



**Strain-life data for type 316 austenitic
stainless steels at temperatures between
–269 and 816°C (–452 and 1501°F)**

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STRAIN-LIFE DATA FOR TYPE 316 AUSTENITIC STAINLESS STEELS AT TEMPERATURES BETWEEN -269 AND 816°C (-452 AND 1501°F)

CONTENTS

	Page
1. INTRODUCTION	1
1.1 Notation	3
2. TEST CONDITIONS	4
3. MECHANICAL PROPERTIES	4
4. DETERMINING FATIGUE PROPERTIES	6
4.1 Strain-Life Relationship	6
4.2 Selecting a Failure Criterion	7
4.3 Approximating Fatigue Properties using Monotonic Data	7
5. STRAIN-LIFE DATA AT CRYOGENIC TEMPERATURES ($\leq -196^{\circ}\text{C}$ (-321°F))	8
6. STRAIN-LIFE DATA AT ROOM TEMPERATURE (23°C (73°F))	9
7. STRAIN-LIFE DATA AT INTERMEDIATE TEMPERATURES (300 TO 450°C (572 TO 842°F))	9
8. STRAIN-LIFE DATA AT ELEVATED TEMPERATURES ($> 450^{\circ}\text{C}$ (842°F))	9
8.1 Strain Life with an Introduced Hold Time	10
9. FATIGUE OF WELDED JOINTS AT ELEVATED TEMPERATURES (500 AND 600°C (932 AND 1112°F))	10
10. ANALYSIS OF STRAIN-LIFE DATA	11
10.1 Summary	11
10.2 Comparison with Monotonic Strain-Life Constants	14
10.3 Regression Analysis of Strain-Life Data	16
11. DERIVATION AND REFERENCES	18
11.1 Derivation	18
11.2 References	20
12. EXAMPLE	20

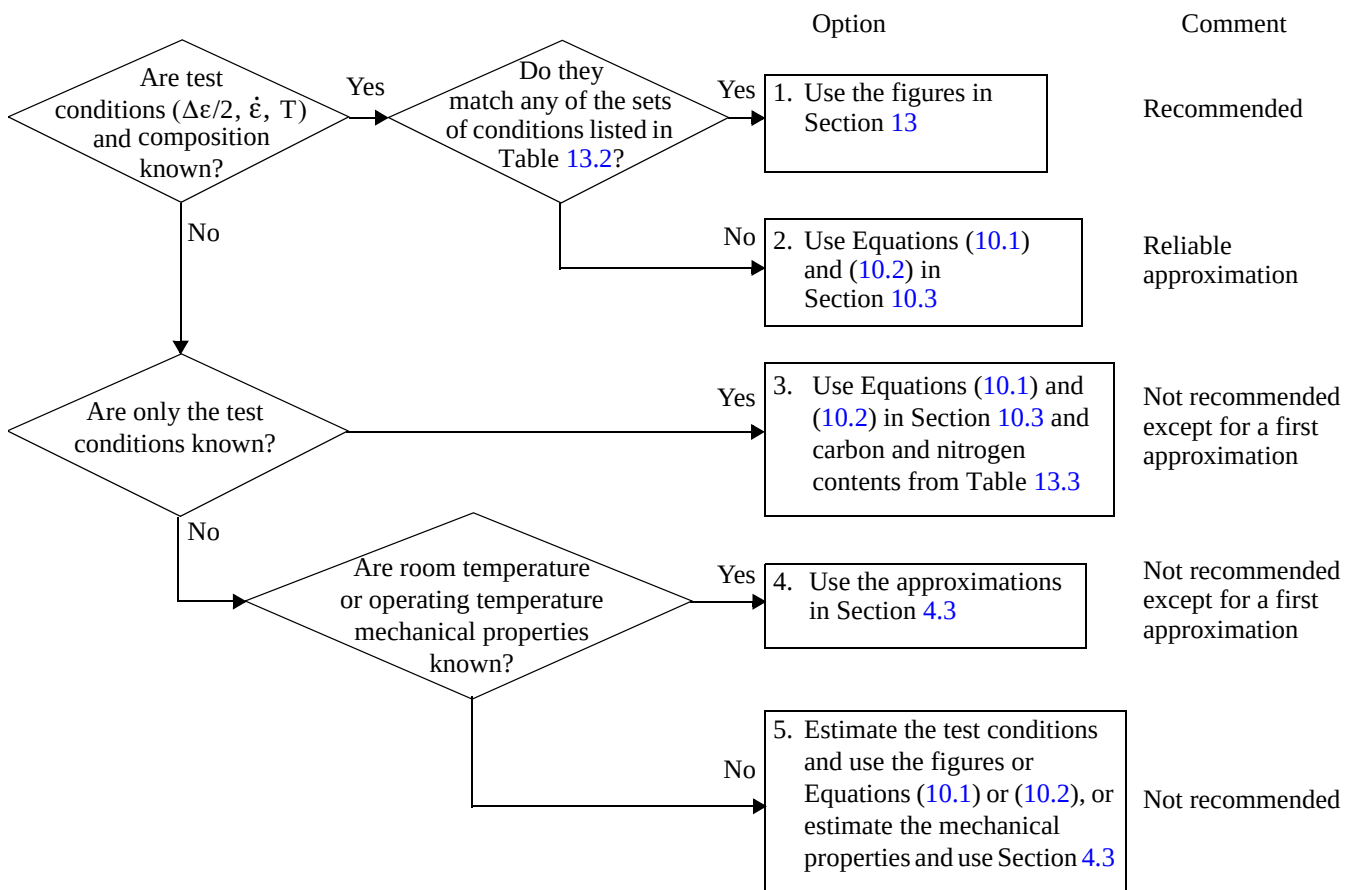
13.	TABLES AND FIGURES	22
13.1	Index to Tables and Figures	22
13.2	General Details of Type 316 Austenitic Stainless Steels	25
13.3	Summary of LCF Constants	28
13.4	Details of Test Conditions	34
13.5	Strain-Life Data at Cryogenic Temperatures (-196°C (-321°F))	47
13.6	Strain-Life Data at Room Temperature (23°C (73°F))	50
13.7	Strain-Life Data at Intermediate Temperatures (300 to 450°C (572 to 842°F))	55
13.8	Strain-Life Data at Elevated Temperatures ($> 450^{\circ}\text{C}$ (842°F))	60
13.9	Fatigue of Welded Joints at Elevated Temperatures (500 and 600°C (932 and 1112°F))	79
	APPENDIX A FAILURE CRITERIA	81
A1.	DETERMINING FAILURE	81
	APPENDIX B MULTIPLE LINEAR REGRESSION ANALYSIS METHOD	85
B1.	ADDITIONAL NOTATION	85
B2.	METHODOLOGY	85

STRAIN-LIFE DATA FOR TYPE 316 AUSTENITIC STAINLESS STEELS AT TEMPERATURES BETWEEN -269 AND 816°C (-452 AND 1501°F)

1. INTRODUCTION

This Data Item presents strain-life data for type 316 austenitic Cr-Ni-Mo stainless steels tested at high load levels, in the low-cycle fatigue (LCF) regime, at a range of temperatures from -269 to 816°C (-452 to 1501°F). Type 316 stainless steels have a wide variety of applications over this range of temperatures. The composition of all 316 austenitic Cr-Ni-Mo stainless steels is essentially the same though some variation in the concentration of elements is used to tailor their properties for different uses; for example increasing the nitrogen content in the steel improves the LCF life below room temperature, and the weldability of the steel can be improved by reducing the carbon content.

The following chart is provided to assist the user in the selection of a method to obtain the LCF properties of a type 316 stainless steel.



Sketch 1.1 Flow chart for use of Data Item

A review of LCF testing is given in Section 2.

The variation in mechanical properties of 316 stainless steels with temperature is discussed in Section 3.

The derivation of the equations used in this Item can be found in ESDU 04022*, and a summary is presented in Section 4.

* ESDU 04022 "An introduction to low-cycle fatigue phenomena".

Section 5 discusses the strain-life data in this Item for nitrogen-alloyed 316 stainless steels at cryogenic temperatures. These steels may be of interest to those involved in the space and energy-generation industries and the design of scientific instruments and to those using super-conducting magnetic structural materials. Austenitic stainless steels are often used at cryogenic temperatures as they do not experience a decrease in toughness as temperature falls below room temperature as other types of stainless steel do.

In Section 6, the room-temperature strain-life data in this Item for 316 stainless steels with low carbon content or high nitrogen content are discussed. Type 316 austenitic stainless steels are widely used for processing equipment in the oil, chemical, food and paper industries owing to their excellent corrosion resistance and mechanical properties at room temperature.

Section 7 discusses the strain-life data in this Item for 316 stainless steels at intermediate temperatures. LCF properties of 316 stainless steels above room temperature, but at temperatures below that at which creep becomes significant, are of interest to designers of pressure vessels, thermonuclear fusion systems, and pipes carrying warm fluids.

