				211
8630	Cast		305	985	1144	29			207

TABLE 2B—STEEL CYCLIC PROPERTIES

Material	Material Condition	Test Condition	BHN	σ_f' (MPa)	b	ε_f'	c	K′ (MPa)	n′	Data Points
1004	HR,CC	As-rec.		1159	–0.142	1.300	–0.649	781-x	0.180-x	
1004	HR,CC			1019	–0.124	1.450	–0.701	561-x	0.180-x	
1005	HR,IC	As-rec.		888	–0.137	0.280	–0.505	1208-x	0.260-x	
1005	HR,IC	As-rec.		878	–0.129	0.460	–0.536	834-x	0.200-x	
1005	HR,IC	As-rec.		1024	–0.151	0.290	–0.509	1254-x	0.270-x	
1005	HR,IC	As-rec.		776	–0.126	0.240	–0.466	626-x	0.170-x	
1008	HR,CC	As-rec.		1225	–0.143	0.350	–0.522	1706-x	0.240-x	
1008	HR,CC	As-rec.		1016	–0.136	0.210	–0.473	958-x	0.220-x	
1008	HR,CC			2012	–0.195	1.050		687-x	0.160-x	
1008	HR,CC			1069	–0.126	0.940		605-x	0.130-x	
1008	HR,SH	As-rec.	86	1124	–0.172	0.460	–0.543	1443-c	0.318-c	16
1008	HR,SH	As-rec.	90	1007	–0.159	0.500	–0.5402	1234-c	0.290-c	51
1010	HR,SH	As-rec.		499	–0.100	0.104	–0.408	867-c	0.244-c	18
1010	HR,SH	As-rec.		634	–0.109	0.145	–0.426	1040-c	0.256-c	39
1010	HR,SH			888	–0.148	0.408	–0.521	1145-c	0.284-c	51
1015	HR,SH	Norm.	80	884	–0.124	0.729	–0.581	945-c	0.213-c	31
1020	HR,SH	As-rec.	109	1384	–0.156	0.337	–0.485	1962-c	0.321-c	12
1020	CR,SH	As-rec.	108	697	–0.116	0.136	–0.405	1233-c	0.286-c	8
1025	HR,SH	As-rec.		934	–0.107	0.590	–0.520	1042-c	0.207-c	9
1035	HR,Bar	As-rec.		2034	–0.172	3.670	–0.860	865-x	0.140-x	
1035	HR,Bar	As-rec.		1491	–0.152	1.560	–0.729	838-x	0.090-x	
1040	CD,Bar	As-rec.		1311	–0.103	0.848	–0.612	915-x	0.131-x	
10V40	HR,Bar	As-rec.		1287	–0.092	0.316	–0.577	1371-x	0.150-x	
1045	CD	Annealed	225	916	–0.079	0.486	–0.520	1022-c	0.152-c	
1045		Q&T	500	2661	–0.093	0.196	–0.643	3371-c	0.145-c	9
1045	HR,Bar	Q&T	595	3294	–0.104	0.220	–0.868	3947-c	0.120-c	9
1045	HR,Bar	Norm.	192	1439	–0.127	0.525	–0.522	1401-c	0.212-c	
1045	HR,Bar	HT	277	2906	–0.161	0.786	–0.579	1770-c	0.191-c	
1045	HR,Bar	HT	336	3403	–0.151	0.458	–0.560	2066-c	0.165-c	
1045	HR,Bar	HT	410	4385	–0.167	0.491	–0.491	3048-c	0.208-c	
1045	HR,Bar	HT	563	5813	–0.154	1.379	–1.082	3083-c	0.075-c	
1045	HR,Bar	HT	500	2636	–0.086	0.210	–0.551	3366-c	0.157-c	9
1045	HR,Bar	HT	390	1785	–0.086	1.207	–0.825	1751-c	0.104-c	10
10B21		HT	318	1204	–0.063	3.709	–0.832	1089-c	0.076-c	8
10B21		HT	255	922	–0.063	2.377	–0.753	858-c	0.083-c	11
10B22		HT	255	841	–0.043	1.928	–0.738	809-c	0.058-c	11

NOTE— x = experimental—from raw data
c = calculated—$K' = \sigma_f'/(\varepsilon_f')^{n'}$—$n' = b/c$

