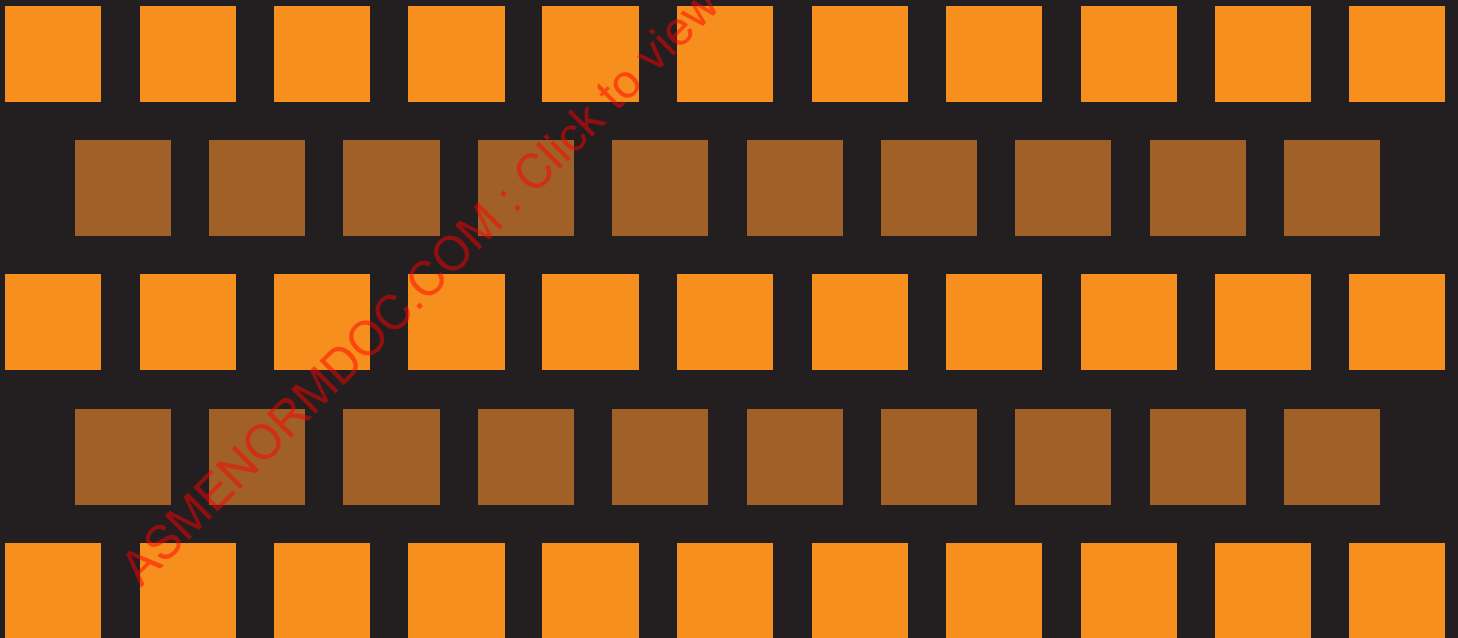


CORRECT AND EXTEND ALLOWABLE STRESS VALUES FOR 304 AND 316 STAINLESS STEEL



STP-NU-063

CORRECT AND EXTEND ALLOWABLE STRESS VALUES FOR 304 AND 316 STAINLESS STEEL

Prepared by:

Mainak Sengupta

James E. Nestell

MPR Associates, Inc.



Date of Issuance: June 28, 2013

This report was prepared as an account of work sponsored by the U.S. Department of Energy (DOE) through the ASME Standards Technology, LLC (ASME ST-LLC).

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, 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 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 the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Neither ASME, ASME ST-LLC, the authors, nor others involved in the preparation or review of this report, nor any of their respective employees, members or persons acting on their behalf, make 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 report, or any agency thereof. The views and opinions of the authors, contributors and reviewers of the report expressed herein do not necessarily reflect those of ASME ST-LLC or others involved in the preparation or review of this report, 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. 978-0-7918-6906-2

Copyright © 2013 by
ASME Standards Technology, LLC
All Rights Reserved

TABLE OF CONTENTS

Foreword	vii
Executive Summary	viii
1 INTRODUCTION	1
1.1 Purpose	1
1.2 Background	1
1.3 Analysis Procedure	1
2 304 STAINLESS STEEL	3
2.1 Introduction	3
2.2 Database	3
2.3 Allowable S_r Values	3
2.3.1 Time-to-Rupture Analysis	3
2.3.2 Calculations and Results	6
2.4 Allowable S_t Values	10
2.4.1 Time-to-Tertiary Creep Analysis	10
2.4.2 Time-to-1% Strain Analysis	13
2.4.3 Results	17
2.5 Allowable S_{mt} Values	19
3 316 STAINLESS STEEL	22
3.1 Introduction	22
3.2 Database	22
3.3 Allowable S_r Values	22
3.3.1 Time-to-Rupture Analysis	22
3.3.2 Calculations and Results	25
3.4 Allowable S_t Values	28
3.4.1 Time-to-Tertiary Creep Analysis	28
3.4.2 Time-to-1% Strain Analysis	31
3.4.3 Results	35
3.5 Allowable S_{mt} Values	37

4	CONCLUSION AND RECOMMENDATIONS	39
4.1	Minimum Stress-to-Rupture (S_r)	39
4.2	Temperature and Time Dependent Stress Intensity (S_t)	39
4.3	S_{mt}	39
	References	41
	Appendix A	42
	Acknowledgments	43
	Abbreviations and Acronyms	44

LIST OF TABLES

Table 2-1	– Results from Regression Analysis for 304 SS Rupture Analysis	4
Table 2-2	– Results from Regression Analysis for 304 SS Time-to-tertiary Creep Analysis	12
Table 2-3	– Stress at 1% Strain in S.I. Units for 304 SS	15
Table 2-4	– Stress at 1% strain in Customary Units for 304 SS	15
Table 2-5	– Results from Regression Analysis for 304 SS for Time-to-1% Strain	16
Table 3-1	– Results from Regression Analysis for 316 SS for Rupture Analysis	23
Table 3-2	– Results from Regression Analysis for 316SS for Time-to-Tertiary Creep Analysis	30
Table 3-3	– Stress at 1% Strain in S.I. Units for 316 SS	33
Table 3-4	– Stress at 1% Strain in Customary Units for 316 SS	33
Table 3-5	– Results from Regression Analysis for 316 SS for Time-to-1% Strain Analysis	34

LIST OF FIGURES

Figure 2-1	– Stress versus LMP for Rupture Analysis of 304 SS	4
Figure 2-2	– Normal Probability Distribution of the Rupture Data	5
Figure 2-3	– Plot of Residual in Log Time versus Temperature in °C for the Rupture Data	5
Figure 2-4	– Data Points versus Residual in Log Time for the Rupture Analysis	6

Figure 2-5 – S_r Values for 304 SS in S.I. units	7
Figure 2-6 – S_r Values for 304 SS in Customary Units	7
Figure 2-7 – S_r versus Time from 800°F to 1500°F in Customary Units	8
Figure 2-8 – Comparison of Revised S_r Values with NH	9
Figure 2-9 – Stress versus Time-to-Rupture at 1200°F (650°C)	9
Figure 2-10 – Classical Creep Curve Showing t_2 – Departure from Minimum Creep Rate and t_{ss} – Time-to-Tertiary Creep	11
Figure 2-11 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 304 SS – Second Order Polynomial Regression Analysis	12
Figure 2-12 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 304 SS – Linear Regression Analysis	13
Figure 2-13 – Hot Tensile Curve for 304 SS at 1000°F	14
Figure 2-14 – Hot Tensile Curve for 304 SS at 1300°F	14
Figure 2-15 – Stress versus LMP for Time-to-1% Strain Analysis of 304 SS - Linear Regression Analysis	16
Figure 2-16 – S_t Values for 304 SS in S.I. Units	17
Figure 2-17 – S_t Values for 304 SS in Customary Units	17
Figure 2-18 – S_t versus Time from 800°F to 1500°F in Customary Units	18
Figure 2-19 – Comparison of Revised S_t Values with NH	19
Figure 2-20 – S_{mt} Values for 304 SS in S.I. Units	20
Figure 2-21 – S_{mt} Values for 304 SS in Customary Units	20
Figure 2-22 – S_{mt} versus Time from 800°F to 1500°F in Customary Units	21
Figure 3-1 – Stress versus LMP for Rupture Analysis of 316 SS	23
Figure 3-2 – Normal Probability Distribution of the Rupture Data	24
Figure 3-3 – Plot of Residual in Log Time versus Temperature in °C for the Rupture Data ..	24
Figure 3-4 – Data Points versus Residual in Log Time for the Rupture Analysis	25
Figure 3-5 – S_r Values for 316 SS in S.I. Units	26

Figure 3-6 – S_r Values for 316 SS in Customary Units	26
Figure 3-7 – S_r versus Time from 800°F to 1500°F in Customary Units	27
Figure 3-8 – Comparison of Revised S_r Values with NH	27
Figure 3-9 – Ratio between Time-to-Tertiary Creep and Time-to-Rupture (t_3/t_r) versus Temperature for 316 SS Shows Large Variation	28
Figure 3-10 – t_3/t_r versus Rupture Time for 316 SS Shows Greater Variation for Short Rupture Time	29
Figure 3-11 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 316 SS – Second Order Polynomial Regression Analysis	30
Figure 3-12 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 316 SS – Linear Regression Analysis	31
Figure 3-13 – Hot Tensile Curve for 316 SS at 1000°F	32
Figure 3-14 – Hot Tensile Curve for 316 SS at 1300°F	32
Figure 3-15 – Stress versus LMP for Time-to-1% Strain Analysis of 316 SS – Second Order Regression Analysis	34
Figure 3-16 – S_t Values for 316 SS in S.I. Units	35
Figure 3-17 – S_t Values for 316 SS in Customary Units	35
Figure 3-18 – S_t versus Time from 800°F to 1500°F in Customary Units	36
Figure 3-19 – Comparison of Revised S_t Values with NH	36
Figure 3-20 – S_{mt} Values for 316 SS in S.I. Units	37
Figure 3-21 – S_{mt} Values for 316 SS in Customary Units	37
Figure 3-22 – S_{mt} versus Time from 800°F to 1500°F in Customary Units	38

FOREWORD

This document is the result of work resulting from Cooperative Agreement DE-NE0000288 between the U.S. Department of Energy (DOE) and ASME Standards Technology, LLC (ASME ST-LLC) for the Generation IV (Gen IV) Reactor Materials Project. The objective of the project is to provide technical information necessary to update and expand appropriate ASME materials, construction and design codes for application in future Gen IV nuclear reactor systems that operate at elevated temperatures. The scope of work is divided into specific areas that are tied to the Generation IV Reactors Integrated Materials Technology Program Plan. This report is the result of work performed under Task 14a titled “Correct and Extend Allowable Stress Values for 304 and 316 Stainless Steel.”

ASME ST-LLC has introduced the results of the project into the American Society of Mechanical Engineers (ASME) volunteer standards committees developing new code rules for Generation IV nuclear reactors. The project deliverables are expected to become vital references for the committees and serve as important technical bases for new rules. These new rules will be developed under ASME’s voluntary consensus process, which requires balance of interest, openness, consensus and due process. Through the course of the project, ASME ST-LLC has involved key stakeholders from industry and government to help ensure that the technical direction of the research supports the anticipated codes and standards needs. This directed approach and early stakeholder involvement is expected to result in consensus building that will ultimately expedite the standards development process as well as commercialization of the technology.

ASME has been involved in nuclear codes and standards since 1956. The Society created Section III of the Boiler and Pressure Vessel Code, which addresses nuclear reactor technology, in 1963. ASME Standards promote safety, reliability and component interchangeability in mechanical systems.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 135,000 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 www.asme.org for more information.

The ASME Standards Technology, LLC (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 newly commercialized technology. The ASME ST-LLC 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 www.stllc.asme.org for more information.

EXECUTIVE SUMMARY

This report was undertaken to correct the existing Subsection NH stress values and extend the time-dependent allowable stress values for 304 and 316 stainless steel to 500,000 hours. Extending the Code allowable stress values to 500,000 hours will allow Generation IV plant components to have a 60-year design life. The current stress values in the NH Code are based on an older and obsolete materials property database. The time-dependent data currently available in the public domain for 304 and 316 stainless steel is much larger and has been used for developing the new allowable stress values.

The allowable stress values that were corrected and extended are the time-dependent minimum stress-to-rupture strength (S_r), and stress intensity (S_t and S_{mt}) values. The values were developed using a Larson-Miller parameter analysis. The S_r and S_t values at long times and high temperatures are lower than the current Code values, and the long time, high temperature S_t values are controlled by the time-to-tertiary creep data. The upper limit on the S_t values was revised from “minimum stress to 1% strain” to “average stress to 1% strain”. Therefore, the short time, low temperature stress values are higher than the current NH Code. Statistical analyses did not reveal any correlation between the time-to-tertiary creep and time-to-rupture.

ASME NUP-063-2013
Click to view the full PDF of ASME NUP-063-2013

1 INTRODUCTION

1.1 Purpose

This report presents revised allowable stress values for 304 and 316 stainless steel for inclusion in the ASME Boiler and Pressure Vessel Code (ASME BPV Code), Section III, Subsection NH – Components in Elevated Temperature Service.

1.2 Background

The U.S. Department of Energy (DOE) has established a program to develop next generation nuclear reactors. This program, known as Generation IV (Gen IV), addresses research and development (R&D) activities that are necessary to develop high efficiency, next generation nuclear power plants such as high temperature gas-cooled and liquid-cooled reactors. One of the challenges identified by this program was the development of necessary codes and standards to support the design and construction of Gen IV reactors. Therefore, a three-year collaborative effort was established between DOE and ASME to address technical issues related to codes and standards applicable to the Generation IV program.

A number of tasks were identified by ASME Standards Technology, LLC (ASME ST-LLC) as high priority items for Gen IV reactors. One of these tasks is Task 14a. The purpose of Task 14a is to correct and extend the allowable stress values for Type 304 and 316 stainless steels (SS) to 500,000 hours in ASME BPV Code, Section III, Subsection NH.

A precursor to this task was ASME ST-LLC Task 6 (STP-NU-037), which reviewed the current creep property databases for materials in NH for consistency, and for the feasibility of extending allowable stress values for a design life of 500,000 hours from 300,000 hours. Task 6 identified several deficiencies in time-independent properties of 304 and 316 SS. It was noted that the current stress allowable values for 304 and 316 SS in NH were developed using databases that were significantly smaller than the currently available database. In addition, the S_t values in NH were based on limited data for time-to-tertiary creep and time-to-1% creep strain, and would need to be revised.

MPR reviewed the final reports prepared for Task 6 and is aware of the statistical challenges associated with this task.

The time dependent stress allowable values, S_t (temperature and time dependent stress intensity) and S_r (expected minimum stress to rupture), the time independent, S_m (lowest stress intensity at a given temperature among time independent strength quantities) and S_{mt} (lower of the two stress intensity values, S_m and S_t) values were developed using augmented databases for 304 and 316 SS as a part of this task.

The time dependent stress values were developed using creep test data. The creep tests were conducted in various institutions and laboratories around the world. The primary sources of test data were American Society of Testing and Materials (ASTM), Oak Ridge National Laboratory (ORNL) and the National Institute of Material Science Japan (NIMS) among others.

