Simulation of Cyclic Behavior of Cold Worked 316L and Solution Annealed 316L

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1. Introduction

316L austenitic stainless steel has been widely used as a major structural material for the SFR due to its excellent strength, ductility, and corrosion resistance at a high temperature environment. Chaboche's combined hardening plasticity model and unified viscoplasticity model were implemented into a general purpose finite element code ABAQUS as a subroutine NONSTA[1]. Kim[2-3] analyzed the temperature dependent inelastic characteristics of 15% cold worked 316L which showed a cyclic softening behavior[4]. In this study, the inelastic material parameters for the solution annealed (SA) 316L showing cyclic hardening behavior were determined and its characteristics were compared to those of cold worked 316L.

2. Material Parameters

The material parameters for the combined hardening constitutive equations of the NONSTA are shown in equations (1) through (4).

$$\dot{\boldsymbol{\sigma}} = \mathrm{E}(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_p) = \mathrm{E}\left\{ \dot{\boldsymbol{\varepsilon}} - \frac{3}{2}\left\langle \frac{J(\mathbf{s}-\boldsymbol{X})-(R+\kappa)}{K} \right\rangle^n \frac{\mathbf{s}-\boldsymbol{X}}{J(\mathbf{s}-\boldsymbol{X})} \right\} \quad (1)$$

$$\dot{\boldsymbol{\varepsilon}}_p = \dot{p}\mathbf{n}, \quad \dot{p} = \left\langle \frac{J(\mathbf{s}-\boldsymbol{X})-(R+\kappa)}{K} \right\rangle^n, \quad \mathbf{n} = \frac{3}{2}\frac{\mathbf{s}-\boldsymbol{X}}{J(\mathbf{s}-\boldsymbol{X})} \quad (2)$$

$$\dot{X} = \frac{2}{3}C\dot{\boldsymbol{\varepsilon}}_p - \gamma\dot{\boldsymbol{X}}\,\dot{p} = \left(\frac{2}{3}C\mathbf{n} - \gamma\dot{\boldsymbol{X}}\right)\dot{p} \quad (3)$$

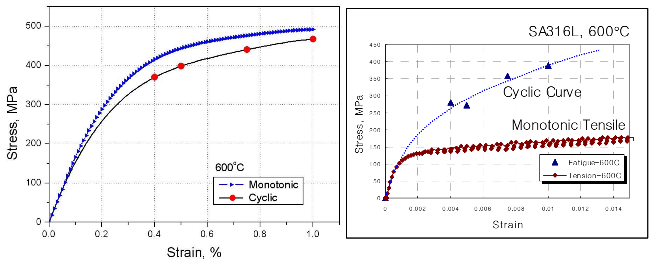
$$\dot{R} = b(Q-R)\dot{p} \quad (4)$$

where X is the back stress, R is the drag stress, p is the accumulated plastic strain and $\dot{p}$ is the accumulated plastic strain rate. C, γ, Q, b, and κ are the material parameters to be determined using the test data.

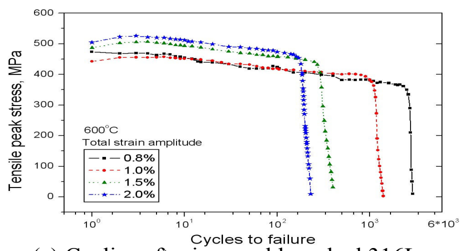
The material parameters for the cold worked 316L are obtained by Kim[3]. In this study, the material parameters for the SA316L are determined based upon the low cycle fatigue tests and tensile tests results[5]. Low cycle fatigue tests were performed at strain ranges of ±0.4, 0.5, 0.75, and 1%, respectively, at the various temperatures of room temperature(20°C), 300°C, 500°C, and 600°C. While the cold worked 316L showed a cyclic softening behavior, the SA316L exhibited a cyclic hardening behavior as shown in Fig. 1 and Fig. 2 respectively. The dynamic strain aging effects are shown near the temperature range of 500°C.

In the first place, the κ representing the average elastic range for the various strain ranges is determined. The kinematic hardening variables C and γ are determined by using a cyclic curve. Alternatively, the above parameters can be obtained by using a monotonic curve, as shown in Fig.1, instead of a cyclic curve.

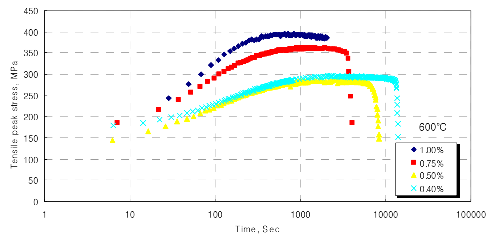
The cyclic hardening (or softening) parameters b and Q shall be obtained from the cyclic hardening (or softening) data as shown in Fig.2. It is noteworthy that the value of Q is negative for the case of a cyclic softening and positive for the case of a cyclic hardening.



