18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-G11-9

TEST OF FATIGUE BEHAVIOR AND VERIFICATION OF S-N CURVE FOR 321 AUSTENITIC STAINLESS STEEL

Weiming Sun
Zhejiang University of Technology
No.6 district, Zhaohui Xincun
Hangzhou, Zhejiang, P.R.China
Phone: +86-0571-88320201, Fax: +86-0571-88320763
E-mail: wmsun@zjut.edu.cn

Xing Ren
Zhejiang University of Technology
No.6 district, Zhaohui Xincun
Hangzhou, Zhejiang, P.R.China
Phone: +86-0571-88320201, Fax: +86-0571-88320763
E-mail: ipece@zjut.edu.cn

Weiya Jin
Zhejiang University of Technology
No.6 district, Zhaohui Xincun
Hangzhou, Zhejiang, P.R.China
Phone: +86-0571-88320201, Fax: +86-0571-88320763
E-mail: jinweiya@zjut.edu.cn

Kangda Zhang
Zhejiang University of Technology
No.6 district, Zhaohui Xincun
Hangzhou, Zhejiang, P.R.China
Phone: +86-0571-88320201, Fax: +86-0571-88320763
E-mail: ipece@zjut.edu.cn

Zhanggen Bao
Shanghai Unclear Engineering Institute,Shanghai, 200233

Weida Yao
Shanghai Unclear Engineering Institute,Shanghai, 200233

ABSTRACT

321 austenitic stainless steel is common used material for unclear and petrochemical pressure vessel. But it is not known that the fatigue property of 321 austenitic stainless steel at elevated temperatures in P. R. China. This research is about the low cycle fatigue behavior of the steel by strain-control test method in accordance with ASTM and state standards(GB) in 350℃ temperature condition. From the test we got the steel’s mechanical and strain fatigue behavior parameters. The test results show that there is no cyclic hardening or cyclic softening phenomena for 321 austenitic stainless steel applied by cyclic loading at 350℃. The 321 austenitic stainless steel strain-life curves are obtained. The axial fatigue test results are processed by adopting ASME CODE Sec.Ⅲ design method based on fatigue analysis. The experiment results show it is suitable and safe to adopt ASME 316 austenitic stainless steel fatigue design curve for 321 austenitic stainless steel.

Keywords: 321 stainless steel, Material property, Fatigue behavior test

1. INTRODUCTION

321 austenitic stainless steel is one of the steels used generally in nuclear power plant and petrochemical factory in P.R.China. There is no report about the steel’s strain fatigue behavior and fracture properties in domestic journals. Many difficulties are brought to general analysis design and fatigue design. This paper presents the

general mechanical properties, fatigue behavior and design fatigue curve of 321 steel, so that this material may be used to in nuclear power plant and petrochemical factory safely.

2. NOMENCLATURE

σ = stress, *MPa*
ε = strain, %
$\Delta\varepsilon_e$ = elastic strain range, %
$\Delta\varepsilon_P$ = plastic strain range, %
$\Delta\varepsilon_t$ = total strain range, %
$\Delta\sigma$ = stress range, MPa
$2N_f$ =reversals to failure, cycle
E = elastic modulus, MPa
S_a = fictitious stress amplitude, MPa
$S_a^{'}$ = fictitious stress amplitude corrected for influence of mean stress, MPa
S_u = ultimate strength, MPa
S_m = cyclic yield strength, MPa
c = fatigue ductility exponent
B =fatigue strength exponent
$\varepsilon_f^{'}$ = fatigue ductility coefficient,%
$\sigma_f^{'}$ = fatigue strength coefficient, MPa
$n^{'}$ =strain hard exponent
$K^{'}$ = strength coefficient, MPa

3. MECHANICAL PROPERTIES IN ROOM TEMPERATURE AND 350℃ CONDITION

The material selected the study is a batch of solution-treated 321 austenitic stainless steel bars from the same operation. Chemical component is provided by the 5th Shanghai Steel Mill. Table 1 shows the chemical composition of the steel. The test direction is in the bar axial direction. The section of tensile test specimens, made in accordance with ASTM E8M and E21, is round. Its diameter is 10 mm.