In Section 8, the strain-life data in this Item from LCF tests carried out above 450°C (842°F) are discussed. The use of austenitic stainless steels at these temperatures is of interest to the power-generation industry where practical experience has shown that LCF is instigated by thermal fluctuations causing heating and cooling gradients associated with start-up/shut-down procedures, or other operating procedures in plant.

In Section 9, the LCF behaviour at elevated temperatures of a 316 stainless steel welded with a high-nitrogen weld metal is considered.

In Section 10 a discussion of the strain-life constants derived from the LCF data in this Item is presented, along with a comparison with values approximated from monotonic test data. A statistical analysis of the LCF data in this Item and the corresponding data given in ESDU 05008*, and the resulting method for predicting the number of cycles to failure are also presented in Section 10.

Section 11 lists the Derivations and References used in the preparation of this Item.

Section 12 presents a worked example using the method for predicting fatigue life given in Section 10.

Section 13 consists of the LCF data themselves, presented as graphs of total, elastic and plastic strain amplitude versus number of cycles to failure. The graphs are accompanied by tables containing information supplementary to that in the figures.

Table 13.1 is an index to the figures and tables in Section 13.

To assist with the location and comparison of data for particular stainless steels, Table 13.3 gives the UNS code of the 316 stainless steels for which data are presented, and some of their common cross-reference specifications and chemical compositions.

The effect of selecting alternative failure criteria on the results of LCF tests is illustrated in Appendix A.

General details of the multiple linear regression approach used to analyse the LCF data are presented in Appendix B.

* ESDU 05008 "Cyclic stress-strain response of type 316 austenitic stainless steels during low-cycle fatigue at temperatures between -269 and 800°C (-452 and 1472°F)".

1.1 Notation

b	fatigue strength exponent		
b_{norm}	normalized fatigue strength exponent		
C	carbon content	wt%	wt%
c	fatigue ductility exponent		
c_{norm}	normalized fatigue ductility exponent		
E	Young's modulus	N/m ²	lbf/in ²
N	nitrogen content	wt%	wt%
N	number of cycles	cycles	cycles
N_f	number of cycles to failure*	cycles	cycles
$N_{f99/95}$	predicted number of cycles to failure corresponding to a 95 per cent confidence level and a 99 per cent probability of survival	cycles	cycles
N_{fpred}	predicted number of cycles to failure	cycles	cycles
N_t	transition fatigue life	cycles	cycles
N_5	number of cycles corresponding to a 5 per cent decrease in the maximum tensile load	cycles	cycles
N_{25}	number of cycles corresponding to a 25 per cent decrease in the maximum tensile load	cycles	cycles
RA	reduction of area (often quoted as a percentage)		
r^2	correlation coefficient		
T	temperature	°C	°F
$\Delta\epsilon/2$	total strain amplitude		
$\Delta\epsilon_e/2$	elastic strain amplitude		
$\Delta\epsilon_p/2$	plastic strain amplitude		
$\Delta\sigma/2$	total stress amplitude	N/m ²	lbf/in ²
$\dot{\epsilon}$	strain rate	s ⁻¹	s ⁻¹
ϵ_f	fracture ductility		

* Note that 'failure' may be defined in several different ways.

ε'_f	fatigue ductility coefficient		
$\varepsilon'_{f\text{norm}}$	normalized fatigue ductility coefficient		
σ_f	true fracture strength	N/m ²	lbf/in ²
σ'_f	fatigue strength coefficient	N/m ²	lbf/in ²
$\sigma'_{f\text{norm}}$	normalized fatigue strength coefficient	N/m ²	lbf/in ²
σ_{ts}	ultimate tensile strength	N/m ²	lbf/in ²
σ_y	yield stress in tension, unless indicated otherwise	N/m ²	lbf/in ²

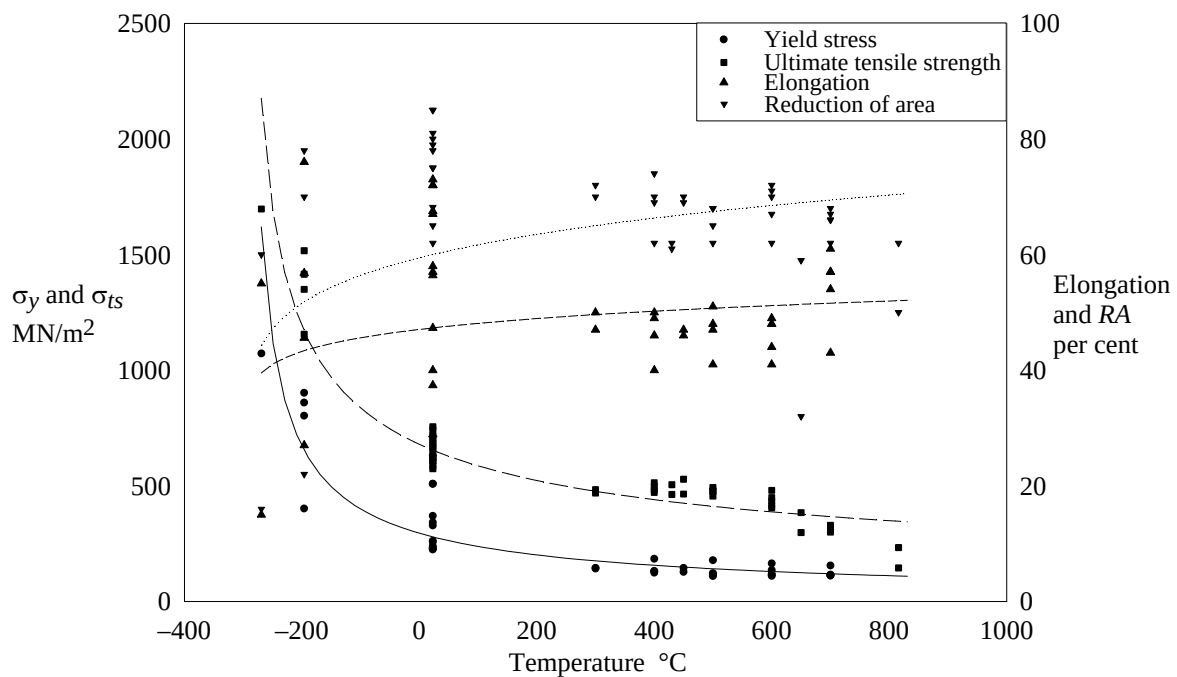
2. TEST CONDITIONS

Typically, to generate strain-life data for 316 stainless steels, constant-amplitude, fully-reversed, axial, strain-controlled LCF tests with zero mean strain are performed and all the data presented in this Item are from such tests. The tests are carried out at room temperature (nominally 23°C (73°F)), at elevated temperature (up to 816°C (1501°F)), in air or a vacuum, or in a cryogenic gas environment for tests carried out below room temperature. Prior to testing, most of the stainless steels are subject to a high-temperature solutionizing treatment to homogenize the microstructure, followed by a water quench to harden the stainless steels and improve their strength by maintaining nitrogen and carbon in solid solution. The stainless steels are machined into standard, un-notched test-piece profiles. Supplementary details of the test piece shape, heat treatment applied and the other LCF test conditions are given in Tables 13.7 to 13.19 which accompany the figures presented in Section 13.

3. MECHANICAL PROPERTIES

In some cases, the fatigue properties of stainless steels can be estimated from their static mechanical properties, see Section 4.3. The mechanical properties of 316 stainless steels at different strain rates and temperatures from -269 to 816°C (-452 to 1501°F) are given in Table 13.4.

