MATERIALS SCIENCE MONOGRAPHS, 42C

MATERIALS DATA FOR CYCLIC LOADING

PART C: HIGH-ALLOY STEELS

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Contents

Introduction

Metal Fatigue has traditionally been related to stress. Since the works of Manson [1.1] and Coffin [1.2], however, it has become clear that as well as stress, strains must be taken into account too. If this is done, then we can get a fairly adequate picture of a material's fatigue behaviour. The reason for this is that in fatigue there is usually an elastic-plastic correlation between stresses and strains, quite often in the region of the endurance limit. Therefore the traditional stress-strain curves for monotonic loading are completed by the stress-strain curves for cyclic loading and the traditional stress life curves by the strain life curves for elastic, plastic and total strains. Mean stress effects are described by so-called mean stress (damage) parameter life curves.

Stress-strain curves, strain life curves and mean stress parameter life curves for cyclic loading are the components of "materials data for cyclic loading".

These materials data provide the basis for materials assessment by direct comparison of data or characteristic values and for estimating the crack initiation lives of structural parts under constant and variable amplitude loading.

In the latter case, local stress-strain paths are evaluated by applying a load notch relationship from finite element calculations or from approximation formulas such as Neuber's rule $\sigma \cdot \varepsilon = K_t^2 \cdot S \cdot e$ (K_t = stress concentration factor, S = nominal stress, e = nominal strain, mainly e = S/E), and the stress-strain curve for cyclic loading of the material being studied. With the help of the material's life curve - and in the case of random loading taking damage accumulation into account - the crack initiation lives of structural parts can be calculated. To achieve satisfactory accuracy with this evaluation method, called the Local Strain or Notch Strain Approach, it must be assumed that the conditions of the unnotched specimen for which the materials data have been determined agree sufficiently with the local notch conditions of a structural part regarding the definition of crack initiation, surface roughness or finish and the size of the highly stressed material volume.

The advantage of this method is a great reduction in the cost of evaluating experimental data. Regarding strengths, the multitude of notch effects are eliminated and transferred to the calculation of local stresses and strains. Of course, the accuracy of the life estimation depends on the accuracy of the local stresses and strains calculated, the transferability

' the materials data used and the validity of the damage accumulation rule)plied.

)r many years now materials data for cyclic loading have been published in ie scientific literature. However, these data have been collected in quite ifferent ways. In this book, these materials data have been gathered)gether, evaluated according to uniform approach and methods and compiled n standardized data sheets.

n gathering the data, special attention was given to ensuring that as far s possible the shape of the specimens and the experimental procedure onformed to ASTM E 606-80 [1.3]. ASTM E 606 is recommended for further valuation of data on cyclic loaded materials.

he data are now published for the first time in a handbook, suitable for a ide range of applications and divided into the following sections ccording to material groups:

Part A: Unalloyed Steels

Part B: Low-Alloy Steels

Part C: High-Alloy Steels

Part D: Aluminium and Titanium Alloys

Part E: Cast and Welded Metals

ach data sheet takes up a maximum of four pages. The first page gives a lescription of the material and testing procedure. In the upper left corner he material designation is given in the following order:

- designation according to DIN 17 006 or DIN 1725
- designation according to DIN 17 007
- usual commercial designation (e.g. ASTM, SAE, JIS)

he chemical composition is always given in weight percent. It corresponds o the values given in the literature referred to.

he second and third pages show the diagrams for

- stress-strain curves for monotonic and cyclic loading
- strain life curve

- mean stress (damage) parameter life curve according to the paramete of Smith, Watson and Topper [1.4].

Unless indicated otherwise in the plots, the experiments were carried c at room temperature in laboratory air.

The diagrams for the stress-strain relationships contain at the most thr curves, one for monotonic and two for cyclic loading, the latter bei evaluated from incremental step tests and constant amplitude tests. A three curves can be described approximately by an analytical function, f monotonic loading by the equation

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + (\frac{\sigma}{K})^{1/n} \qquad (1$$

and for cyclic loading by the equation

$$\varepsilon_a = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_a}{E} + (\frac{\sigma_a}{K'})^{1/n'} \qquad (1$$

