



**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)**

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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)

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CYCLIC STRESS-STRAIN RESPONSE OF TYPE 316 AUSTENITIC STAINLESS STEELS DURING LOW-CYCLE FATIGUE AT TEMPERATURES BETWEEN -269°C AND 800°C (-452°F AND 1472°F)

1. INTRODUCTION

This Item presents data on the cyclic stress-strain response of type 316 austenitic stainless steels tested at high load levels, in the low-cycle fatigue (LCF) regime, and a discussion of the factors that influence fatigue life and cyclic stress-strain response. Strain-life data for 316 stainless steels are presented in ESDU 05007^{*}. Type 316 stainless steels have a wide variety of applications ranging from use at cryogenic temperatures (down to -269°C (-452°F)) up to elevated temperatures (800°C (1472°F)).

Type 316 austenitic stainless steels are used to fabricate components for use at cryogenic temperatures as they do not experience a decrease in toughness at temperatures below room temperature, unlike other types of stainless steel. 316 stainless steels are also used at room temperature, and just above, by the oil, chemical, food and paper industries, and in general for pipes that carry warm fluids. At high temperatures, above 450°C (842°F), experience has shown that LCF failures may occur in 316 stainless steel structures during start-up/shut-down procedures, or other operating procedures, in power-generating plant.

The derivation of the equations used in this Item is given in Section 3 and a general discussion of low-cycle fatigue phenomena can be found in ESDU 04022[†].

Data on the effect of cyclic loading on stress during LCF tests of 316 stainless steels at temperatures between -269 and 625°C (-452 and 1157°F) are discussed in Sections 4 to 7. A summary of Sections 4 to 7 is given in Section 8.

The cyclic stress-strain behaviour of 316 stainless steels is discussed in Section 9, along with the calculation of cyclic hardening constants.

Section 10 lists the Derivations and References used in the preparation of the Data Item.

In Section 11, two worked examples are presented to illustrate the calculation of cyclic stress-strain constants from test data and a prediction of LCF life using the results of the multiple linear regression analysis described in ESDU 05007.

An index to the figures and tables in this Item is given in Section 12.1.

To assist with the location and comparison of data for particular stainless steels, Table 12.3 gives the UNS code of the 316 stainless steels for which data are presented, their chemical compositions and some of their common cross-reference specifications.

* ESDU 05007 "Strain-life data for type 316 austenitic stainless steels at temperatures between -269°C and 816°C (-452 and 1501°F)".

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

1.1 Notation

b	fatigue strength exponent		
C	carbon content	wt%	wt%
c	fatigue ductility exponent		
E	modulus of elasticity	N/m ²	lbf/in ²
$H_{\Delta\epsilon/2}$	degree of strain-hardening at strain amplitude of $\Delta\epsilon/2$ (see Equation (8.1))	per cent	per cent
$H_{\Delta\epsilon/2norm}$	normalized degree of strain-hardening at strain amplitude of $\Delta\epsilon/2$	per cent	per cent
K'_{sc}	cyclic strength coefficient	N/m ²	lbf/in ²
$K'_{sc,calc}$	calculated cyclic strength coefficient	N/m ²	lbf/in ²
K'_{scnorm}	normalized cyclic strength coefficient	N/m ²	lbf/in ²
n'	cyclic strain-hardening exponent		
n'_{calc}	calculated cyclic strain-hardening exponent		
n'_{norm}	normalized cyclic strain-hardening exponent		
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_{fnorm}	normalized number of cycles to failure	cycles	cycles
N_{fpred}	predicted number of cycles to failure	cycles	cycles
N_5	number of cycles corresponding to a 5 per cent decrease in the maximum tensile load	cycles	cycles
N_{10}	number of cycles corresponding to a 10 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

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

T	temperature	°C	°F
$\Delta\epsilon/2$	total strain amplitude		
$\Delta\sigma/2$	total stress amplitude	N/m ²	lbf/in ²
$(\Delta\sigma/2)_I$	initial stress amplitude	N/m ²	lbf/in ²
$(\Delta\sigma/2)_P$	peak stress amplitude	N/m ²	lbf/in ²
$(\Delta\sigma/2)_{Pnorm}$	normalized peak stress amplitude	N/m ²	lbf/in ²
$\dot{\epsilon}$	strain rate	s ⁻¹	s ⁻¹
ϵ'_f	fatigue ductility coefficient		
σ'_f	fatigue strength coefficient	N/m ²	lbf/in ²

2. TEST CONDITIONS

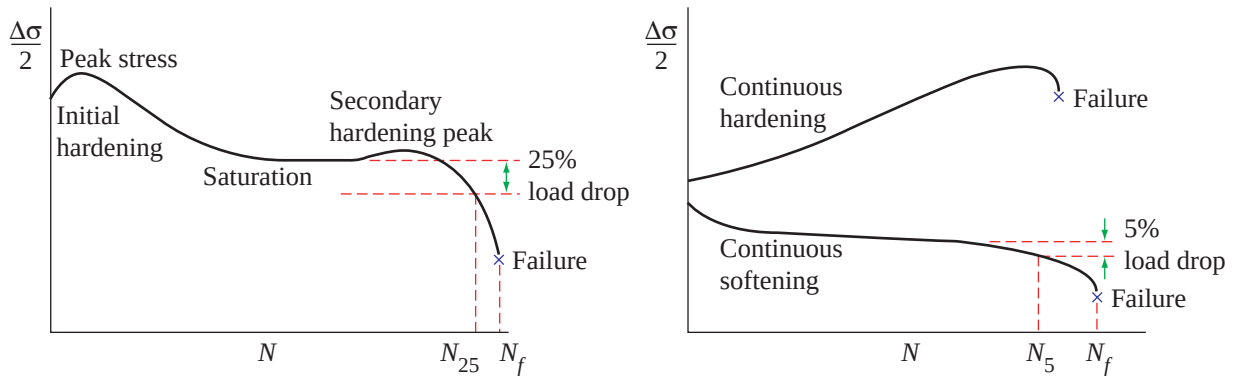
Typically, to generate data to determine stress response curves and cyclic stress-strain curves for 316 stainless steels, constant amplitude, fully-reversed, axial, strain-controlled LCF tests with zero mean strain are performed and all the data presented in this Item are from such tests. The tests are 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 below room temperature in a cryogenic gas environment. 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. Details of the test piece shape, heat treatment applied and the testing conditions are given in the tables that accompany the figures in Section 12, see Tables 12.4 to 12.17.