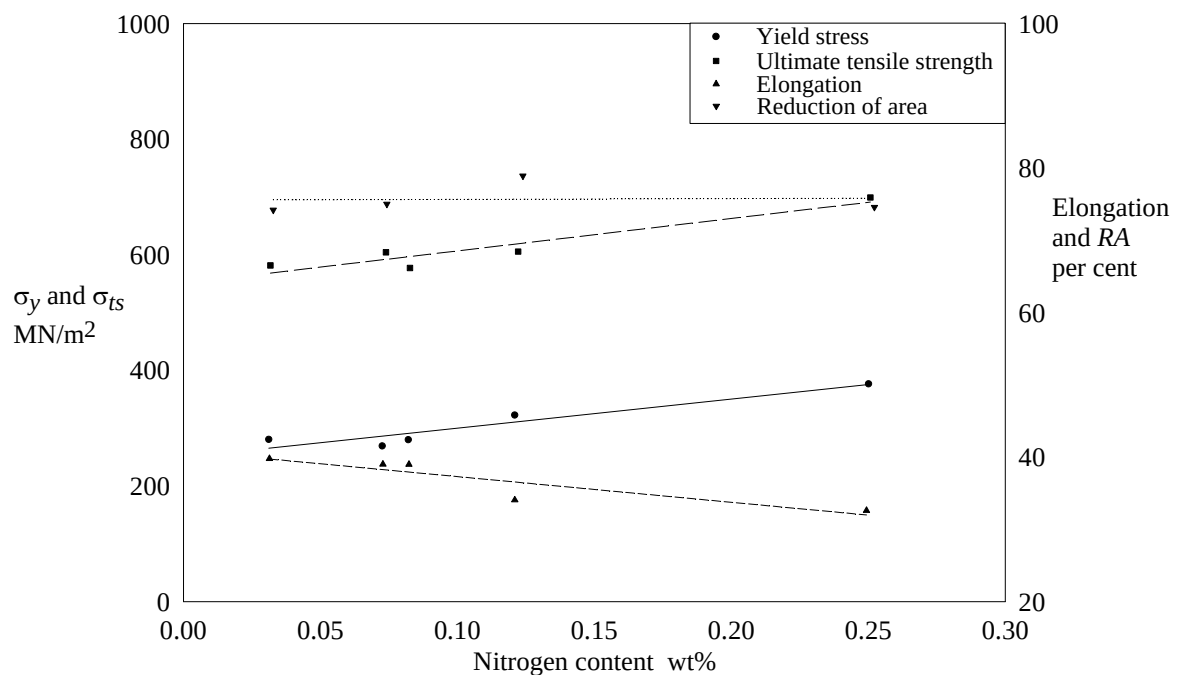
As temperature increases, reduction of area (RA) and elongation increase, and the yield stress and the tensile strength, σ_y and σ_{ts} , respectively, of 316 stainless steels tend to decrease, see Sketch 3.1. The yield stress and tensile strength are generally lower for low carbon S31603 stainless steels than for other more highly-alloyed grades. This is because when the carbon content of austenitic stainless steels is reduced to minimize sensitization effects there is a concomitant effect of reduction of strength. Replacing carbon with nitrogen will maintain the strength of the stainless steel, or even improve it, without detrimental effects on the intergranular corrosion properties of the stainless steel.



Sketch 3.1 Variation in mechanical properties with temperature for 316 stainless steels
(see Table 13.4)

As can be seen in Table 13.4, when the strain rate is reduced, the tensile strength of S31600 stainless steels tested at 430°C (806°F) increases. However, at 650°C (1202°F) and 816°C (1501°F), lower strain rates cause the tensile strength to decrease. Reducing the strain rate also lowers the reduction of area of S31600 stainless steel, more so at 650°C (1202°F).

At room temperature, increasing the nitrogen content of S31603 stainless steels causes the yield stress and tensile strength to increase, see Sketch 3.2. Nitrogen content has little discernible effect on reduction of area but elongation decreases slightly for a nitrogen content above 0.1wt%.



Sketch 3.2 Variation in mechanical properties with nitrogen content for S31603 stainless steels
(see Table 13.4)

4. DETERMINING FATIGUE PROPERTIES

Full details of the determination of fatigue properties by various means are given in ESDU 04022.

4.1 Strain-Life Relationship

During strain-controlled fatigue tests at a constant temperature, the total strain and stress amplitude for each cycle and the number of cycles to failure are recorded. The total strain amplitude can be separated into its elastic and plastic components:

$$\frac{\Delta \epsilon}{2} = \frac{\Delta \epsilon_e}{2} + \frac{\Delta \epsilon_p}{2}. \quad (4.1)$$

The elastic strain amplitude, $\Delta \epsilon_e/2$, is found by dividing the stress amplitude $\Delta \sigma/2$ by the Young's modulus of the material, E :

$$\frac{\Delta \epsilon_e}{2} = \frac{\Delta \sigma}{2E}. \quad (4.2)$$

For a given strain rate and temperature, a log-log plot of the plastic strain amplitude versus the number of cycles to failure, N_f , produces a band of points scattered about a straight line. Coffin and Manson (References 22 and 23), working independently, established that the equation for the cyclic plastic strain amplitude that is tolerated for a given fatigue life can be expressed in the form

$$\frac{\Delta \epsilon_p}{2} = \epsilon'_f N_f^c. \quad (4.3)$$

The plastic strain intercept at one quarter cycle is an estimate of the overall level of fatigue ductility and is called the fatigue ductility coefficient, ϵ'_f . The slope of the straight line is also a fatigue property and is termed the fatigue ductility exponent, c , see Sketch 4.1.

Stress-life data, obtained from strain- or stress-controlled fatigue tests, can also be represented as a straight-line when plotted using log scales:

$$\frac{\Delta \sigma}{2} = \sigma'_f N_f^b, \quad (4.4)$$

where σ'_f is the fatigue strength coefficient and b is the fatigue strength exponent.

In Equation (4.4), σ'_f is the stress amplitude at one quarter cycle and b is the slope of the line. Equation (4.4) remains linear for elastic strains, but becomes non-linear for inelastic strains.

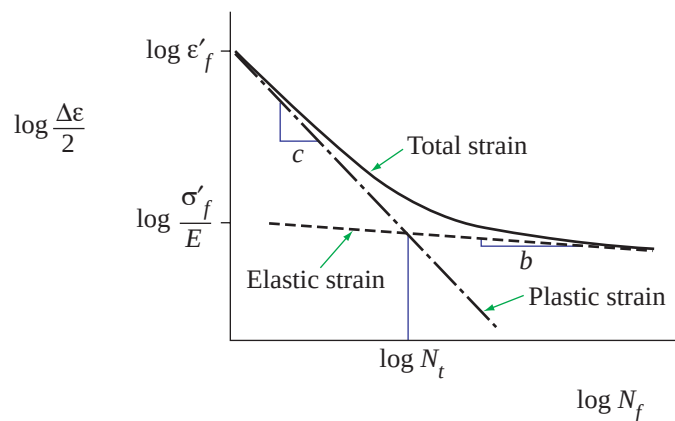
Dividing Equation (4.4) by the Young's modulus gives the elastic strain amplitude in terms of the fatigue strength coefficient and exponent:

$$\frac{\Delta \epsilon_e}{2} = \frac{\sigma'_f}{E} N_f^b. \quad (4.5)$$

The fatigue ductility and fatigue strength constants (ϵ'_f , c , σ'_f and b) are properties of the material that express its fatigue resistance to total cyclic strain. Equations (4.3) and (4.5) can be substituted into Equation (4.1) to give an expression for the total strain amplitude as a function of fatigue life, otherwise known as the strain-life equation:

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E} N_f^b + \epsilon'_f N_f^c. \quad (4.6)$$

Equation (4.6) provides the basis of the strain-life relationship, shown graphically in Sketch 4.1. The number of cycles to failure at which elastic strain and plastic strain are equal is called the transition fatigue life, N_t , and it is sometimes used to define a fairly arbitrary boundary between the low- and high-cycle fatigue regimes.



Sketch 4.1 Parameters in the strain-life (Coffin-Manson) equation

4.2 Selecting a Failure Criterion

The failure criterion for a low-cycle fatigue test is, in general, complete test piece separation. Sometimes other failure criteria are used, for example a 5 or 25 per cent decrease in the maximum tensile load, N_5 or N_{25} respectively (Derivations 1 and 4).

The effects of using alternative failure criteria are discussed in Appendix A. In practice, the use of different failure criteria often has very little effect on the fatigue life, or the calculated fatigue ductility and fatigue strength constants, of stainless steels.

4.3 Approximating Fatigue Properties using Monotonic Data

The LCF properties of most metallic materials can be calculated from their monotonic properties using the following useful, but approximate, methods. However, these estimates of cyclic fatigue properties based on monotonic data are not always suitable, see Section 10.2.

An approximation of the fatigue strength coefficient from the true fracture strength is

$$\sigma'_f \approx \sigma_f \text{ (corrected for necking)}. \quad (4.7)$$

For stainless steels with a hardness value of less than 500 BHN (Brinell Hardness Number), σ_f may be approximated as

$$\sigma_f \approx \sigma_{ts} + 345 \text{ MN/m}^2$$

$$\text{or } \sigma_f \approx \sigma_{ts} + 50 \times 10^3 \text{ lbf/in}^2. \quad (4.8)$$

An approximation of the fatigue ductility coefficient, based on the fracture ductility (Reference 24), is

$$\epsilon'_f \approx \frac{\epsilon_f}{4}, \quad (4.9)$$

$$\text{where } \epsilon_f = \ln \left[\frac{1}{1 - RA} \right]. \quad (4.10)$$

The fatigue strength exponent, b , is typically taken to be between -0.05 to -0.12 for most metals; for the 316 stainless steels featured in this Item, b varies from -0.012 to -0.287 over the temperature range -196 to 816°C (-321 to 1501°F), see Sketch 10.3. The fatigue ductility exponent, c , is generally less well defined but is thought to be between -0.5 and -0.7 for most metals; for the 316 stainless steels featured in this Item, c varies from -0.37 to -0.928 over the temperature range -269 to 816°C (-452 to 1501°F), see Sketch 10.4. For fairly ductile materials, where $\epsilon_f \approx 1$, the average value of c is around -0.6 . For strong metals, for which $\epsilon_f \approx 0.5$, the average value of c is about -0.5 .