TABLE 2B—STEEL CYCLIC PROPERTIES

Material	Material Condition	Test Condition	BHN	σ_f' (MPa)	b	ε_f'	c	K′ (MPa)	n′	Data Points
15B27		HT	250	938	–0.057	1.689	–0.784	903-c	0.072-c	6
15B27		HT	264	1062	–0.059	1.575	–0.782	1026-c	0.075-c	6
HF 50	HR	As-rec.		112	–0.117	0.940	–0.676	694-x	0.132-x	
HF 50	HR	As-rec.		686	–0.074	0.337	–0.540	761-x	0.129-x	
HF 50	HR	As-rec.		732	–0.09	1.384	–0.703	684-x	0.124-x	
HF 50	HR	As-rec.		889	–0.055	0.345	–0.563	632-x	0.092-x	
HF 50	HR	As-rec.		959	–0.102	3.189	–0.794	745-x	0.116-x	
HF 50	HR	As-rec.		1088	–0.116	2.828	–0.790	785-x	0.127-x	
HF 50	HR	As-rec.		1000	–0.102	0.563	–0.622	1014-x	0.151-x	
HF 50	HR	As-rec.		1218	–0.118	1.932	–0.771	1056-x	0.147-x	
HF 50	HR	As-rec.		1378	–0.143	3.091	–0.807	694-x	0.110-x	
HF 60	HR	As-rec.		895	–0.091	0.967	–0.750	687-x	0.094-x	
HF 60	HR	As-rec.		1113	–0.109	0.754	–0.670	1029-x	0.143-x	
HF 60	HR	As-rec.		1074	–0.105	0.429	–0.598	1152-x	0.163-x	
HF 60	HR	As-rec.		913	–0.091	0.226	–0.552	1134-x	0.161-x	
HF 60	HR	As-rec.		744	–0.063	0.451	–0.598	792-x	0.103-x	
HF 60	HR	As-rec.		976	–0.88	1.007	–0.705	876-x	0.106-x	
HF 70	HR	As-rec.		1461	–0.123	6.052	–0.904	937-x	0.101-x	
HF 70	HR	As-rec.		1230	–0.104	4.202	–0.843	1251-x	0.173-x	
HF 80	HR	As-rec.		1239	–0.108	1.053	–0.771	1125-x	0.122-x	
HF 80	HR	As-rec.		1428	–0.105	1.816	–0.861	1287-x	0.118-x	
HF 80	HR	As-rec.		2126	–0.152	3.217	–0.934	1389-x	0.133-x	
HF 80	HR	As-rec.		1145	–0.091	1.104	–0.717	1091-x	0.124-x	
HF 80	HR	As-rec.		1451	–0.113	5.289	–0.958	1122-x	0.170-x	
HF 80	HR	As-rec.		1379	–0.112	1.979	–0.820	984-x	0.100-x	
HF 80	HR	As-rec.		1512	–0.119	2.214	–0.826	981-x	0.096-x	
HF 80	HR	As-rec.		1818	–0.134	1.641	–0.830	1387-x	0.139-x	
HF 80	HR	As-rec.		2008	–0.131	7.185	–0.985	1285-x	0.115-x	
HF 80	HR	As-rec.		1704	–0.118	0.764	–0.670	1061-x	0.117-x	
DDQ+	CR,BA	As-rec.		607	–0.116	0.125	–0.437	832-x	0.234-x	
DQSK	CR,BA	As-rec.		591	–0.105	0.155	–0.450	694-x	0.196-x	
HF 40	CR,BA	As-rec.		753	–0.103	0.222	–0.477	596-x	0.134-x	
HF 50	CR,BA	As-rec.		536	–0.047	4.118	–0.883	481-x	0.049-x	
HF 50	CR,BA	As-rec.		571	–0.057	2.046	–0.787	516-x	0.64-x	
50Y60T	CR,CA	As-rec.		912	–0.095	0.127	–0.366	935-x	0.174-x	
80Y90T	CR,CA	As-rec.		2744	–0.173	0.448	–0.548	2221-x	0.267-x	
DDQ+	GA	As-rec.		430	–0.083	0.066	–0.430	641-x	0.201-x	
DDQ+	HDG	As-rec.		564	–0.103	0.122	–0.428	635-x	0.178-x	
DDQ	HA	As-rec.		545	–0.102	0.082	–0.388	1143-x	0.289-x	
DQSK	HDG	As-rec.		875	–0.134	0.142	–0.418	824-x	0.214-x	
CQ	HDG	As-rec.		561	–0.089	15.240	–0.956	419-x	0.088-x	

NOTE— x = experimental—from raw data
c = calculated—$K' = \sigma_f'/(\varepsilon_f')^{n'}$—$n' = b/c$