3. DETERMINING FATIGUE PROPERTIES

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

3.1 Stress-Response Curves

The stress response, or hardening and softening behaviour, of a material is shown by the evolution of stress as cycles of constant strain amplitude are applied. Sketch 3.1 illustrates some features of stress-response curves. Peak stresses are measured after initial hardening, and before stabilization (sometimes called saturation) of the curve. In certain cases, there may be a secondary hardening peak before final failure. It is not possible to estimate a peak stress for cases where continuous hardening or softening occurs.



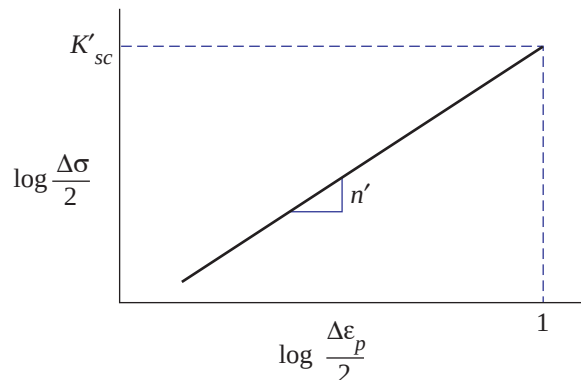
Sketch 3.1 Some typical stress response curves and examples of failure criteria, N_f , N_5 and N_{25}

3.2 Cyclic Stress-Strain Curves

Values of stress and strain, taken at half life-to-failure or when the cycling has stabilized, are used to obtain plots of cyclic true stress versus true plastic strain curves (see Sketch 3.2). The relationship between the stress amplitude and the strain amplitude may be expressed using the cyclic strength coefficient, K'_{sc} , and the cyclic strain hardening exponent, n' :

$$\frac{\Delta\sigma}{2} = K'_{sc} \left(\frac{\Delta\epsilon_p}{2} \right)^{n'} \quad (3.1)$$

Using this relationship, and a log-log plot of the form of Sketch 3.2, K'_{sc} and n' can be calculated.



Sketch 3.2 Log-log plot of cyclic stress versus cyclic plastic strain

Re-arranging Equation (3.1) gives

$$\frac{\Delta\epsilon_p}{2} = \left(\frac{\Delta\sigma}{2K'_{sc}} \right)^{\frac{1}{n'}} \quad (3.2)$$

The total strain is the sum of the elastic and plastic components. Therefore, using Equation (3.2) and Hooke's law $\frac{\Delta \epsilon_e}{2} = \frac{\Delta \sigma}{2E}$, the total strain amplitude may be expressed in the form:

$$\frac{\Delta \epsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'_{sc}} \right)^{\frac{1}{n'}} \quad (3.3)$$

3.3 Calculation of Cyclic Hardening Constants Using Strain-Life Data

Values of the fatigue strength coefficient, σ'_f , and the fatigue ductility coefficient, ϵ'_f , can be calculated from strain-life data (see ESDU 05007) using the strain-life relationship

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E} N_f^b + \epsilon'_f N_f^c, \quad (3.4)$$

where N_f is the number of cycles to failure, b is the fatigue strength exponent, and c is the fatigue ductility exponent.

Combining Equations (3.3) and (3.4) gives

$$n'_{calc} = \frac{b}{c} \quad (3.5)$$

$$\text{and} \quad K'_{sc, calc} = \frac{\sigma'_f}{\epsilon'^{\frac{1}{n'}}_f} \quad (3.6)$$

4. STRESS RESPONSE AT CRYOGENIC TEMPERATURES ($\leq -196^\circ\text{C}$ (-321°F))

Figures 1a to 3b show the cyclic stress response of S31653 stainless steels cycled at different strain amplitudes at -269 and -196°C (-452 and -321°F), and that of S31603 stainless steels cycled at a temperature of -196°C (-321°F). Supplementary information, including the initial and peak stresses ($(\Delta\sigma/2)_I$ and $(\Delta\sigma/2)_P$, respectively), and the fatigue life, N_f , from the stress-response curves are given in Table 12.18.

4.1 Effect of Cycling on Stresses at Cryogenic Temperatures

For S31653 stainless steels tested at -269 and -196°C (-452 and -321°F), slight cyclic hardening occurs before stabilisation of stress prior to failure for applied strain amplitudes up to 0.0075, see Figures 1a and 3b. When the strain amplitude increases above 0.01, a secondary hardening peak occurs before final failure.

At -196°C (-321°F), S31603 stainless steel shows an initial stress peak followed by continuous softening for an applied strain amplitude of 0.0125, see Figure 2. For S31653 stainless steels the initial stress is greater at -296°C (-452°F) than at -196°C (-321°F).

After initial hardening, the peak stresses of S31653 stainless steels are greater at -269°C (-452°F) than at -196°C (-321°F), see Table 12.18; also, as the strain amplitude increases, the peak stresses increase because of work hardening or as a result of the heat treatment (500°C (932°F) for 200 hours) applied to the stainless steels prior to testing.

4.2 Effect of Cycling on LCF Life at Cryogenic Temperatures

For S31653 stainless steels, all else being equal, fatigue life is greatest at -196°C (-321°F), apart from below strain amplitudes of 0.008 when the fatigue life at -269°C (-452°F) is greatest, see Table 12.18. A reason for greater fatigue lives below room temperature is the decrease in the plastic strain range due to the increase in yield strength (Derivation 9).

