

DETERMINATION OF STRESS STRAIN CURVES OF 304, 304L, 316, 316L FOR STRAIN-BASED DESIGN CRITERIA



STP-PT-094

DETERMINATION OF STRESS STRAIN CURVES OF 304, 304L, 316, 316L FOR STRAIN-BASED DESIGN CRITERIA

Prepared by:

Wolfgang Hoffelner
RWH consult GmbH



Date of Issuance: February 28, 2022

This publication was prepared by ASME Standards Technology, LLC (“ASME ST-LLC”) and sponsored by The American Society of Mechanical Engineers (“ASME”).

Neither ASME, ASME ST-LLC, the author, nor others involved in the preparation or review of this publication, nor any of their respective employees, members, or persons acting on their behalf, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe upon privately owned rights.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by ASME ST-LLC or others involved in the preparation or review of this publication, or any agency thereof. The views and opinions of the authors, contributors and reviewers of the publication expressed herein do not necessarily reflect those of ASME ST-LLC or others involved in the preparation or review of this publication, or any agency thereof.

ASME ST-LLC does not take any position with respect to the validity of any patent rights asserted in connection with any items mentioned in this document, and does not undertake to insure anyone utilizing a publication against liability for infringement of any applicable Letters Patent, nor assumes any such liability. Users of a publication are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Participation by federal agency representative(s) or person(s) affiliated with industry is not to be interpreted as government or industry endorsement of this publication.

ASME is the registered trademark of The American Society of Mechanical Engineers.

No part of this document may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.

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

ISBN No. 978-0-7918-7512-4
Copyright © 2022
ASME Standards Technology, LLC
All Rights Reserved

TABLE OF CONTENTS

Abstract	iii
1 Introduction	1
2 Choice of Stress-Strain Curve	2
3 Determination of Strain at Ultimate Tensile Stress	4
4 Ultimate Tensile Stress and Rupture Strain.....	5
5 Maximum and Minimum YS/UTS.....	6
6 Maximum/Minimum True Stress/Strain at Fracture	9
7 Temperature Dependence of Yield stress and Ultimate Tensile Stress.....	11
8 True Fracture Strain.....	12
9 Low-Temperature Stress-Strain Curves	13
10 Strain-Rate Dependence	16
11 Final Curves: Some Examples.....	18
References.....	22
Appendix A: Short- and Long-Term Goals for the Task Group on Materials Supporting Division 3 Strain-Based Criteria	33
A.1 Short-Term Goals	34
A.2 Long-Term Goals.....	35

LIST OF TABLES

Table 5-1: Relationships between UTS, YS and Hardness.....	8
Table 9-1: Temperatures when 50% Martensite is Formed after 30% Strain (Md(30/50) C)	15
Table 10-1: Strain-Rate Adjustment Factors	17
Table A-1: Permitted Material Specifications and Products.....	34

LIST OF FIGURES

Figure 2-1: Comparison of Measured Strain at Ultimate Tensile Stress of Experimental Values (INL) [1] with calculated values (m2 in Section VIII, Division 2)	2
Figure 2-2: Comparison of Calculated Stress-Strain Curves with Measured Curves	3
Figure 3-1: Engineering Fracture Strain as a Function of Engineering Strain at UTS Using Different Data Sources where Strain at UTS and Engineering Fracture Strain were available.....	4
Figure 3-2: Relationship between engineering strain at ultimate tensile stress (UTstrain) and engineering fracture strain (EFS). Data replotted from Figure 3-1.....	4
Figure 4-1: Dependence of Fracture Elongation on UTS: No significant correlation exists	5
Figure 5-1: Relation between YS and UTS for Austenitic Steel at Room Temperature.....	6
Figure 5-2: Influence of a 20% Yield Stress Difference on Stress-Strain Curve for Same UTS Values	7
Figure 6-1: Extreme Possibilities to Obtain True Stress-Strain Curves between UTS and Final Fracture	9
Figure 6-2: Tangent Moduli for Different 304 and 316 Tests (metric units) at Various Temperatures; Scatterband Upper Bound 700, Lower Bound 400	10
Figure 7-1: Yield Stress and Ultimate Tensile Stress for Several 304-Type and 316L Type Data	11
Figure 7-2: Comparison of INL Data with YS and U-Table Values	11
Figure 8-1: True Fracture Strain of 304L and 316L	12
Figure 9-1: Typical Stress-Strain Curves for 304L (Engineering) and 316L (True) at -20F (INL data)	13