Table 1 Chemical composition of 321 austenitic stainless steel (wt %)

	C	Cr	Ni	Ti	Mn	Si	S	P	Mo	Co
Special range	≤ 0.08	16.00 ～ 19.00	11.00 ～ 14.00	5×C% ～ 0.7	≤ 2.00	≤ 1.00	≤ 0.020	≤ 0.025	1.8 ～ 2.5	≤ 0.06
Actual value	0.072	18.03	13.80	0.59 ～ 0.67	1.82	0.67	0.0025	0.0225	2.33	0.04

Tensile tests are carried out in accordance with ASTM E8M and E21. In 350℃ condition, All specimens are tested in air at 350±3℃. In strain control phase, Strain rate in specimen parallel length is 3×10^{-4} 1/s. In displacement control phase, the rate in specimen parallel length is 2mm/min. The test results are shown in Table 2.

Table2 321steel static tensile test result

Elastic modulus (GPa)		Yield strength (MPa)		Tensile strength (MPa)		Total elongation (%)		Percent reduction in area (%)	
Room temp.	350℃	Room temp.	350℃	Room temp.	350℃	Room temp.	350℃	Room temp.	350℃

195	174	229.4	163.8	575	409	54.2	32.2	71.4	59.2

The tensile curves equations are given as follows.
In room temperature condition:

$$\varepsilon = 5.0\times10^{-6} + 1.7\times10^{-23}\sigma^{8.4} \quad (1)$$

In 350℃ condition:

$$\varepsilon = 5.8\times10^{-6} + 1.3\times10^{-20}\sigma^{7.7} \quad (2)$$

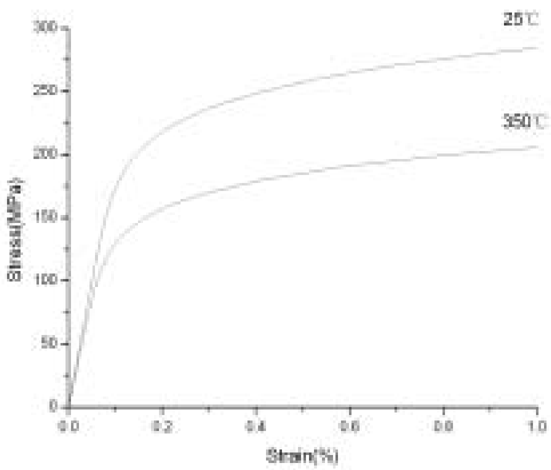

Fig.1 321 steel tensile curve in Room Temperature and 350℃ condition

4 LOW CYCLE AXIAL FATIGUE TEST IN 350℃ CONDITION

The section of fatigue test specimens made in accordance with ASTM is round. The diameter is 10 mm. All specimens are finished through fine mechanical polishing.
Low cycle fatigue properties in 350℃ Condition are established through push-pull Strain-controlled test at a constant strain rate with a triangle wave and for strain range between 4×10^{-3} and 2×10^{-2}. Three or more tests per strain level are performed. Table 3 shows test data and the number of cycle to failure.

Following local strain method and ASTM, The same strain amplitude leads to same fatigue damage. Material fatigue life lies on strain amplitude only. In constant amplitude strain fatigue, the relationship of total strain amplitude and fatigue life may be described Basquin equation and Manson-Coffin equation as follow:

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$

The equations are obtained by processing the data in table 3.
Elastic strain amplitude- life equation:

$$\frac{\Delta\varepsilon_e}{2} = 0.4360\times(2N_f)^{-0.1297} \quad (3)$$

Plastic strain amplitude-fatigue life equation:

$$\frac{\Delta\varepsilon_p}{2} = 14.15\times(2N_f)^{-0.3862} \quad (4)$$

Total strain amplitude - fatigue life equation:

$$\frac{\Delta\varepsilon_t}{2} = 0.4360\times(2N_f)^{-0.1297} + 14.15\times(2N_f)^{-0.3862} \quad (5)$$