Nitrogen-alloyed S31653 stainless steels are often used below room temperature as nitrogen stabilises the austenitic grain structure of 316 stainless steels against strain-induced transformation to martensite at low temperatures. However, above a critical strain amplitude of about 0.01, strain-induced martensite still forms during LCF at -196°C (-321°F) which leads to the production of martensite islands which act as additional obstacles to early growth of fatigue cracks (Derivation 17). A small improvement in fatigue life is seen for heat-treated S31653 stainless steels.

5. STRESS RESPONSE AT ROOM TEMPERATURE (23°C (73°F))

The cyclic stress responses of S31603, S31600 and S31653 stainless steels cycled at room temperature (nominally 23°C (73°F)) are given in Figures 4 to 6c; supplementary information is given in Table 12.18.

5.1 Effect of Cycling on Stress at Room Temperature

For all the 316 stainless steels for which room temperature data are presented, peak stress increases with increasing applied strain amplitude, see Figures 4, 5 and 6c, though there is a lot of scatter in the data. Even when the peak stress data are normalized* to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt% and a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$ to give $(\Delta\sigma/2)_{P_{norm}}$, there is still a lot of scatter in the data, see Figure 7.

For S31603 stainless steels tested at room temperature, initial cyclic hardening is followed by a saturation stage, the duration of which decreases as strain amplitude increases, see Figure 4. An exception to this is found in the results for the S31603 stainless steels from Derivations 13 and 23, which show continuous softening until failure, see Table 12.18.

Initially, cyclic hardening occurs as dislocations are generated in the relatively dislocation-free microstructure. As more dislocations are generated, they interact and restrict dislocation movement to produce a hardening effect. The anomaly for S31603 stainless steels, where the stress-response curve shows continuous softening until failure, can be explained by dislocation starvation (difficulty in generating dislocations to carry the applied strain) and dislocation annihilation (cancelling out of dislocations when those of opposite sign meet on the same plane). Therefore, higher stresses are induced during the initial cycles to carry the applied strain, and softening occurs with a decrease in the induced stress as the availability of dislocations diminishes (Derivation 21).

For S31653 stainless steels with nitrogen contents of up to 0.18 wt%, and with strain amplitudes of up to 0.016, a slight amount of initial hardening occurs before saturation, see Figures 6a and 6b. As for S31603 stainless steels, the duration of the saturation stage before failure decreases up to a strain amplitude of 0.016.

* 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} :

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

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

Heat-treated S31653 stainless steels show higher initial and peak stresses than their un-heat-treated counterparts, except for at a low strain amplitude of 0.003, where the heat-treated S31653 stainless steel shows continuous softening, see Figure 6c.

When the nitrogen content of S31653 stainless steel is high (0.235 wt%) the stainless steel hardens continuously. Since it is unlikely that precipitation occurs at room temperature, this hardening is attributed to the formation of dislocation cell networks (Derivation 12).

Figure 8 shows $(\Delta\sigma/2)_p$ of 316 stainless steels normalized to a nitrogen content of 0.1wt%, a carbon content of 0.02 wt% and a strain amplitude of 0.005. There are no clear trends on Figure 8.

Increasing the applied strain rate raises the peak stress for S31653 and S31603 stainless steels. At a strain rate of $4 \times 10^{-3} \text{ s}^{-1}$, the peak stress of S31653 stainless steel is less than that of S31603 stainless steel (433.5 MN/m^2 ($62.9 \times 10^3 \text{ lbf/in}^2$) and 509.2 MN/m^2 ($73.9 \times 10^3 \text{ lbf/in}^2$), respectively). However, for a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$, the peak stress of S31653 stainless steel is slightly larger than that of S31603 stainless steel (383.2 MN/m^2 ($55.6 \times 10^3 \text{ lbf/in}^2$) and 336 MN/m^2 ($48.7 \times 10^3 \text{ lbf/in}^2$), respectively).

In Figure 9, when the carbon content, strain rate and strain amplitude are normalized to 0.02 wt%, $3 \times 10^{-3} \text{ s}^{-1}$ and 0.005, respectively, $(\Delta\sigma/2)_{p\text{norm}}$ increases with increasing nitrogen content for 316 stainless steels though the scatter in the data makes the drawing of clear conclusions difficult.

5.2 Effect of Cycling on LCF Life at Room Temperature

As strain amplitude increases, the fatigue life of 316 stainless steels decreases. Figure 10 shows the fatigue life of 316 stainless steels normalized to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt% and a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$ to give $N_{f\text{norm}}$. The fatigue life of heat-treated S31653 stainless steels is greater than that of S31603 and S31653 stainless steels at strain amplitudes below 0.005.

Increasing the strain rate appears to reduce the fatigue life for both S31603 and S31653 stainless steels, see Table 12.18. However, when the fatigue life is normalized to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt% and a strain amplitude of 0.005, there is little evidence of this effect, see Figure 11.

Nitrogen content also appears to have no discernible effect on the fatigue life of 316 stainless steels, see Table 12.18 and Figure 12 which shows the variation with nitrogen content of fatigue life normalized to a carbon content of 0.02 wt%, a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$, and a strain amplitude of 0.005.

The effect of carbon content on the peak stress and fatigue life during LCF is thought to be small.

6. STRESS RESPONSE AT TEMPERATURES BETWEEN 40 AND 450°C (104 AND 842°F)

The evolution of stress at constant strain amplitude at intermediate temperatures (40 to 450°C (104 to 842°F)) is given in Figures 13 to 16; supplementary information is given in Table 12.18.

6.1 Effect of Cycling on Stress at Intermediate Temperatures

For the data available, S31603 stainless steels appear to show continuous softening between 40 and 200°C (104 and 392°F), though for strain amplitudes of less than 0.002, both an initial and a small secondary hardening peak occur before failure, see Figure 13. For temperatures between 200 and 430°C (392 and 806°F), S31603 and S31653 stainless steels show initial cyclic hardening. There is also some secondary hardening before failure at lower strain amplitudes at 300 and 400°C (572 and 752°F), see Figures 14a to 16.

