TENSILE AND CREEP DATA OF 316L (N) STAINLESS STEEL ANALYSIS

V. Bindu Neeharika, K. S. Narayana, V. Krishna and M. Prasanth Kumar
Mechanical Department, ANITS, Sangivalasa, Visakhapatnam India
binduneeharika@yahoo.co.in

ABSTRACT

The design of Liquid Metal Fast Breeder Reactor systems (LMFBR) requires consideration of elevated-temperature, time-dependent deformation, since many components will be operating at temperatures in the creep range of the materials of construction. Therefore a suitable method of establishing the stress-strain-time-temperature relationships for these materials is necessary for use in the design of such high temperature components. Although 316 L(N) Stainless Steel is specified by ASME nitrogen in range of 0.1 to 0.16 Wt.%, for Prototype Fast Breeder Reactor (PFBR), nitrogen content is limited to 0.08 Wt. %, in view of improved weld ability, code data availability and for minimizing scatter mechanical properties. For high temperature components operating in creep Range 316L (N) has been favored. Other major advantages of austenitic stainless steel 316L (N) include existence of vast data on mechanical properties including very long term creep data, ease of availability and fabrication above all the availability of design data in the ASME code selected for PFBR design.

Keywords: stainless steel, temperature, creep, S_t and S_m curves.

1. INTRODUCTION

One such method, now in common usage, is the graphical representation of creep behavior in the form of isochronous stress-strain curves. An isochronous stress-strain curve represents a cross plot obtained by taking constant-time cuts through a family of isothermal creep curves generated at various stress levels. The design and construction of Liquid Metal Fast Breeder Reactor systems (LMFBR) components largely depend on thermal loading, normally coupled with cyclic operation. The structural behavior of materials must be assessed in relation to high temperature and time-dependent characteristic material data, and in that sense, estimation of allowable stresses plays a predominant role in nuclear components design.

Low carbon austenitic stainless steel grade 316, alloyed with 0.06-0.08Wt% nitrogen, designated as 316L (N) Stainless Steel, is observed as suitable material for the structural components of prototype fast breeder reactor (PFBR). Low carbon grades have been chosen to ensure freedom from sensitization during welding of components and to avoid risk of chloride stress corrosion cracking during storage in coastal site. Since low carbon grades have lower strength than normal grades, nitrogen is specified as an alloying element to improve the mechanical properties so that the strength is comparable to 316Stainless Steel.

2. DESIGN PROCEDURE

ASME boiler and pressure vessel code design procedure and data analysis [4]

2.1. Estimation of time dependent allowable stress (s_t)

Time dependent allowable stress (S_t) and minimum stress for rupture (S_r) are the stresses as a function of temperature θ and application time t. For a given temperature θ and application time t, the value of S_r is equal to the minimum stress which at this temperature θ induces fracture after time t. For a given temperature θ and application time t, the value of S_t is equal to the smaller of the following quantities. (a) 100% of the average stress required to obtain a total (elastic, plastic, primary and secondary creep) strain 1 %. (b) 80% of the minimum stress to cause initiation of tertiary creep; and (c) 67% of the minimum stress to cause ruptures. The procedure for determination of average stress required obtaining a total strain of 1%, minimum stress to cause initiation of tertiary creep, and minimum stress to cause rupture at a particular time and temperature are discussed in following steps.

Importance of isochronous curves

These are Constant-Time curves those are plotted between Stress and Strain. These are important to calculate the above condition i.e., 100% average stress required to obtain a total strain of 1% which is used to calculate the S_t i.e., time dependent allowable Stress values.

The isochronous curves generated from the test data of this investigation were extended to longer times and lower stresses using several extrapolation techniques. These extrapolations were necessary to define the material behavior in the 30 to 40 year design life.

2.2. Evaluation of 100% average stresses required for 1% total strain

Step-1: Plotting creep curves [1] from the available strain-time data plotting of creep curves is done, i.e. strain vs. time curves.