TABLE 2B—STEEL CYCLIC PROPERTIES

Material	Material Condition	Test Condition	BHN	σ_f' (MPa)	b	ε_f'	c	K′ (MPa)	n′	Data Points
HF 60	HDG	As-rec.		572	–0.053	20.116	–0.810	531-x	0.068-x	
4130	HT		366	1655	–0.076	0.803	–0.672	1696-c	0.114-c	14
4130	HT		259	1261	–0.077	0.985	–0.648	1264-c	0.119-c	21
4140	HT		293	1163	–0.062	2.360	–0.765	1084-c	0.082-c	18
4140	HT		475	1832	–0.070	0.400	–0.867	1974-c	0.081-c	10
4142	HT		400	1787	–0.084	1.195	–0.859	1756-c	0.098-c	10
4142	HT		450	2079	–0.086	2.620	–0.972	1910-c	0.088-c	9
4142	HT		380	2143	–0.094	0.637	–0.761	2266-c	0.124-c	8
4142	HT		670	2549	–0.078	0.003	–0.436	7119-c	0.179-c	10
4142	HT		450	1937	–0.076	0.706	–0.869	1997-c	0.088-c	10
4142	HT		475	2161	–0.081	0.331	–0.854	2399-c	0.094-c	7
4340	HT		409	1879	–0.0859	0.640	–0.636	1996-c	0.135-c	14
4340	HT		275	1276	–0.075	1.224	–0.714	1249-c	0.105-c	6
4340	HR		243	1198	–0.095	0.522	–0.563	1337-c	0.168-c	11
4340	HT			1165	–0.058	5.492	–0.850	1037-c	0.069-c	10
5160	HT		430	2054	–0.081	1.571	–0.821	1964-c	0.099-c	24
5160	MOD			3553	–0.125	11.532	–1.095	2065-x	0.089-x	
51V45				4585	–0.150	35.560	–1.442	2799-x	0.090-x	
52100	HT		519	2709	–0.096	0.243	–0.642	3348-c	0.150-c	16
	Cast Steel									
0030	Cast		137	655	–0.083	0.280	–0.552	738-c	0.136-c	
0050A	Cast		192	1338	–0.127	0.300	–0.569	1165-c	0.171-c	
	Cast		174	869	–0.101	0.150	–0.514	896-c	0.141-c	
	Cast		206	1117	–0.101	0.780	–0.729	786-c	0.960-c	
8630	Cast		305	1936	–0.121	0.420	–0.693	1502-c	0.122-c	

NOTE— x = experimental—from raw data

c = calculated—$K' = \sigma_f'/(\varepsilon_f')^{n'}$—$n' = b/c$

TABLE 3A—STAINLESS STEEL AND LIGHT NONFERROUS ALLOYS—MONOTONIC PROPERTIES

Material	Material Condition	Test Condition	BHN	Yield—0.2% (MPa)	UTS (MPa)	RA %	K (MPa)	n	E (GPa)
	Stainless Steel								
304	CD		327	744	951	68.8			172
304	ANN	As-rec.		276	572				190
310	ANN	As-rec.		230	592				144
310	ANN		142	221	641	63.5			193
	Aluminum								
1100	T6		26	97		87.6			69
2014	T6		255	461	510	25			69
5086				217					72
5182	O			116	279	60	318	0.119	75
5456	H311		95	234	400	34.6			69
6009	T4			103	226	60	256	0.112	74
6009	T6			259	301	59	351	0.03	66
A356	T6	Cast	93	229	283	5.7	388	0.083	70
A356	T6	Cast	93	224	266	3	397	0.087	70
A356	T6	Cast	89	181	268	8.5			69
	Cast Aluminum MMC								
A356	T6	Cast		280	318	3	585	0.107	102
	Cast Magnesium								
AZ91E	T6	Cast		142	318	12.8	639	0.137	45

TABLE 3B—STAINLESS STEEL AND LIGHT NONFERROUS ALLOYS—CYCLIC PROPERTIES

Material	Material Condition	Test Condition	BHN	σ_f' (MPa)	b	ε_f'	c	K′ (MPa)	n′	Data Points
	Stainless Steel									
304	CD		327	2047	–0.112	0.554	–0.635	2270-x	0.176-c	11
304	ANN	As-rec.		1267	–0.139	0.174	–0.415	2275-c	0.334-c	8
310	ANN	As-rec.		1036	–0.140	0.334	–0.465	1442-c	0.302-c	8
310	ANN		142	1660	–0.155	0.553	–0.553	1960-c	0.281-c	15
	Aluminum									
1100	T6		26	166	–0.096	1.643	–0.669	154-c	0.144-c	12
2014	T6		255	1008	–0.114	1.418	–0.870	963-c	0.132-c	12
5086				491	–0.081	0.118	–0.578	662-c	0.139-c	7
5182	O			768	–0.114	0.293	–0.592	974-c	0.193-c	10
5456	H311		95	826	–0.115	1.076	–0.797	817-c	0.145-c	11
6009	T4			571	–0.0983	0.924	–0.794	577-c	0.124-c	11
6009	T6			588	–0.0957	0.561	–0.746	633-c	0.128-c	12
A356	T6	Cast	93	594	–0.124	0.027	–0.530	379-x	0.043-c	
A356	T6	Cast	93	502	–0.119	0.017	–0.544	383-x	0.050-c	
A356	T6	Cast	89	491	–0.087	0.063	–0.540	372-x	0.044-c	
	Cast Aluminum MMC									
A356	T6	Cast		520	–0.104	0.019	–0.717	925-c	0.155-c	
	Cast Magnesium									
AZ91E	T6	Cast		831	–0.148	0.089	–0.451	552-c	0.184-c	