Figure 9-2: True Stress-Strain Curves for 304L Measured at -20°F up to UTS compared to Proposed Minimum and Maximum Stress-Strain Curves..... 13

Figure 9-3: Formation of Martensite in Austenites..... 14

Figure 10-1: Yield Stress Ratio as a Function of Strain Rate 16

Figure 11-1: Upper and Lower Bound Stress-Strain Curves for 304L at Room Temperature 18

Figure 11-2: Comparison of true stress-strain curve determined with Ramberg-Osgood-type of evaluation (blue line) with parametric approach (green line). Material 304L measured at room temperature 19

Figure 11-3: Parameter a as function of temperature (a low represents the lower bound curve and a high refers to the upper bound curve) 19

Figure 11-4: Parameter b as function of temperature (b low represents the lower bound curve and b high refers to the upper bound curve) 20

Figure 11-5: Parameter c as function of temperature (c low represents the lower bound curve and c high refers to the upper bound curve) 20

Figure 11-6: Parameter d as function of temperature (c low represents the lower bound curve and c high refers to the upper bound curve) 21

Figure 11-7: Parameter e as function of temperature (c low represents the lower bound curve and c high refers to the upper bound curve) 21

ABSTRACT

True stress-strain curves up to final fracture (flow curves) are used for the assessment of materials behavior and determine the acceptability of Spent Nuclear Fuel (SNF) containers. To cover possible damage events like dropping of containers, several conditions must be considered. Different temperatures covering the effect of loads with high radioactivity and low ambient temperatures during loading and transport of such containers determine the required material properties. Austenitic steels like 304, 304L, 316, 316L show a tendency for strain-induced martensitic transformation at low temperatures which needs specific consideration. Strain rates are also important when dropping events are considered. In this report, true stress strain curves were determined in a true strain range from 0 to 100 percent. Up to Ultimate Tensile Strength (UTS), a Ramberg-Osgood type of analysis using strain at UTS was employed. Temperature dependence of UTS and yield stress (YS) was determined from experimental data and ASME Sect II Table D / Y-1 and U values. The stress-strain behavior at higher strains was determined on the basis of measured tangent moduli. Effects of strain rate were assessed with the Cowper-Symonds relation. A set of curves for temperatures ranging from -20°F to 600°F was developed.

Established in 1880, the ASME is a professional not-for-profit organization with more than 100,000 members and volunteers promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit <https://www.asme.org/> for more information.

ASME ST-LLC is a not-for-profit Limited Liability Company, with ASME as the sole member, formed in 2004 to carry out work related to new and developing technology. ASME ST-LLC's mission includes meeting the needs of industry and government by providing new standards-related products and services, which advance the application of emerging and newly commercialized science and technology, and providing the research and technology development needed to establish and maintain the technical relevance of codes and standards. Visit <http://asmestllc.org/> for more information.

1 INTRODUCTION

True stress-strain curves up to final fracture (flow curves) are used for the assessment of materials behavior and determine the acceptability of Spent Nuclear Fuel (SNF) containers as a result of energy-limited events. This is required for determination of deformation and containment in case of transportation accidents (see goals of Task Group in Appendix A). The results presented in this report are limited to 304/304L and 316/316L.

Due to decay heat coming from the SNF and temperature conditions on the outside of the container, temperature must also be considered. In the case of dropping of containers, strain-rate dependence must also be considered. Due to the differences in behavior of the various cask components resulting from the material property assumptions, minimum and maximum design curves are needed. For example, one reason for the maximum design line is the fact that this curve can result in a condition where stress concentrations can be responsible for high local stresses. Similarly, the minimum curve may predict higher deformations of components which may lead to a change in load path. The design curves should be connected to YS and UTS in the Section II, Part D tables. These complex requirements for design lines require the following clarifications:

- What is an appropriate stress-strain curve parametrization?
- How do those curves look between UTS and final fracture?
- What are maximum YS and UTS assuming that the minimum curve is defined by YS and UTS given in ASME Section II, Part D tables?
- What is the role of temperature (taking into consideration that at low temperatures strain-induced martensite can occur)?
- What is the role of high strain rates?

Based on these questions, minimum and maximum design curves were developed where:

- Minimum curves are based on minimum YS and UTS (IID) at temperature.
- Maximum curves are based on maximum YS and UTS (IID modified) at temperature and high strain rates.

The considerations are based on experimental data from Idaho National Laboratory (INL) [1], Keith Morton (INL) private communication 2015, and data from the Nuclear Regulatory Commission (NRC) private communication 2015.