The values of the constants K, n and K', n' are given in the data sheets. Th were evaluated by regression analysis (minimum of the squares of the distanc rectangular to the regression line) from the values of the appropria experimental data in the literature referred to. For unalloyed and low-all steels the analytical description of the stress-strain curve for monoton loading according to eq. (1a) is sometimes only meaningful for strains beyo 2%, because yield strength and Lüder's area cannot be accounted for in th equation. The stress-strain curves for cyclic loading were determined on t basis of constant amplitude and/or incremental step test data. Unless not otherwise in the data sheet, the results are valid for a stabilized state half fatigue life, respectively. The stress-strain curves obtained fr constant amplitude tests are represented by a solid line in the experimental proved part and by a dashed line in the remaining part. Their constants K' a n' are denoted once more in the diagrams. The stress-strain curves obtain from incremental step tests are drawn up to the maximum strain amplitu tested. Irrespective of the number of curves drawn in the diagram, the lege always contains the symbols for all three curves.

The analytical description for the strain life curves corresponds to th functions of Manson [1.5] and Morrow [1.6]:

$$\varepsilon_{a,e}(N) = \frac{\sigma_f'}{E} \cdot (2N)^b \qquad (2)$$

$$\varepsilon_{a,p}(N) = \varepsilon_f' \cdot (2N)^c \qquad (3)$$

$$\varepsilon_a(N) = \varepsilon_{a,e}(N) + \varepsilon_{a,p}(N) \qquad (4)$$

The number of cycles N characterizes crack initiation or rupture of the specimen according to its loading conditions.

For datasets with no runouts, or only a few, the constants σ_f', b, ε_f' and c were evaluated on the basis of experimental σ_a-ε_a-N data from the literature by the aforementioned regression analysis for elastic strains and plastic strains separately. If only a few runouts were available, they were neglected as they give no reliable information about the endurance limit. There is no significant difference between these evaluations of the constants and those obtained according to ASTM E 739-80 [1.7], even though the types of regression analysis are slightly different.

For some data sets with a large number of experimental results in the region of the endurance limit, the constants were evaluated by maximum likelihood method. This was again done separately for elastic and plastic strain according to a proposal made in [1.8] for the evaluation of S-N-curves. The endurance limits obtained are denoted by horizontal straight lines in the strain life curves. The endurance limit for total strain was obtained according to eq. (4). In general, the endurance limits obtained here must be seen as approximate values as they are based only on a few experimental results of unbroken specimens (runouts).

One of the three equations (1b), (2) and (3) is dependent on the remaining two equations. Therefore a dependency of the constants exists in the form n'= b/c and $K'=\sigma_f'/\varepsilon_f'^{b/c}$. This dependency, however, has been neglected in this handbook as it requires a large amount of calculation in the statistical analysis. Comparative studies show that this dependency is sufficiently fulfilled even though the three equations are treated as independent.

Unless noted otherwise, experimental results with plastic strain amplitudes of less than 0.01% have been neglected in the regression analysis, as they mainly lead to an unsatisfactory description of the life curve according to eqs. (2)-(4) in the low cycle regime. All three life curves for elastic, plastic and total strain are denoted with their appropriate constants in the diagram. The curves are solid in the part where experimental results have been taken into account for regression analysis and dashed in the other parts.

In the diagram of the damage parameter life curve the parameter according to Smith, Watson and Topper [1.4]

$$P_{SWT} = \sqrt{(\sigma_a + \sigma_m) \cdot \varepsilon_a \cdot E} \quad (5)$$

was chosen. The analytical description of the damage parameter life curve is obtained by using eqs. (2)-(4) in eq. (5) with $\sigma_m = 0$ leading to

$$P_{SWT}\ (N) = \sqrt{\sigma_f'^2 \cdot (2N)^{2b} + E \cdot \sigma_f' \cdot \varepsilon_f' \cdot (2N)^{(b+c)}} \quad (6)$$

For reasons of uniformity, datasets with experimental results $\varepsilon_m \neq 0$ and $\sigma \neq 0$ were treated as if the regression line had been evaluated for $\sigma_m \neq 0$. From the idea that P_{SWT} accounts for mean stresses, P_{SWT}-life curves evaluated from the experimental results with $\sigma_m = 0$ should be plotted into the diagrams with experimental results $\sigma_m \neq 0$, leading to better coincidence between life curve and experiments.

For uniformity, the experimental results for high and low temperatures are presented in a P_{SWT} diagram as well. How far Smith, Watson and Topper's parameter is valid for high and low temperatures has not yet been proven.

The criteria for the solid and dashed part of the curves are the same as for the strain life curves. The endurance limit obtained by maximum likelihood was calculated according to eq. (5) and is indicated in the plot.