1.3 Analysis Procedure

The allowable stress values for the two stainless steels were developed using Larson Miller Parameter (LMP) analysis. The LMP analysis is widely used to extend the creep properties to times and temperatures beyond the test data. Long-term creep data (greater than 100,000 hours or approximately 12 years) is difficult to develop as these tests are impractical. The LMP method provides a convenient method to extrapolate the stress values to times greater than 100,000 hours and

high temperatures. The LMP method is an established procedure and widely used by ASME BPV Code material scientists and consultants.

The LMP is calculated in accordance with the following formula:

$$LMP = T \times (\log_{10} t_r + C) \quad \text{Equation 1.1}$$

where,

LMP - Larson Miller Parameter

T - temperature, *K*

t_r - the time-to-rupture, hours

C - the heat or overall lot constant

The LMP in the above equation can be expressed as a function of stress. In order to perform a regression analysis on the database, Equation 1 can be rewritten as:

$$\log(t_r) = \left\{ \frac{(a_0 + a_1 \times \log(S) + a_2 \times (\log(S))^2)}{T} \right\} - C \quad \text{Equation 1.2}$$

where,

S - the applied stress, MPa

a₀, *a₁* and *a₂* - constants calculated from the regression analysis

Equation 1.2 is written in terms of a second order polynomial function because we found that a second order polynomial function best fit the data. In addition, we found that extrapolation of allowable stress values based on a polynomial function higher than second order can lead to non-conservative estimates of creep properties. In some cases, databases with a relatively small amount of data were analyzed using a linear stress function instead of a second order polynomial stress function.

The next two chapters present the regression analyses for 304 and 316 SS.

2 304 STAINLESS STEEL

2.1 Introduction

304 SS is one of the five materials included in NH that is permitted for constructing Class 1 components operating in the time dependent creep regime. Currently, the allowable stress values for 304 SS are provided for up to 300,000 hours service. Task 14a requires that these values be developed for 500,000 hours. This will allow components to be designed and constructed with a 60-year design life.

2.2 Database

The 304 SS database used for this task is the same database that was used for Task 6. This database was provided by the authors of Task 6, and consisted of approximately 1600 data points ranging from 427°C (800°F) to 1076°C (1970°F). The maximum rupture time was approximately 180,000 hours. However, only 1273 data points provided rupture data. The time-to-tertiary creep and time-to-1% strain data were meager with only 114 and 66 data points respectively.

2.3 Allowable S_r Values

2.3.1 Time-to-Rupture Analysis

The time-to-rupture data were used for calculating the S_r values. The rupture data was censored based on three criteria:

- (a) Any data point that was ten (10) standard deviations from the mean. The rationale for deleting data points that were ten standard deviations from the mean is to censor “out-of-range” data points. These “out-of-range” data points were incorrectly reported data that could not be considered for the analysis. In case of 304 stainless steel, no data were actually censored using this criterion.
- (b) Time-to-rupture data less than 100 hours. All the data points for time-to-rupture less than 100 hours were censored from the database. Extrapolating allowable stress values to long time (more than 100,000 hours) based on short time-to-rupture experimental data was judged inappropriate. In order to verify this assertion, a LMP analysis was performed on the entire database. The lot constant for the entire database was calculated as 14.03 and the standard error of estimate (SEE) was 0.77. The SEE for the entire database (without censoring based on rupture life) is higher than the SEE for the 100 hour rupture life censored database (0.54). This shows that there is greater deviation in the uncensored data, which is undesirable. The stress-to-rupture values calculated using the lot constant and SEE for the uncensored database were higher and non-conservative compared to the stress values calculated from the censored database. Therefore, censoring the database for rupture life less than 100 hours was appropriate. The effect of censoring based on rupture time is reported in detail in Task 6 [1],[2].
- (c) Heats with poor strength properties, identified in [3]. The 304 SS NIMS heats were characterized for long time, rupture strength in Task 14 [3]. Task 14 identified one heat – ABA, which had poor strength characteristics at long (100,000 hours) rupture times. The creep rupture strength of Heat ABA rapidly dropped at higher temperatures. This behavior was atypical and attributed to abnormally low free nitrogen levels that are not expected in modern heats of steel. Time-to-rupture data for heat ABA were censored.

After the data were censored, the time-to-rupture database consisted of 903 data points. A second order polynomial regression analysis was used along with a lot-centered approach. The lot constant was calculated as 15.27. A plot of the stress versus LMP and comparison with the calculated stress function of the Larson-Miller parameter for the total database is shown in Figure 2-1. The data distribution is shown in blue and the stress function of the LMP is shown as a black line. The values of the regression parameters are given in Table 2-1. The variance for the data is 0.29 and the SEE is 0.54.

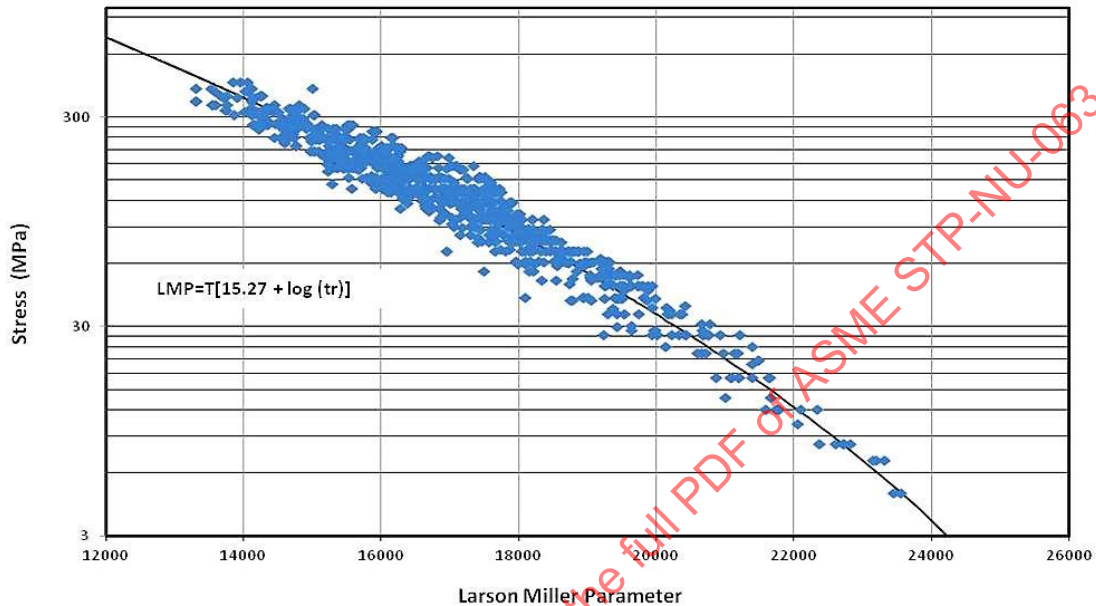


Figure 2-1 – Stress versus LMP for Rupture Analysis of 304 SS

Table 2-1 – Results from Regression Analysis for 304 SS Rupture Analysis

Coefficients in Log Stress (a)	Values
a_0	25496.03
a_1	-2250.02
a_2	-864.43

The probability plot of the residual time-to-rupture data is shown in Figure 2-2. The approximately linear data plot indicates that the residual data is normally distributed. The residual is calculated by subtracting the log time calculated per the regression analysis from the log rupture time reported in the database.

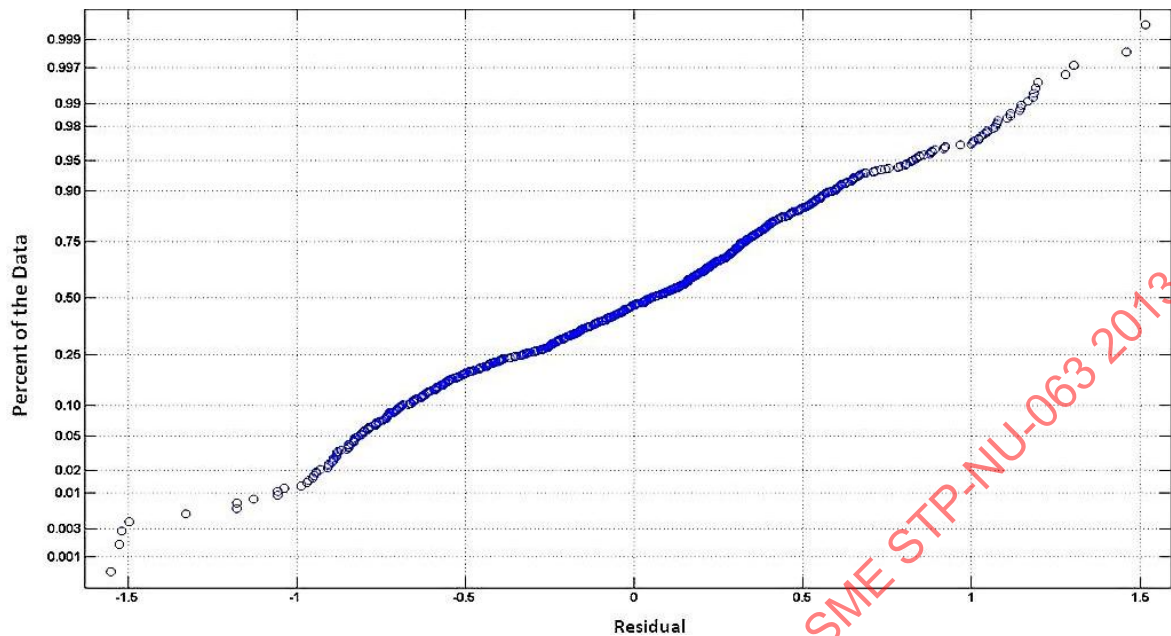


Figure 2-2 – Normal Probability Distribution of the Rupture Data

A plot of the residual in log time versus temperature in °C is shown in Figure 2-3. The maximum variation in the residual is at 600°C (1110°F). A histogram showing the number of data points over the range of residual is shown in Figure 2-4.

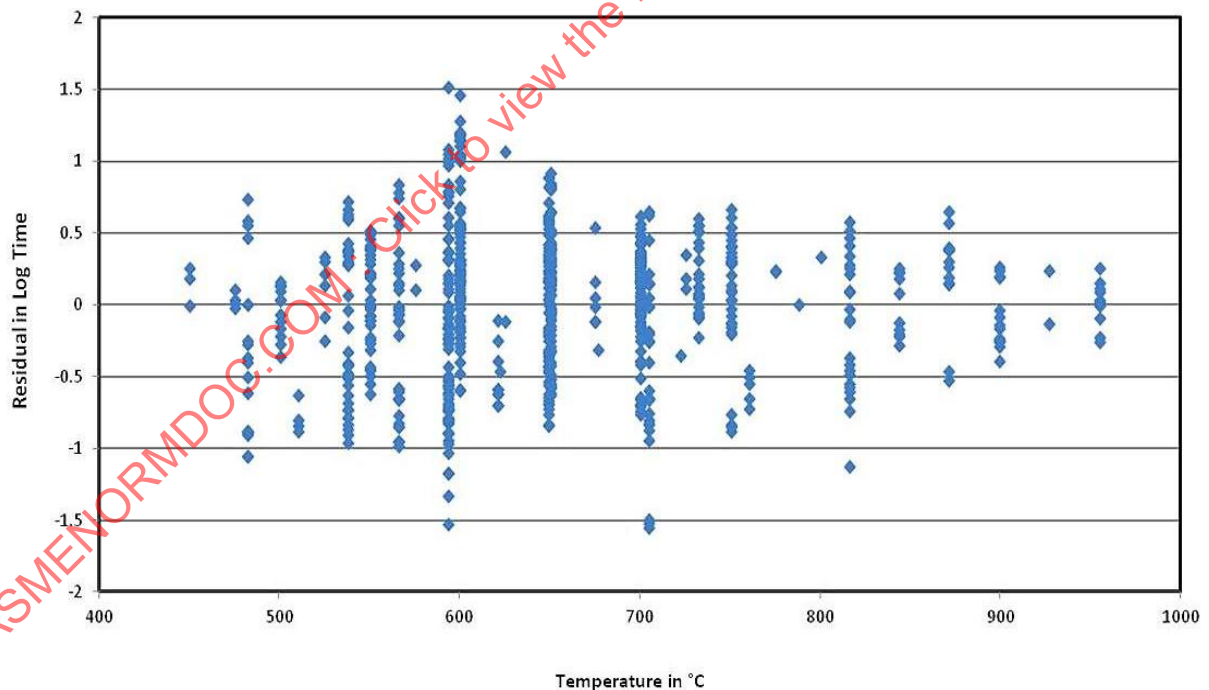


Figure 2-3 – Plot of Residual in Log Time versus Temperature in °C for the Rupture Data

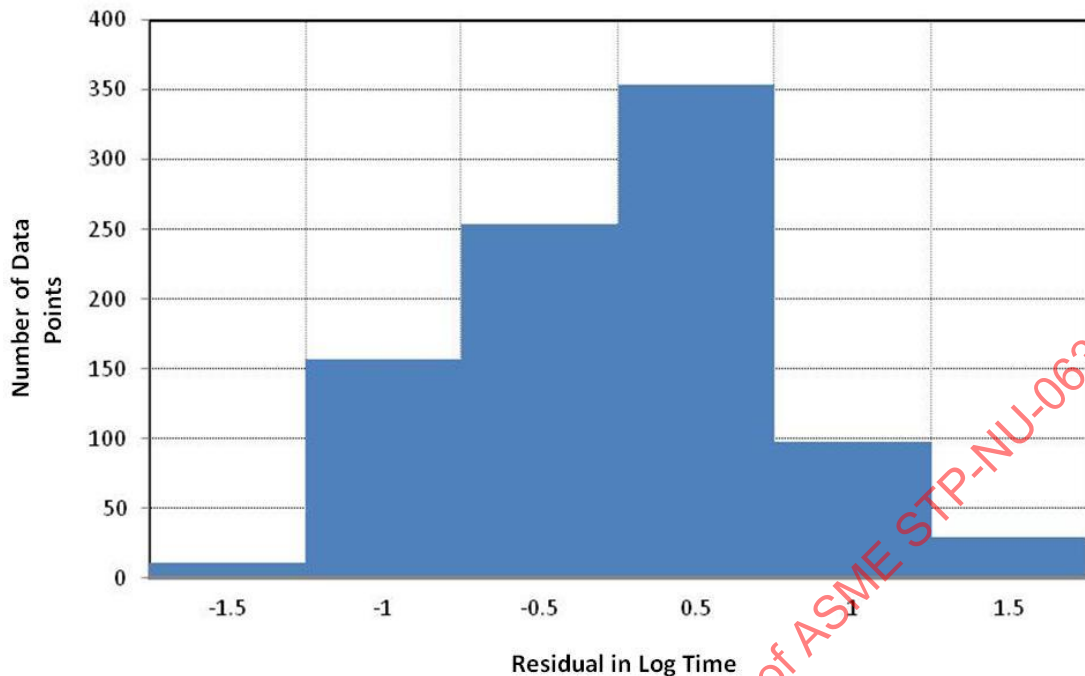


Figure 2-4 – Data Points versus Residual in Log Time for the Rupture Analysis

2.3.2 Calculations and Results

The ASME NH rules require a lower bound estimate of the rupture life, called the minimum-stress-to-rupture. The minimum stress-to-rupture, S_r is calculated from the regression analysis by shortening the rupture life by 1.65 times the SEE. This yields a lower stress value compared to average stress-to-rupture for a particular rupture life as shown in Figure 2-9. Numerically, this is accomplished by adding 0.891 (1.65 times the standard error of estimate) to the rupture life in Equation 1.2 and solving for stress in the polynomial function. A MathCAD program was developed for performing this calculation and is attached in Appendix A.

