*Transactions of the Korean Nuclear Society Autumn Meeting*
*Busan, Korea, October 27-28, 2005*

# The Temperature Dependent Inelastic Material Characteristics of Cold Worked 316L for NONSTA

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## 1. Introduction

The 316L austenitic stainless steel (SS) has excellent strength, ductility, and corrosion resistance at a high temperature environment so that it has been widely used as materials for several high temperature components including the reactor vessel and piping. Chaboche's unified viscoplasticity model was implemented into a general purpose finite element code ABAQUS as a subroutine NONSTA[1]. Jeon[2] and Kim[3] analyzed the effects of material parameters in the NONSTA code. In this study, the determination methodology of the inelastic material parameters for the NONSTA code is presented[4] and the parameter values for 15% cold worked 316L stainless steel have been obtained in various temperatures from 20$^o$C to 600$^o$C utilizing the results of the low cycle fatigue (LCF) tests and the tensile tests[5].

## 2. Material Parameters

The constitutive equations implemented into the NONSTA code are explained briefly. The stress-strain relationship can be defined as

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

The viscoplastic strain rate( $\dot{\boldsymbol{\varepsilon}}_p$ ) and the accumulated plastic strain rate( $\dot{p}$ ) are

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

The kinematic hardening and isotropic hardening evolutions are defined as

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

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

where C, γ, Q, b, and κ are the material parameters. X is the back stress, R is the drag stress, $p$ is the accumulated plastic strain, and function <x> is defined as: <x>=x if $x \geq o$, <x>=0 if $x < 0$.

The kinematic hardening variables C and γ in Eq.(3) are determined using a cyclic curve. The kinematic hardening term represents the tensile hardening behavior according to Masing's rule as well as the movement of a center of the yield surface. The cyclic curve is used for the determination of C and γ. It is worth noticing the above parameters can be obtained using a monotonic tensile curve, shown in Fig.1, instead of a cyclic curve and this procedure is not affected by other material parameters.

The cyclic hardening parameters b and Q in Eq.(4) shall be obtained from cyclic hardening (or softening) data as shown in Fig.2. The cold worked 316L shows the typical softening behavior as in Fig.1. In this process, the effects of the previously obtained kinematic hardening variables and the viscoplastic stress terms need to be included and the parameter κ needs to be adjusted properly with considerable caution. Optimal values of b, Q, and κ are 0.97, -52MPa, and 279MPa, respectively. It is noteworthy that the value of Q is negative so that it can express the cyclic softening behavior of the cold worked SS316L properly.

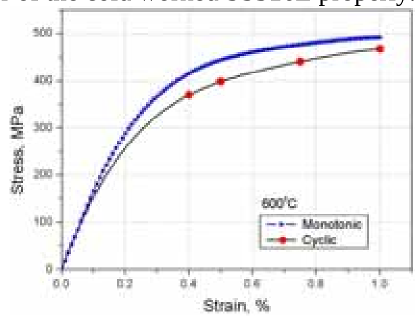



Figure 1. Tensile curve and cyclic curve at 600$^o$C.

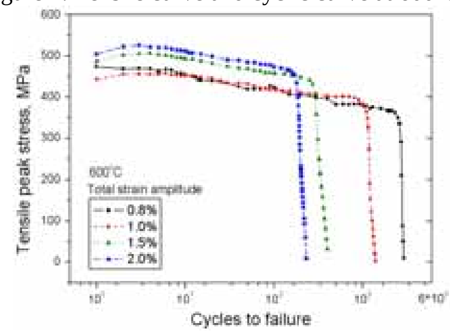



Figure 2. Cyclic softening of cold worked 316L

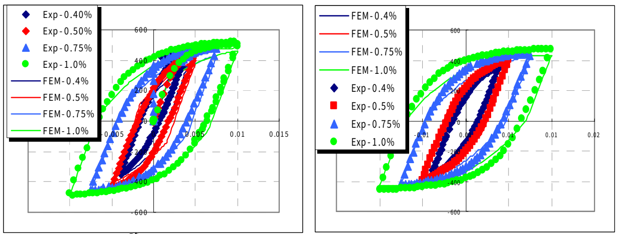
Table 1. Material parameters at various temperatures

| 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* |

The material parameters at the various temperatures were summarized in Table 1. It is noted that the last two rows in Table 1 show the kinematic hardening variables obtained using a monotonic tensile curve instead of a cyclic curve.