NOTE— x = experimental—from raw data
c = calculated—$K' = \sigma_f'/(\varepsilon_f')^{n'}$—$n' = b/c$

TABLE 4A—MISCELLANEOUS MATERIALS—MONOTONIC PROPERTIES—LIMITED DATA
Caution—no long life data points

Material	Material Condition	Test Condition	BHN	Yield—0.2% (MPa)	UTS (MPa)	RA %	K (MPa)	n	E (GPa)
1005	HR		86	236	356	81.2	617	0.214	207
1005	HR		86	245	323	68.9	536	0.191	207
1005	HR		86	225	321	73.4	549	0.207	207
1005	HR		86	267	359	70.2	602	0.19	207
1045		HT	450	1515	1584	55		0.041	207
4340		HT	350	1178	1240	57	1580	0.066	193
Maraging		HT	405	1482	1515	67		0.03	186
Maraging		HT	460	1791	1860	56		0.02	186
Maraging		HT		1903	1982				190
Maraging		HT	480	1929	1998	55		0.015	179
Copper				30	207				114
Incon 713		HT	336	813	1045				207
Incon 713		HT	344	788	928				207
Incon 718		Aged		1110	1304				204

Caution—no long life data points—10^2 to 10^5 data only

TABLE 4B—MISCELLANEOUS MATERIALS—CYCLIC PROPERTIES—LIMITED DATA

Material	Material Condition	Test Condition	BHN	σ_f' (MPa)	b	ε_f'	c	K′ (MPa)	n′	Data Points
1005	HR		86	832	–0.122	0.450	–0.534	999-c	0.229-c	12
1005	HR		86	872	–0.134	0.271	–0.503	1234-c	0.266-c	7
1005	HR		86	829	–0.129	0.246	–0.492	1199-c	0.263-c	7
1005	HR		86	483	–0.079	0.215	–0.450	631-c	0.174-c	15
1045		HT	450	1728	–0.060	0.934	–0.819	1737-c	0.073-c	9
4340		HT	350	1917	–0.099	1.122	–0.720	1887-x	0.137-x	8
Maraging		HT	405	2156	–0.083	0.417	–0.682	2399-c	0.122-c	7
Maraging		HT	460	2851	–0.094	2.627	–0.992	2602-c	0.095-c	7
Maraging		HT		2742	–0.087	10.188	–1.006	2245-c	0.086-c	7
Maraging		HT	480	3113	–0.102	2.331	–0.968	2847-c	0.106-c	9
Copper				564	–0.141	0.483	–0.535	683-c	0.263-c	6
Incon 713		HT	336	1319	–0.075	0.052	–0.560	1962-c	0.134-c	5
Incon 713		HT	344	1294	–0.065	0.034	–0.521	1969-c	0.124-c	5
Incon 718		Aged		2295	–0.100	3.637	–0.894	1986-c	0.112-c	12

Caution—no long life data points—10^2 to 10^5 data only

NOTE— x = experimental—from raw data
c = calculated—$K' = \sigma_f'/(\varepsilon_f')^{n'}$—$n' = b/c$