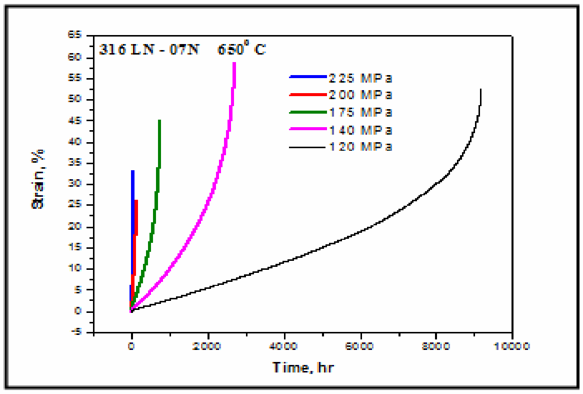

Figure-1. Strain Vs Time curves (Creep curves at different stress levels).

Step-2: Determination of onset of primary, secondary and tertiary regions [1]

Determination of onset of primary, secondary and tertiary regions is done by plotting a tangent to the creep curves. Here the secondary region lies along the tangent drawn and the onset of tertiary is observed from the point where the deviation of the curve occurs at the end of the secondary region. By considering the deviation at the front end of secondary region we determine the onset of secondary region i.e., the end of the primary region. The end point of the secondary is known as the onset of tertiary, as shown in Figure-2.

Step-3: Determination of secondary creep rate [1]

Consider a creep curve and find out the slope of the curve in the secondary region which is usually a constant value. This value is taken as the rate of secondary creep. Thus the secondary creep rate is obtained for creep curves at different stress levels.

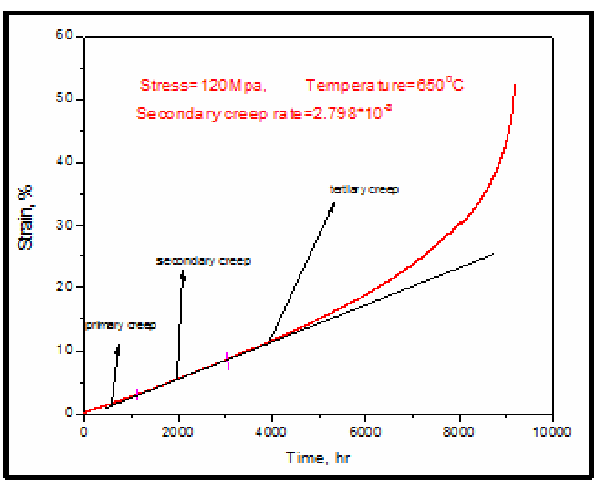

Figure-2(a). Creep curve at stress value of 120 Mpa.

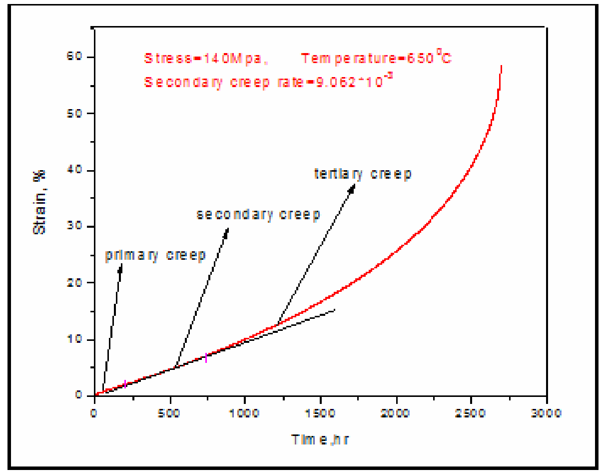

Figure-2(b). Creep curve at stress value of 140 Mpa. Figure-2(a), (b): Individual Creep curves at different stresses

Step-4: Plotting stress-strain curves [1]

By plotting 15 cuts along the creep curves we collected the stress-strain data at some respective hours, by using this data stress-strain curves are generated. The Figure-3 shows the different stress-strain curves at different times.

