ASME STANDARDS TECHNOLOGY, LLC

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CYCLIC STRESS-STRAIN CURVES

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Prepared by:

Wolfgang Hoffelner
RWH consult GmbH

ASME STANDARDS TECHNOLOGY, LLC

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ASME Standards Technology, LLC
Two Park Avenue, New York, NY 10016-5990

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FOREWORD

The report develops rules for determination of cyclic stress-strain curves for materials contained in the ASME Boiler and Pressure Vessel Code (BPVC), Section II, Tables IID from monotonic data. The following classes of materials were considered:

- Carbon steel (all strength levels)
- Chromium Molybdenum (Vanadium) steels (i.e., 1.25Cr-1Mo or 2.25 Cr-1Mo), including enhanced alloys (all strength levels)
- Ferritic-martensitic steels (e.g., 9-12% Cr), including enhanced alloys
- Stainless steels (austenitic, ferritic-martensitic, duplex, precipitation hardening)
- Nickel-base alloys (e.g., N06600, N06625, N08800).
- Aluminum based alloys
- Titanium based alloys
- Copper based alloys
- Zirconium based alloys

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SUMMARY

Monotonic strength values of materials like Yield Strength or Ultimate Tensile Strength are usually determined with well-defined and well-established testing equipment and sample geometries. For many materials, a wide database exists which accelerates statistical analyses and determination of minimum values, however, cyclic stress-strain curves do not benefit from such an established knowledgebase. Fatigue testing is much more complex than tensile testing, and different approaches exist in determining the representative hysteresis loop.

Figure S-1: Proposed procedures for determination of cyclic stress-strain curves for different materials

	Conservative	Average	Comments
Carbon steels	YS'=YS for YS<= 350 MPa YS'=average for YS>350 MPa	YS'=f1(YS) n'= 0.167	Results compare well with literature
Low alloy steels	YS'=YS for YS<= 400 MPa YS'=average for YS>400 MPa	YS'=f2(YS) n'= 0.130	Results compare well with literature
Martensitic 9-13% Cr	YS'=average	YS'=f3(YS) n'= 0.116	Results compare well with literature
Austenitic steels	YS'=YS	YS'=f4(YS, T) n'=f5(T)	Temperature is important
Nickel-base alloys	YS'=YS	YS'=f6(YS) n'= 0.150	Results compare well with literature
Aluminum alloys	YS'=YS	YS'=YS for high strength temper (T4, T6) YS'=f7(YS) for other alloys n'= 0.086	
Titanium alloys	YS'=average	YS'= f8(YS) n'= 0.085	Only limited amount of data available
Copper and Zirconium alloys	N.A.	N.A.	Not sufficient data available

*Notes: YS=Yield stress, YS'=Cyclic yield stress, n'=cyclic strain hardening exponent, YS'=K'*0.002^n', fi (i=1-8). Material dependent functions are derived in the body of this report.*

Cyclic stress-strain curves can therefore be only considered as an average description of a material.

As materials can cyclic soften and cyclic harden, the relationship between monotonic and cyclic yield strength is of particular importance. The cyclic stress-strain curve for strain-controlled fatigue near zero mean stress is usually described by the following relationship:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$$

Where:

$\Delta\varepsilon$=total strain range, $\Delta\sigma$=(representative) total stress range, E=Young's modulus, K'=cyclic strength coefficient, n'=cyclic hardening exponent.

The cyclic stress range usually changes as a function of a number of cycles (hardening/softening) and therefore a “typical” stress range must be chosen. By convention, the stress range at $N_f/2$ is used in almost all cases. Other definitions are occasionally used, but in this report the $N_f/2$ approach is used almost exclusively.

K’ (YS’) and n’ were determined by analysis of literature data for the different groups of materials. The results are summarized in Figure S-1. The procedures given are only valid for materials not hardened by cold deformation or yield stresses far outside the ASME code specifications. They should only be used for temperatures governed by time-independent properties. For higher temperatures, creep effects might impact the cyclic behavior. Within these limitations, it is possible to determine representative cyclic stress-strain curves for several materials presented in the ASME BPVC Section II Tables IID.

It is important to stress that, with this approach, only typical average values could be determined which allow an assessment of the cyclic response of a material (e.g., for J-integral assessments). Excel worksheets for monotonic and cyclic stress-strain curves were developed.

Raw data created during the project and literature used is also presented and discussed with respect to eventual implementation into the ASME Materials Database. In addition to the literature cited in the document, the References section contains all literature used to establish the results of this report.

Details are summarized in Appendices A-D:

- Appendix A: Description of the Excel Worksheet for determination of stress-strain curves
- Appendix B: Representation of cyclic data for eventual inclusion into the ASME database
- Appendix C: Example for inconsistencies once not well correlated monotonic and cyclic data are used
- Appendix D: Examples for validity of concept

Important Remarks:
In contrast to monotonic stress-strain curves, the procedure for determination of cyclic stress-strain curves is not very well established, and large differences between the results of different investigations exist. For this investigation, results from single-specimen tests were used, and the representative hysteresis loop was the loop at half lifetime.

The cyclic strains leading to fatigue failure are in the 1-2 percent range. Therefore, no discrimination between engineering and true stresses and strains is necessary.

The spreadsheet for evaluation of stress-strain curves is not part of the report.

Disclaimer:
Results gained with the introduced worksheet can only serve as technical information to assess materials properties. At the current stage they may not be used for any safety-relevant calculations or considerations.