Stress amplitude-fatigue life equation:

$$\frac{\Delta\sigma}{2} = 697.7 \times (2\mathrm{N_f})^{-0.1297} \quad (6)$$

The cyclic stress-strain characteristic curve relation:

$$\frac{\Delta\sigma}{2} = 274.7 \times (\frac{\Delta\varepsilon_p}{2})^{0.2873} \quad (7)$$

Table3 Low Cycle constant amplitude axial fatigue test result in 350℃ condition

Specimen No.	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_e$ (%)	$\Delta\varepsilon_p$ (%)	$\Delta\sigma$ ①(MPa)	$2N_f$ (cycle)
1	2.00	0.32	1.68	509.72	3052
2	2.00	0.40	1.60	634.16	1228
3	1.50	0.27	1.23	432.14	4314
4	1.50	0.25	1.25	404.44	10408
5	1.50	0.35	1.15	556.02	2768
6	1.00	0.23	0.77	372.90	12440
7	1.00	0.23	0.77	372.54	13974
8	1.00	0.23	0.77	370.60	10878
9	0.70	0.22	0.48	356.62	18008
10	0.70	0.22	0.48	357.48	16334
11	0.56	0.20	0.36	323.70	33670
12	0.50	0.19	0.31	308.06	53068
13	0.50	0.20	0.30	316.66	124080
14	0.50	0.21	0.29	329.32	49822
15	0.46	0.21	0.25	343.48	833924
16	0.46	0.19	0.27	310.08	247158
17	0.46	0.21	0.25	333.64	247160
18	0.40	0.19	0.21	309.28	86552

Note: ① $\Delta\sigma$ is stress amplitude when cycle is $\frac{1}{2}N_f$.

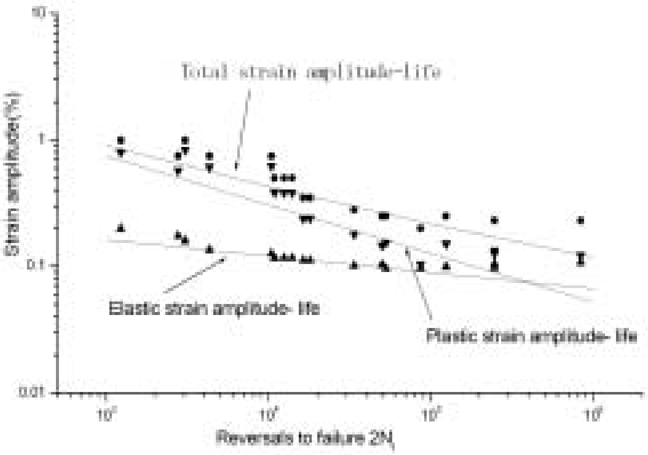

Fig.2 relation between strain amplitude and reversals to failure

Fatigue properties of 321 austenitic stainless steel are given by the above relationship in 350℃ condition. Six cyclic property parameters are got form equation (3)-(7) and shown in table 4. $\frac{\Delta\varepsilon}{2} \sim 2N_f$ curve is shown in Fig 2.