## 3. Validations

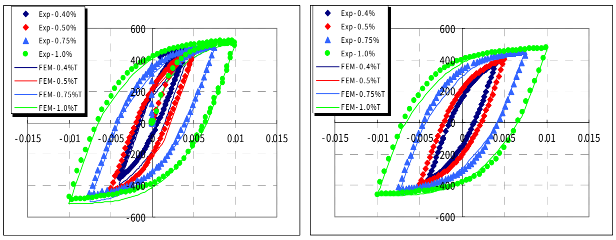
With the determined parameter values, the calculated results were compared to those of the test results. Figure 3 shows the comparison of the test results with the calculated results with the material parameters obtained using a cyclic curve at 600°C. It is confirmed that the saturated cycle showed better agreement than the 1st cycle since the material parameters were obtained utilizing a saturated cyclic curve.



(a) 1st Cycle (b) Saturated Cycle

Figure 3. Comparions of hysterisys curves at 600°C based upon cyclic data

The material parameters obtained using a tensile curve were applied to the analysis and compared with the test results as shown in Fig.4. Both the 1st cycle and the steady state cycle showed an excellent agreement between the test and the analysis. Due to the limited number of strain range in the fatigue tests, a cyclic curve should be generated based upon small number of points; i.e., 4 points in this study as shown in Fig.1. This may cause the uncertainty in the material identification procedure.



(a) 1st Cycle (b) Saturated Cycle

Figure 4. Comparions of hysterisys curves at 600°C based upon tensile data

The steady state stress-strain hysterisys at the various temperatures from 20°C to 600°C were compared with the test results as shown in Fig.5. As temperature goes up, the stress range decreases except 500°C. Since the DSA(Dynamic Strain Ageing) effect increased material strength at 500°C[5], the material parameters in Table 1 showed a certain degree of irregularity at this temperature and the analysis results were consistent.

The saturated stress ranges obtained from two different sets of material parameters were compared to those of the test results. The analysis results using a tensile curve over-predict while the analysis results using a cyclic curve under-predict the stress range of the test results.

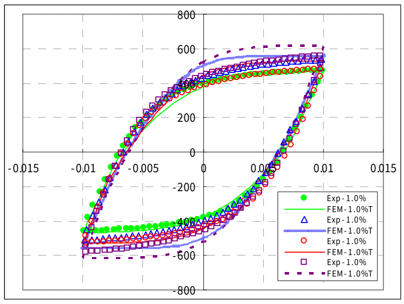


Figure 5. Saturated hysterisys curves at various temperatures

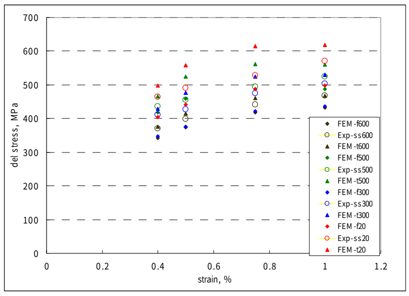


Figure 6. Cyclic curves at various temperatures

## 4. Conclusion

The temperature dependent inelastic material parameters for a cold worked SS316L are obtained. The inelastic analysis by using the tensile properties showed better agreement with the test result than the analysis using the cyclic properties due to the limited number of strain ranges in the fatigue test.


## ACKNOWLEDGMENT

This study was supported by the Korean Ministry of Science and Technology through its National Nuclear Technology Program.


## REFERENCES


[1] J.B. Kim, Development of NONSTA Code for the Design and Analysis of LMR High Temperature Structures, KAERI/TR-1256, KAERI, Daejeon, 1999.

[2] G.P.Jeon, J.B.Kim, C.G.Park, and J.H.Lee, "On the Characterization and Effects of Material Constants of the Inelastic Structural Analysis Code," Proc. of the KNS, May, 2004.

[3] J.B.Kim, el.al, Comparison Study of Inelastic Analysis Codes for High Temperature Structure, KAERI/TR-2704/2004, KAERI, 2004.

[4] J.B.Kim, et.al., "The Determination of the Inelastic Material Parameters for the NONSTA Code", Proc. of the KNS, May, 2005.

[5] Y.S. Ju, et.al., "High Temperature Low Cycle Properties of Cold Worked 316L Stainless Steel", Proc. of the KNS, May, 2005.