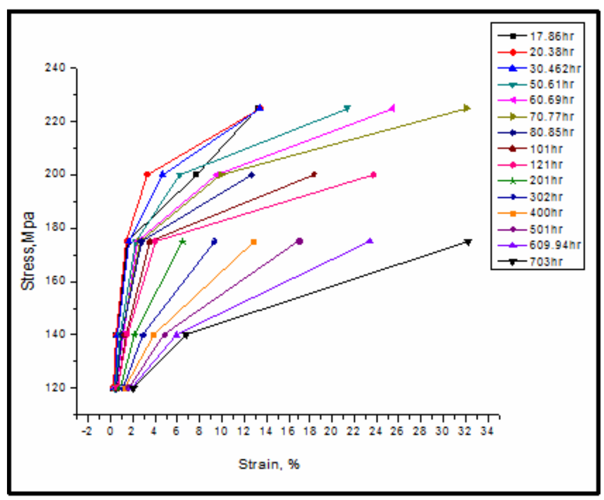

Figure-3. Stress-Strain Curves at different time values.

Step-5: Extrapolation of the curves [1]

After generation of the stress strain curves at respective hours, a longest hour stress-strain curve is taken for the extrapolation. Here we have taken the 703hr curve and noted the value of strain at different stress levels for the extrapolation. This 703hr (y hr) is taken as the reference curve. The time difference between the taken reference curve and the curve to be extrapolated is taken. i.e., if the curve to be extrapolated is of x hr then we take the value of (x-y) hr.

Now this time difference is multiplied with secondary creep rate obtained at different stress levels and

ARPN Journal of Engineering and Applied Sciences

values are noted down. These values are now added to the strain values noted down before. i.e., the strain values at the y hr time curve. The can be formulated in an equation as.
Extrapolated strain data for **x** hr = [(x-y)*Secondary creep rate] + ϵ_y
Where, ϵ_y = strain at y hr time curve (%)
Extrapolated strain data for **x** hr (%)

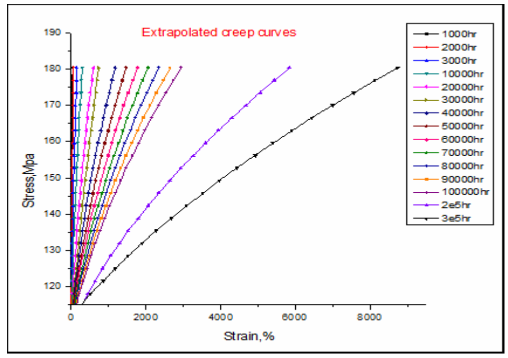

Figure-4. Extrapolated Stress-Strain curves for different time values.

Table-1. Exponential equations for extrapolated data.

Time (hr)	**Exponential equation**	**R^2 value**
1000	€ = 0.73252*exp (σ/39.505)-8.5737	0.99675
2000	€ =1.02545*exp (σ/41.3445)-11.64539	0.9961
3000	€ = 6.676*exp (σ/54.605)-41.44	1
10000	€ = 36.694*exp (σ/70.458)-173.497	1
20000	€ =15.874*exp(σ/46.73946)-136.57	0.99455
30000	€ = 676.356*exp (σ/160.33)-134.497	0.9997
40000	€ =32.5705*exp(σ/47.09503)-275.57	0.9943
50000	€ =40.922295*exp(σ/47.16701)-345.118	0.9944
60000	€ =49.27657*exp(σ/47.2153)-414.6574	0.99438
70000	€ =57.62974*exp(σ/47.24964)-484.1945	0.99437
80000	€ =65.9823*exp(σ/47.2753)-553.7277	0.99436
90000	€= 74.333*exp(σ/47.293)-623.25277	0.99435
100000	€ = 453.719*exp (σ/76.09)-1917.88	1
200000	€=166.23711*exp(σ/47.3848)-1388.2234	0.99432
300000	€ = 2285.4833*exp (σ/91.0052)-7829.1784	1
€ = Strain (%)	σ = Stress (Mpa)	

Exponential equations

Fitted exponential equations for extrapolated data. We obtained the following equations and by using these equations we obtained the strain values for different stresses. The Table-2 shows the exponential equations for extrapolated data at different times

Step-6: Extrapolation of curves for 1000hr, 3000hr, 10000hr, 30000hr, 1e5hr, 3e5hr has been done.

Step-7[5]**:** Calculate the elastic strain for each strain value using the following equation.