The upper bound on the S_r values is controlled by the ultimate strength of the material at any particular temperature. This is because the values calculated from the LMP analysis can be larger than the ultimate strength of the material. The upper bound on S_r has been set at $S_u/1.1$, where S_u is the ultimate strength of the material [6]. The S_u values used in this analysis were taken from Section II, Part D and Section III, NH [10]. The minimum stress to rupture values in S.I. and Customary units are shown in Figure 2-5 and Figure 2-6. The stress-to-rupture values are plotted over time and temperature in customary units in Figure 2-7.

Temperature in C	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
425	394	394	394	394	394	394	394	363	323	284	252	239
450	390	390	390	390	390	390	347	304	269	235	207	195
475	384	384	384	384	380	332	293	255	224	194	169	159
500	375	375	375	367	323	280	246	212	185	159	138	129
525	365	365	365	314	274	236	205	176	152	130	111	104
550	353	353	311	267	232	198	171	145	125	105	90	83
575	339	307	266	227	195	165	142	119	102	85	72	66
600	323	264	227	192	164	138	117	98	82	68	57	52
625	305	226	193	162	137	114	96	79	66	54	45	41
650	270	193	164	136	114	94	79	64	53	43	35	32
675	233	164	138	114	95	77	64	51	42	33	27	24
700	201	139	116	95	78	63	52	41	33	26	21	18
725	173	118	97	79	64	51	41	32	26	20	15	14
750	148	99	81	65	53	41	33	25	20	15	12	10
775	127	83	68	53	43	33	26	20	15	11	8	7
800	108	70	56	44	34	26	20	15	11	8	6	5

Figure 2-5 – S_r Values for 304 SS in S.I. units

Temperature in F	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
800	57.1	57.1	57.1	57.1	57.1	57.1	56.6	52.1	46.4	40.8	36.2	34.2
850	56.4	56.4	56.4	56.4	56.3	55.1	49.0	42.9	37.9	33.0	29.1	27.4
900	55.3	55.3	55.3	55.0	52.7	45.9	40.5	35.1	30.8	26.6	23.3	21.8
950	53.9	53.9	53.9	50.1	44.0	38.1	33.3	28.6	24.9	21.3	18.5	17.2
1000	52.1	52.1	49.0	42.0	36.6	31.4	27.2	23.2	20.0	17.0	14.5	13.5
1050	49.9	47.0	41.0	35.1	30.3	25.8	22.2	18.7	16.0	13.4	11.4	10.5
1100	47.4	39.9	34.4	29.2	25.0	21.1	17.9	15.0	12.7	10.5	8.8	8.1
1150	44.6	33.6	28.7	24.1	20.5	17.1	14.4	11.9	10.0	8.1	6.7	6.2
1200	39.4	28.2	23.9	19.9	16.7	13.8	11.5	9.4	7.8	6.3	5.1	4.6
1250	33.5	23.6	19.8	16.3	13.6	11.1	9.1	7.4	6.0	4.8	3.8	3.5
1300	28.5	19.7	16.4	13.3	11.0	8.9	7.2	5.7	4.6	3.6	2.8	2.5
1350	24.1	16.3	13.5	10.8	8.8	7.0	5.6	4.4	3.5	2.7	2.1	1.8
1400	20.3	13.5	11.0	8.7	7.0	5.5	4.4	3.4	2.6	2.0	1.5	1.3
1450	17.0	11.1	8.9	7.0	5.6	4.3	3.4	2.5	1.9	1.4	1.0	0.9
1500	14.2	9.6	7.2	5.6	4.4	3.3	2.5	1.9	1.4	1.0	0.7	0.6

Figure 2-6 – S_r Values for 304 SS in Customary Units

The short time, low temperature S_r values are similar to the current NH Code. There is some difference due to rounding the values to the nearest significant number. The S_r values at high temperature and long times are lower than the current allowable stress values in NH.

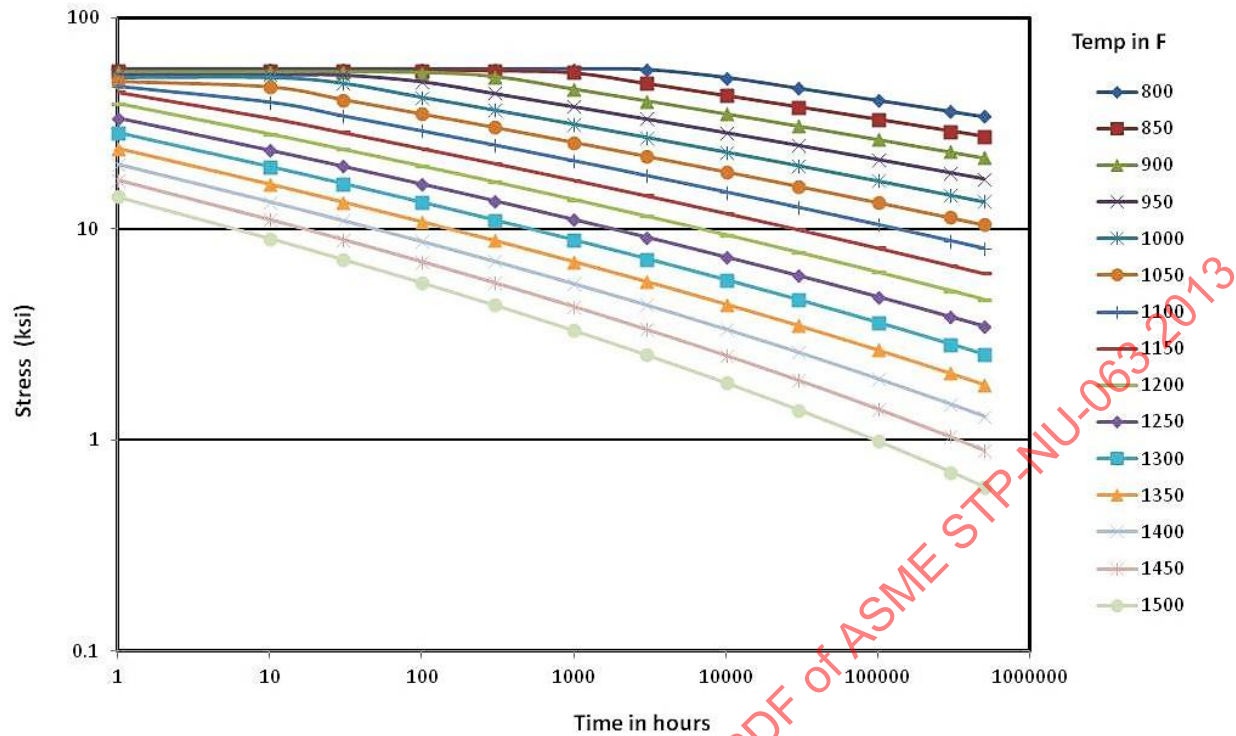


Figure 2-7 – S_r versus Time from 800°F to 1500°F in Customary Units

A comparison of the revised S_r values with NH values is shown in Figure 2-8 below. The data are presented for two time-to-rupture times: 1000 hours and 300,000 hours. The 1000 hour data show that the revised values are similar or lower than the present NH values. The 300,000 hour revised values are lower than the present NH values.

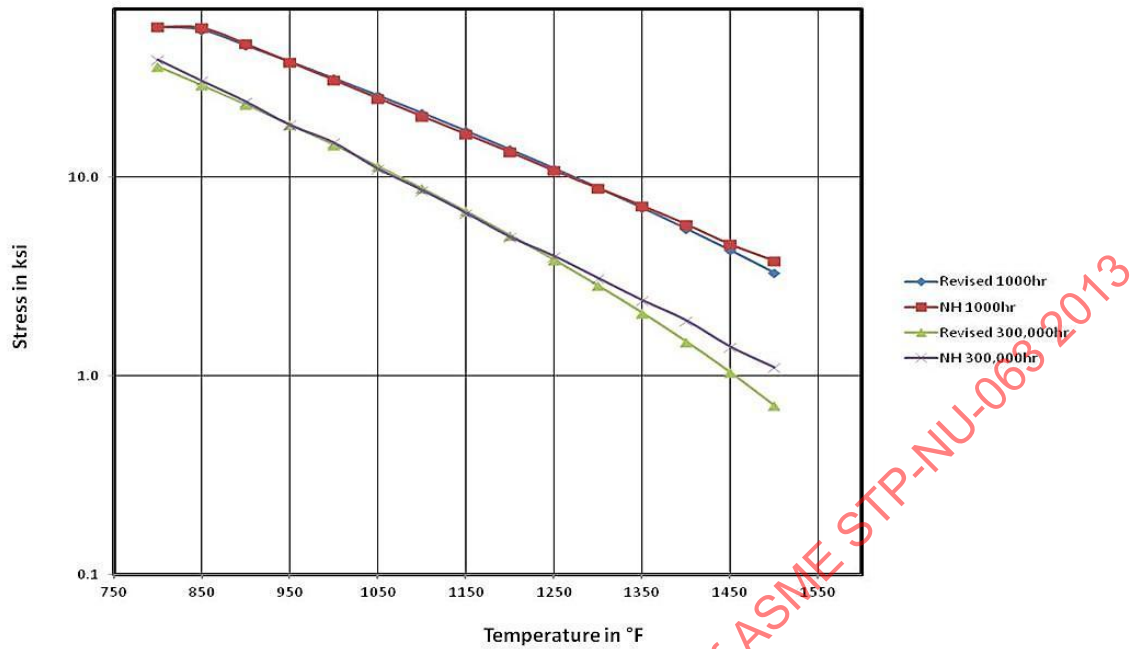
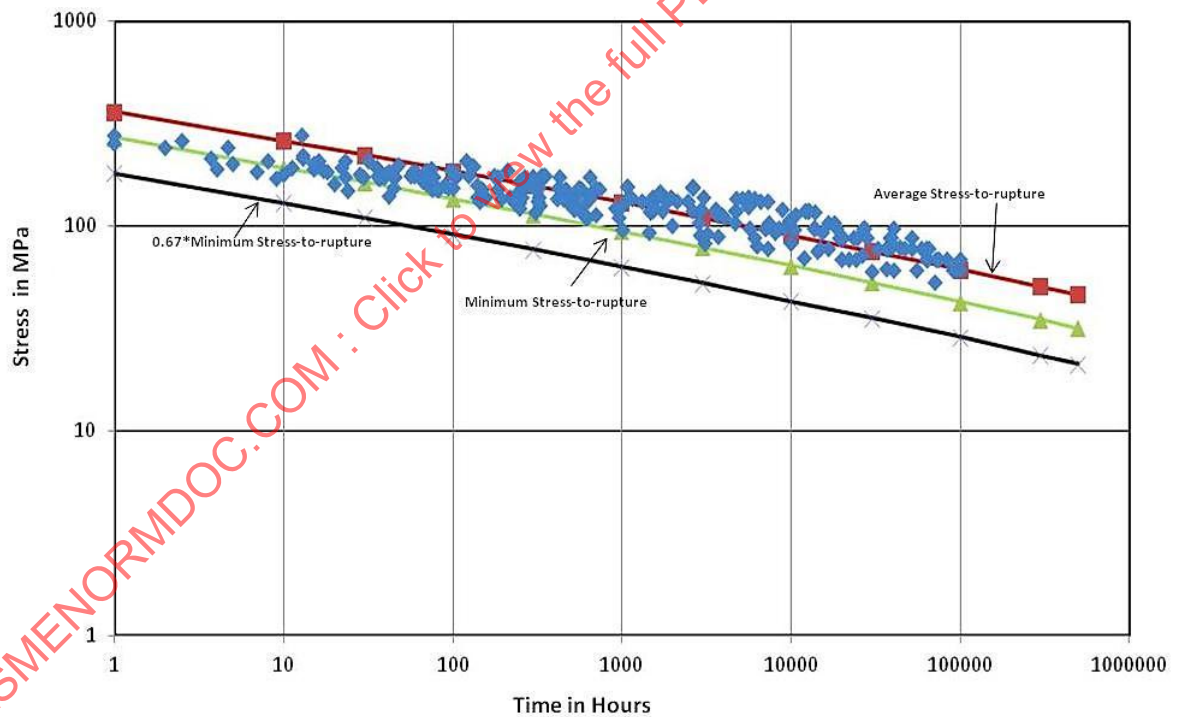
Figure 2-8 – Comparison of Revised S_r Values with NH

Figure 2-9 – Stress versus Time-to-Rupture at 1200°F (650°C)

2.4 Allowable S_t Values

The temperature and time dependent stress intensity, S_t is the lowest of the following three criteria:

- (a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1% ($S_{1\%}$)
- (b) 80% of the minimum stress to cause initiation of tertiary creep (S_{t3})
- (c) 67% of the minimum stress-to-rupture (S_r)

The upper limit on S_t is governed by the stress-to-1% strain limit from the hot tensile curves. Currently, the upper limit in NH is based on the “minimum stress at 1% strain” from the hot tensile curves. The Subgroup on Elevated Temperature Design (SGETD) in its August 14th, 2012 Code week meeting in Washington D.C. agreed to revise the upper limit to the “average stress at 1% strain” in the hot tensile curve. This will make the upper limit for S_t consistent with the above criteria. The hot tensile curves for 304 SS were re-constructed using the Blackburn equations [5], which were originally used for constructing the hot tensile curves for 304 SS in the NH Code. This is explained in more detail in Section 2.4.2.

2.4.1 Time-to-Tertiary Creep Analysis

The tertiary creep criterion for temperature and time dependent stress allowable S_t values is unique to the NH Code. The time-to-tertiary creep is defined as the 0.2% offset strain from a slope tangent to the minimum or “steady state” classical creep curve. This criterion was developed in the formative days of Code Case 1331-5. The rationale for including tertiary creep as a criterion is that tertiary creep is synonymous with the void nucleation and coalescence in metals. Void coalescence would typically lead to micro-cracks resulting in fracture or fissure in critical components. The onset of tertiary creep occurs late (close to rupture) in life for most metals. However, in certain metals such as Alloy 800H, the onset of tertiary creep occurs early. Therefore, tertiary creep was considered important and was included for establishing the temperature and time dependent, S_t stress allowable.

Leyda and Rowe [4] have studied this phenomenon and have proposed that a correlation exists between the time-to-initiate tertiary creep and time-to-rupture. This is expected as tertiary creep is a manifestation of creep damage. The correlation between tertiary creep and the rupture is valid for materials that demonstrate a “classical” creep behavior. A classical creep curve is shown in Figure 2-10. Figure 2-10 shows a creep curve which has primary creep, followed by steady state secondary creep and finally tertiary creep. Time t_2 is the departure from minimum creep rate and t_{ss} marks the onset of time-to-tertiary creep (where 0.2% offset strain intercepts the creep curve).