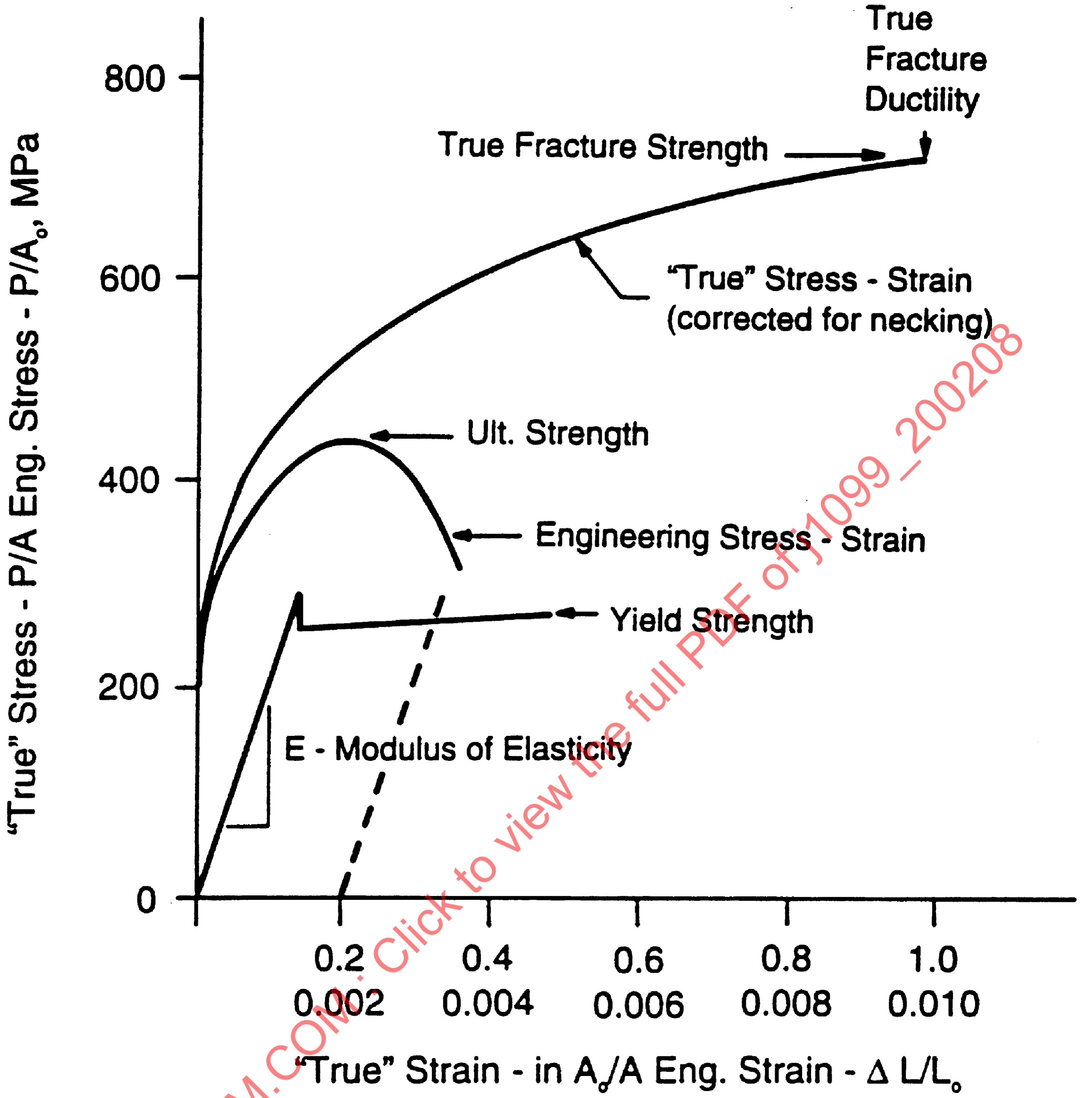

FIGURE 1—ENGINEERING AND "TRUE" STRESS-STRAIN PLOT

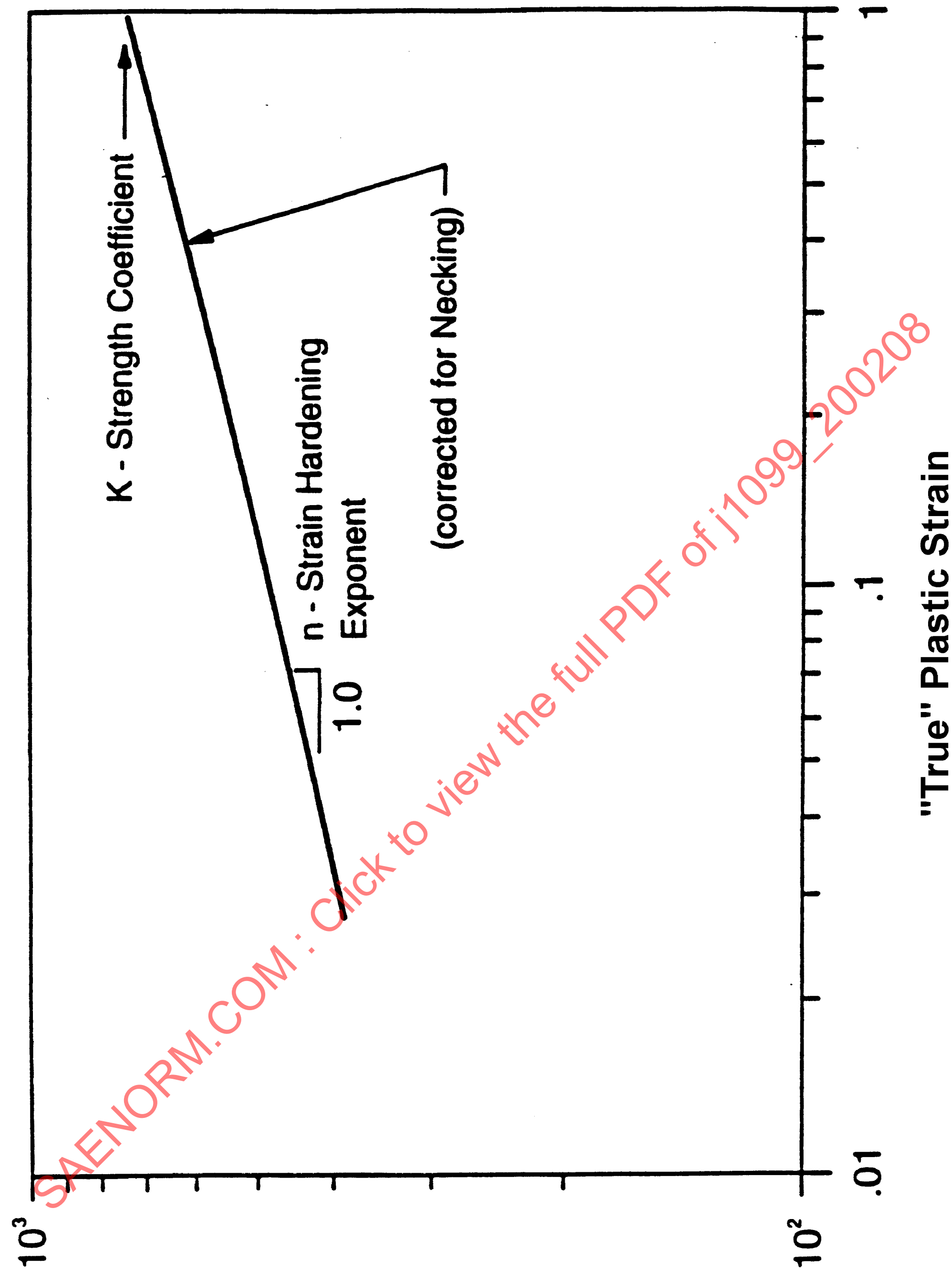