ϵ_{el} = (σ / E) x 100
Where,
ϵ_{el}= Elastic strain (%)
σ = Stress (Mpa)
E = Young's modulus given as a function of temperature θ (^{0}C) in Mpa
Young's modulus of 316L (N) SS (0.06-0.08% N) is given
E = 201660 - 84.8 θ [20≤ θ (^{0}C) ≤ 700]

Step-8[T.1]**:** Find the true stress and true strain values using the equation
True strain= ln (1+Engineering strain)

VOL. 9, NO. 5, MAY 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

True stress = Engineering stress *(1+Engineering strain)
Where
True strain, Engineering strain are in %.
True stress, Engineering stress are in Mpa.

Step-9[1]**:** Then we calculate the plastic strain by using the following equation
ϵ_p= [True strain-(True stress/E)]*100
Where, ϵ_p = plastic strain (%)

Step-10[6]**:** The Plastic strain is derived from the tensile hardening Equation (average stress-strain relation)

The average tensile stress-strain curves are given (for plastic strain limited to 1.5%) by,
$\sigma = C_0 \times (Y.S)_{0.2\%} \times (\epsilon_p)^{no}$
Where, $(Y.S)_{0.2\%}$ = average yield strength at 0.2% Offset given as function of temperature θ, in Mpa. C_0, n_0 are material constants
ϵ_p = Plastic strain induced by stress (σ)

Step-11[5]**:** Since we are calculating the creep strains using extrapolation technique as shown in STEP 5, primary creep strains are automatically taken into account. There is no need to calculate the primary and secondary creep values individually.

Step-12[5]**:** Add elastic, plastic and creep strains to get total strain values.
Total strain = ϵ_{el}+ ϵ_p+ ϵ_c
Where
ϵ_{el} = Elastic strain (%)
ϵ_p= Plastic strain (%)
ϵ_c= Creep strain (%)

Step-13: We obtain the total strain values up to 2.2% and we plot the average isochronous stress-strain curves at 1hr, 10hr, 30hr, 1000hr, 3000hr, 1e4, 3e4, 1e5, 3e5hr, respectively.

Step-14: Plotted a vertical line at 1% total strain across the average isochronous curves then we collected the average stresses required to obtain 1% of total strain.

2.3. Evaluation of minimum stresses causes the initiation of tertiary creep step-1[5]

In the creep curve (creep strain versus time), draw 0.2% offset to secondary creep strain and obtain the value of time corresponding to appearance of tertiary creep at temperature θ and stress σ.

Step-2: Plot the graph between stress and time for 0.2% offset to secondary creep strain at temperature θ on log-log scale and obtain the power law fit of the form, $S_{it}= C_2 \, t_{0.2\%}^{\,n2}$

where, S_{it} = stress causes the initiation of tertiary $t_{0.2\%}$ = time at the end of secondary creep, i.e., 0.2% offset to secondary creep strain
C_2, n_2 are temperature dependent material constants

Step-3: The average stress leading to appearance of tertiary creep is obtained for any value of time using the model derived as above.

Step-4[4]**:** The minimum stress value for 0.2% offset to secondary creep is obtained by 0.8 times the average value.

2.4. Evaluation of minimum rupture stresses (S_r)

Step-1: Plot the values of rupture time against corresponding average stress at constant temperature on a log-log scale, taking rupture time along x-axis and average stress along y-axis.

Step-2: Fit a power law relation between average rupture stress and corresponding time as:
$S_r = C_1 \, t_r^{\,n1}$
Where
S_r = Average stress inducing fracture (Mpa)
t_r = Creep rupture time (hr)
$C_{1,}$ n_1 are temperature dependent material constants

Step-3: The average stress inducing fracture is obtained for any value of time using the model derived as above.

Step-4[4]**:** The minimum rupture stress value is obtained by 0.8 times the average rupture stress value.

By finding out the minimum of the three conditions we obtained the S_t Values at different time values.

Table-2. S_t values of 316L (N) SS with 0.07Wt% nitrogen at 923K.