For a given strain amplitude, the peak stress decreases in S31603 stainless steels for temperatures from 40 to 200°C (104 to 392°F) but increases for temperatures from 300°C to 400°C (572°F to 752°F). Generally, for a given temperature, increasing the applied strain amplitude raises the peak stress for S31603 stainless steels, see Figure 17 where $(\Delta\sigma/2)_P$ is normalized to a temperature of 200°C (392°F) and a strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ to give $(\Delta\sigma/2)_{Pnorm}$.

Peak stresses are lower at intermediate temperatures than at room or cryogenic temperatures. This is because of the decrease in tensile and yield strength with temperature. At room temperature, interstitial carbon and nitrogen atoms are relatively immobile and raise the yield strength of the stainless steel by hindering dislocation movement. However, above 100°C (212°F), interstitial atoms are so mobile that they are no longer effective dislocation obstructions. Yield strength decreases steeply up to 300°C (572°F), then more slowly up to 600°C (1112°F), with a 'quasi-plateau' in the temperature range 300 to 400°C (572 to 752°F). At temperatures between 200 and 400°C (392 and 752°F), dynamic strain ageing (DSA) begins. See Section 3.2.1 of ESDU 04022 for a description of DSA.

For S31653 stainless steel cycled at 300°C (572°F), increasing the nitrogen content from 0.042 to 0.151 wt% raises the peak stress from 246 to 284 MN/m² (35.6×10^3 to 41.3×10^3 lbf/in²), see Figure 14a. However, at 300°C (572°F), a S31603 stainless steel tested with the same strain rate and strain amplitude shows a higher peak stress of 306 MN/m² (44.4×10^3 lbf/in²) than the S31653 stainless steels, see Figures 14a and 14b.

The contribution of nitrogen to the strengthening of 316 stainless steels above room temperature is made up of two components:

- a thermal component due to solid solution strengthening, proportional to $\sqrt{\text{nitrogen content}}$, which is strong below 300°C (572°F), and
- an athermal component (attributed to short-range order of dislocations that are present and which inhibit cross slip) which is proportional to the nitrogen content and/or the degree of grain refinement.

6.2 Effect of Cycling on LCF Life at Intermediate Temperatures

For a given temperature, fatigue life normalized to a temperature of 200°C (392°F) and a strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ decreases when the strain amplitude is increased for S31603 stainless steel, see Figure 18.

For S31653 stainless steels cycled at 300°C (572°F), nitrogen content appears to have little effect on fatigue life (9576, 10 655 and 9231 cycles for nitrogen contents from 0.042 to 0.151 wt%), see Figure 14a. The fatigue life of S31653 stainless steels at 300°C (572°F) is less than that of S31603 stainless steels tested under the same conditions, see Figure 14b.

7. STRESS RESPONSE AT TEMPERATURES ABOVE 450°C (842°F)

The evolution of stress for S31603 stainless steels during cycling at 500 and 600°C (932 and 1112°F) for a range of nitrogen contents, strain rates and strain amplitudes is shown in Figures 19 and 20a. The effect of prior ageing on the stress response of S31603 stainless steels at 625°C (1157°F) is shown in Figure 21. See Table 12.18 for supplementary information.

7.1 Effect of Cycling on Stress at Elevated Temperatures

At 500°C (932°F), a S31603 stainless steel shows continuous hardening over life, with a clear increase in the rate of hardening prior to failure, see Figure 19. At 600°C (1112°F), S31653 and S31603 stainless steels tend to harden toward a peak stress which increases with nitrogen content, strain rate and strain amplitude – apart from S31603 stainless steels cycled at a very low strain amplitude (0.0006) which show continuous hardening until failure, see Figure 20a (Derivation 16).

For S31603 stainless steels, elevating the temperature from 500 to 600°C (932 to 1112°F) increases the peak stress from 236 to 281 MN/m² (34.2×10^3 to 40.8×10^3 lbf/in²) for the same strain rate and applied strain amplitude. At 600°C (1112°F), increasing the strain amplitude from 0.0006 to 0.005 raises the peak stress for a given strain rate. Also, reducing the strain rate from $10 \times 10^{-3} \text{ s}^{-1}$ to $0.2 \times 10^{-3} \text{ s}^{-1}$ causes an increase in the peak stress for a given temperature.

The effect of prior ageing (800°C (1472°F) for 10 hours or 700°C (1292°F) for 400 hours) on S31603 stainless steels cycled at temperatures above 625°C (1157°F) is to increase their strength, see Figure 21. However, the prior-aged stainless steels do not harden at the same rate as the stainless steels that have only been solution heat treated, and the stress in the saturation stage is lower for the prior-aged stainless steels.

During cycling at these temperatures, fatigue-induced precipitation and/or DSA can occur, and one or both of these is likely to be responsible for the initial hardening (Derivation 18). DSA at elevated temperatures, above 450°C (842°F), occurs by the diffusion of chromium to dislocations; the diffusivity of chromium is related to the nitrogen content of the stainless steel.

7.2 Effect of Cycling on LCF Life at Elevated Temperatures

At elevated temperatures, increasing the strain rate increases the number of cycles to failure at a given test temperature, see Figure 20b. For a S31653 stainless steel, a fatigue life of 2160 cycles is recorded for a strain rate of $0.2 \times 10^{-3} \text{ s}^{-1}$, and 5059 cycles for a strain rate of $10 \times 10^{-3} \text{ s}^{-1}$. Ageing S31603 stainless steels prior to testing decreases fatigue life, see Figure 21.

As at 300°C (572°F), increasing the nitrogen content in S31653 stainless steels cycled at 600°C (1112°F) does not have a significant effect on fatigue life (2562, 3065 and 2180 cycles for nitrogen contents from 0.042 to 0.151 wt%), see Figure 20a.

8. SUMMARY OF DATA FROM STRESS-RESPONSE CURVES

The effect of test conditions and nitrogen content on peak stress data, $(\Delta\sigma/2)_p$, is discussed in Section 8.1. In Section 8.2, the effect of test conditions on N_f is considered. In Section 8.3, the amount of hardening or softening during an LCF test, $H_{\Delta\epsilon/2}$, is discussed.