1 INTRODUCTION AND DESCRIPTION OF THE PROBLEM

Cyclic stress-strain curves describe the stress-strain behavior under cyclic loads. Usually, the cyclic stress amplitude $\Delta\sigma/2$ is plotted as a function of the cyclic strain amplitude $\Delta\varepsilon/2$ for a defined cycle. The fact that the stress-strain response of a material is usually cycle-dependent requires a reference cycle which can be considered as representative for the cyclic stress-strain curve.

In contrast to monotonic stress-strain curves which deliver a unique relationship between the stress and strain of a material, the cyclic stress-strain relationships may undergo cycle-dependent changes. The material can be:

- Cyclic hardening
- Cyclic softening
- Cyclic stable
- Combinations of cyclic softening and cyclic hardening

This means that the stress-strain relationship determined in strain fatigue tests is usually cycle dependent. Figure 1-1 shows the change of stress amplitude with a number of cycles for a low carbon steel as an example [1].

Figure 1-1: Cyclic hardening-softening curves of a low carbon steel at different total strain amplitudes, ε_a. (Replotted from [1])

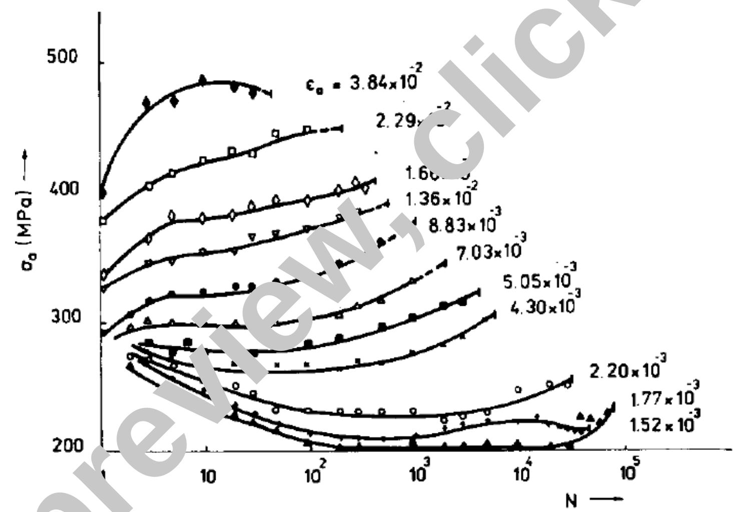

Figure 1-2 shows the cyclic stress-strain response of IN 600 at a different number of cycles (replotted from [2].

Figure 1-2: Cycle dependence of stress-strain curves for IN 600 (replotted from literature [2])

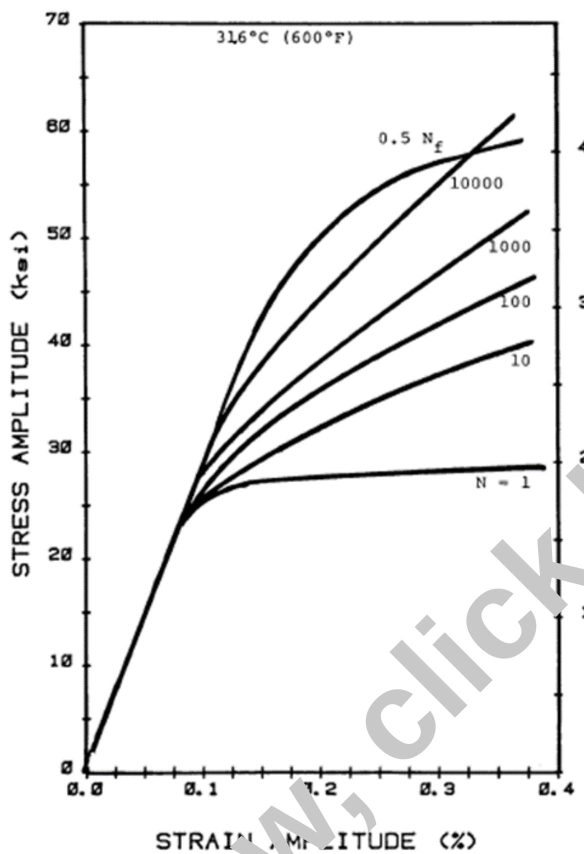

Figure 3-16. Cyclic stress strain curves for Alloy 600 at 316°C at 1/4, 10, 100, 1000, 10,000 cycles and midlife

When a cyclic stable hysteresis loop is obtained, this stabilized loop can be used as a reference. If a cyclic stable hysteresis loop is not established, the cycle at half the time to rupture (Nf/2) is taken as a reference independent of whether the material is cyclic softening, cyclic hardening or shows a mixed behavior. These cycles are usually obtained from reversed strain cycling tests on a number of companion specimens, but shortcut procedures are also used by various investigators. Such shortcut methods use only a single specimen, which is cycled a certain number of times or until saturation is reached. The levels of cyclic straining are stepwise increased (incremental step test). This means that cyclic pre-deformed samples are used, which can lead to artifacts in cases where cycle-dependent microstructural changes can happen. It is also worth mentioning that low cycle fatigue (LCF) is primarily crack growth from short cracks, which can also affect the behavior of pre-deformed material. The fact that materials can cyclically harden or soften makes the relationship between cyclic and monotonic curves important.

A cyclic stress-strain curve alone, without any relation to the monotonic properties, is only of very limited use for design or safety considerations.

An independent choice of a cyclic stress-strain curve without reference to the monotonic behavior might cause misleading results. Cyclic softening material can appear as cyclic hardening and vice-versa (an example from ASME BPVC Section VIII/2 is given in Appendix C:). Therefore, relationships between