In Table 13.6, Equations (4.8) and (4.9) are evaluated and the results are compared to the values of ϵ'_f and σ'_f derived from the LCF data.

5. STRAIN-LIFE DATA AT CRYOGENIC TEMPERATURES ($\leq -196^\circ\text{C}$ (-321°F))

Strain-life data for S31653 stainless steels tested at cryogenic temperatures are given in Figures 1 to 5. The values of σ'_f , b , ϵ'_f , c , and the transition fatigue life, N_t , calculated from the data are given in Table 13.5. Also given in Table 13.5 are the calculated values of the number of cycles to failure at an applied plastic strain amplitude of 0.01, $\Delta\epsilon_p/2_{0.01}$, from which the fatigue life at the same plastic strain amplitudes may be compared for different test conditions.

In Table 13.5, it can be seen that the fatigue ductility coefficient and exponent, ϵ'_f and c respectively, of S31653 and heat-treated S31653 stainless steels decrease as the test temperature increases from -269 to -196°C (-452 to -321°F). The fatigue strength and ductility coefficients, σ'_f and ϵ'_f , decrease over that temperature range for heat-treated S31653 stainless steels. The S31653 stainless steel from Derivation 17 has larger values of ϵ'_f and σ'_f than a similar stainless steel from Derivation 9. This could be due to the fact that the test piece from Derivation 17 was taken at 45° degrees to the rolling direction.

The transition fatigue life, N_t , increases with temperature, or when a heat treatment is applied to S31653 stainless steels. One S31653 stainless steel (Derivation 17) tested at -196°C (-321°F) has a transition fatigue life of $N_t = 11\,636$ cycles, compared with a value of 2388 cycles for a similar material tested under similar conditions, indicating that this particular steel is able to accommodate a larger number of cycles before transition into elastic fatigue failure; the inelastic portion of this strain-life curve dominates, and therefore the fatigue ductility coefficient is higher.

For the stainless steel mentioned above (Derivation 17), the fatigue life for a plastic strain amplitude of 0.01 is 1226 cycles (see Figure 4), about five times larger than for the other S31653 stainless steels tested at -196°C (-321°F) (see Figures 3 and 5). A possible explanation of this is the high degree of polishing to which the test piece was subjected prior to testing.

6. STRAIN-LIFE DATA AT ROOM TEMPERATURE (23°C (73°F))

Strain-life data for S31603, S31600 and S31653 stainless steels tested at room temperature are given in Figures 6 to 14. The LCF constants, σ'_f , b , ϵ'_f , c , N_t , and N_f at $\Delta\epsilon_p/2_{0.01}$, calculated from the data are given in Table 13.5.

The fatigue strength coefficient, σ'_f , varies between 575 MN/m² (83.4×10^3 lbf/in²) for a heat-treated S31653 stainless steel and 3399 MN/m² (493×10^3 lbf/in²) for a S31600 stainless steel cycled at a strain rate of 6.7×10^{-3} s⁻¹, see Table 13.5. The fatigue ductility coefficient, ϵ'_f , also shows a great deal of variability, ranging between 0.104 (heat-treated S31653 stainless steel, 4×10^{-3} s⁻¹ strain rate, Figure 14) and 0.651 (S31600 stainless steel, 0.67×10^{-3} s⁻¹ strain rate, Figure 11). The fatigue strength exponent, b , varies by a factor of over four from -0.054 for a heat-treated S31653 stainless steel to -0.236 for a S31600-B11 stainless steel.

Transition fatigue lives for 316 stainless steels at room temperature do not appear to be dependent on the stainless steel type or strain rate, or on ϵ'_f and σ'_f . The calculated fatigue life for an applied plastic strain amplitude of 0.01 is generally lowest for S31653 stainless steels, apart from the very high fatigue life (1275 cycles) calculated for a S31653 stainless steel from Derivation 17 (see Figure 13).

7. STRAIN-LIFE DATA AT INTERMEDIATE TEMPERATURES (300 to 450°C (572 to 842°F))

Strain-life data for LCF tests carried out at 'intermediate' temperatures are given in Figures 15 to 24. The LCF constants, σ'_f , b , ϵ'_f , c , N_t , and N_f at $\Delta\epsilon_p/2_{0.01}$, calculated from the data are given in Table 13.5.

The fatigue ductility coefficient, ϵ'_f , varies between 0.07 at 400°C (752°F) and 0.356 at 450°C (842°F), and the fatigue strength coefficient, σ'_f , varies from 844 to 3130 MN/m² (122×10^3 to 454×10^3 lbf/in²), see Table 13.5. ϵ'_f and σ'_f are largest for a S31600-C stainless steel tested at 450°C (842°F) with a strain rate of 6.7×10^{-3} s⁻¹, see Figure 23.

For temperatures of 400 and 450°C (752 and 842°F), decreasing the strain rate from 1×10^{-3} to 0.01×10^{-3} s⁻¹ reduces the transition fatigue life, N_t , and the fatigue life at applied plastic strain amplitude of 0.01, see Figures 16 to 24. These trends are not seen for the fatigue ductility coefficient, which does not vary consistently with strain rate.

8. STRAIN-LIFE DATA AT ELEVATED TEMPERATURES (> 450°C (842°F))

Strain-life data for 316 stainless steels cycled at elevated temperatures are given in Figures 25 to 61. The LCF constants, σ'_f , b , ϵ'_f , c , N_t , and N_f at $\Delta\epsilon_p/2_{0.01}$, calculated from the data are given in Table 13.5.

As temperature increases from 500 to 816°C (932 to 1501°F), the fatigue strength coefficient, σ'_f , decreases; it also tends to decrease with decreasing strain rate. The transition fatigue life, N_t , and fatigue ductility coefficient, ϵ'_f , tend to increase with increasing temperature and are also dependent on strain rate.

In general, for a constant temperature, fatigue life decreases with decreasing strain rate. The relationship between the fatigue ductility coefficient, ϵ'_f , and transition fatigue life, N_t , is less easy to define. As ϵ'_f increases to 0.151, N_t also increases, but as ϵ'_f increases above 0.151, N_t decreases.

8.1 Strain Life with an Introduced Hold Time

Most LCF tests are carried out using uninterrupted cycling but a closer simulation of actual service conditions is effected by introducing a hold time at a constant stress (or strain) during each cycle (Reference 25). The introduction of a hold time at the maximum stress allows the time-dependent creep process to become active and creep-fatigue interaction can thus be reproduced.

For S31600 stainless steel, when a hold time of 5 minutes at the maximum tensile stress in the cycle is used whilst testing at 750°C (1382°F), the number of cycles to failure decreases, see Figure 56, and the transition fatigue life decreases (from 7788 to 1995 cycles). Under conditions of continuous cycling, the damage due to plasticity is dominant. When a hold time is introduced, there is a significant reduction in the number of cycles to crack initiation due to creep at this temperature (Derivation 8).

If the duration of the hold time is increased, there is a clear detrimental effect on fatigue life for any given strain range, see Table 8.1.

TABLE 8.1 Cyclic Test Results with a Hold Time for a S31603 Stainless Steel at 625°C (1157°F) (Derivation 11)

Hold time minutes	$\Delta\epsilon/2$	$\Delta\epsilon_p/2$	N_f cycles	N_5^* cycles	$\Delta\sigma/2$ MN/m ² (10 ³ lbf/in ²)
1	0.0103	0.0081	351	328	171.3 (24.8)
3	0.0104	0.0083	179	166	165.5 (24.0)
20	0.01	0.0084	162	137	165.6 (24.0)
60	0.0102	0.0084	160	157	148.6 (21.5)
1	0.0051	0.0035	733	700	122.8 (17.8)
3	0.0052	0.0036	583	515	125.9 (18.3)
30	0.0052	0.0036	287	284	119.7 (17.4)
36	0.0052	0.0036	(a)	-	111.3 (16.1)
1	0.0028	0.0016	1732	1356	95.96 (13.9)
1	0.0028	0.0016	1523	1316	101.1 (14.7)
30	0.0029	0.0018	(a)	> 489	88.25 (12.8)

* Number of cycles required to produce a 5 per cent decrease in the maximum tensile load.

(a) Test interrupted before a 5 per cent decrease in the maximum tensile load occurred.

9. FATIGUE OF WELDED JOINTS AT ELEVATED TEMPERATURES (500 AND 600°C (932 AND 1112°F))

To investigate the LCF life of a welded joint, test pieces are taken from the base metal, the weld metal, and across the weldment, see Table 13.20. In Figures 62 and 63, plastic strain amplitude is plotted against the number of cycles to failure for the S31653 base metal, S31600 weld metal and the welded joint at 500 and 600°C (932 and 1112°F). The calculated fatigue ductility constants, ϵ'_f and c , and the fatigue life at an applied plastic strain amplitude of 0.01 are given in Table 13.20.