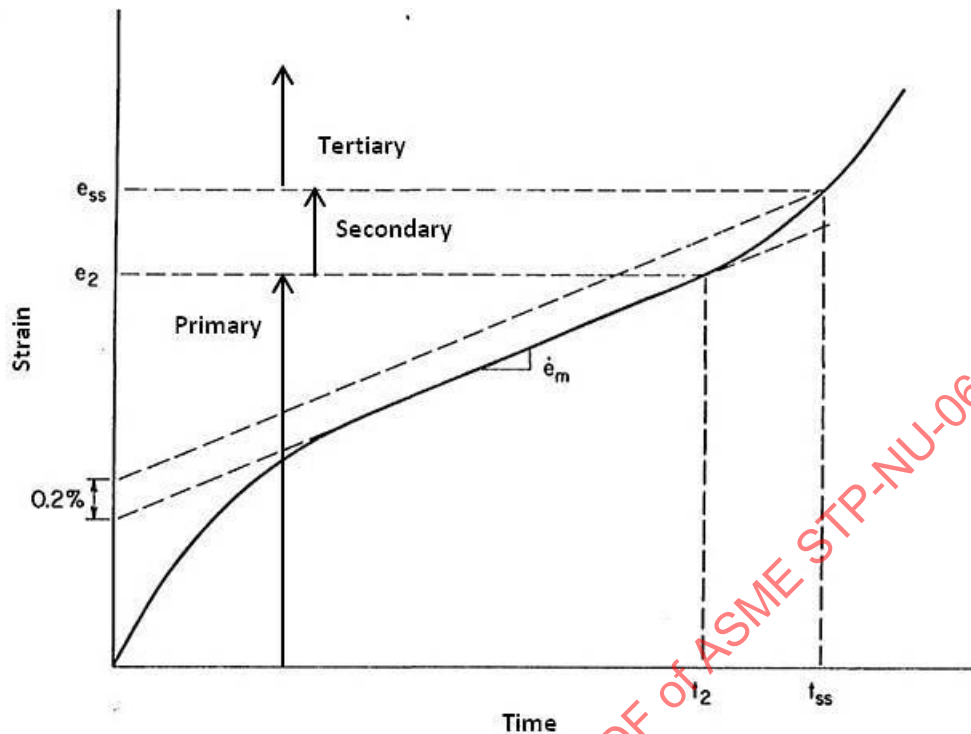


Figure 2-10 – Classical Creep Curve Showing t_2 – Departure from Minimum Creep Rate and t_{ss} – Time-to-Tertiary Creep

The stress required to initiate tertiary creep could be calculated by developing a correlation (if one expects) between time-to-tertiary creep and time-to-rupture, and then using these correlated values in the regression analyses. As the rupture database is much larger than the tertiary creep database, it may be expected that analyzing a larger database would result in a more statistically robust solution.

The tertiary database for 304 SS consisted of only 125 data points. Correlating the time-to-tertiary creep and time-to-rupture for a broad range of temperatures and times was difficult as there were insufficient data. Instead of attempting to develop a correlation with the rupture life, the time-to-tertiary creep data were analyzed using the LMP regression analysis on the limited data available, as described in Section 1.3.

Before the analysis, the time-to-tertiary database was censored based on three criteria, similar to the previous rupture analysis:

- (a) Any data point that was 10 standard deviations from the mean
- (b) Data points that had a rupture time less than 100 hours
- (c) Heats with poor strength properties, identified in [3]

After censoring, only 116 data points from 13 heats remained and these were used for the analysis. A second order polynomial regression analysis was used along with a lot-centered approach. The lot constant was calculated as 14.49. A plot of the stress versus LMP and comparison with the calculated stress function of the Larson-Miller parameter for the complete database is shown in Figure 2-11. The data distribution is shown in blue and the stress function is shown as a black line. The trend of the second order polynomial function dips down at long time and high temperatures, resulting in very low stresses. This was judged to be too conservative and a linear regression analysis was performed.

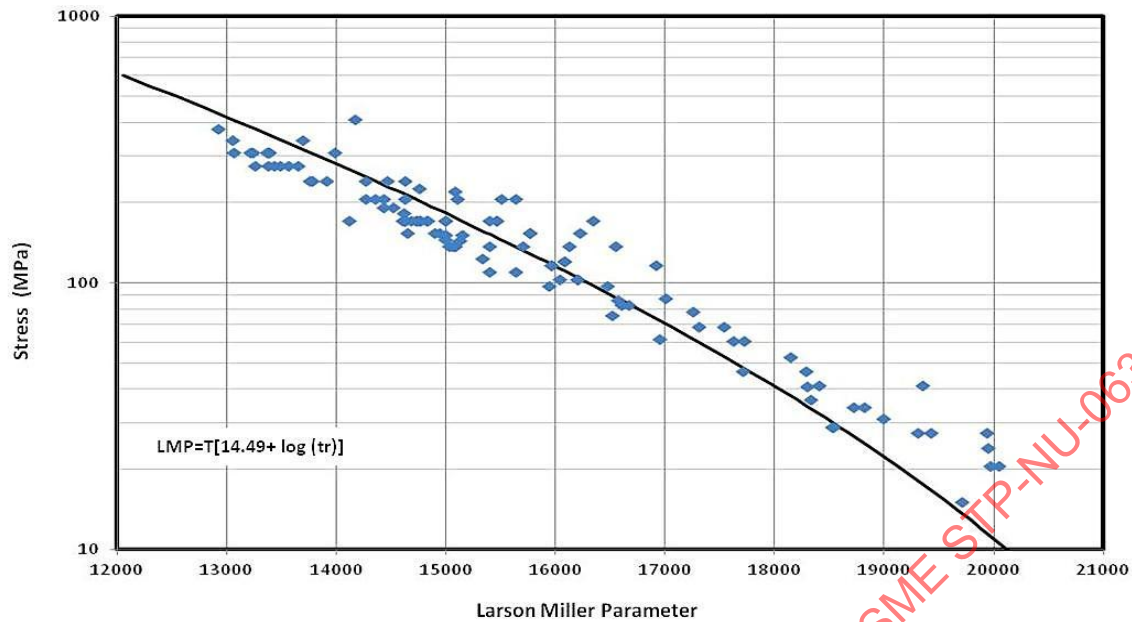


Figure 2-11 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 304 SS – Second Order Polynomial Regression Analysis

In the linear regression analysis, the lot constant was calculated to be 14.45. A plot of the stress versus LMP for the complete database is shown in Figure 2-12. The data distribution is shown in blue and the stress function is shown as a black line.

The values of the regression parameters are given in Table 2-2. The variance for the data is 0.31 and the standard error of estimate is 0.56.

**Table 2-2 – Results from Regression Analysis for 304 SS
Time-to-tertiary Creep Analysis**

Coefficients in Log Stress (a)	Values
a_0	25740.94
a_1	-4789.45

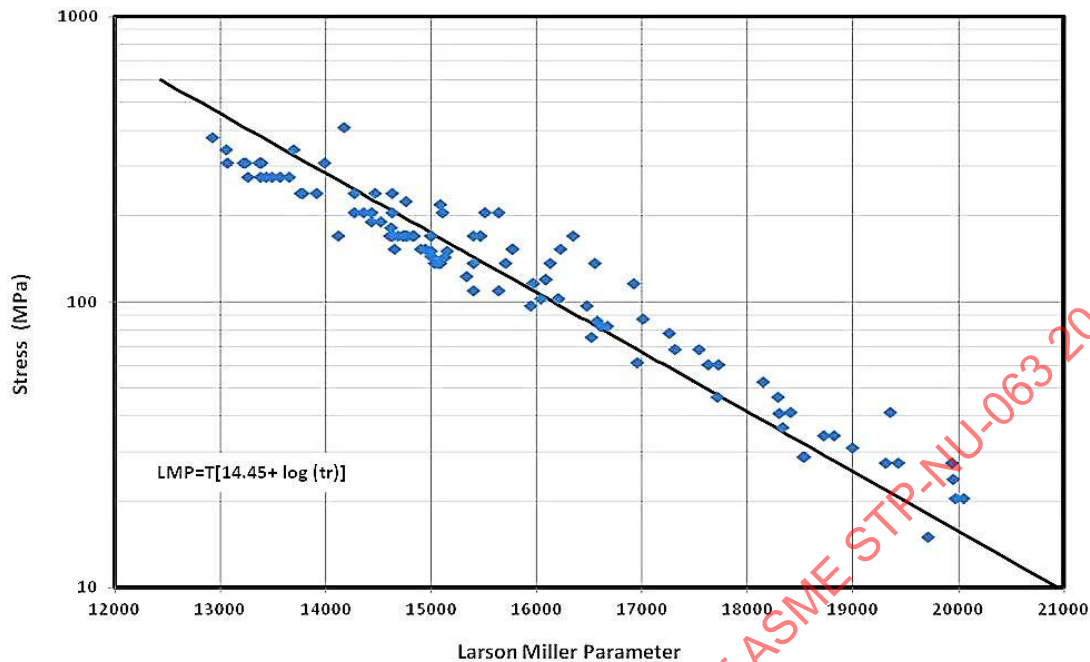


Figure 2-12 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 304 SS – Linear Regression Analysis

The linear regression analysis was used for calculating the minimum stress to initiate tertiary creep.

2.4.2 Time-to-1% Strain Analysis

2.4.2.1 Hot Tensile Curve

The hot tensile curves were re-created in order to calculate an upper limit for S_t . The upper limit on S_t is the stress at 1% strain from the hot tensile curves. The hot tensile curves in NH were constructed using the Blackburn equations. The Blackburn equations used for calculating the hot tensile curves is shown below. The equation which yields the lower value of true strain was used for calculating the stress at 1% strain [5].

$$\varepsilon_L = \frac{\sigma}{E} + \left[\frac{(\sigma - \sigma_p)}{K_1} \right]^{\frac{1}{m_1}} \quad \text{Equation 2.1}$$

$$\varepsilon_L = \frac{\sigma}{E} + \left[\frac{(\sigma - \sigma_p)}{K_2} \right]^{\frac{1}{m_2}} \quad \text{Equation 2.2}$$

where,

ε_L - total true strain, elastic plus plastic

σ - total true stress

E - elastic modulus

σ_p - proportional limit

K_1, K_2, m_1 , and m_2 are constants

These equations were used to calculate the average stress at 1% strain. The total true strain is the lesser of the two values from Equations 2.1 and 2.2.

A comparison of the hot tensile curves with the NH curves is shown at 1000°F and 1300°F in the Figure 2-13 and Figure 2-14. The hot tensile curves developed compare well with the hot tensile curves in NH.

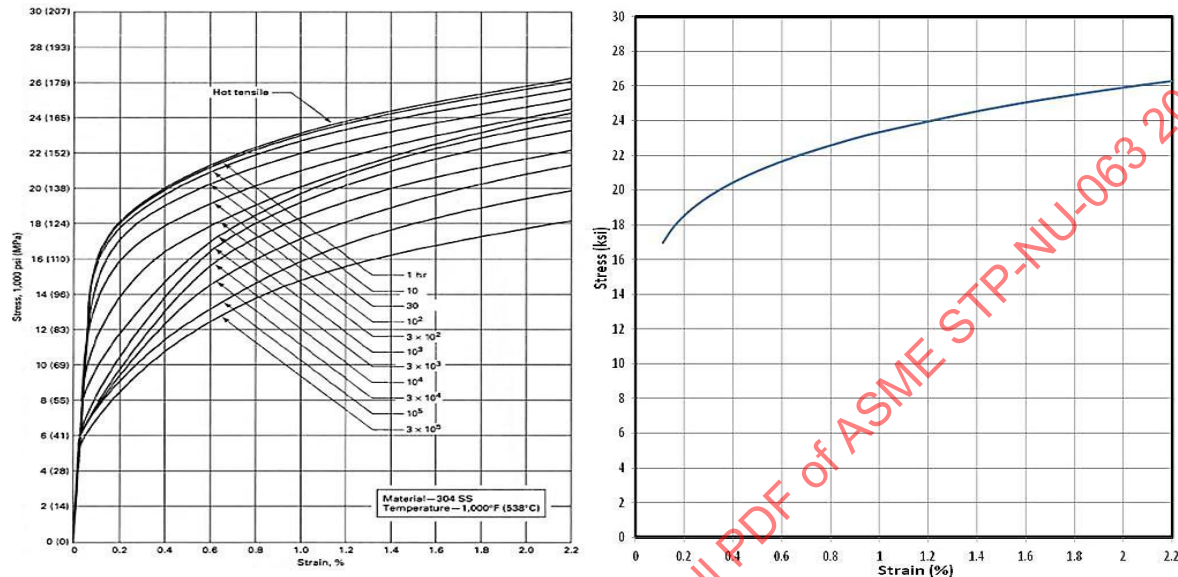


Figure 2-13 – Hot Tensile Curve for 304 SS at 1000°F

Figure on Left Shows the NH Curve. Figure on Right Shows the Curve Developed in this Analysis.

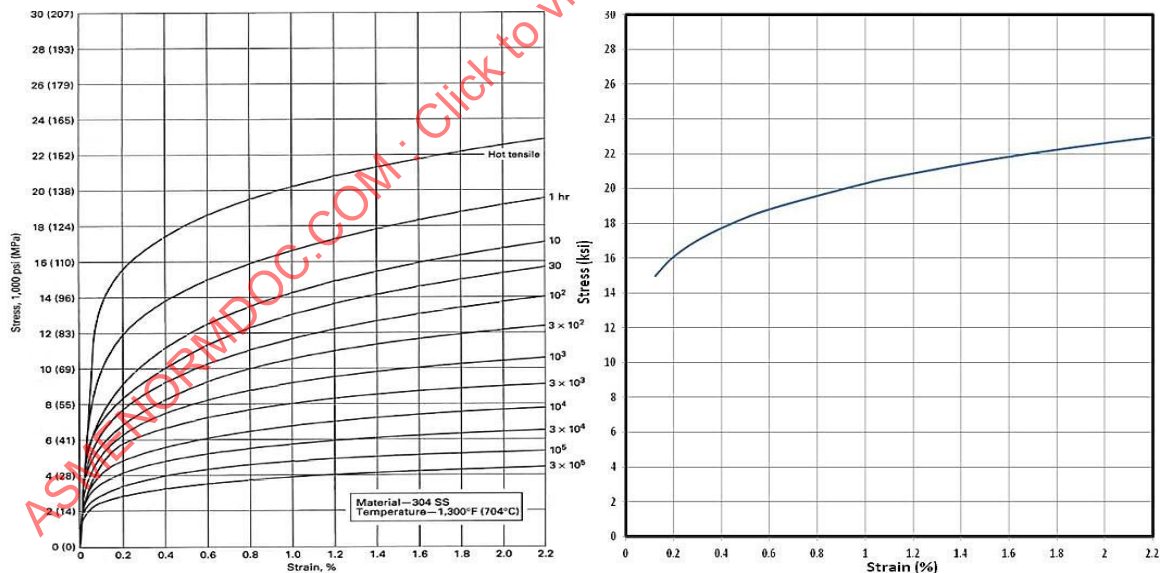


Figure 2-14 – Hot Tensile Curve for 304 SS at 1300°F

Figure on Left Shows the NH Curve. Figure on Right Shows the Curve Developed in this Analysis.

The values of average stress at 1% strain over a range of temperatures are provided in Table 2-3 and Table 2-4.