8.1 Peak Stress, $(\Delta\sigma/2)_p$

Temperature

When the test temperature is increased from -269°C to 625°C (-452 to 1157°F), $(\Delta\sigma/2)_p$ decreases to a minimum value at around 300°C (572°F) for both S31603 and S31653 stainless steels. Figure 22 shows $(\Delta\sigma/2)_p$ normalized to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt%, a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$, and a strain amplitude of 0.005, plotted against temperature. There is a lot of scatter in the data and no clear trend can be observed.

Strain amplitude

For S31603 stainless steels (0.022 wt% carbon and 0.069 wt% nitrogen) cycled at a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$ and a constant applied strain amplitude, $(\Delta\sigma/2)_p$ decreases to a minimum at 300°C (572°F), except when the strain amplitude is 0.0006 where $(\Delta\sigma/2)_p$ decreases continuously with temperature, see Figure 23. At any given temperature, $(\Delta\sigma/2)_p$ of S31603 stainless steels increases with increasing strain amplitude.

Nitrogen content

For a given temperature, increasing the nitrogen content of S31653 stainless steels (approximate carbon content of 0.019 wt%) increases $(\Delta\sigma/2)_p$ when they are cycled at a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$ and a strain amplitude of 0.005, see Figure 24. For a given nitrogen content, $(\Delta\sigma/2)_p$ is highest at room temperature, and lowest at 300°C (572°F).

8.2 Number of Cycles to Failure, N_f

Temperature

For 316 stainless steels, there is no clear correlation between test temperature and N_f normalized to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt%, a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$, and a strain amplitude of 0.005, see Figure 25.

In Reference 25, it is reported that a peak in the fatigue life of 316 stainless steels occurs at about 300°C (572°F). No such peak is observed for the data in this Item, emphasizing the complex interaction between various temperature-related factors and their effect on fatigue life. For example, DSA occurs at temperatures above 300°C (572°F) which reduces the number of cycles to crack initiation and increases crack propagation rates, thereby reducing the fatigue life. Above 600°C (1112°F), an interaction between creep and fatigue may reduce the number of cycles to failure. By comparing the results of tests carried out above 600°C (1112°F) in air with those of tests carried out at the same temperature in a vacuum, it can be seen that oxidation reduces the fatigue life of 316 stainless steels (Reference 22). Below room temperature, LCF life is affected by strain-induced martensite which creates preferential sites of crack initiation and can increase fatigue crack growth rates by increasing the stress amplitude (Derivation 17).

Strain amplitude

For S31603 stainless steels (0.022 wt% carbon and 0.069 wt% nitrogen) cycled at a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$ and applied strain amplitudes of 0.0006 and 0.002, a peak in N_f occurs at 300°C (572°F), and for strain amplitudes of 0.005, N_f peaks at 400°C (752°C), see Figure 26. For a given temperature, the fatigue life of S31603 stainless steels increases as applied strain amplitude decreases from 0.005 to 0.0006.

A reason for the improvement in fatigue life during cycling at 'intermediate' temperatures (40 to 450°C (104 to 842°F)) is a change in the dislocation structures and slip characteristics, associated with the interaction of dislocations with carbon and nitrogen solute atoms (which also causes DSA). This improved dislocation structure accommodates plastic strains because of a dense homogeneous slip distribution; it is also responsible for secondary hardening (Reference 23).

Nitrogen content

Figure 27 shows that fatigue life is much greater at 23 and 300°C (73 and 572°F) than at 600°C (1112°F), and though there is a slight peak in N_f at a nitrogen content of around 0.1 wt%, nitrogen has little effect on N_f .

Fatigue life is expected to decrease continuously with a decrease in strain rate for S31653 stainless steels cycled at a constant temperature between 500 and 600°C (932 and 1112°F) because of enhanced crack initiation and propagation due to the influence of DSA (Reference 24).

The application of hold times simulates creep-fatigue interaction which reduces the number of cycles to failure in 316 stainless steels (see Section 8.1 of ESDU 05007).

8.3 Degree of Hardening, $H_{\Delta\epsilon/2}$

From the stress-response curves, the percentage of the degree of hardening at a particular strain amplitude, $H_{\Delta\epsilon/2}$, can be calculated as the difference between the peak and the initial stresses using the equation

$$H_{\Delta\epsilon/2} = \frac{(\Delta\sigma/2)_P - (\Delta\sigma/2)_I}{(\Delta\sigma/2)_I} \times 100, \quad (8.1)$$

where $(\Delta\sigma/2)_P$ is the stress amplitude at the peak of the stress-response curve or at stabilisation, and $(\Delta\sigma/2)_I$ is the stress amplitude of the first cycle.

Values of the degree of hardening calculated from the stress-response curves are reported in Table 12.18 for temperatures from -269 to 625°C (-452 to 1157°F). When a stainless steel shows continuous softening or hardening, it is clearly not possible to determine a peak stress. For these cases, an estimation of the stress amplitude at the number of cycles at which the peak stress is found in similar stainless steels at the same test temperature is used.

Temperature

As temperature increases, both $(\Delta\sigma/2)_P$ and $(\Delta\sigma/2)_I$ decrease. Figure 28 shows $H_{\Delta\epsilon/2}$ normalized to a nitrogen content of 0.1 wt%, a carbon content of 0.02 wt%, a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$ and a strain amplitude of 0.005 to give $H_{\Delta\epsilon/2 \text{ norm}} \cdot H_{\Delta\epsilon/2 \text{ norm}}$ increases with temperature indicating a divergence between the initial and the peak stresses at higher temperatures. There is a large amount of variability in $H_{\Delta\epsilon/2 \text{ norm}}$ because of other test conditions. Negative values on Figure 28 indicate softening.

Strain amplitude

For all strain amplitudes, $H_{\Delta\epsilon/2}$ increases with temperature from 23 to 600°C (73 to 1112°F), except for a strain amplitude of 0.005, for which the degree of hardening decreases slightly above 400°C (752°F), see Figure 29.