At 500°C (932°F), the S31653 base metal has the highest fatigue resistance at most plastic strain amplitudes. LCF life is governed by the fracture ductility of the material; therefore the weld metal (which has a cast structure) is expected to have a lower LCF life than the more ductile base metal.

At 600°C (1112°F), the weld metal has a longer fatigue life than the base metal due to differences in the manner in which cracks propagate in the weld and in the base metal. The base metal has a coarse microstructure, whereas the weld metal has a fine, duplex microstructure containing many transformed phase boundaries and a high density of dislocations. This fine microstructure offers a high resistance to, and deflection of, fatigue crack growth.

The S31653/S31600 weldment has the lowest fatigue resistance at all plastic strain amplitudes and at both test temperatures because of the change from a transgranular crack-initiation mode in the base metal and weld metal, to an intergranular mode in the heat-affected zone. Surface intergranular crack initiation in the weldment shortens the crack-initiation phase, and there is poor crack-propagation resistance in the coarse-grained region of the heat-affected zone.

10. ANALYSIS OF STRAIN-LIFE DATA

In Table 13.5, values of ϵ'_f , σ'_f , b , c , N_t and N_f at $\Delta\epsilon_p/2_{0.01}$ calculated from the data presented in the figures of Section 13 are collated and the effect of temperature on the constants is summarized in Section 10.1. In Section 10.2, values of σ_f and $\epsilon_f/4$ calculated from monotonic tensile test data are compared with values of σ'_f and ϵ'_f , respectively, derived from the cyclic data in this Item. The results of a regression analysis of the strain-life data in this Item are presented in Section 10.3.

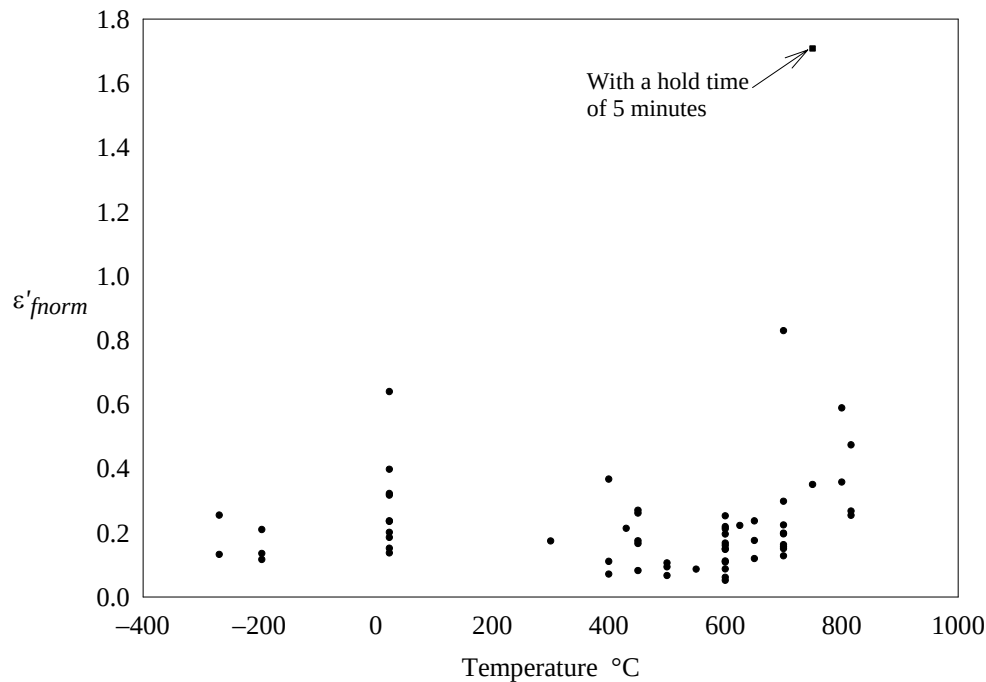
10.1 Summary

There is a lot of variation of fatigue ductility coefficient, ϵ'_f (0.039 to 0.651) with temperature, see Table 13.5. At 750°C (1382°F) with a hold time of 5 minutes at maximum stress, a value of ϵ'_f of 1.51 is calculated. Sketch 10.1 shows the variation of fatigue ductility with temperature; the values of $\epsilon'_{f\text{norm}}$ in Sketch 10.1 are the values of ϵ'_f normalized* to carbon and nitrogen contents of 0.05 wt% and a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$. A minimum in ϵ'_f occurs at around 600°C (1112°F).

* The independent variable, such as temperature, strain rate or amplitude, carbon or nitrogen content, x , is plotted against the dependent variable, y , fatigue life in this case. The regression equation ($y = mx + c$) of the scatter plot is then used to normalize y to a given value of the independent variable, x_{norm} , thus removing the influence of the independent variable on the dependent variable, y_{norm} :

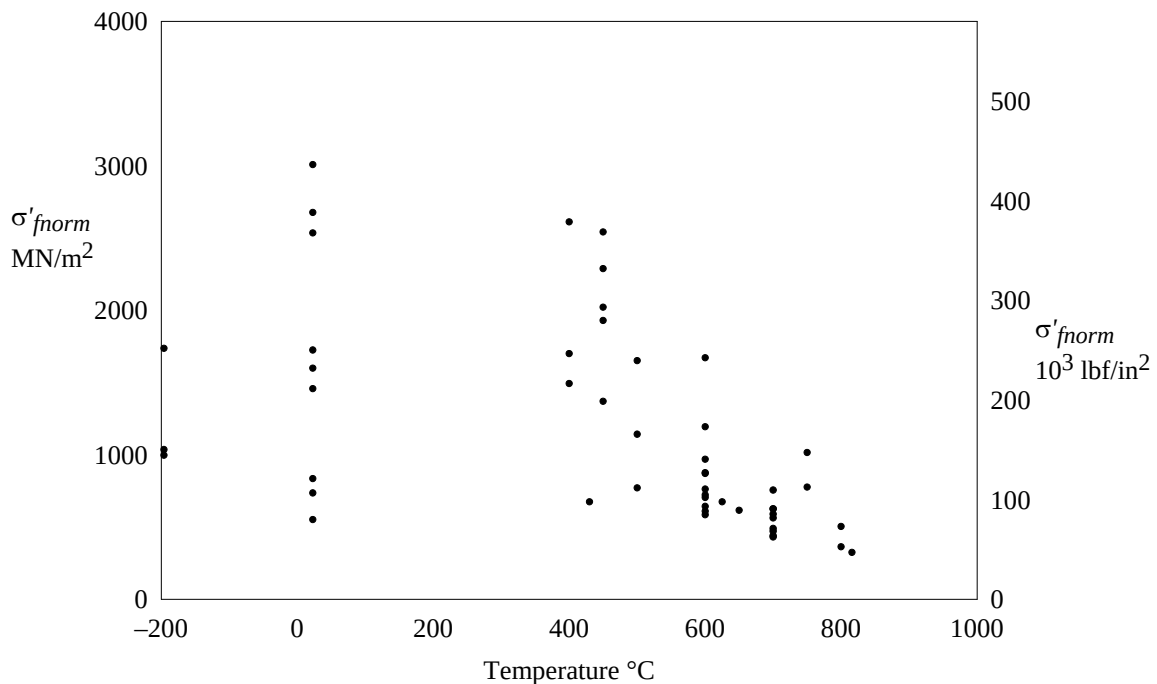
$$y_{\text{norm}} = [(mx_{\text{norm}} + c)/(mx + c)] \times y.$$

This process is repeated for each independent variable of interest, using the previous y_{norm} to find the new y_{norm} .



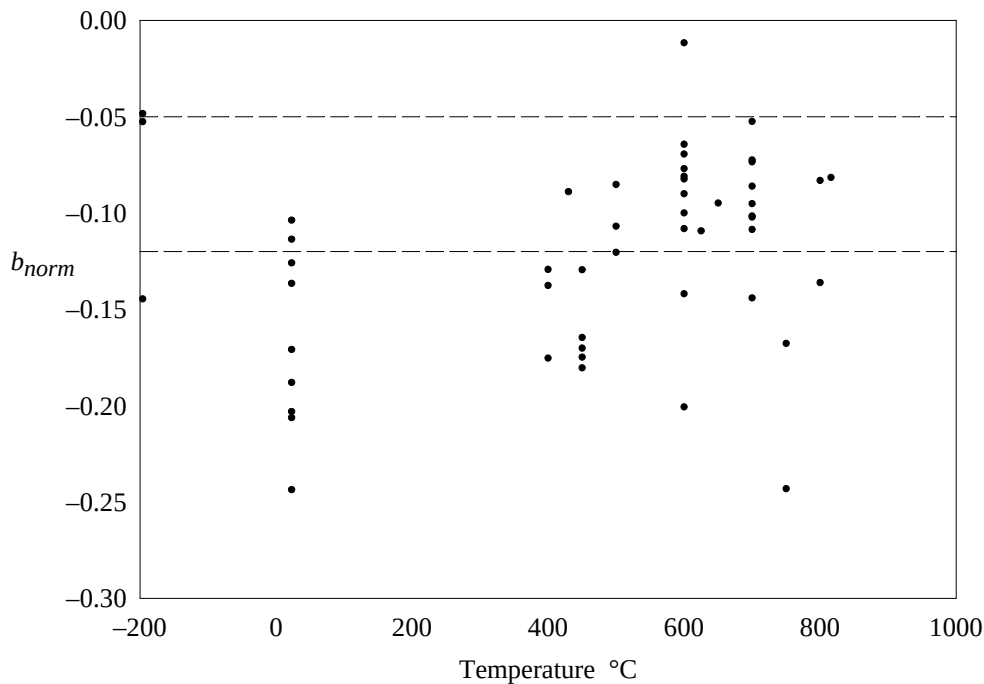
Sketch 10.1 Effect of temperature on $\varepsilon'_{f norm}$