Table 4 Cyclic properties of 321 steel at 350 ℃

c	B	$\varepsilon_f^{'}$	$\sigma_f^{'}$	$n^{'}$	$K^{'}$
-0.3862	-0.1297	14.15	697.7 MPa	0.2873	274.7 MPa

Bearing cyclic load, material will appear cyclic hardening or cyclic softening phenomena. It is easy to judge these phenomena by comparison of monotonic stress-strain curve and cyclic stress-strain curve. Cyclic stress-strain curve be described by equation $\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K^{'}}\right)^{\frac{1}{n}}$ as monotonic stress-strain curve equation. The cyclic stress-strain curve equation of 321steel is given by the relationship:

$$\frac{\Delta\varepsilon_t}{2} = 6.11\times10^{-6}\left(\frac{\Delta\sigma}{2}\right) + 5.2626\times10^{-11}\left(\frac{\Delta\sigma}{2}\right)^{5.2626} \quad (8)$$

Putting relationship curves of equation (2) and equation (8) in one figure (Fig.3), we find that two curves are identical approximatively. It shows there is no cyclic hardening or cyclic softening phenomena for 321 austenitic stainless steel applied by cyclic loading at 350℃.

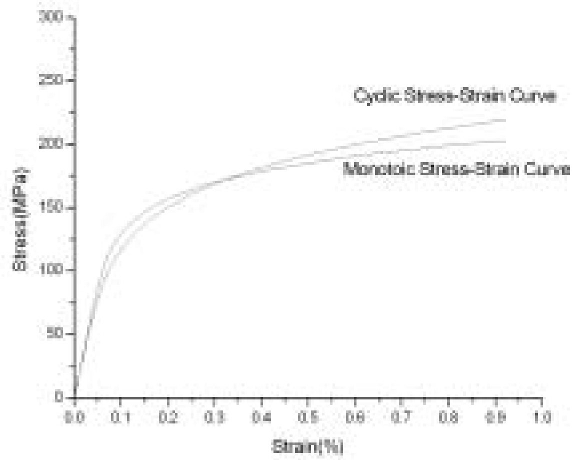

Fig.3 cyclic stress-strain curve and Monotonic stress-strain

5 S-NCURVE IN 350℃ CONDITION

Fig.4shows a plot of 321 steel S-N curve at 350 ℃. Design fatigue curve are constructed by applying a factor of safety of either 2.0 on the fictitious stress amplitude or factor of 20 on cycles to failure. Since the maximum stress that a material can maintain while being cycled is determined by its cyclic stress-strain properties, the large mean stress that can be maintained during cycling is equal to the yield stress. The curve that is less than the yield stress should be corrected for maximum stress by the relationship:

$$S_a^{'} = \frac{S_a(S_u - S_m)}{(S_u - S_a)} \quad \text{for} \quad S_a < S_m \quad (9)$$

$$S_a^{'} = S_a \quad \text{for} \quad S_a \geq S_m \quad (10)$$

In this test, the cyclic stress-strain curve closes to the monotonic tensile curve in test temperature. It isn't important to consider cyclic stress-strain response in estimating the effect of mean stress on fatigue life. S_m may approximated by 0.2% percent offset yield strength at test temperature.

Following ASME Sec.Ⅲ, the design fatigue curves for 3×× austenitic stainless steel is constructed with material's elastic modulus (1.95×105MPa) in room temperature condition. When the temperature is less than 800F (426℃), the stress amplitude should be corrected by multiplying the ratio of elastic modulus given by the design fatigue curves to the one used in the analysis. There are the design fatigue curves of 304 steel and 316 steel in Sec. Ⅲ div. 1-Subsection NH "Rules For Construction of Nuclear Power Components" (T-1420-1A and 1B). For convenient analysis and safety, the corrected curve of NH-T1420-1B at 100°F（38℃）is adopted to compare with the test curve. Fig.7 indicates that all 321 curves constructed following the safety factor in ASME, are above the corrected design fatigue curves of 316 steel in ASME Sec. Ⅲ div.1NH T1420-1B. Therefore, the design fatigue curves at 350℃ in ASME Sec. Ⅲ div. 1 NH T1420-1B may be used in 321 components fatigue analysis and design.

6 CONCLUSIONS

6.1 The S-N curve of 321 austenitic stainless steel is close approximately to the design fatigue curve of austenitic stainless steel in ASME. The component made of 321austenitic stainless steel which is made in P.R.China can be fatigue analyzed and designed feasibly and safely by adopting the design fatigue curves in ASME Sec. Ⅲ div. 1 NH T1420-1B.
6.2 The test results show that there is no cyclic hardening or cyclic softening phenomena for 321 austenitic stainless steel applied by cyclic loading at 350℃.