Nitrogen content

For S31653 stainless steels cycled at constant temperature, $H_{\Delta\epsilon/2}$ decreases as nitrogen content is increased to 0.1 wt%, but then increases with higher nitrogen contents, see Figure 30. For each nitrogen content, the degree of hardening is greatest at 600°C (1112°F).

The variation in the degree of hardening suggests that cyclic hardening mechanisms are nitrogen- and temperature-dependent (*e.g.* dependent on precipitates and ageing processes), and therefore probably not dislocation-dependent. This is because at elevated temperatures the dislocation density decreases over time. Also, at these temperatures, it is likely that chromium carbides may precipitate and harden the stainless steel; however, the diffusivity of chromium is retarded by nitrogen. Since it is thought that chromium diffusion is responsible for DSA, increasing the nitrogen content of 316 stainless steel will reduce the hardening effects due to DSA (Derivation 18).

9. CYCLIC STRESS-STRAIN BEHAVIOUR

Figures 31 to 49 show half-life cyclic stress-strain curves at temperatures from room temperature to 800°C (1472°F). The cyclic strength coefficient, K'_{sc} , and the strain-hardening exponent, n' , are given in Table 12.19. K'_{sc} is the estimated stress at a plastic strain amplitude equal to 1 and n' is a measure of the cyclic ductility of the material; the closer the value to 1, the more ductile is the material.

Generally, the cyclic strength coefficient and cyclic hardening exponent are sensitive to changes in temperature and strain rate. On Figures 50 and 51, K'_{sc} and n' normalized to a nitrogen content of 0.03 wt%, a carbon content of 0.06 wt% and a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ to give $K'_{sc \text{ norm}}$ and n'_{norm} are plotted. Increasing the temperature to 450°C (842°F) increases $K'_{sc \text{ norm}}$ of 316 stainless steels, but above this temperature $K'_{sc \text{ norm}}$ decreases linearly with increasing temperature, see Figure 50. A similar linear decrease in n'_{norm} at temperatures above 450°C (842°F) is seen in Figure 51. The constants K'_{sc} and n' both increase at higher strain rates for a given test temperature, see Table 12.19. For each strain rate, as temperature is increased, both K'_{sc} and n' decrease.

There is a strong relationship between the cyclic strength coefficient and the cyclic hardening exponent. As K'_{sc} increases, so n' also increases in a linear fashion, see Figure 52. There is some scatter of the points around the line of best-fit, which has the equation

$$n' = 8 \times 10^{-5} K'_{sc} + 0.1199. \quad (9.1)$$

9.1 Calculating Cyclic Stress-strain Constants

The calculated cyclic strength coefficient and strain-hardening exponent ($K'_{sc, calc}$ and n'_{calc}) obtained using Equations (3.5) and (3.6) with the fatigue strength and ductility constants (σ'_f , ϵ'_f , b and c) determined elsewhere* are reported in Table 12.19. The correlation between the measured values of K'_{sc} and n' and the calculated values, $K'_{sc, calc}$ and n'_{calc} , is shown in Figures 53 and 54.

There is good correlation between the measured and calculated cyclic stress-strain constants at low values but at higher values $K'_{sc, calc}$ is much greater than the measured values, see Figure 53. There is a lot of scatter in the measured and calculated values of the strain-hardening exponent, see Figure 54.

The differences in the measured and calculated cyclic stress-strain constants arise because cyclic stress-strain curves are plotted using data from half life-to-failure whereas the fatigue constants are calculated at failure. At most temperatures, the stresses recorded at half-life are usually greater than those at failure, except in some cases when rapid secondary hardening is observed.

* See ESDU 05007.

10. DERIVATION AND REFERENCES

This section is identical to the corresponding section in ESDU 05007. The derivations that are used in that Item but not in this are marked with an asterisk.

10.1 Derivation

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11. EXAMPLES

11.1 Example 1. Calculation of Cyclic Stress-strain Constants

Design information on the cyclic stress-strain properties of SUS316 (S31600) stainless steel bar is required. In order to obtain the information, a programme of testing is carried out and that yields the data presented in Table 11.1. The total, plastic and elastic strain amplitudes, and the maximum stress amplitude for three different strain rates are given. The test temperature is 600°C (1112°F).

In Section 11.1.1, the cyclic strength coefficient, K'_{sc} , and the cyclic strain-hardening exponent, n' , are calculated directly from the test data using Equation (3.1).

The cyclic strength coefficient, K'_{sc} , and the cyclic strain-hardening exponent, n' , can also be derived from the fatigue constants ϵ'_f , σ'_f , b and c using Equations (3.5) and (3.6) and, in Section 11.1.2, this method is employed.

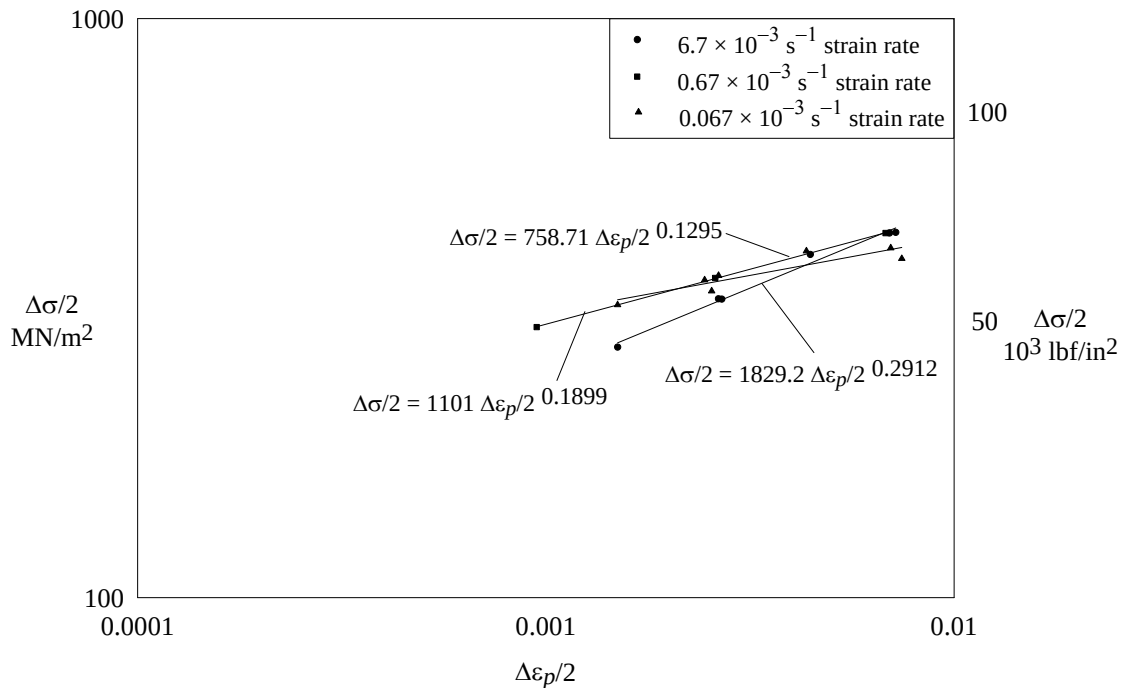
The results from the two approaches are compared in Section 11.1.3.