As can be seen in Table 13.5, the fatigue strength coefficient, σ'_f , varies with temperature, tending to decrease as temperature is increased; a minimum value of σ'_f of 255 MN/m² (37×10^3 lbf/in²) occurs at 700°C (1292°F) for S31600 stainless steels. There is also a wide band of scatter in σ'_f at 23°C (73°F), from 745 MN/m² (108×10^3 lbf/in²) for a S31603 stainless steel to 3399 MN/m² (493×10^3 lbf/in²) for a S31600 stainless steel. Sketch 10.2 shows the variation of $\sigma'_{f norm}$ (σ'_f normalized to carbon and nitrogen contents of 0.05 wt% and a strain rate of 2×10^{-3} s⁻¹) with temperature.



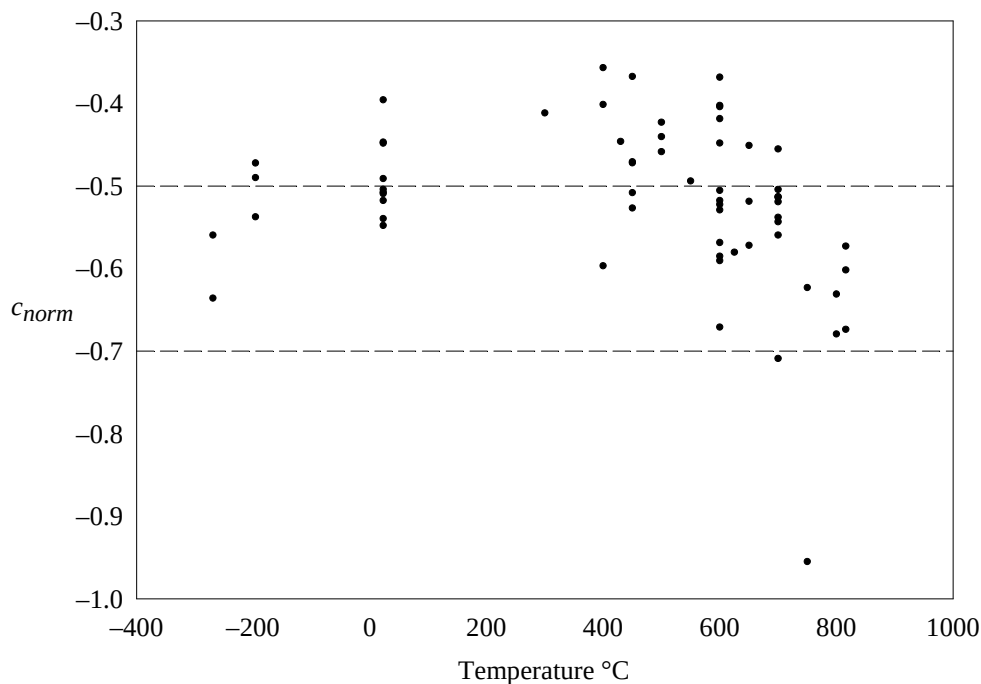
Sketch 10.2 Effect of temperature on $\sigma'_{f norm}$

The fatigue ductility exponent, c , varies between -0.37 and -0.928 and the fatigue strength exponent, b , varies between -0.012 and -0.287 , see Table 13.5. Sketches 10.3 and 10.4 show the variation of b_{norm} and c_{norm} , respectively, with temperature. Both b_{norm} and c_{norm} are the values of b and c normalized to carbon and nitrogen contents of 0.05 wt% and a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$. Neither b_{norm} nor c_{norm} shows a significant trend with temperature, though at higher temperatures ($> 600^\circ\text{C}$ (1112°F)), and for S31600 stainless steels in particular, c decreases and b increases with increasing temperature.



The dashed lines indicate the expected range of scatter (see Section 4.3).

Sketch 10.3 Effect of temperature on b_{norm}



The dashed lines indicate the expected range of scatter (see Section 4.3).

Sketch 10.4 Effect of temperature on c_{norm}

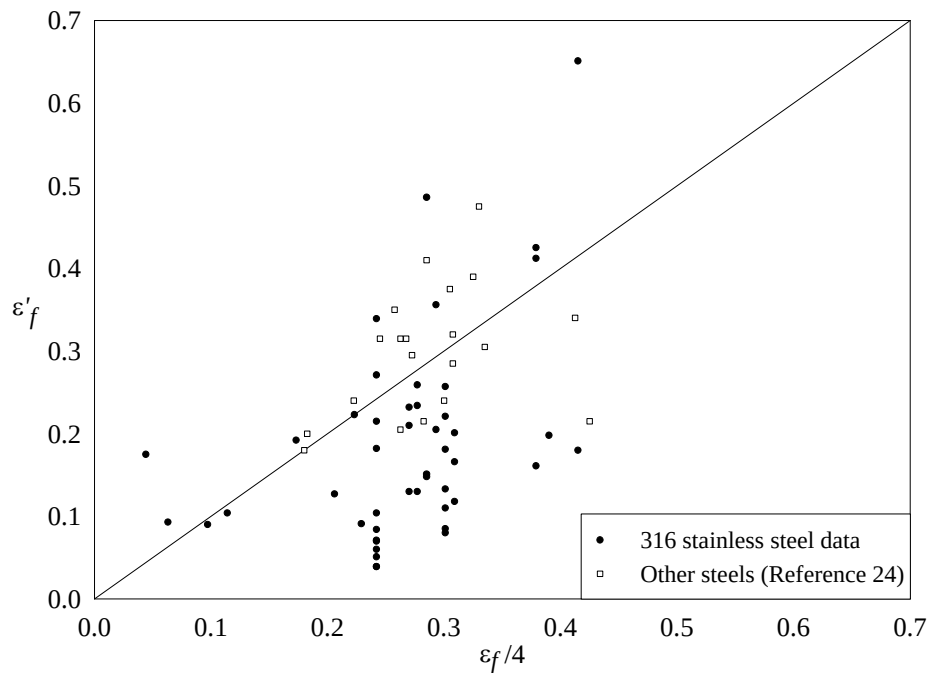
For S31600 stainless steels, the transition fatigue life decreases as temperature increases from 23 to 500°C (73 to 932°F), but then increases slightly with rising temperature, see Table 13.5. For S31603 stainless steels, increasing the temperature above room temperature reduces N_t , and for S31653 stainless steels, increasing the temperature from -269°C (-452°F) to room temperature increases N_t .

Increasing the temperature from -269°C (-452°F) to around 450°C (842°F) increases the fatigue life at an applied plastic strain amplitude of 0.01, see Table 13.5. There is a large amount of scatter in the fatigue life data at room temperature, 23°C (73°F).