(a) Cold worked 316L (b) Solution annealed 316L
Figure 1. Tensile and cyclic curves at 600°C



(a) Cyclic softening - cold worked 316L



(b) Cyclic hardening – SA 316L
Figure 2. Cyclic behaviors of 316L

Table 1. Material parameters for cold worked 316L SS

Temp(°C)	20	300	500	600
C(MPa)	115010	81120	147680	68770
γ	371	312	568	299
b	**1.73**	**1.81**	**1.08**	**0.98**
Q(MPa)	**-94**	**-90**	**-42**	**-54**
κ(MPa)	283	270	267	260
E(GPa)	193	172	160	150
ν	0.3	0.3	0.3	0.3
C(MPa)	*226180*	*167650*	*235720*	*104000*
γ	*526*	*479*	*710*	*400*

Table 2. Material parameters for SA 316L SS

Temp(°C)	20	300	500	600
C(MPa)	76700	44850	95770	79750
γ	260	195	314	275
b	**5.1**	**4.6**	**3.6**	**5.9**
Q(MPa)	**95**	**125**	**171**	**148**
κ(MPa)	172	168	110	100
E(GPa)	193	172	160	150
ν	0.3	0.3	0.3	0.3
C(MPa)	*72906*	*7120*	*12000*	*11700*
γ	*419*	*89*	*120*	*130*

The material parameters at the various temperatures are summarized in Table 1 and Table 2. It is noted that the negative values of b and Q in Table 1 represent a cyclic softening behavior while the positive values in Table 2 indicate a cyclic hardening behavior. The last two rows in each Table show the kinematic hardening variables obtained by using a monotonic tensile curve instead of a cyclic curve.

3. Simulation and Comparisons

The simulation for a cold worked 316L using a combined hardening model with the above material parameters shown in Table 1 showed a good agreement with the test results[3]. The saturated stress ranges were over-predicted by the analysis using the material parameters from a cyclic curve while they were over-predicted by the case of a tensile curve as shown in Fig. 3.

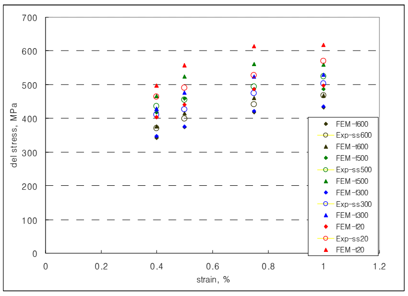
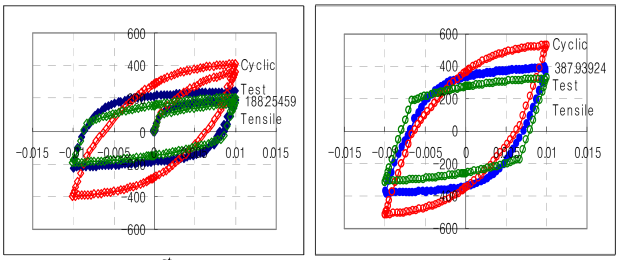


Figure 3. Cyclic curves of tests and analyses

Fig. 4(a) shows a comparison of the test result of the first cycle and the simulation for a solution annealed 316L with the material parameters shown in Table 2. The case of the material parameters from a tensile curve under-predicted by 9% and that of a cyclic curve over-predicted by 91%. This is caused by the huge difference between a tensile curve and a cyclic curve as shown in Fig. 1(b) for SA 316L. Therefore, one should determine the material parameters carefully by satisfying the objective for an analysis since they are dependent upon the temperatures, strain ranges of the analyses, strain rates, etc.

Fig. 4(b) shows a comparison for the saturated cycles of both the test and the analyses. The case of the material parameters from a tensile curve under-predicted by 18% and that of a cyclic curve over-predicted by 35%. It is noteworthy that the 1st cycle result of the case with a cyclic curve over-predicted the saturated cycle by only 5.4%. The material parameters obtained by a cyclic curve yield results close to a saturated cycle at a 1st cycle analysis.



(a) 1st Cycle (b) Saturated Cycle

Figure 4. Comparions of hysterisys curves at 600°C

Due to the limited number of the strain range in the fatigue tests, a cyclic curve generated based upon 4 points caused an uncertainty in the material identification procedure. The steady state stress-strain hysterisys at the various temperatures from 20°C to 600°C were compared and the effect of a DSA(Dynamic Strain Ageing) was significant near 500°C.

4. Conclusion

The temperature dependent inelastic material parameters for a solution annealed 316L were obtained and the inelastic analysis using the obtained parameters showed a good agreement with the test results. In addition, the cyclic hardening behavior of SA 316L was compared to the cyclic softening behavior of cold worked 316L. The capability of a combined hardening model to simulate both a cyclic hardening and softening was demonstrated however care should be taken for a proper determination of the material parameters.

ACKNOWLEDGMENT

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