FIGURE 2—"TRUE" STRESS-PLASTIC STRAIN PLOT

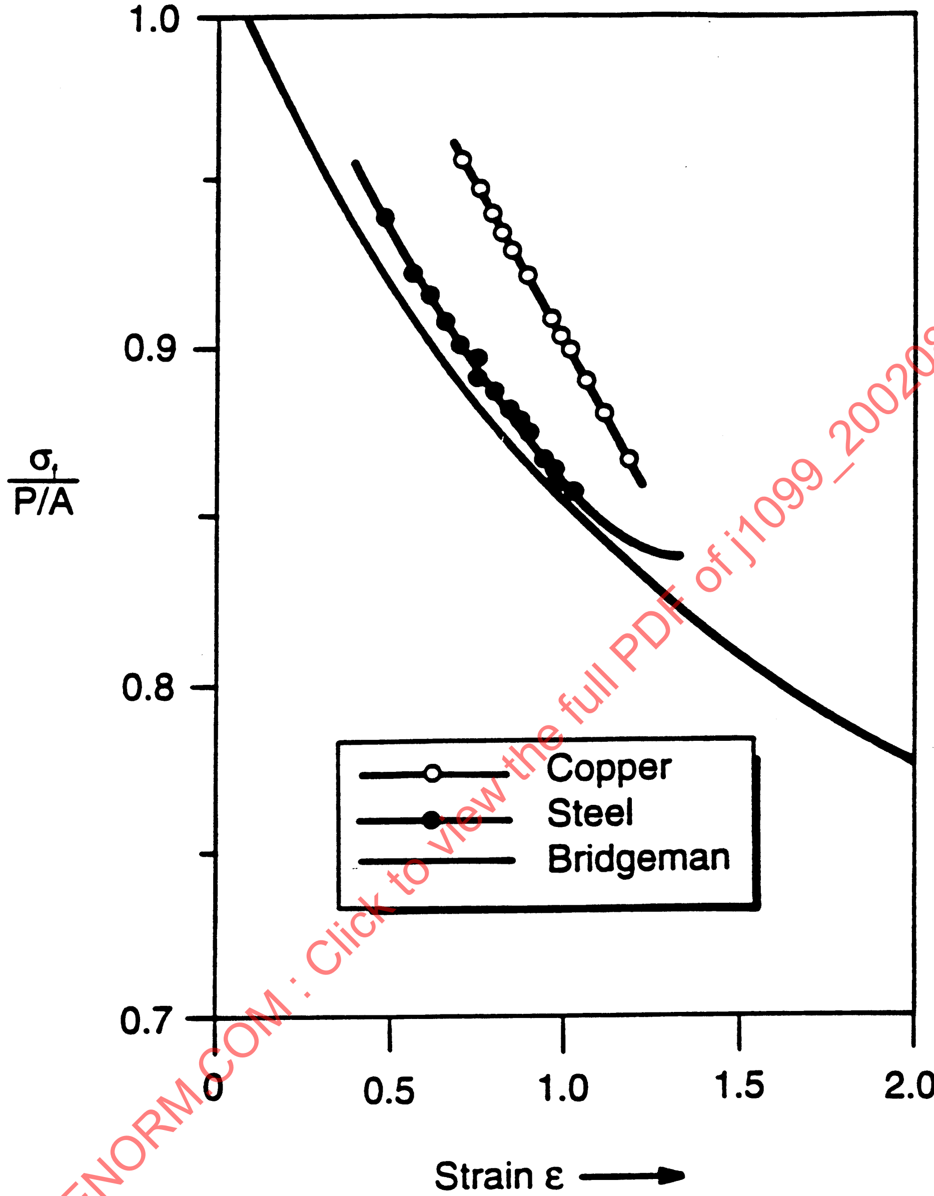

FIGURE 3—RELATIONSHIP BETWEEN BRIDGEMEN CORRECTION FACTOR, $\sigma_f/(P/A)$ AND "TRUE" TENSILE STRAIN