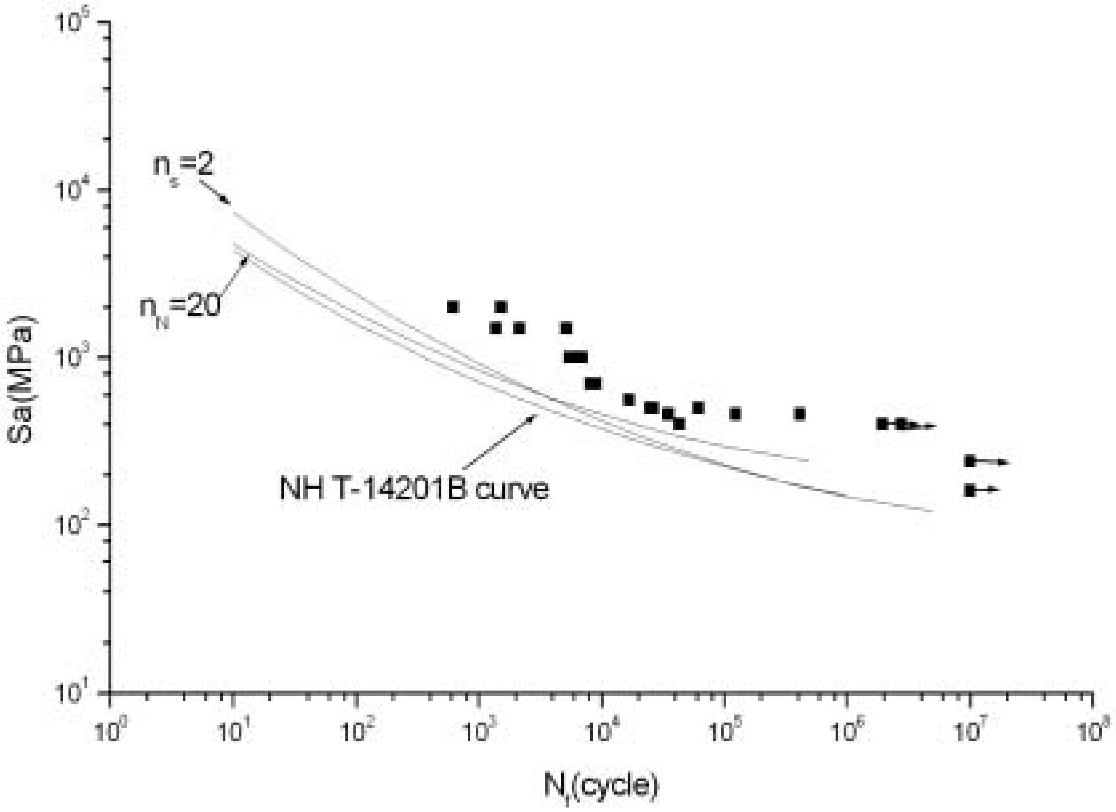

Fig.4 321Steel S-N Curve

7 ACKNOWLEDGMENTS

This investigation is partially sponsored by the Zhejiang nature science foundation under contract number M503224.

9 REFERENCES

[1] GB 6397-86, “Metal Tensile Test Specimens”.
[2] GB 228-2000, “Metal Tensile Test Method”.
[3] Weiming Sun, Kangda zhang, Anji Guo, “Measurement of Fatigue Properties of 0Cr18Ni12Mo2Ti Austenitic Stainless Steel and Validation of S-N Curve”, Nuclear Power Engineering，August 1998, Vol.19, No.4, pp.360-363.
[4]ASME Boiler and Pressure Vessel Code, Sec. Ⅲ Division 1, 2001.