Table 2-3 – Stress at 1% Strain in S.I. Units for 304 SS

Temperature in °C	Stress at 1% Strain (MPa)
425	176
450	173
475	169
500	166
525	163
550	160
575	156
600	153
625	150
650	147
675	144
700	141
725	137
750	134
775	131
800	128

Table 2-4 – Stress at 1% strain in Customary Units for 304 SS

Temperature in °F	Stress at 1% Strain (ksi)
800	25.5
850	24.9
900	24.4
950	23.9
1000	23.4
1050	22.9
1100	22.3
1150	21.8
1200	21.3
1250	20.8
1300	20.3
1350	19.8
1400	19.3
1450	18.8
1500	18.4

2.4.2.2 LMP Analyses

LMP regression analysis was performed on the time-to-1% strain data. The database for time-to-1% strain included the loading strains. The database consisted of only 66 data points. The database was censored based on the following criteria:

- Any data point that was 10 standard deviations from the mean
- Time-to-rupture data less than 100 hours
- Heats with poor strength properties, identified in [3]

After the database was censored, only 54 data points remained that could be used for the LMP regression analysis. A linear regression analysis was performed on the database due to the limited data available.

The lot constant was calculated as 19.12. A plot of the stress versus LMP is shown in Figure 2-15. The data distribution is shown in blue and the stress function is shown as a black line. The values of the regression parameters are given in Table 2-5. The variance for the data is 0.55 and the standard error of estimate is 0.74. The standard error of estimate is larger compared to the other databases. The variability in the data can be reduced if a larger database of time-to-1% strain is used.

**Table 2-5 – Results from Regression Analysis for 304 SS
for Time-to-1% Strain**

Coefficients in Log Stress (a)	Values
a_0	31855.58
a_1	-5842.29

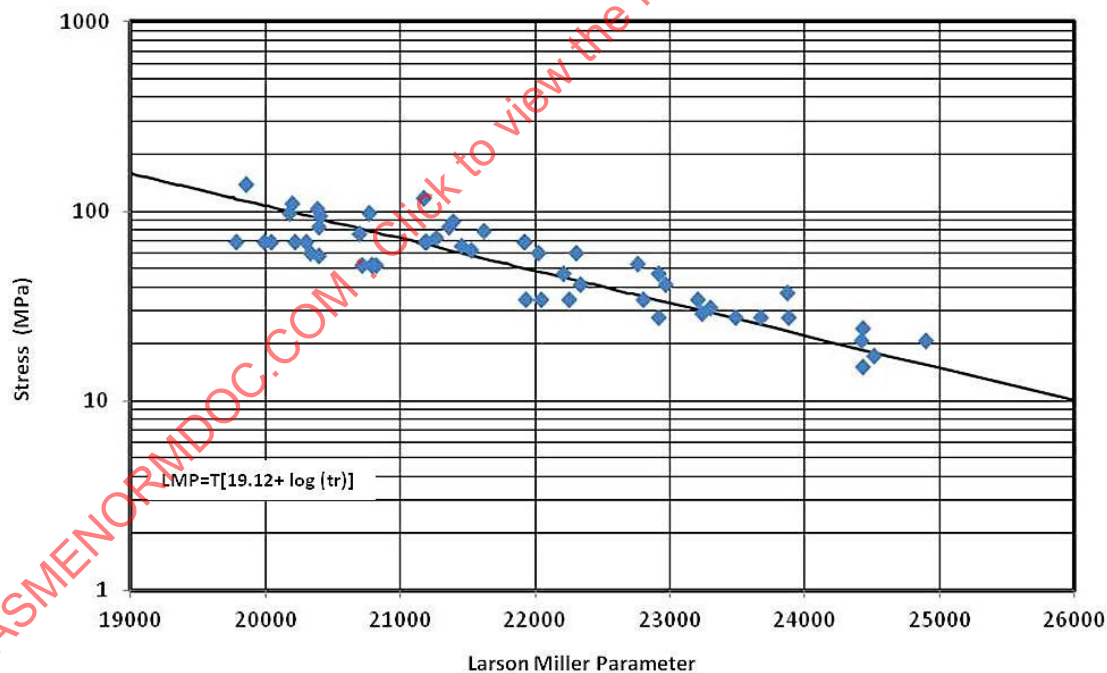


Figure 2-15 – Stress versus LMP for Time-to-1% Strain Analysis of 304 SS - Linear Regression Analysis

2.4.3 Results

The temperature and time dependent stress intensity, S_t is calculated from the minimum of the three criteria given in Section 2.4. The S_t values are presented in S.I. and Customary units and are shown in Figure 2-16 and Figure 2-17. The stress values are plotted over time for different temperatures in Figure 2-18.

Temperature in C	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
425	179	179	179	179	179	179	179	179	179	179	169	160
450	176	176	176	176	176	176	176	176	176	158	135	125
475	173	173	173	173	173	173	173	171	150	125	105	97
500	169	169	169	169	169	169	164	141	118	98	82	75
525	166	166	166	166	166	158	137	112	93	76	64	58
550	163	163	163	163	155	132	109	89	74	60	50	45
575	160	160	160	152	131	106	87	70	58	47	39	35
600	156	156	152	129	106	85	69	56	46	37	30	27
625	153	151	129	105	85	68	55	44	36	29	23	21
650	150	129	107	85	69	55	44	35	28	22	18	16
675	147	109	88	69	55	44	35	28	22	18	14	13
700	135	89	71	56	45	35	28	22	18	14	11	10
725	116	73	58	45	36	28	22	17	14	11	9	8
750	99	60	48	37	29	23	18	14	11	8	7	6
775	82	50	39	30	24	18	14	11	9	7	5	5
800	68	41	32	24	19	14	11	9	7	5	4	3

Figure 2-16 – S_t Values for 304 SS in S.I. Units

Temperature in F	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
800	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	25.8	24.2	22.9
850	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	24.8	22.0	18.8	17.4
900	24.9	24.9	24.9	24.9	24.9	24.9	24.7	23.5	20.4	16.9	14.3	13.2
950	24.4	24.4	24.4	24.4	24.4	23.9	22.3	18.8	15.7	12.9	10.8	9.9
1000	23.8	23.8	23.8	23.8	23.3	21.0	17.8	14.5	12.1	9.8	8.2	7.5
1050	23.3	23.3	23.3	22.6	20.3	16.8	13.8	11.2	9.3	7.5	6.2	5.7
1100	22.8	22.8	22.3	19.5	16.3	13.1	10.8	8.7	7.1	5.7	4.7	4.3
1150	22.3	22.1	19.3	15.7	12.8	10.2	8.3	6.7	5.4	4.3	3.5	3.2
1200	21.8	18.9	15.7	12.5	10.1	8.0	6.5	5.1	4.2	3.3	2.7	2.4
1250	21.2	15.6	12.5	9.9	7.9	6.3	5.0	4.0	3.2	2.5	2.0	1.8
1300	19.1	12.5	10.0	7.8	6.3	4.9	3.9	3.1	2.5	1.9	1.5	1.4
1350	16.1	10.1	8.0	6.2	4.9	3.8	3.1	2.4	1.9	1.5	1.2	1.0
1400	13.3	8.1	6.4	4.9	3.9	3.0	2.4	1.8	1.4	1.1	0.9	0.8
1450	10.9	6.5	5.1	3.9	3.1	2.4	1.8	1.4	1.1	0.9	0.7	0.6
1500	8.8	5.2	4.1	3.1	2.4	1.8	1.4	1.1	0.9	0.6	0.5	0.4

Figure 2-17 – S_t Values for 304 SS in Customary Units

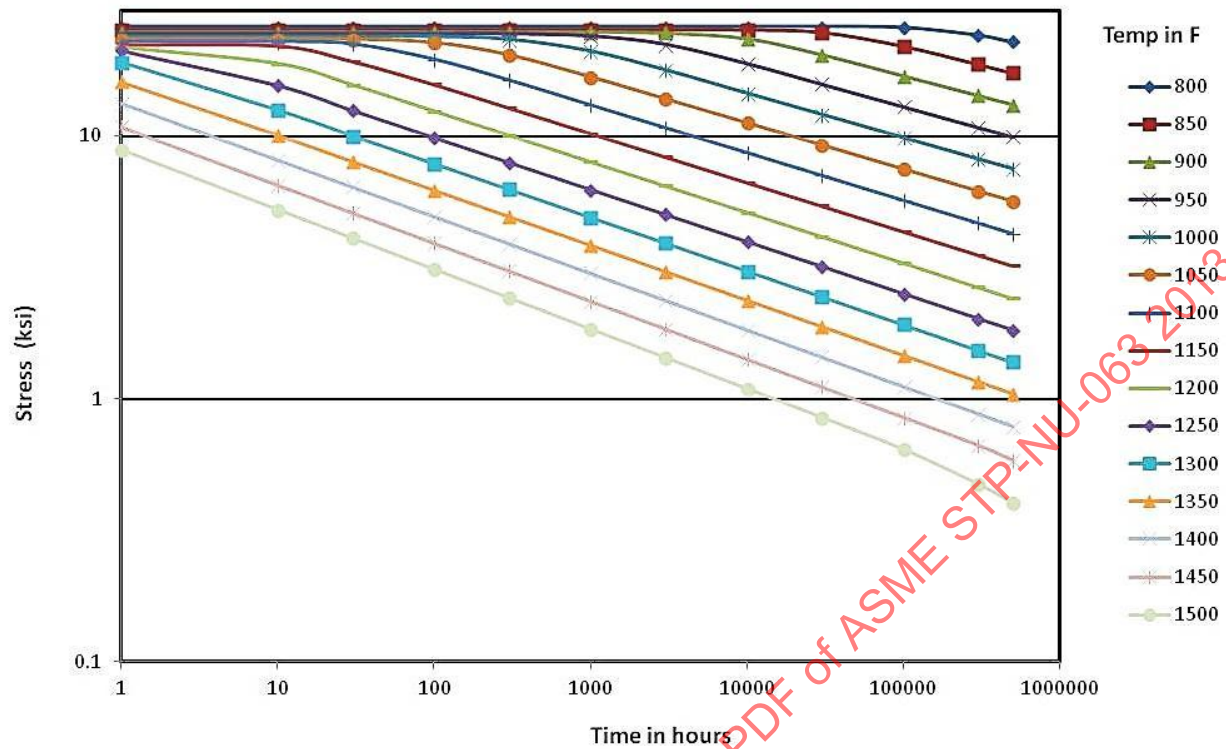


Figure 2-18 – S_t versus Time from 800°F to 1500°F in Customary Units

The short time, low temperature S_t values are controlled by the “average stress at 1% strain”. Since the upper limit was revised from minimum stress, these values are greater by a factor of approximately 1.25 compared to the values in NH. The intermediate time, moderate temperature stress values are controlled by the time-to-tertiary creep or the 0.67 times stress to rupture values. The long time, high temperature values are all controlled by the time-to-tertiary creep values. The values developed from the time-to-1% strain analyses did not control any S_t values.

A comparison of the revised S_t values with the NH values is shown in Figure 2-19 below. The data are presented for two time-to-rupture times: 1000 hours and 300,000 hours. The 1000 hour data shows that the revised values are higher at lower temperatures (controlled by the revised “average stress to 1% strain” criterion) and lower at high temperatures (controlled by the time-to-tertiary creep criterion) than the present NH values. The 300,000 hour revised values are lower than the present NH values, except at 800°F where the average stress at 1% strain controls the S_t values.

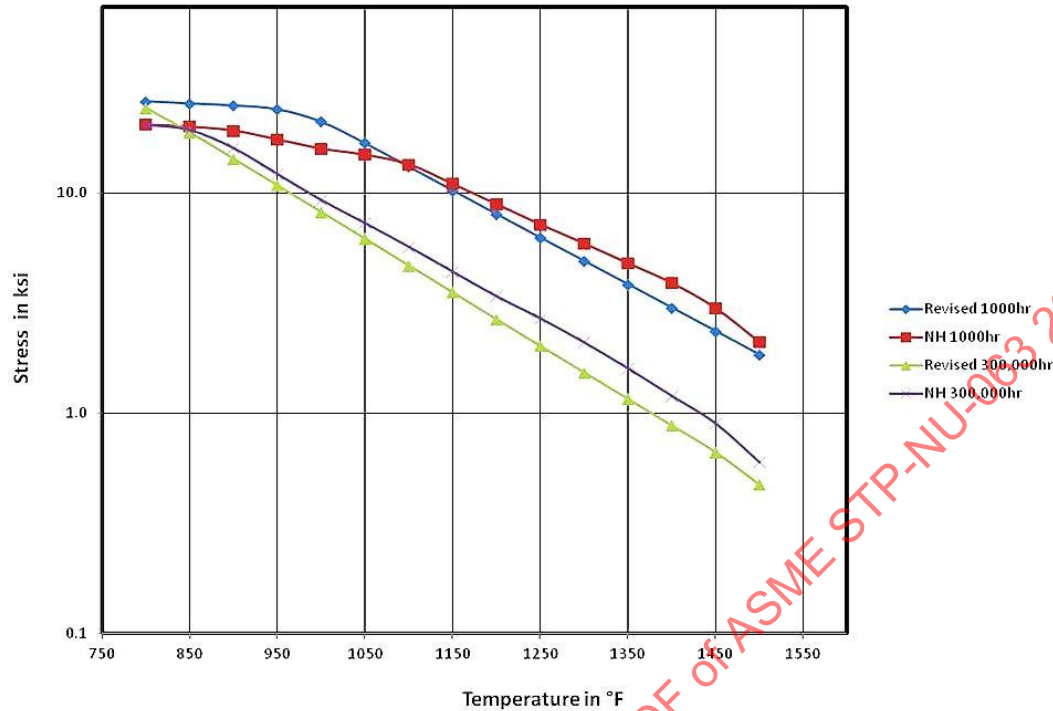


Figure 2-19 – Comparison of Revised S_t Values with NH

2.5 Allowable S_{mt} Values

The S_{mt} values are developed from the lower of the two stress intensity values, S_m (time independent) and S_t (time dependent) values.

The S_m values are defined as the lowest stress intensity value at a given temperature among the time-independent strength properties.

- The product of one-third of the specified minimum tensile strength at room temperature (Table NH-3225-1) and the tensile strength reduction factor (Table NH-3225-2).
- The product of one-third of the tensile strength at temperature (Table NH-3225-1) and the tensile strength reduction factor (Table NH-3225-2).
- The product of two-thirds of the specified minimum yield strength at room temperature (Table 1-14.5) and the yield strength reduction factor (Table NH-3225-2).
- For 304 and 316 austenitic SSs and Alloy 800H, the product of 90% of the yield strength at temperature (Table 1-14.5) and the yield strength reduction factor (Table NH-3225-2).

The low temperature and short-time values for S_{mt} are controlled by the S_m values. The remaining values are controlled by the S_t values.

The S_{mt} values are presented in S.I. and Customary units in Figure 2-20 and Figure 2-21. The stress values are plotted over time for different temperatures in Figure 2-22.