10.2 Comparison with Monotonic Strain-Life Constants

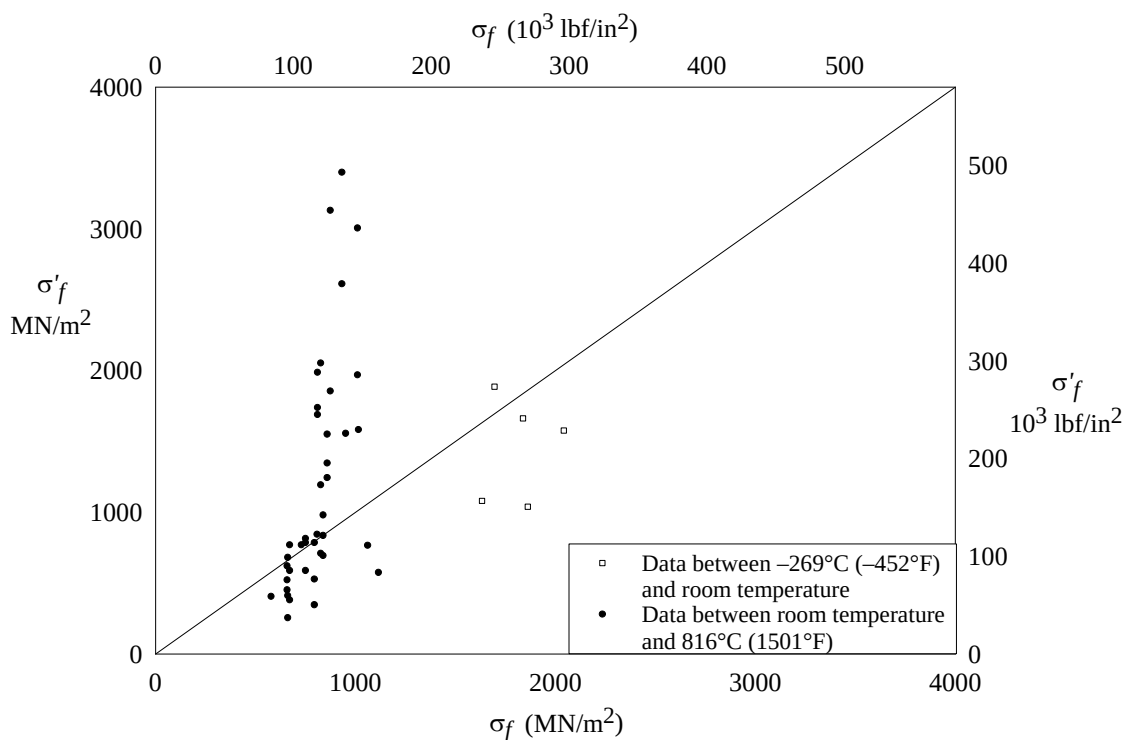
Where monotonic tensile test data are available for the appropriate temperature and for strain rates of the same order, true fracture strength and fracture ductility can be estimated using Equations (4.8) and (4.10), see Table 13.6. Table 13.6 also lists the corresponding fatigue strength coefficients and fatigue ductility coefficients obtained from the LCF data in this Item.

The fatigue ductility coefficient, ϵ'_f , varies between 0.039 and 1.51 and $\epsilon_f/4$ (to which ϵ'_f should be compared, see Equation (4.9)) varies from 0.044 to 0.415, see Table 13.6. The agreement between ϵ'_f and $\epsilon_f/4$ is reasonable in about 25 per cent of the cases in Table 13.6 and the disagreement in the remaining cases is often great, with $\epsilon_f/4$ tending to be greater than ϵ'_f , see Sketch 10.5. Sketch 10.5 also shows data for other steels from Reference 24.



Sketch 10.5 Relationship between ϵ'_f and $\epsilon_f/4$ (see Table 13.6) for 316 stainless steel and other steels from Reference 24

It is proposed in Equation (4.7) that σ'_f is approximately equal to σ_f . The agreement between σ'_f and σ_f is reasonable in about 30 per cent of the cases in Table 13.6 and, as with ϵ'_f and $\epsilon_f/4$, the disagreement in the remaining cases is often great, particularly for lower values of σ_f , see Sketch 10.6. The agreement is significantly better above 500°C (932°F), but, in general, Equation (4.7) does not give a reliable prediction of the fracture strength coefficient.



Sketch 10.6 Relationship between σ'_f and σ_f (see Table 13.6)

10.3 Regression Analysis of Strain-Life Data

An analysis of the strain-life data was carried out to quantify the effect of test conditions and composition on fatigue life. The data that were analysed were taken from this Data Item and also from the stress-response curves in ESDU 05008. Only **total** strain-life data from tests for which complete specimen separation was the failure criterion were analysed.

To analyse the effects of total strain amplitude, strain rate, temperature and carbon and nitrogen content on the number of cycles to failure, a multiple linear regression analysis was carried out based on the methodology given in Appendix B.

Following preliminary analyses, it was assumed that the relationships between the logarithms of total strain amplitude, $\Delta\epsilon/2$, strain rate, $\dot{\epsilon}$, and carbon content, C, and the logarithm of fatigue life, N_f , were linear and that the relationships between temperature, T, (in °C) and the logarithm of nitrogen content, N, and the logarithm of fatigue life, N_f , were sinusoidal, that is $\log N_f$ is a function of

$$\sin \pi \frac{x - x_{\min}}{x_{\max} - x_{\min}},$$

where x can be either T or $\log N$.

The analysis of the data yielded the following expression for the predicted mean fatigue life, $N_{f_{pred}}$:

$$\begin{aligned} \log N_{f_{pred}} = & -2.31 \log \frac{\Delta\epsilon}{2} + 0.496 \sin \pi \frac{T + 269}{816 + 269} + 0.247 \log \dot{\epsilon} - 1.045 \log C \\ & + 0.064 \sin \pi \frac{\log N + 1.77}{-0.629 + 1.77} - 3.469. \end{aligned} \quad (10.1)$$

A plot of the predicted fatigue life, $\log N_{f_{pred}}$ versus the actual fatigue life, $\log N_f$, is shown in Sketch 10.7. The agreement is seen to be fairly good and this is reflected in the relatively high value of the correlation coefficient, r^2 , of 0.833. Sketch 10.7 also shows that some of the data are in the high-cycle fatigue regime (more than 10 000 cycles to failure).

The modified Anderson-Darling test statistic* for the residuals (the difference between $\log N_f$ and $\log N_{f_{pred}}$) is 1.13 which is greater than the critical value of 0.752 indicating that the hypothesis of normality should be rejected at a significance level of 5 per cent.

Further analysis of the residuals was performed to obtain an estimate of the value above which 99 per cent of the population of the residuals lies with 95 per cent confidence; that value is 0.775. Equation (10.1) can then be modified to provide a 95 per cent confidence, 99 per cent lower bound prediction of fatigue life:

$$\log N_{f_{99/95}} = \log N_{f_{pred}} - 0.775. \quad (10.2)$$

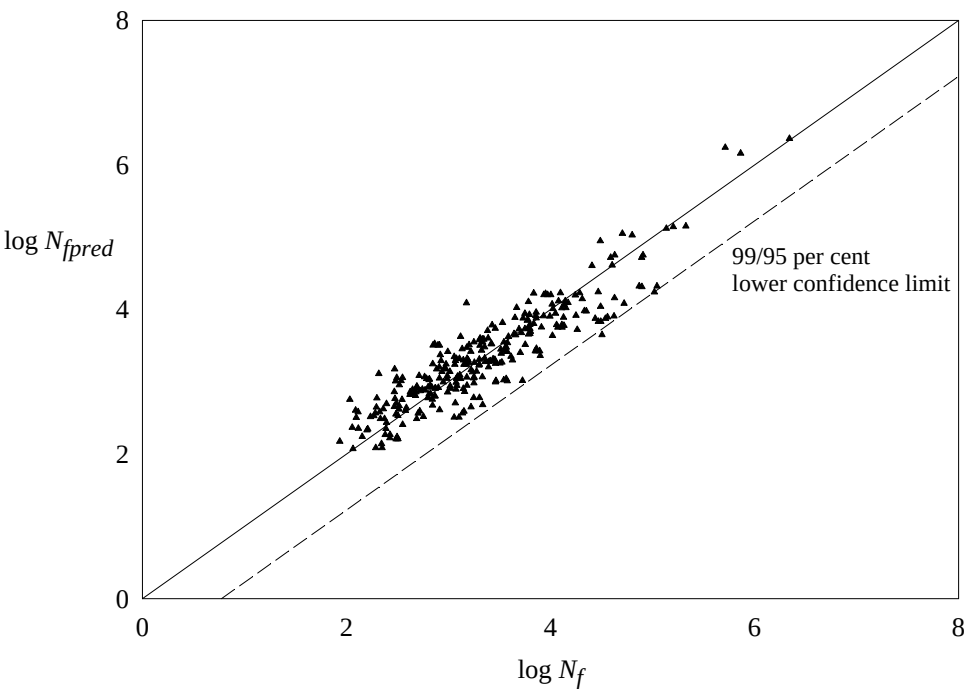
The ranges of the parameters included in the analysis from which Equation (10.1) is derived are given below. Equation (10.1), and therefore Equation (10.2), may be considered valid only within these limits.

If the material specification is known but the exact composition is not, Equation (10.1) may still be used assuming the limits for carbon and nitrogen composition given in Table 13.3.

* The test statistic was obtained using JAVApac 9141A v1.0, a program that accompanies ESDU 91041, "The statistical analysis of data from Normal distributions, with particular reference to small samples".

Parameter	Minimum	Maximum
$\Delta\epsilon/2$	0.0006	0.0251
T	-269°C (-452°F)	816°C (1501°F)
$\dot{\epsilon}$	$0.01 \times 10^{-3} \text{ s}^{-1}$	$6.7 \times 10^{-3} \text{ s}^{-1}$
C	0.017 wt%	0.086 wt%
N	0.017 wt%	0.235 wt%

A short example of the use of Equations (10.1) and (10.2) is given in Section 12.



Sketch 10.7 Predicted versus actual log fatigue lives from Equation (10.1)

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11. DERIVATION AND REFERENCES

This section is identical to the corresponding section in ESDU 05008. The derivations that are used in that Item but not in this are marked with an asterisk.