The results of stress- and strain-controlled constant amplitude tests are listed on the third and if necessary on the fourth page, specifying the following:

- specimen number
- stress amplitude
- mean stress
- amplitude of total strain
- number of cycles

Unless stated otherwise, stresses and strains are noted in the data sheet fo
stabilized material behaviour or half failure life.

Blanks in the data sheets indicate that the information was not given in th
literature referred to.

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113

Nomenclature

A_5	elongation related to 5x diameter of specimen
A_{25}	elongation related to 25x diameter of specimen
b	fatigue strength exponent
c	fatigue ductility exponent
E	Young's modulus
ε	strain
ε_f	true fracture strain
ε_f'	fatigue ductility coefficient
K	monotonic hardening coefficient
K'	cyclic hardening coefficient
N	number of cycles until rupture
N_i	number of cycles until crack initiation
N_T	number of cycles for $\varepsilon_{a,e}=\varepsilon_{a,p}$ (transition point)
n	monotonic hardening exponent
n'	cyclic hardening exponent
ν	Poisson's ratio
P_{SWT}	damage parameter according to Smith, Watson and Topper
R	stress ratio
R_m	ultimate tensile strength
$R_{p0.2}$	monotonic 0.2% proof stress
$R'_{p0.2}$	cyclic 0.2% proof stress
σ	stress
σ_f	true fracture stress
σ_f'	fatigue strength coefficient
T_σ	$\sigma_{a,10\%}/\sigma_{a,90\%}$ scatter ratio of stress amplitudes for 10% and 90% probability of survival
$T_{\varepsilon p}$	$\varepsilon_{a,10\%}/\varepsilon_{a,90\%}$ scatter ratio of plastic strain amplitudes for 10% and 90% probability of survival
Z	reduction of area

Indexes

a	amplitude
e	elastic
g	value at $2 \cdot 10^6$ cycles
m	mean value
p	plastic

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X 4 NiCrTi 73 15 3		Inconel X

Heat treatment : 1120°C/4h, air, 843°C/24h, air, 704°C/20h, air
Test temperature : +23°C
Semifinished material : blanks, Ø 19 mm
Reference : [4.12]
Year : 1963

Chemical composition

C	Mn	Si	Cr	Ni	Cb	Ti	Al	Fe
0.04	0.70	0.30	15.0	72.56	1.0	2.5	0.30	7.0

Monotonic properties

E =	214055	N/mm²		ν =	0.31	-
$R_{p0.2}$ =	704	N/mm²		K =	1522	N/mm²
R_m =	1215	N/mm²		n =	0.135	-
A_5 =		%		σ_f =	1512	N/mm²
Z =	20	%		ε_f =	0.22	-

Cyclic properties

$R'_{p0.2}$ =	962	N/mm²		K' =	2130	N/mm²
σ_g =	405	N/mm²		n' =	0.128	-
ε_g =	0.191	%		σ'_f =	1990	N/mm²
N_T =	195	cycles		ε'_f =	0.177	-
T_σ =	1.259	-		b =	-0.105	-
$T_{\varepsilon p}$ =	3.858	-		c =	-0.599	-
Incremental step test :				K' =		N/mm²
				n' =		-

Failure criterion : complete rupture
σ/ε-values valid for : half failure life
Remarks :

Hardness : Rockwell C-34 to 35

Microstructure :