TABLE 11.1 Low-cycle Fatigue Test Data for SUS316 Stainless Steel Bar at 600°C (1112°F)

$\dot{\epsilon}$ 10^{-3} s^{-1}	$\Delta\epsilon/2$	$\Delta\epsilon_p/2$	$\Delta\epsilon_e/2$	$\Delta\sigma/2$ MN/m ² (10 ³ lbf/in ²)	N_f cycles
6.7	0.01	0.006 95	0.003 05	426.11 (61.8)	481
	0.009 95	0.0072	0.002 75	427.09 (61.9)	422
	0.0072	0.004 45	0.002 75	391.29 (56.8)	917
	0.005 05	0.0027	0.002 35	327.55 (47.5)	2168
	0.004 85	0.002 65	0.0022	328.04 (47.6)	2224
	0.003 35	0.0015	0.001 85	270.67 (39.3)	7237
0.67	0.01	0.0068	0.0032	426.11 (61.8)	820
	0.005 05	0.0026	0.0024	356.48 (51.7)	1402
	0.0029	0.000 95	0.001 95	293.22 (42.5)	6030
0.067	0.0102	0.007 45	0.002 75	384.92 (55.8)	162
	0.010 05	0.007	0.003 05	401.59 (58.2)	131
	0.007 35	0.004 35	0.003	396.69 (57.5)	698
	0.0051	0.002 65	0.002 45	359.91 (52.2)	1318
	0.005	0.002 55	0.002 45	338.33 (49.1)	1516
	0.004 95	0.002 45	0.0025	353.54 (51.3)	1229
	0.0036	0.0015	0.0021	320.19 (46.4)	3292

11.1.1 Calculation of cyclic stress-strain constants using Equation (3.1)

Using the data in Table 11.2, cyclic stress-plastic strain curves ($\Delta\sigma/2$ versus $\Delta\epsilon_p/2$) are plotted for the data at the three strain rates, see Sketch 11.1. From these graphs, the cyclic strength coefficient, K'_{sc} , and the cyclic strain-hardening exponent, n' , are calculated using Equation (3.1).



Sketch 11.1 Cyclic stress-plastic strain curve for SUS316 stainless steel cycled at 600°C (1112°F)

TABLE 11.2 Cyclic Stress-strain Constants from Equation (3.1)

$\dot{\epsilon}$ 10^{-3} s^{-1}	K'_{sc} MN/m ² (10 ³ lbf/in ²)	n'
6.7	1829.2 (265.3)	0.29
0.67	1101.0 (159.7)	0.19
0.067	758.7 (110.0)	0.13

It can be seen that both the cyclic strength coefficient, K'_{sc} , and the cyclic strain-hardening exponent, n' , increase with increasing strain rate.

11.1.2 Calculation of cyclic stress-strain constants using Equations (3.5) and (3.6)

The stress-strain constants, K'_{sc} and n' , can also be derived from the fatigue constants ϵ'_f , σ'_f , b and c^* using Equations (3.5) and (3.6):

$$n'_{calc} = \frac{b}{c}, \quad \text{and} \quad K'_{sc, calc} = \frac{\sigma'_f}{\epsilon'_f n'}.$$

The fatigue constants from tests carried out on SUS316 stainless steel at 600°C (1112°F) for strain rates from $6.7 \times 10^{-3} \text{ s}^{-1}$ to $0.067 \times 10^{-3} \text{ s}^{-1}$ are given in Table 11.3, along with the values of K'_{sc} and n' calculated using Equations (3.5) and (3.6).

TABLE 11.3 Cyclic Stress-strain Constants from Equations (3.5) and (3.6)

$\dot{\epsilon}$ 10^{-3} s^{-1}	σ'_f MN/m ² (10 ³ lbf/in ²)	b	ϵ'_f	c	K'_{sc} MN/m ² (10 ³ lbf/in ²)	n'
6.7	1192.5 (172.9)	-0.162	0.221	-0.568	1834.2 (266.0)	0.285
0.67	2052.9 (297.7)	-0.226	2.753	-0.924	1602.5 (232.4)	0.245
0.067	709.5 (102.9)	-0.091	0.085	-0.485	1126.6 (163.4)	0.187

11.1.3 Comparison of cyclic stress-strain constants

The values of the cyclic stress-strain constants obtained in Sections 11.1.1 and 11.1.2 are compared in Table 11.4.

TABLE 11.4 Comparison of Values of Cyclic Stress-strain Constants

$\dot{\epsilon}$ 10^{-3} s^{-1}	Equation (3.1)		Equations (3.5) and (3.6)		Equation (3.1) Equations (3.5) and (3.6)	
	K'_{sc} MN/m ² (10 ³ lbf/in ²)	n'	K'_{sc} MN/m ² (10 ³ lbf/in ²)	n'	K'_{sc}	n'
6.7	1829.2 (265.3)	0.29	1834.2 (266.0)	0.285	0.997	1.018
0.67	1101.0 (159.7)	0.19	1602.5 (232.4)	0.245	0.687	0.776
0.067	758.7 (110.0)	0.13	1126.6 (163.4)	0.187	0.673	0.695

For a strain rate of $6.7 \times 10^{-3} \text{ s}^{-1}$, there is very good correlation between the values obtained using the two approaches, but, as the strain rate decreases, the differences between the two sets of values increase, see Section 9.1.