11.1 Derivation

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11.2 References

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12. EXAMPLE

It is necessary to carry out a preliminary assessment of the adequacy, or otherwise, of a component subject to low-cycle fatigue. The component is to be fabricated from a 316 stainless steel containing 0.08 wt% carbon and 0.03 wt% nitrogen. The component is to operate at room temperature (23°C (73°F)) and be subject to a total strain amplitude of 0.005; the time to reach peak strain from the unloaded condition is approximately 10 seconds, giving a strain rate of $\sim 0.5 \times 10^{-3} \text{ s}^{-1}$.

Substituting the information given above into Equation (10.1) gives

$$\begin{aligned} \log N_{f_{pred}} &= -2.31 \times -2.301 + 0.496 \sin \pi \frac{23 + 269}{816 + 269} + 0.247 \times -3.301 \\ &\quad - 1.045 \times -1.097 + 0.064 \sin \pi \frac{-1.523 + 1.77}{-0.629 + 1.77} - 3.469 \\ &= 3.353, \end{aligned}$$

from which, $N_{f_{pred}} = 2255$ cycles.

To obtain a 95 per cent confidence, 99 per cent lower bound, the shift of Equation (10.2) is applied, giving

$$\log N_{f_{99/95}} = 3.353 - 0.775,$$

from which, $N_{f_{99/95}} = 378$ cycles.

Data for similar materials and strain rate are given in Figures 9 and 11: Figure 9 provides data for an S31600-B11 stainless steel with 0.075 wt% carbon and 0.026 wt% nitrogen tested at room temperature and at a strain rate of $0.67 \times 10^{-3} \text{ s}^{-1}$; Figure 11 provides data for a S31600-C stainless steel with 0.081 wt%

carbon and 0.04 wt% nitrogen, again tested at room temperature and at a strain rate of $0.67 \times 10^{-3} \text{ s}^{-1}$. For a total strain amplitude of 0.005, Figure 9 gives a mean fatigue life of about 5650 cycles and Figure 11 gives a mean life of about 8800 cycles.

In this example, using Equations (10.1) and (10.2) gives quite a conservative prediction of fatigue life.

If the strain amplitude could be reduced to, say, 0.003, the predicted number of cycles to failure becomes

$$\begin{aligned} \log N_{f_{pred}} &= (-2.31 \times (-2.523)) + \left(0.496 \sin \pi \frac{23 + 269}{816 + 269} \right) + (0.247 \times (-3.301)) \\ &\quad (-1.045 \times (-1.097)) + \left(0.064 \sin \pi \frac{-1.523 + 1.77}{-0.629 + 1.77} \right) - 3.469 \\ &= 3.861, \end{aligned}$$

from which $N_{f_{pred}} = 7265$ cycles.

To obtain a 95/99 per cent confidence level (Equation (10.2)) giving

$$\log N_{f_{99/95}} = 3.861 - 0.775,$$

from which, $N_{f_{99/95}} = 1219$ cycles. From the above calculations, it is clear that a relatively small change in strain amplitude gives a more than three-fold increase in the predicted life.

13. TABLES AND FIGURES

13.1 Index to Tables and Figures

TABLE 13.1 Index to Tables

Table number	Title
13.1	Index to Tables
13.2	Index to Figures
13.3	Details of 316 austenitic stainless steels
13.4	Mechanical properties of 316 stainless steels
13.5	Summary of fatigue strength and ductility constants, transition fatigue life and fatigue life at an applied plastic strain amplitude of 0.01
13.6	Calculated fracture strength and fracture ductility from monotonic test data (see Table 13.4) compared with fatigue strength and ductility coefficients calculated from cyclic data
13.7	Test conditions for Figures 19, 43 to 45 and 59 to 61
13.8	Test conditions for Figures 8 to 11, 20 to 24, 32 to 37, 46 to 51, 57 and 58
13.9	Test conditions for Figures 7, 16 to 18, 25 to 27, 38 to 40 and 52 to 54
13.10	Test conditions for Figure 31
13.11	Test conditions for Figure 41
13.12	Test conditions for Figures 55 and 56
13.13	Test conditions for Figures 1 to 3, 5, 12 and 14
13.14	Test conditions for Figures 29 and 42
13.15	Test conditions for Figures 62 and 63
13.16	Test conditions for Figure 28
13.17	Test conditions for Figures 6, 15 and 30
13.18	Test conditions for Figures 4 and 13
13.19	Test conditions for Derivation 21
13.20	Fatigue ductility coefficients and exponents for S31653/S31600 weldments

TABLE 13.2 Index to Figures

Figure	Stainless steel	Test temperature °C (°F)	Strain rate 10^{-3} s^{-1}	Test conditions given in Table:	Derivation
1	S31653	-269 (-452)	4	13.13	9
2	S31653 ^{HT}				
3	S31653	-196 (-321)	4	13.13	9
4	S31653	-196 (-321)	4	13.18	17
5	S31653 ^{HT}	-196 (-321)	4	13.13	9
6	S31603	23 (73)	2	13.17	16
7	S31600	23 (73)	1	13.9	4
8	S31600-B11	23 (73)	6.7	13.8	3
9			0.67		
10	S31600-C	23 (73)	6.7	13.8	3
11			0.67		
12	S31653	23 (73)	4	13.13	9
13	S31653	23 (73)	4	13.18	17
14	S31653 ^{HT}	23 (73)	4	13.13	9
15	S31603	300 (572)	2	13.17	16
16	S31600	400 (752)	1	13.9	4
17			0.1		
18			0.01		
19	S31600	430 (806)	4	13.7	1
20	S31600-B11	450 (842)	6.7	13.8	3
21			0.67		
22			0.067		
23	S31600-C	450 (842)	6.7	13.8	3
24			0.067		
25	S31600	500 (932)	1	13.9	4
26			0.1		
27			0.01		
28	S31603	550 (1022)	0.003	13.16	15
29	S31603	600 (1112)	NA	13.14	11
30	S31603	600 (1112)	2	13.17	16
31	S31600	600 (1112)	5	13.10	5
32	S31600-B11	600 (1112)	6.7	13.8	3
33			0.67		
34			0.067		
35	S31600-C	600 (1112)	6.7	13.8	3
36			0.067		
37			0.067		
38	S31600	600 (1112)	1	13.9	4
39			0.1		
40			0.01		

^{HT} Heat treated for 200 h at 500°C (932°F).

TABLE 13.2 Index to Figures (Continued)

Figure	Stainless steel	Test temperature °C (°F)	Strain rate 10^{-3} s^{-1}	Test conditions given in Table:	Derivation
41	S31653	600 (1112)	5	13.11	6
42	S31603	625 (1157)	NA	13.14	11
43	S31600	650 (1202)	4	13.7	1
44			0.4		
45			0.04		
46	S31600-B11	700 (1292)	6.7	13.8	3
47			0.67		
48			0.067		
49	S31600-C	700 (1292)	6.7	13.8	3
50			0.67		
51			0.067		
52	S31600	700 (1292)	1	13.9	4
53			0.1		
54			0.01		
55	S31600	750 (1382)	1	13.12	8
56		750 (1382)*			
57	S31600-B11	800 (1472)	6.7	13.8	3
58			0.067		
59	S31600	816 (1501)	4	13.7	1
60			0.4		
61			0.04		
62	S31653/ S31600 weld	500 (932)	3	13.15	14
63	S31653/ S31600 weld	600 (1112)	3	13.15	14

* Included hold time of 5 minutes at maximum stress for each cycle.

13.2 General Details of Type 316 Austenitic Stainless Steels

TABLE 13.3 Details of 316 Austenitic Stainless Steels

UNS Number	Cross-reference specifications	Description	Composition wt%									
				C	Si	Mn	P	S	Ni	Cr	Mo	N
S31600	SUS316, SUS316-HP, AISI316	Austenitic Cr-Ni-Mo stainless steel	<i>min.</i>						10.00	16.00	2.00	
			<i>max.</i>	0.08	1.00	2.00	0.045	0.030	14.00	18.00	3.00	
S31603	SUS316L, AISI316L, 316L, 17-12 SPH	Austenitic Cr-Ni-Mo stainless steel (low carbon)	<i>min.</i>						10.00	16.00	2.00	
			<i>max.</i>	0.03	1.00	2.00	0.045	0.030	14.00	18.00	3.00	
S31653	SUS316LN, AISI316LN, 316LN	Austenitic nitrogen-bearing Cr-Ni-Mo stainless steel	<i>min.</i>						10.00	16.00	2.00	0.10
			<i>max.</i>	0.03	1.00	2.00	0.045	0.030	14.00	18.00	3.00	0.16

Note that a UNS designation is not, in itself, a specification, since it establishes no requirements for form, condition, properties or quality. It is a unified identifier of a metal or an alloy for which controlling limits have been established in specifications published elsewhere.