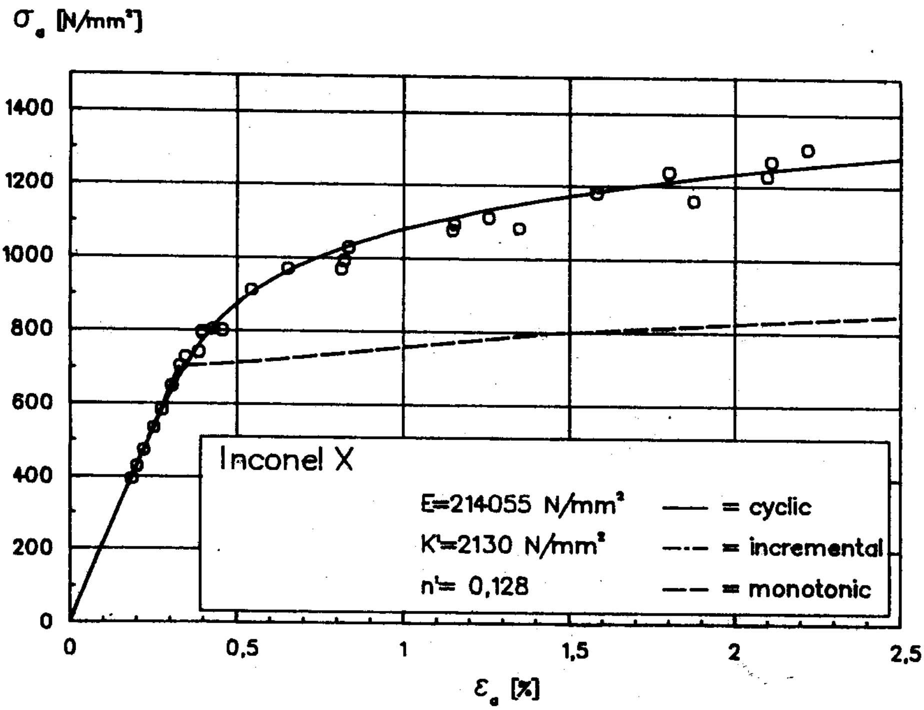
Monotonic test

Loading condition :
Specimen : cylindrical, Ø 6.35 mm
Specimen location : in rolling direction
Gauge length : 38.1 mm
Testing machine : Rhiele, universal testing machine
Strain rate :

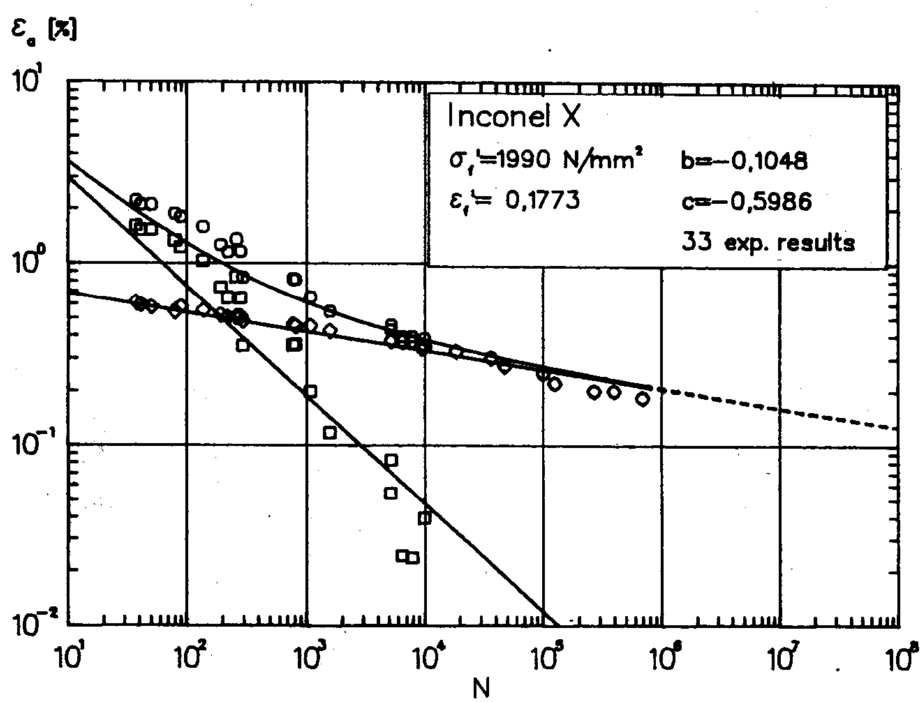
Cyclic test

Loading condition : total diametral strain control, $R_{\varepsilon d} = -1$
Specimen : hourglass shaped, Ø 6.35 mm
Surface : machined
Specimen location : in rolling direction
Gauge length : diametral
Testing machine : self designed
Frequency :
Strain rate :
Waveform :

Remarks :



σa [N/mm²]
1400
1200
1000
800
600
400
200
0
0
0,5
1
1,5
2
2,5
εa [%]
Inconel X
E=214055 N/mm²
K'=2130 N/mm²
n'= 0,128
—— = cyclic
-·- = incremental
— — = monotonic



εa [%]
10¹
10⁰
10⁻¹
10⁻²
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
N
Inconel X
σf'=1990 N/mm²
εf'= 0,1773
b=-0,1048
c=-0,5986
33 exp. results