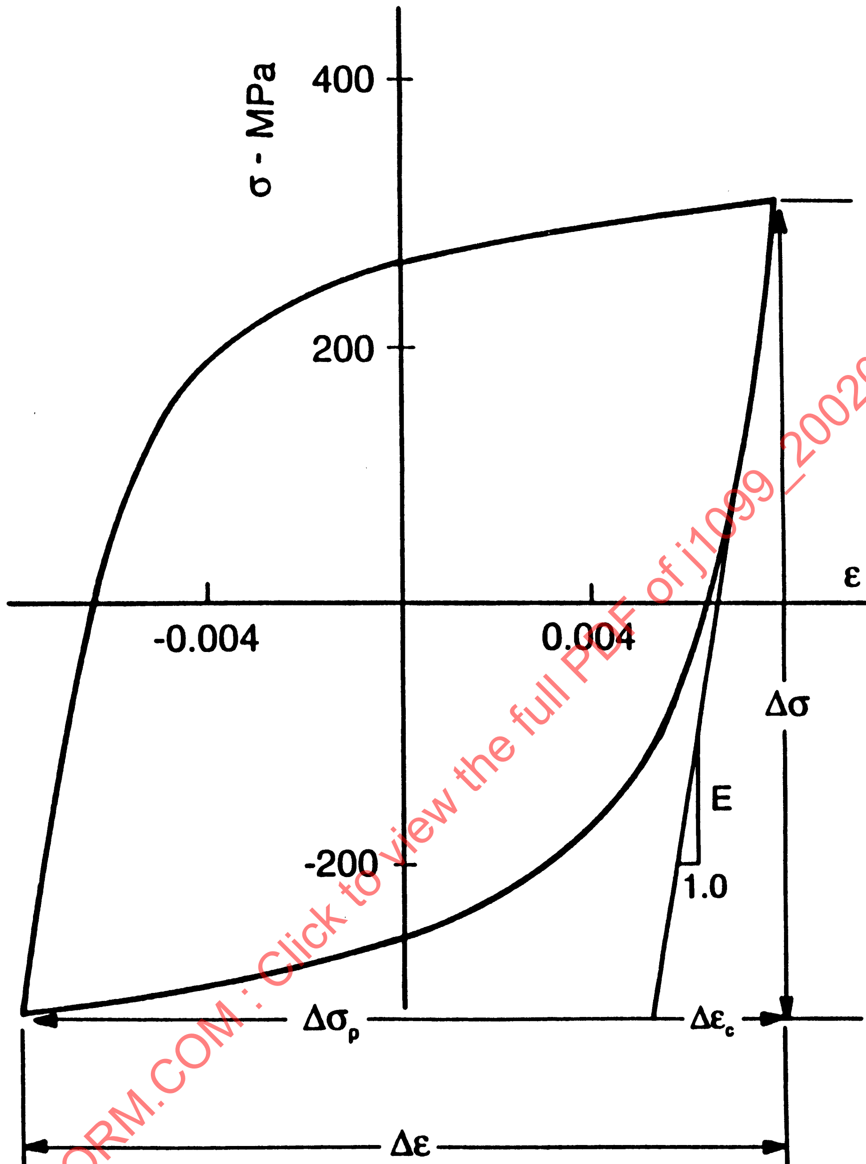

FIGURE 4—STABLE STRESS-STRAIN HYSTERESIS LOOP

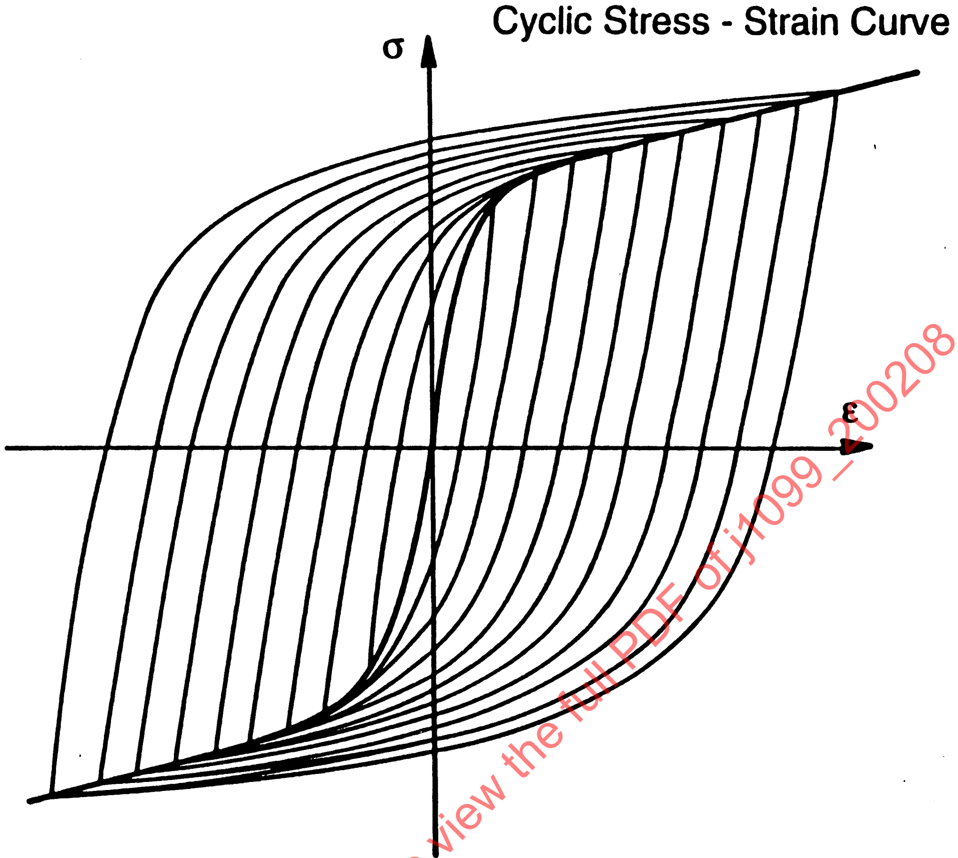