* The values used here are taken from ESDU 05007.

11.2 Example 2. Prediction of Fatigue Life

It is necessary to predict the fatigue life of a component fabricated from 316 stainless steel. The stainless steel has a carbon content of 0.02 wt% and a nitrogen content of 0.19 wt%. The component is to operate at room temperature (23°C (73°F)) with a strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ and a total strain amplitude of 0.005.

A method of life prediction is described in ESDU 05007. The method is based on a multiple linear regression analysis of LCF test data obtained from tests conducted over the following ranges of the relevant parameters.

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%

The equation for the predicted fatigue life, N_{fpred} , is

$$\log N_{fpred} = -2.31 \log \frac{\Delta\epsilon}{2} + 0.496 \sin \pi \frac{T + 269}{816 + 269} + 0.247 \log \dot{\epsilon} - 1.045 \log C + 0.064 \sin \pi \frac{\log N + 1.77}{-0.629 + 1.77} - 3.469. \quad (11.1)$$

Substituting the test conditions above into Equation (11.1) gives

$$\log N_{fpred} = -2.31 \times -2.301 + 0.496 \sin \pi \frac{23 + 269}{816 + 269} + 0.247 \times -2.309 - 1.045 \times -1.699 + 0.064 \sin \pi \frac{\log N + 1.77}{-0.629 + 1.77} - 3.469,$$

from which, $N_{fpred} = 14\,920$ cycles.

Equation (11.1) can be modified to obtain a fatigue life corresponding to a 99 per cent probability of survival with a 95 per cent confidence level, $N_{f99/95}$:

$$\log N_{f99/95} = \log N_{fpred} - 0.775. \quad (11.2)$$

$$\log N_{f99/95} = 4.174 - 0.775,$$

from which, $N_{f99/95} = 2506$ cycles.

The 316 stainless steel given in this example is similar to a S31653 stainless steel from Derivation 9 cycled at a strain amplitude of 0.005 (see Figure 6a) for which the fatigue life is 8618 cycles (see Table 12.19).

12. TABLES AND FIGURES

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TABLE 12.2 Index to Figures

Figure	Stainless steel	E MN/m ² (10 ³ lbf/in ²)	Test temperature °C (°F)	Strain rate 10 ⁻³ s ⁻¹	Strain amplitude	Test conditions given in Table:	Derivation
1a	S31653	213 075 ^e (30 304)	-269 (-452)	4	0.005, 0.0075, 0.0125	12.9	9
1b	S31653 ^{HT}	213 075 ^e (30 304)	-269 (-452)	4	0.006, 0.0075, 0.0125	12.9	9
2	S31603	Not reported	-196 (-321)	4	0.0125	12.11	12
3a	S31653	213 075 ^e (30 304) 205 000 (29 733) Not reported	-196 (-321)	4	0.006, 0.010, 0.0125 0.010, 0.016, 0.0225 0.0125	12.9 12.14 12.11	9 17 12
3b	S31653 ^{HT}	213 075 ^e (30 304)	-196 (-321)	4	0.006, 0.010, 0.0125	12.9	9
4	S31603	Not reported	23 (73)	2	0.0006, 0.002, 0.005	12.13	16
		Not reported		3	0.011	12.7	7
		Not reported		4	0.0125	12.11	12
		Not reported		5	0.005	12.12	13
		175 000 (25 382)		2.75 ^e	0.003, 0.004, 0.008	12.17	21
5	S31600	Not reported	23 (73)	3	0.011	12.7	7
6a 6b	S31653	Not reported	23 (73)	2	0.005	12.15	18
		Not reported		3	0.011	12.7	7
		191 680 ^e (27 801)		4	0.003, 0.005, 0.010	12.9	9
		Not reported		4	0.0125	12.11	12
		205 000 (29 733)		4	0.010, 0.016	12.11	17
6c	S31653 ^{HT}	191 680 ^e (27 801)	23 (73)	4	0.003, 0.005, 0.010	12.9	9
7	The effect of applied strain amplitude on $(\Delta\sigma/2)_{P_{norm}}$ at 23°C (73°F)						
8	The effect of strain rate on $(\Delta\sigma/2)_{P_{norm}}$ at 23°C (73°F)						
9	The effect of nitrogen content on $(\Delta\sigma/2)_{P_{norm}}$ at 23°C (73°F)						
10	The effect of applied strain amplitude on $N_{f_{norm}}$ at 23°C (73°F)						
11	The effect of strain rate on $N_{f_{norm}}$ at 23°C (73°F)						
12	The effect of nitrogen content on $N_{f_{norm}}$ at 23°C (73°F)						
13	S31603	Not reported	40 (104) 70 (158) 100 (212) 200 (392)	5	0.005	12.12	13
		Not reported	200 (392)	2	0.0006, 0.002	12.13	16
14a	S31653	Not reported	300 (572)	2	0.005	12.15	18
14b	S31603	Not reported	300 (572)	2	0.0006, 0.002, 0.005	12.13	16
15	S31603	Not reported	400 (752)	2	0.0006, 0.002, 0.005	12.13	16
16	S31603	Not reported	430 (806)	4	0.002 55, 0.003 55, 0.004 55, 0.006 65, 0.008 85	12.4	1
17	The effect of applied strain amplitude on $(\Delta\sigma/2)_{P_{norm}}$ for S31603 stainless steels cycled between 40 and 430°C (104 and 806°F)						
18	The effect of applied strain amplitude on $N_{f_{norm}}$ for S31603 stainless steels cycled between 40 and 430°C (104 and 806°F)						

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

^e Estimated value.