Time (hr)	**100% average stress for 1% total strain** (Mpa)	**Min. Stress for onset of tertiary with FOS** (Mpa)	**Min. Rupture stress with FOS** (Mpa)	$\mathbf{S_t}$ (Mpa)
1	134.99	218.49	190.05	134.99
10	133.79	165.74	147.53	133.79
30	132.11	145.27	130.74	130.74
100	124.96	125.73	114.52	114.52
300	116.79	110.2	101.48	101.48
1000	112.8	95.37	88.9	88.9
3000	111.97	83.59	78.78	78.78
10000	116	72.35	69.00	69.00
30000	114	63.41	61.15	61.15
100000	111	54.88	53.56	53.56
300000	109	48.10	47.47	47.47

2.5. Material constants for S_t curve generation

Table-3. Estimated material constants For S_t -Curve Generation: - Material: - 316LN SS of 0.07Wt%, Temperature= 650^{0}C.

$S_{it}=C_2 t_{0.2\%}^{\ n2}$	$C_2 = 341.4$ $n_2 = -0.12$
$S_r = C_1\ t_r^{\ n1}$	$C_1 = 354.6$ $n_1 = -0.11$

2.6. Estimation of time independent allowable stress (S_m)

The values of time independent allowable stress(S_m) are equal to the smaller of the stresses obtained by applying the following Coefficients of reduction to the minimum mechanical properties values. (a) of the specified minimum tensile strength at room temperature (b) of the tensile strength at temperature (c) of the specified minimum yield strength at room temperature (d) of the yield strength at temperature, except that for austenitic stainless steels and specific non-ferrous materials; this value may be longer than 90% of the yield strength at temperature.

The procedure for determining the above conditions discussed in detail in the following steps.

Step-1[5]**:** From the uniaxial tensile strength experiment estimate the average yield strength values $(R^t_{p0.2})_{moy}$ as well as average ultimate tensile strength values $(R_m)_{moy}$ at different temperatures θ(^{0}C).

Step-2[5]**:** The minimum yield strength values at any temperature estimated by the following relation,
$(R^t_{p0.2})_{moy} = 1.28\ (R^t_{p0.2})_{min}$ Where,
$(R^t_{p0.2})_{moy}$ =Average yield strength at 0.2% offset (Mpa)
$(R^t_{p0.2})_{min}$= Minimum yieldstrength at0.2%offset (Mpa)

Step-3[5]**:** The minimum ultimate tensile strength values at any temperature estimated by the following relation, $(R_m)_{moy} = 1.112\ (R_m)_{min}$ Where $(R_m)_{moy}$ = Average ultimate tensile strength (Mpa) $(R_m)_{min}$ = Minimum ultimate tensile strength (Mpa)

Step-4[5]**:** The minimum yield strength values with factor of safety estimated by the following relations At room temperature;minimum yield strength values with factor of safety =2/3 (minimum yield strength values)
At other temperatures; minimum yield strength values with factor of safety = 2/3 (minimum yield strength values)

Step-5[5]**:** The minimum ultimate tensile strength values with factor of safety estimated by the following relations. At room temperature; minimum ultimate tensile strength values with factor of safety = 1/3 (minimum ultimate tensile strength values). At other temperatures; minimum ultimate tensile strength values with factor of safety = 1/3 (minimum ultimate tensile strength values)

Step-6: Time independent allowable stress values (S_m) are equal to the smaller of the stresses obtained by the earlier Steps, (i.e., Step-4 and Step-5.)

2.7. Generation of time independent allowable stress (S_m) curve

Obtain S_m curves by plotting the graph between time independent allowable stress value (Mpa) and temperature (^{0}C).

VOL. 9, NO. 5, MAY 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-4. S_m values of 316L (N) SS with 0.07Wt% nitrogen.

Temperature (^{0}C)	**Average Yield Strength** (Mpa)	**Min. Yield Strength** (Mpa)	**Avg. UTS** (Mpa)	**Min. UTS** (Mpa)
27	274	214.0625	568	510.7914
250	187	146.0938	452	406.4748
350	167	130.4688	438	393.8849
450	142	110.9375	434	390.2878
500	130	101.5625	416	374.1007
550	117	91.40625	403	362.4101
600	115	89.84375	371	333.6331
650	111	86.71875	336	302.1583
700	109	85.15625	298	267.9856
750	106	82.8125	257	231.1151
850	96	75	166	149.2806

Table-5. S_m values of 316L (N) SS with 0.07Wt% nitrogen.