FIGURE 5—CYCLIC STRESS-STRAIN CURVE DRAWN THROUGH STABLE LOOP TIPS

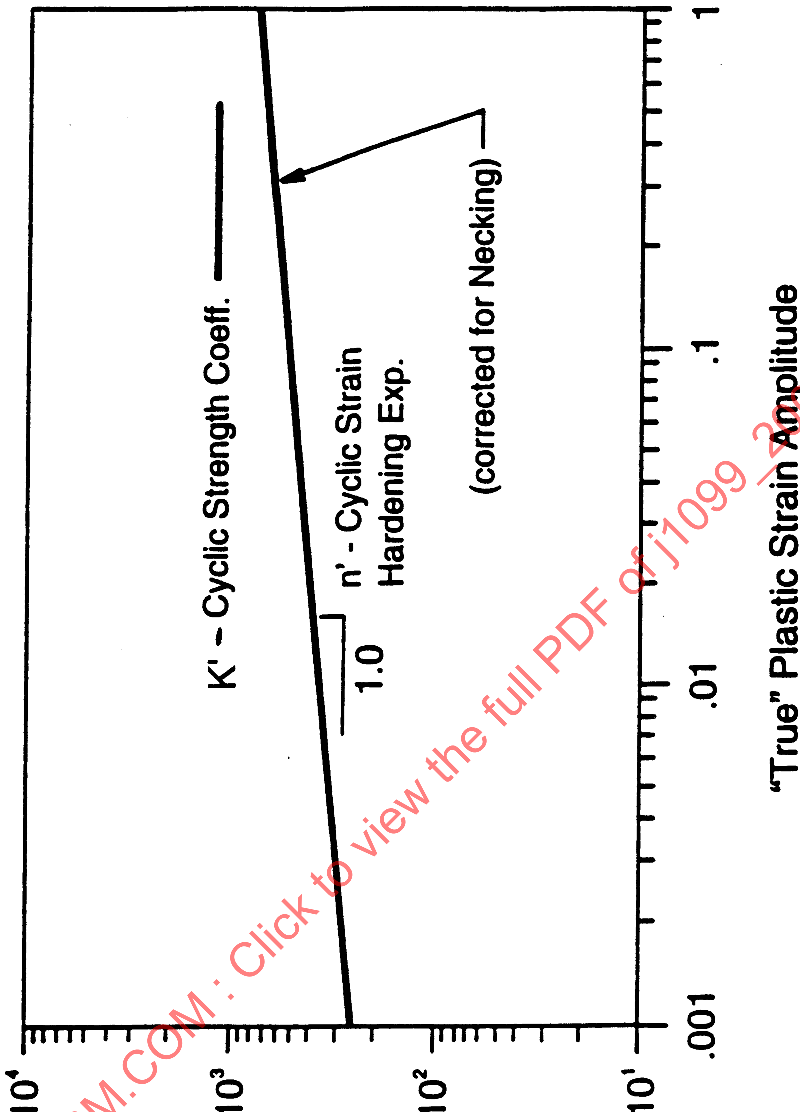

FIGURE 6—CYCLIC STRESS-PLASTIC STRAIN PLOT