Temperature in C	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
425	105	105	105	105	105	105	105	105	105	105	105	105
450	103	103	103	103	103	103	103	103	103	103	103	103
475	101	101	101	101	101	101	101	101	101	101	101	97
500	99	99	99	99	99	99	99	99	99	98	82	75
525	97	97	97	97	97	97	97	97	93	76	64	58
550	95	95	95	95	95	95	95	89	74	60	50	45
575	94	94	94	94	94	94	87	70	58	47	39	35
600	92	92	92	92	92	85	69	56	46	37	30	27
625	89	89	89	89	85	68	55	44	36	29	23	21
650	84	84	84	84	69	55	44	35	28	22	18	16
675	77	77	77	69	55	44	35	28	22	18	14	13
700	70	70	70	56	45	35	28	22	18	14	11	10
725	63	63	58	45	36	28	22	17	14	11	9	8
750	56	56	48	37	29	23	18	14	11	8	7	6
775	49	49	39	30	24	18	14	11	9	7	5	5
800	42	41	32	24	19	14	11	9	7	5	4	3

Figure 2-20 – S_{mt} Values for 304 SS in S.I. Units

Temperature in F	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
800	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
850	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.7
900	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	13.8	13.2
950	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.0	12.9	10.8	9.9
1000	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5	12.1	9.8	8.2	7.5
1050	13.7	13.7	13.7	13.7	13.7	13.7	13.1	11.2	9.3	7.5	6.2	5.7
1100	13.4	13.4	13.4	13.4	13.4	12.6	10.8	8.7	7.1	5.7	4.7	4.3
1150	13.0	13.0	13.0	13.0	12.5	10.2	8.3	6.7	5.4	4.3	3.5	3.2
1200	12.2	12.2	12.2	12.2	10.1	8.0	6.5	5.1	4.2	3.3	2.7	2.4
1250	11.1	11.1	11.1	9.9	7.9	6.3	5.0	4.0	3.2	2.5	2.0	1.8
1300	10.0	10.0	9.9	7.8	6.3	4.9	3.9	3.1	2.5	1.9	1.5	1.4
1350	8.9	8.9	8.0	6.2	4.9	3.8	3.1	2.4	1.9	1.5	1.2	1.0
1400	7.8	7.8	6.4	4.9	3.9	3.0	2.4	1.8	1.4	1.1	0.9	0.8
1450	6.6	6.5	5.1	3.9	3.1	2.4	1.8	1.4	1.1	0.9	0.7	0.6
1500	5.6	5.2	4.1	3.1	2.4	1.8	1.4	1.1	0.9	0.6	0.5	0.4

Figure 2-21 – S_{mt} Values for 304 SS in Customary Units

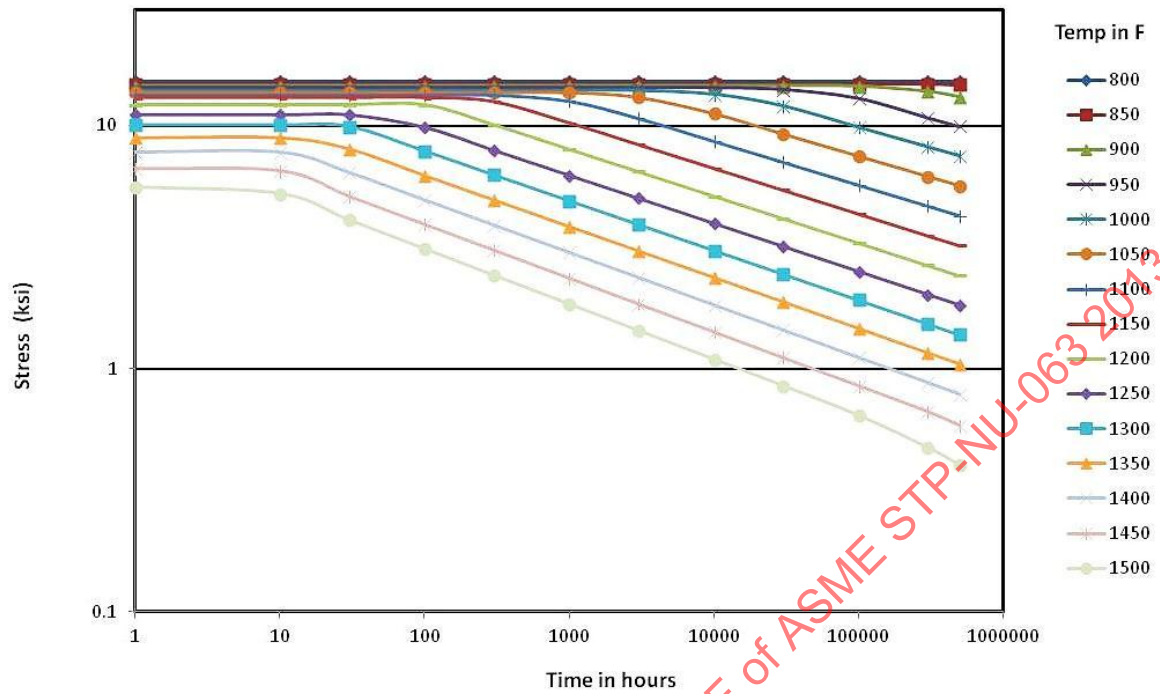


Figure 2-22 – S_{mt} versus Time from 800°F to 1500°F in Customary Units

3 316 STAINLESS STEEL

3.1 Introduction

Another material that is qualified for use in elevated temperature service is 316 SS. The allowable stress values for 316 SS are provided for up to 300,000 hours service in NH. Task 14a requires that these values be revised and developed for 500,000 hours. This will allow components to be designed and constructed with a 60-year design life.

3.2 Database

The 316 SS database used for this task is the same database used for Task 6. The 316 SS database was provided by the authors of Task 6. This database was larger than the 304 SS database and consisted of approximately 1950 data points from 485°C (900°F) to 985°C (1800°F). The maximum rupture time was 222,700 hours. Only 1770 data points provided rupture data. The time-to-tertiary creep and time-to-1% strain database were much smaller, with only 307 and 163 data points respectively.

3.3 Allowable S_r Values

3.3.1 Time-to-Rupture Analysis

The time-to-rupture data were used for calculating the S_r values. The rupture data were censored based on three criteria:

- (a) Any data point that was ten (10) standard deviations from the mean.
Only one data point was ten standard deviations from the mean and was censored from the database.
- (b) Time-to-rupture data less than 100 hours.
- (c) Heats with poor strength properties, identified in previous Task 14 work [3].
Task 14 identified three heats – AAD, AAE and AAF in the NIMS database, which had poor strength characteristics. The rupture strength of these three heats dropped at higher temperatures. In particular, the rupture strength of Heat AAF dropped below the NH allowable strength at 100,000 hours and 700°C, which is undesirable. The data from these heats were not considered in the analyses.

After the data were censored, the time-to-rupture database consisted of 1462 data points. A second order polynomial regression analysis was used along with a lot-centered approach. The lot constant was calculated as 16.28. A plot of the stress versus LMP and comparison with the calculated stress function of the Larson-Miller parameter for the total database is shown in Figure 3-1. The data distribution is shown in blue and the stress function is shown as a black line. The values of the regression parameters are given in Table 3-1. The variance for the data is 0.12 and the standard error of estimate is 0.35.

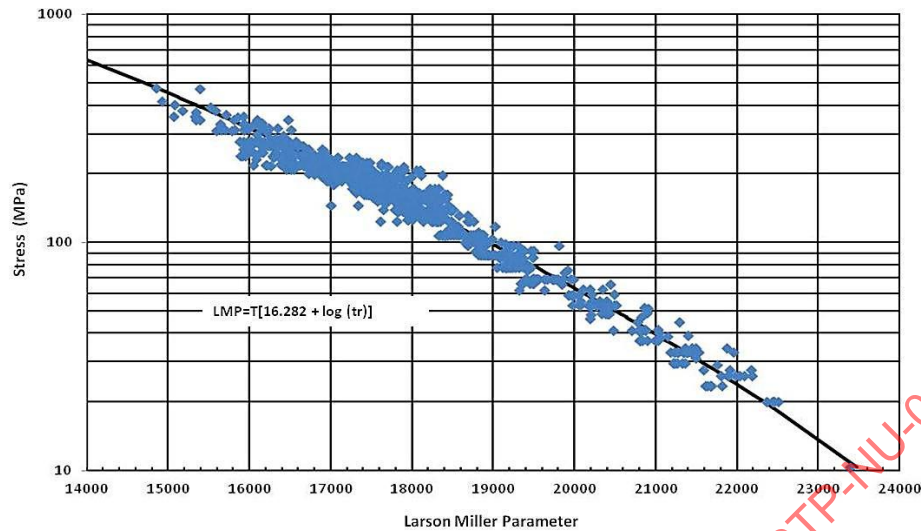


Figure 3-1 – Stress versus LMP for Rupture Analysis of 316 SS

Table 3-1 – Results from Regression Analysis for 316 SS for Rupture Analysis

Coefficients in Log Stress (a)	Values
a_0	26377.99
a_1	-1982.62
a_2	-866.40

A probability plot of the rupture data is shown in Figure 3-2. The probability plot shows the percent of data versus the residual in log time for the rupture data. The residual is calculated by subtracting the log time calculated per the regression analysis from the log rupture time reported in the database. Figure 3-2 shows that the data distribution is approximately linear which indicates that the residual data is normally distributed.

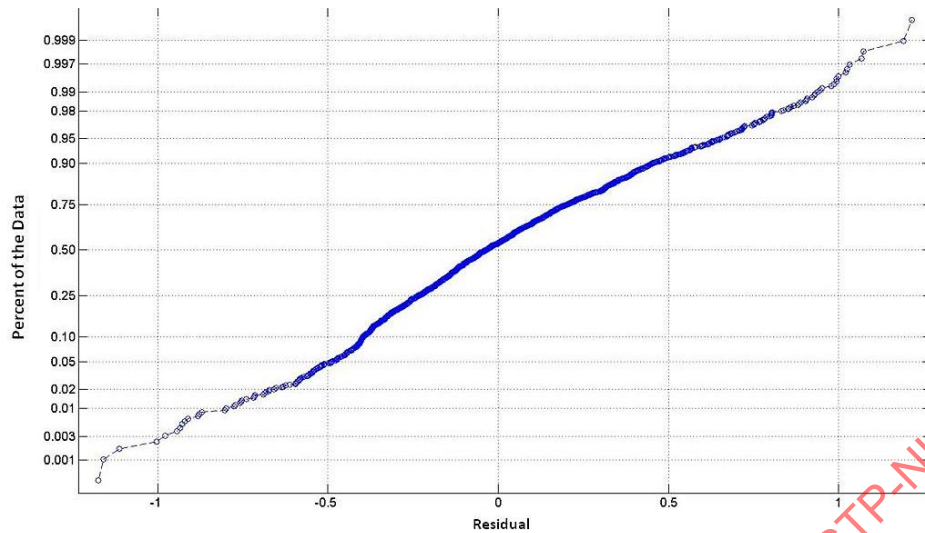


Figure 3-2 – Normal Probability Distribution of the Rupture Data

A plot of the residual in log time versus temperature in S.I. units is shown in Figure 3-3. The maximum variation in the residual is at 600°C (1110°F) and 625°C (1150°F). A histogram showing the number of data points for the range of residual is shown in Figure 3-4.

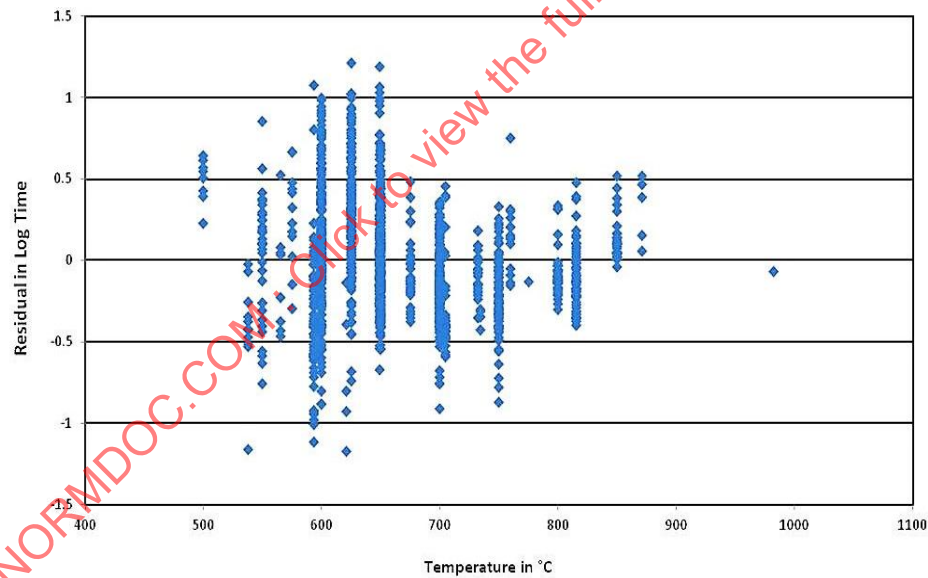


Figure 3-3 – Plot of Residual in Log Time versus Temperature in °C for the Rupture Data

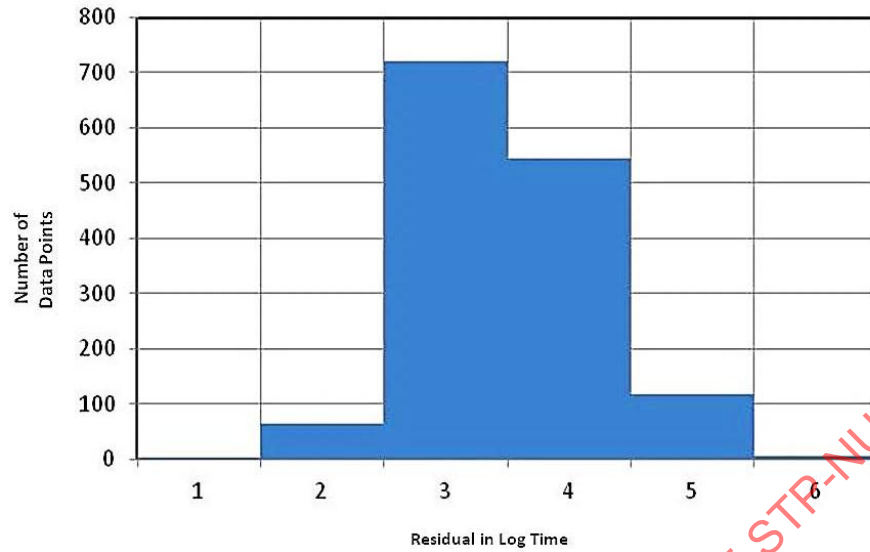


Figure 3-4 – Data Points versus Residual in Log Time for the Rupture Analysis

3.3.2 Calculations and Results

The ASME NH rules require a lower bound estimate of the rupture life, called the minimum-stress-to-rupture. The minimum stress-to-rupture, S_r is calculated from the regression analysis by shortening the rupture life by 1.65 times the SEE. This yields a lower stress value compared to average stress-to-rupture for a particular rupture life as shown in Figure 2-9. Numerically, this is done by adding 0.578 (1.65 times the standard error of estimate) to the rupture life in Equation 1.2 and solving for stress in the polynomial function. The stress values were solved with a help of the MathCAD program. An example program is attached in Appendix A.

The upper bound on the S_r values is controlled by the ultimate strength of the material at any particular temperature. This is because the values calculated from the LMP analysis can be larger than the ultimate strength of the material. The upper bound on S_r has been set at $S_u/1.1$, where S_u is the ultimate strength of the material [6]. The S_u values used in this analysis were taken from Section II, Part D and Section III, NH [10]. The minimum stress to rupture values in S.I. and Customary units are shown in Figure 3-5 and Figure 3-6. The S_r values are plotted over time and temperature in Figure 3-7.