Temperature (^{0}C)	**1/3 of min. tensile strength at room temperature** (Mpa)	**1/3 of tensile strength at operating temperature** (Mpa)	**2/3 of min. yeildstrength at room temperature** (Mpa)	**2/3 of yeildstrength at operating temperature** (Mpa)	S_m (Mpa)
27	181.65	202	153.12	196	153.12
250	181.65	161.33	153.12	122.66	122.66
350	181.65	158	153.12	111.33	111.33
450	181.65	159.33	153.12	107.33	107.33
500	181.65	157.33	153.12	99.33	99.33
550	181.65	143.33	153.12	94.66	94.66
600	181.65	133.33	153.12	90.66	90.66
650	181.65	127.33	153.12	88	88
700	181.65	109.33	153.12	84.66	84.33
750	181.65	95.33	153.12	81.33	81.33
850	181.65	64	153.12	74	64

3. RESULTS AND DISCUSSIONS

Table-6. Comparison between S_t values of ASME and RCC-MR codes [8].

Time, hr	S_t, (ASME code) (Mpa)	S_t, (RCCMR code)(Mpa)
1	134.99	125.0368
10	133.79	106.9528
30	130.74	103.1504
100	114.52	96.3752
300	101.48	87.664
1000	88.9	77.7088
3000	78.78	69.1352
10000	69.00	60.4248
30000	61.15	51.91064
100000	53.56	43.50714
300000	47.47	37.03193

The following Graph for Comparison between S_t values of ASME code and RCC-MR code

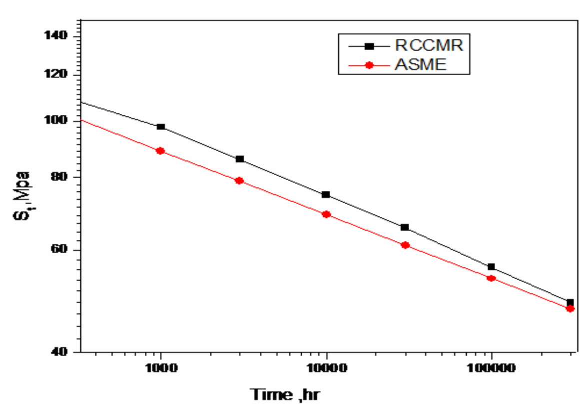

Figure-5. Comparison between S_t values of ASME code and RCC-MR code.

4. CONCLUSIONS

The average isochronous stress-strain curves were developed according to ASME Code procedure.

S_t and S_m curves were plotted for the material, 316 LN SS which contains 0.07Wt% nitrogen.

The S_t Curve that is obtained according to ASME code was compared with the S_t Curve, obtained according to RCC-MR code. The table and figure shows the comparison.

REFERENCES

[1] Bynum, J.E. and Roberts, B.W. 1972. Creep behavior of formed plate of Type 304 Stainless Steel", Combustion Engineering,Inc. ASME Boiler and Pressure vessel Code. p. 49-64.

[2] Swindeman, R.W. and Pugh, C.E. 1972. Isochronous stress-strain behavior of laboratory Reannealed Type304 Stainless Steel. (Heat 9T2796) to 5000 HR, Oak Ridge National Laboratory, ASME Boiler and Pressure vessel Code.

[3] Matera, R. 1988. High temperature time dependent allowable stress and isochronous curves of an Austenitic Mn-Cr steel. Journal of nuclear materials. 155-157, pp.639-643.

[4] 2007. ASME Boiler and pressure vessel code, Section III, Division 1, Subsection NH. The American Society of Mechanical Engineers, New York, USA.

[5] 2007. Design and construction rules for mechanical components of nuclear installations. RCC-MR, Section 1, subsection Z, AFCEN.

[6] Tavassoli, A.A.F. 1998. Material design data for fusion reactors. Journal of nuclear materials. 85-96, pp. 258-264.

[7] Swindeman, R.W. Isochronous stress versus strain curves for normalized-and-tempered 2 ¼ Cr-1Mo steel, Metals and Ceramics division, OAK Ridge, TN 37831-6155.

[8] J. Ganesh kumar, M. Chowdary, V. Ganesan, R.K. Paretkar, K. Bhanu Sankar Rao and M.D. Mathew. 2010. High temperature design curves for high nitrogen grades of 316LN Stainless Steel, 18th February. pp. 1363-1370.