Temperature in C	Time in Hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
425	445	445	445	445	445	445	445	445	445	414	368	348
450	438	438	438	438	438	438	438	438	390	340	300	283
475	431	431	431	431	431	431	421	366	322	279	244	229
500	421	421	421	421	421	400	351	303	264	227	197	184
525	409	409	409	409	389	335	292	250	216	184	158	148
550	395	395	395	377	327	279	241	205	176	148	126	117
575	379	379	373	318	274	232	199	167	142	119	100	93
600	360	360	316	267	229	192	163	136	114	94	79	72
625	339	313	267	224	190	158	133	109	91	75	62	56
650	315	265	225	187	157	129	108	88	72	58	48	43
675	289	224	188	155	129	105	87	70	57	45	36	33
700	262	189	157	128	106	85	69	55	44	35	27	25
725	232	158	131	105	86	68	55	43	34	26	20	18
750	199	132	108	86	70	55	44	34	26	20	15	13
775	168	110	89	70	56	43	34	26	20	14	11	9
800	135	91	73	57	45	34	26	19	15	10	8	6

Figure 3-5 – S_r Values for 316 SS in S.I. Units

Temperature in F	Time in hours											
	1	10	30	100	300	1000	3000	10000	30000	100000	300000	500000
800	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.0	59.3	52.7	49.8
850	63.3	63.3	63.3	63.3	63.3	63.3	63.1	61.7	54.8	47.8	42.1	39.7
900	62.1	62.1	62.1	62.1	62.1	61.2	58.1	50.4	44.3	38.3	33.4	31.4
950	60.4	60.4	60.4	60.4	59.2	54.3	47.4	40.8	35.5	30.4	26.3	24.6
1000	58.3	58.3	58.3	56.9	51.8	44.5	38.6	32.9	28.4	24.0	20.6	19.2
1050	55.8	55.8	55.3	49.3	42.6	36.2	31.2	26.3	22.5	18.8	16.0	14.8
1100	52.9	52.9	48.1	40.7	34.9	29.4	25.0	20.9	17.7	14.6	12.3	11.3
1150	49.6	46.4	39.8	33.4	28.4	23.7	19.9	16.5	13.8	11.3	9.3	8.5
1200	45.8	38.8	32.9	27.3	23.0	18.9	15.8	12.9	10.6	8.6	7.0	6.3
1250	41.7	32.2	27.0	22.2	18.5	15.1	12.4	10.0	8.1	6.5	5.2	4.7
1300	37.2	26.6	22.1	18.0	14.8	11.9	9.7	7.7	6.2	4.8	3.8	3.4
1350	32.2	21.9	18.0	14.5	11.8	9.4	7.5	5.9	4.6	3.5	2.7	2.4
1400	27.0	17.9	14.6	11.6	9.3	7.3	5.8	4.4	3.4	2.6	1.9	1.7
1450	21.9	14.6	11.7	9.2	7.3	5.6	4.4	3.3	2.5	1.8	1.3	1.1
1500	18.2	11.8	9.4	7.2	5.6	4.3	3.2	2.4	1.8	1.2	0.9	0.7

Figure 3-6 – S_r Values for 316 SS in Customary Units

The short time, low temperature S_r values are similar to the current NH Code. There is some difference due to rounding the values to the nearest significant number. The S_r values at high temperature and long times are lower than the current allowable stress values in NH.

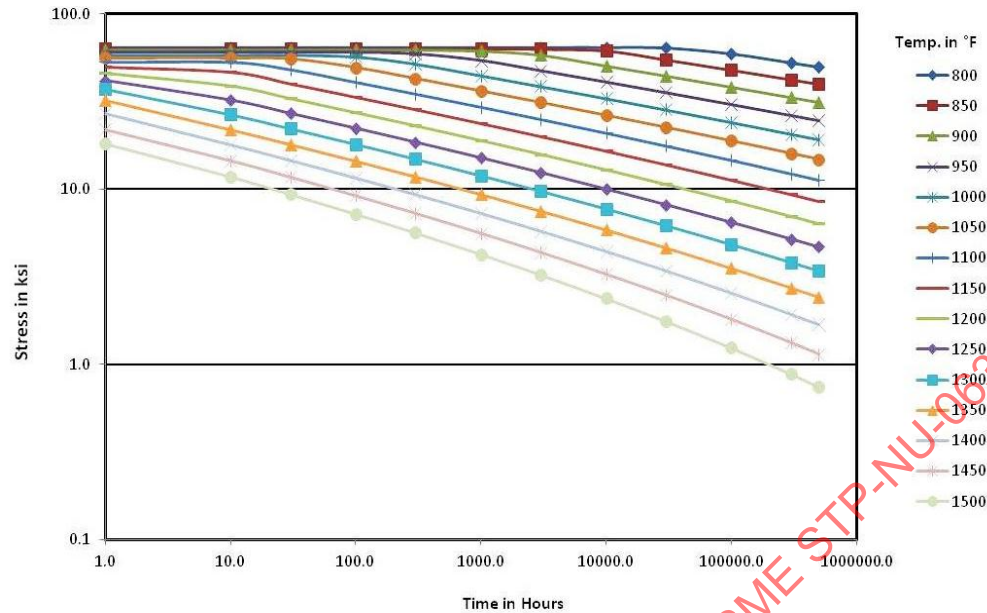


Figure 3-7 – S_r versus Time from 800°F to 1500°F in Customary Units

A comparison of the revised S_r values with the NH values is shown in Figure 3-8 below. The data are presented for two time-to-rupture times: 1000 hours and 300,000 hours. The 1000 hour data show that the values are similar or lower than the NH values. The 300,000 hour revised values are similar or lower than the NH values. Some of the values are slightly higher than the NH values, but the difference is not significant.

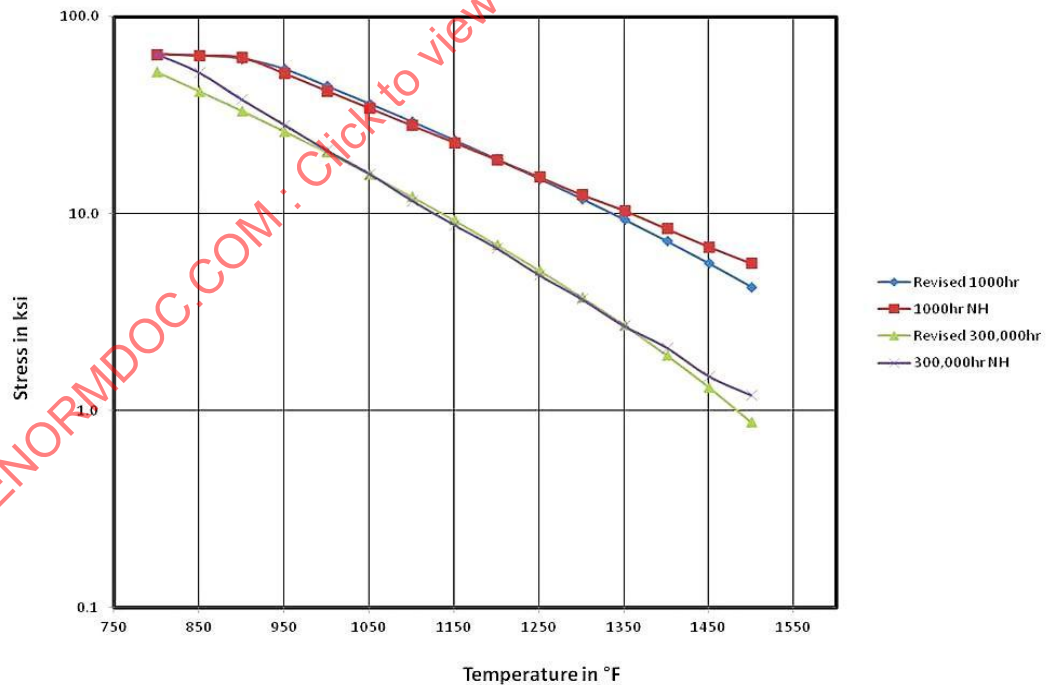


Figure 3-8 – Comparison of Revised S_r Values with NH

3.4 Allowable S_t Values

The temperature and time dependent stress intensity, S_t is the lowest of the following three criteria:

- (a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1% ($S_{1\%}$)
- (b) 80% of the minimum stress to cause initiation of tertiary creep (S_{t3})
- (c) 67% of the minimum stress-to-rupture (S_r)

The upper limit on S_t is governed by the stress-to-1% strain limit from the hot tensile curves. Currently, the upper limit in NH is based on the “minimum stress at 1% strain” from the hot tensile curves. The Subgroup on Elevated Temperature Design (SGETD) in its August 14th, 2012 Code week meeting in Washington D.C. agreed to revise the upper limit to the “average stress at 1% strain” in the hot tensile curve. This will make the upper limit for S_t consistent with the above criteria.

The hot tensile curves for 316 SS were re-constructed using the Blackburn equations [5]. This is explained in more detail in Section 3.4.2.

3.4.1 Time-to-Tertiary Creep Analysis

The rationale for including the tertiary creep criterion for temperature and time dependent allowable S_t values is explained in Section 2.4.1. Since the tertiary creep database for 316 SS was larger than the 304 SS database, a Leyda and Rowe [4] analysis was performed on the data. Figure 3-9 shows the data distribution for the ratio between the time-to-tertiary creep and time-to-rupture (t_3/t_r) versus temperature. There is wide variation in t_3/t_r over the temperature range. This is contrary to the Leyda and Rowe observation, which states that t_3/t_r is approximately constant at a particular temperature. A heat from the NIMS database, AaA was analyzed. The ratio t_3/t_r varies from 0.143 to 0.46 at 750°C for this heat. The scatter in the data indicates that creep in 316 SS does not follow the classical creep curve shown in Figure 2-10. Previous authors such as Booker and Sikka at ORNL have also reported similar “non-classical” creep behavior in 316 SS [7].

A plot was developed for analyzing the behavior of t_3/t_r over rupture time, shown in Figure 3-10. There is more variation in t_3/t_r for the short time rupture data as compared to the long time rupture data.

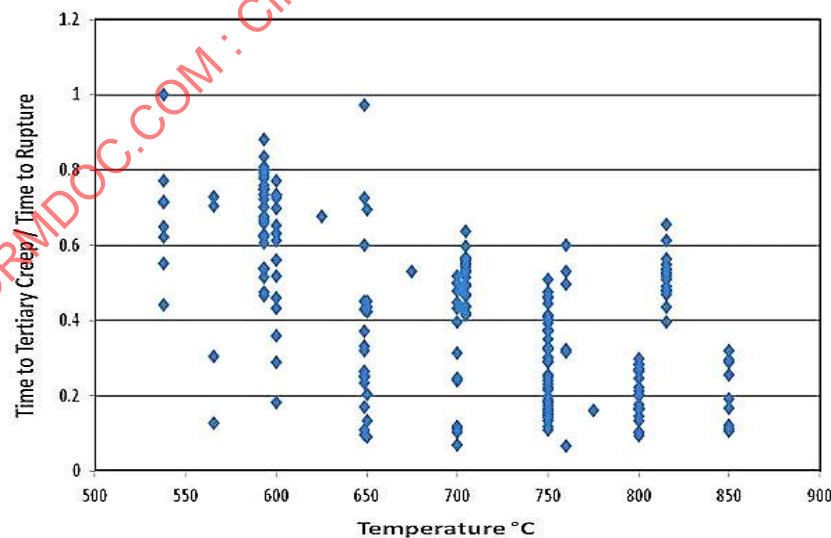


Figure 3-9 – Ratio between Time-to-Tertiary Creep and Time-to-Rupture (t_3/t_r) versus Temperature for 316 SS Shows Large Variation

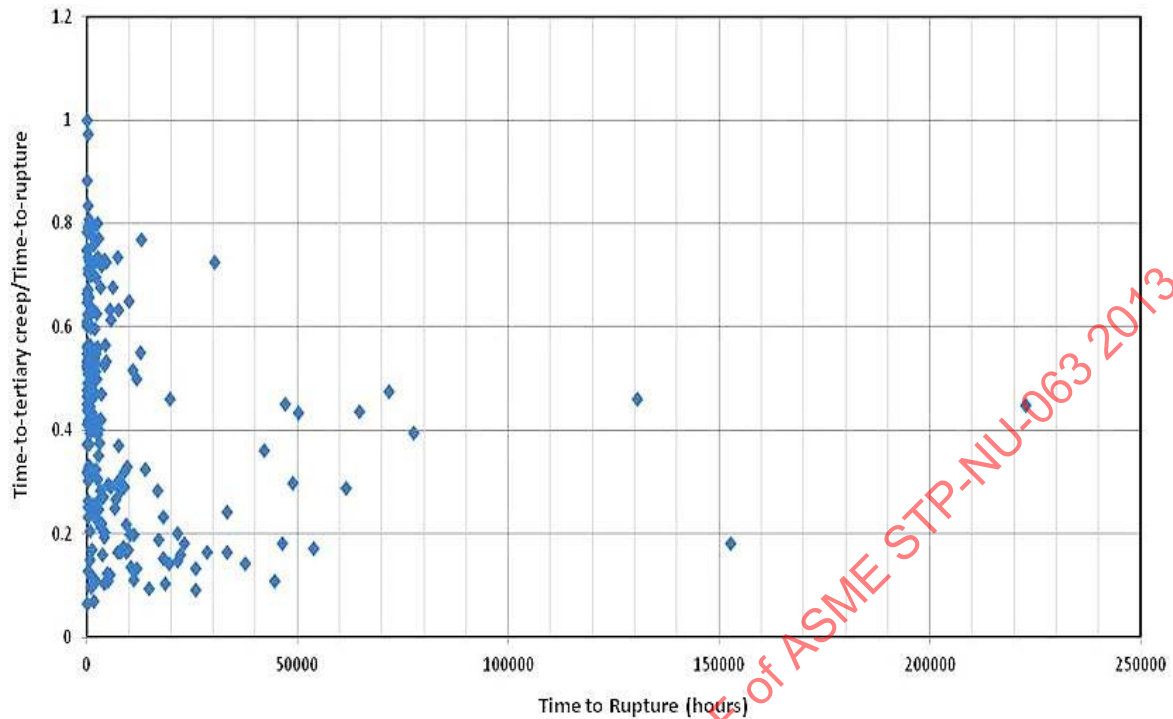


Figure 3-10 – t_3/t_r versus Rupture Time for 316 SS Shows Greater Variation for Short Rupture Time

Since time-to-tertiary data and time-to-rupture were not correlated, a regression analysis was undertaken for the 316 SS. The time-to-tertiary data were censored based on three criteria, similar to the previous rupture analyses:

- (a) Any data point which was 10 standard deviations from the mean
- (b) Data points which had a rupture time less than 100 hours
- (c) Heats with poor strength properties, identified in Task 14 [3]

The time-to-tertiary creep data were analyzed using the LMP regression analysis described in Section 1.3.

After the censoring, only 233 data points from 17 heats could be used for the tertiary creep analysis. A second order polynomial regression analysis was used along with a lot-centered approach. The lot constant was calculated as 13.24. A plot of the stress versus LMP and comparison with the calculated stress function of the Larson-Miller parameter for the total database is shown in Figure 3-11. The data distribution is shown in blue and the stress function is shown as a black line.

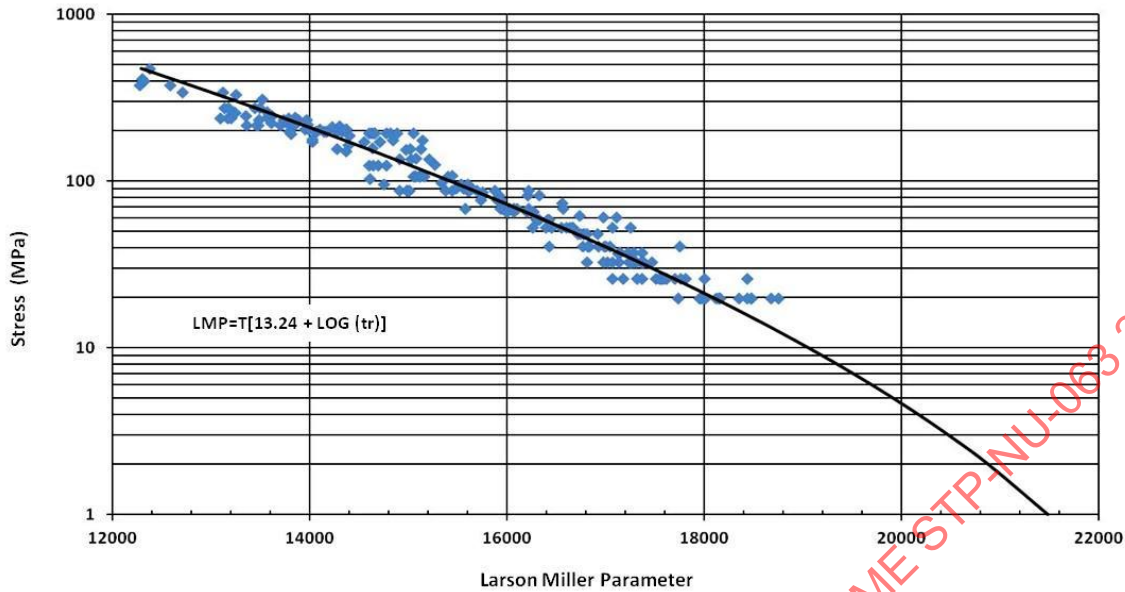


Figure 3-11 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 316 SS – Second Order Polynomial Regression Analysis

The trend of the second order polynomial function dips down at long time and high temperatures, resulting in very low stresses. This was judged to be too conservative and a linear regression analysis was performed.

In the linear regression analysis, the lot constant was calculated as 12. A plot of the stress versus LMP is shown in Figure 3-12. The data distribution is shown in blue and the stress function is shown as a black line.

The values of the regression parameters are given in Table 3-2. The variance for the data is 0.13 and the standard error of estimate is 0.35.

**Table 3-2 – Results from Regression Analysis for 316SS
for Time-to-Tertiary Creep Analysis**

Coefficients in Log Stress (a)	Values
a_0	22740.43
a_1	-4002.24

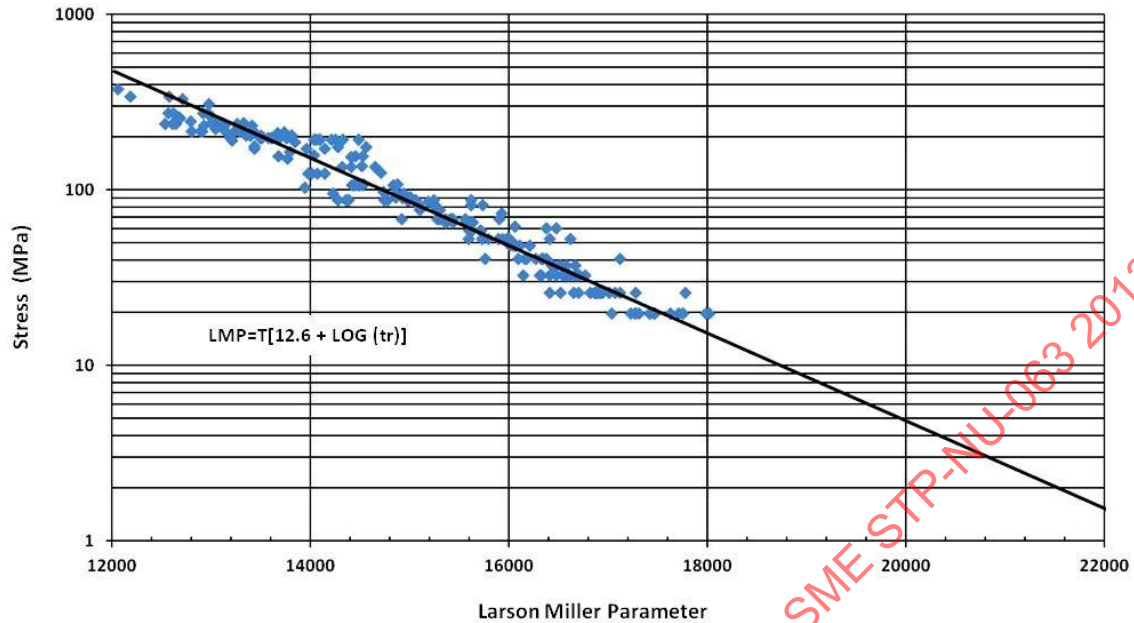


Figure 3-12 – Stress versus LMP for Time-to-Tertiary Strain Analysis of 316 SS – Linear Regression Analysis

The results of the linear regression analysis were used for calculating the minimum stress to initiating of tertiary creep.

3.4.2 Time-to-1% Strain Analysis

3.4.2.1 Hot Tensile Curve

The hot tensile curves were re-created in order to calculate an upper limit for S_t . The upper limit on S_t is the stress at 1% strain from the hot tensile curves. The hot tensile curves in NH were constructed using the Blackburn equations. The Blackburn equations used for calculating the hot tensile curves is shown below. The equation which yields the lower value of true strain was used for calculating the stress at 1% strain [5].

$$\varepsilon_L = \frac{\sigma}{E} + \left[\frac{(\sigma - \sigma_p)}{K_1} \right]^{\frac{1}{m_1}} \quad \text{Equation 3.1}$$

$$\varepsilon_L = \frac{\sigma}{E} + \left[\frac{(\sigma - \sigma_p)}{K_2} \right]^{\frac{1}{m_2}} \quad \text{Equation 3.2}$$

where,

ε_L - total true strain, elastic plus plastic

σ - total true stress

E - elastic modulus

σ_p - proportional limit

K_1, K_2, m_1 , and m_2 are constants

A comparison of the hot tensile curves with the NH curves is shown for 1000°F and 1300°F in Figure 3-13 and Figure 3-14. The hot tensile curves we developed compare well with the hot tensile curves in NH.

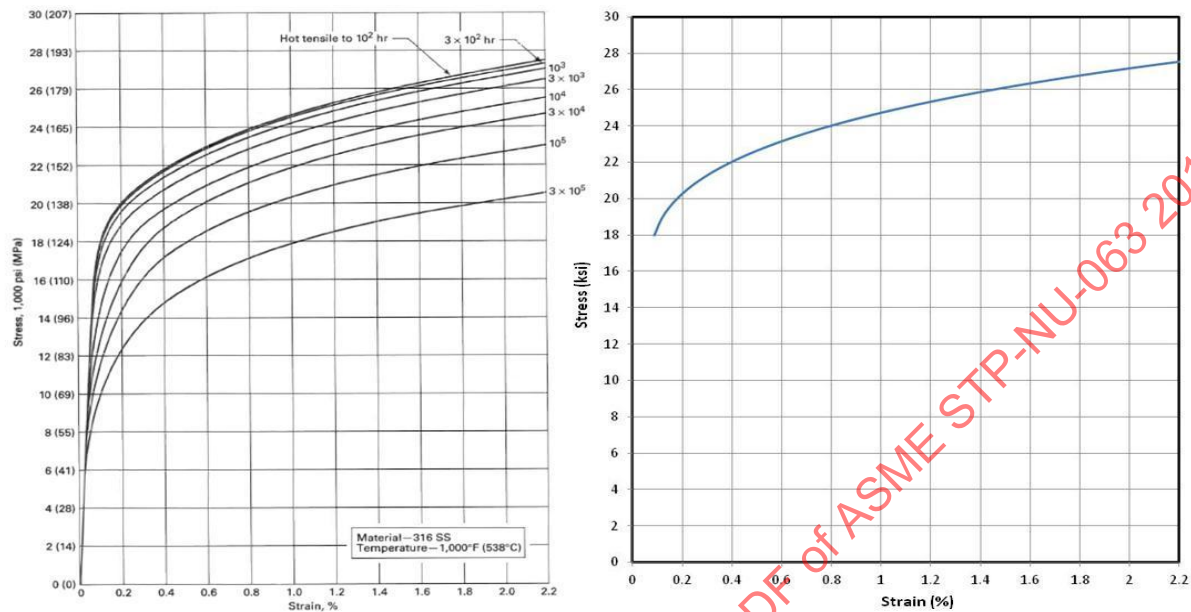


Figure 3-13 – Hot Tensile Curve for 316 SS at 1000°F

Figure on Left Shows the NH Curve. Figure on Right Shows the Curve Developed in this Analysis.

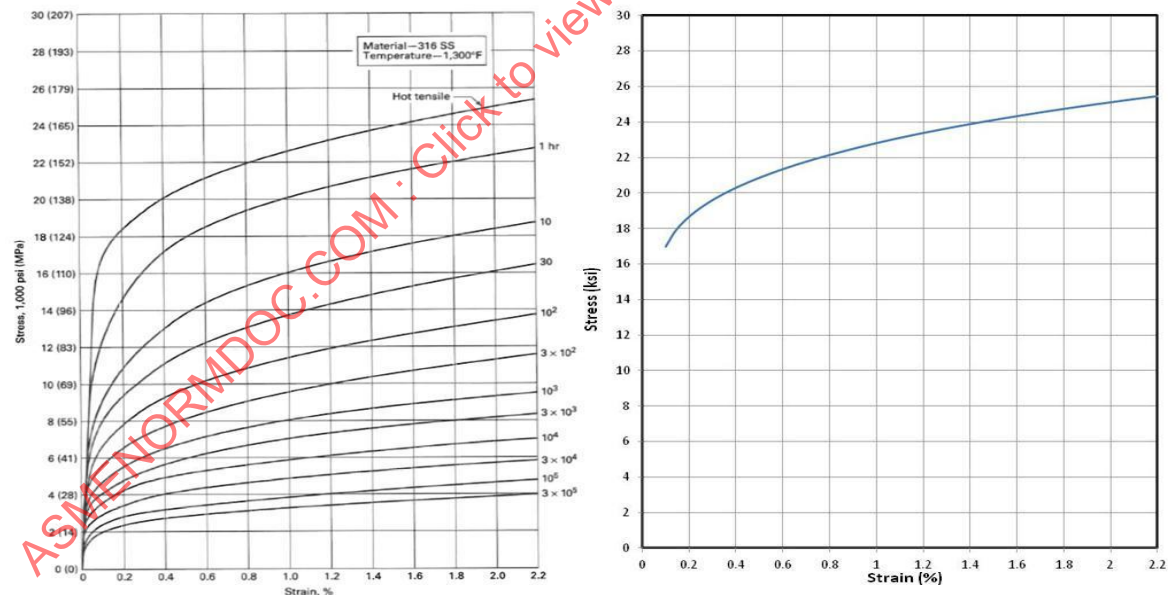


Figure 3-14 – Hot Tensile Curve for 316 SS at 1300°F

Figure on Left Shows the NH Curve. Figure on Right Shows the Curve Developed in this Analysis.

The values of average stress at 1% strain over a range of temperatures are provided in Table 3-3 and Table 3-4.

Table 3-3 – Stress at 1% Strain in S.I. Units for 316 SS

Temperature in °C	Stress at 1% Strain (MPa)
425	180
450	178
475	176
500	174
525	172
550	170
575	168
600	166
625	164
650	162
675	160
700	158
725	156
750	154
775	152
800	150

Table 3-4 – Stress at 1% Strain in Customary Units for 316 SS

Temperature in °F	Stress at 1% Strain (ksi)
800	26.1
850	25.7
900	25.4
950	25.1
1000	24.8
1050	24.4
1100	24.1
1150	23.8
1200	23.5
1250	23.1
1300	22.8
1350	22.5
1400	22.2
1450	21.9
1500	21.6

3.4.2.2 LMP Analyses

LMP regression analysis was performed on the time-to-1% strain data. The database for time-to-1% strain included the loading strains and consisted of 163 data points. The database was censored based on the following criteria.

- (a) Any data point that was 10 standard deviations from the mean
- (b) Time-to-rupture data less than 100 hours
- (c) Heats with poor strength properties, identified in [3]

A detailed explanation of the above three criteria is given in Section 2.3.1.

After the database was censored, only 144 data points could be used for the regression analysis. A second-order regression analysis was used for analyzing the database as there is no significant difference compared to a linear regression analysis. The stress-to-1% strain from this analysis did not control the long time, high temperature S_t values and a comparison with linear regression analysis produced similar results.

The lot constant was calculated as 21.52. A plot of the stress versus LMP is shown in Figure 3-15. The data distribution is shown in blue and the stress function is shown as a black line. The values of the regression parameters are given in Table 3-5. The variance for the data is 0.24 and the standard error of estimate is 0.49.

**Table 3-5 – Results from Regression Analysis for 316 SS
for Time-to-1% Strain Analysis**

Coefficients in Log Stress (a)	Values
a_0	33153.60
a_1	-2781.35
a_2	-1272.38

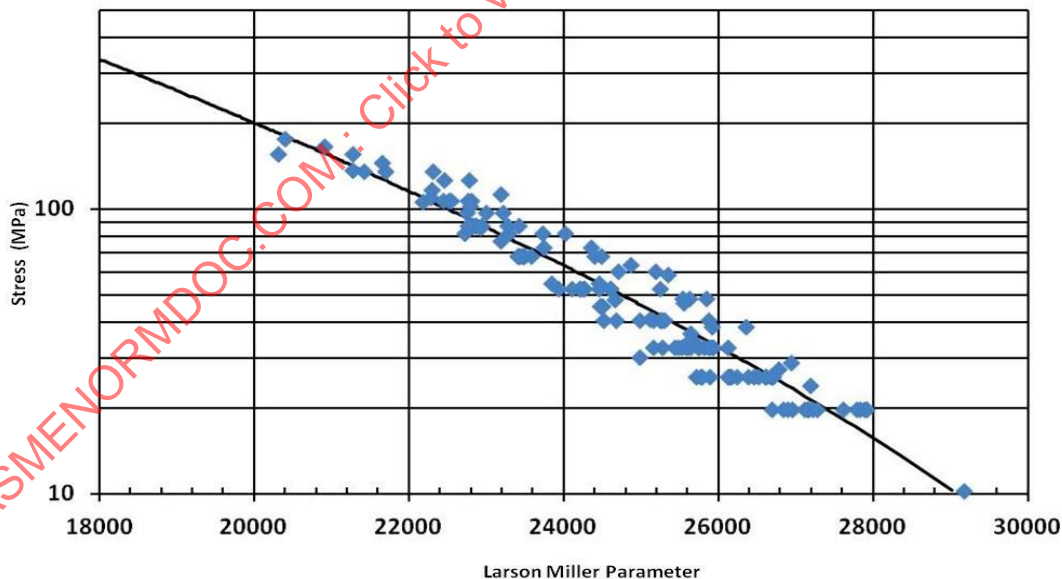


Figure 3-15 – Stress versus LMP for Time-to-1% Strain Analysis of 316 SS – Second Order Regression Analysis