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BILINEAR CYCLIC STRESS-STRAIN ANALYSIS FOR INCOLOY 800

by

P. S. Maiya

APPLIED TECHNOLOGY

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BILINEAR CYCLIC STRESS-STRAIN ANALYSIS FOR INCOLOY 800

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ABSTRACT

This report describes the bilinear stress-strain analysis under cyclic loading conditions for the alloy Incoloy 800. Although the method for determining the bilinear stress-strain parameters is based on a procedure proposed in the RDT Standard F9-1 for inelastic analysis of Fast Flux Test Facility (FFTF) components, the accuracy and consistency of results have been improved by an analytical technique, which also resulted in certain simplifications. The bilinear stress-strain parameters of solution-annealed Incoloy 800 (Heat HH7058A) under cyclic loading conditions at a strain rate ($\dot{\epsilon}_t$) of $8.6 \times 10^{-5} \text{ s}^{-1}$, total strain range ($\Delta\epsilon_t$) of 0.2-0.8%, and temperatures of room temperature to 593°C (1100°F) have been determined. The dependence of bilinear parameters on temperature and strain is discussed. The cyclic-hardening characteristics based on correlation of yield parameter k with accumulated plastic strain are also presented.

INTRODUCTION

To perform a detailed inelastic analysis of nuclear structural components, the designer must have constitutive equations that consider time-independent elastic-plastic behavior as well as time-dependent creep behavior. Usually, the elastic-plastic analysis is formulated independent of creep and is based on the von Mises or Tresca yield condition, the classical kinematic hardening rule, and bilinear stress-strain relationships. The present report describes bilinear stress-strain parameters of solution-annealed Incoloy 800 (Heat HH7058A) determined under cyclic loading conditions at a strain rate ($\dot{\epsilon}_t$) of $8.6 \times 10^{-5} \text{ s}^{-1}$, total strain range ($\Delta\epsilon_t$) of 0.2-0.8%, and temperatures of room temperature to 593°C (1100°F).

EXPERIMENTAL MATERIAL AND PROCEDURE

The chemical composition of Incoloy 800 (Heat HH7058A) is listed in Table I. The hourglass-shape specimens obtained from 0.75-in. (19-mm) plate material were solution-annealed at 1135°C (2075°F) for 1 h. The ASTM grain

size of the annealed material (Fig. 1) is 4.4, as determined by the intercept method.¹ The cyclic tests were performed in air in the axial strain-control mode until saturation in stress was achieved. All tests were conducted at a strain rate of $8.6 \times 10^{-5} \text{ s}^{-1}$, total strain ranges of 0.2-0.8%, and at temperatures between room temperature and 593°C (1100°F).

TABLE I. Chemical Composition of 19.05-mm Plate of Incoloy 800 (Heat HH7058A)

Elements	Analysis, wt %
C	0.08
Mn	0.78
S	0.002
Si	0.46
Cu	0.65
Al	0.46
Ti	0.44
Fe	43.46
Ni	33.90
Cr	19.77

Fig. 1. Microstructure of Solution-annealed Incoloy 800. Etchant: Glyceregia. ANL Neg. No. 306-77-238.

BILINEAR CYCLIC STRESS-STRAIN ANALYSIS

The bilinear stress-strain analysis of the hysteresis loops was performed using the procedure outlined in Refs. 2 and 3. Figure 2 shows the procedure for determining bilinear representation of monotonic, initial-loading stress-strain curves. The elastic line (with a slope equal to Young's modulus) is drawn from the origin O. The elastic constants for Incoloy 800 were obtained from Ref. 4 and are displayed in Table II. The elastic-plastic segment of the bilinear curve is determined by a straight line connecting the stress at the maximum strain, $\epsilon_{\max}$, to the stress at strain, $\epsilon_{\max}/2$. The bilinear yield stress σ_0 , defined by the intersection of the two straight lines OP and PQR, is related to parameter k_0 by

$$\sigma_0 = \sqrt{3k_0}. \quad (1)$$

The quantity C is related to the slope E_m (Fig. 2) as follows:

$$C = \frac{2}{3} \frac{EE_m}{E - E_m}, \quad (2)$$

where E is Young's modulus. The parameter C is actually the slope of the elastic-plastic line in terms of deviatoric stress versus plastic strain ϵ_p .

From the value of C , the bilinear parameter k for any cycle can be determined. The bilinear parameters k_1 , k_2 , and k_3 for the first cycle, tenth cycle, and cycle at saturation, respectively, are determined so that the value of C for any of the hysteresis loops is the same as the value established for the monotonic stress-strain curve. The bilinear parameter k for any cycle from one to ten cycles is also determined assuming the same value of C . Furthermore, the intersection of the elastic and elastic-plastic lines are located so that the shaded areas above and below the actual curve are equal on both tensile and compressive portions of the cyclic curve (see Fig. 3). Conventionally, the location of the elastic-plastic line is established with the help of planimeter, but this procedure^{5,6} is tedious and has poor reproducibility. In the present study, the intersection of the elastic and elastic-plastic lines is determined by using an analytical procedure illustrated in Fig. 4.

Fig. 2. Bilinear Representation of Monotonic, Initial-loading Stress-strain Curve. Neg. No. MSD-64607.

TABLE II. Elastic Constants for Incoloy 800

Temperature, °C (°F)	Young's Modulus, 10^3 MPa (10^3 ksi)	Poisson's Ratio
RT ^a	196.50 (28.5)	0.339
427 (800)	169.61 (24.6)	0.363
538 (1000)	162.03 (23.5)	0.367
593 (1100)	157.89 (22.9)	0.372

^aRoom Temperature.

Fig. 3. Bilinear Representation of Initial and Tenth-cycle Stress-strain Curves. Neg. No. MSD-64606.

Fig. 4. Schematic Representation of a Hysteresis Loop Used in Bilinear Cycle Stress-strain Analysis. ANL Neg. No. 306-77-207 Rev. 1.

Consider the upper half OBQG of a closed hysteresis loop NOBQGN. For determining the bilinear stress parameter, it is required to draw a line ABPD (see Fig. 4) with a slope equal to E_m so that the area OABO is equal to area BQDB. This is accomplished by equating area OAPDHO to area OBQHO. With reference to Fig. 4, defining $AF = \sigma$, $\epsilon_{tp} = \epsilon_{tt} - \sigma/E$, and $DJ = \epsilon_{tp}E_m$ and designating the area OBQHO by A_t , we have

$$A_t = \text{area OAPDHO} = \sigma^2/2E + \frac{2\sigma + \epsilon_{tp}E_m}{2}\epsilon_{tp}. \quad (3)$$

Substituting $(\epsilon_{tt} - \sigma/E)$ for ϵ_{tp} and expanding Eq. 3, we obtain the following quadratic equation in σ :

$$\sigma^2(E_m - E) + 2\sigma(E^2\epsilon_{tt} - \epsilon_{tt}EE_m) + E_m\epsilon_{tt}^2E^2 - 2A_tE^2 = 0. \quad (4)$$

The solutions of the above quadratic equation can be simplified and are represented by

$$\sigma = \epsilon_{tt}E \pm \epsilon_{tt}E\{1 - [(2A_t/\epsilon_{tt}^2) - E_m]/(E - E_m)\}^{1/2}. \quad (5)$$

For the problem under consideration, it can be easily shown that the only physically acceptable solution is

$$\sigma = \epsilon_{tt}E - \epsilon_{tt}E\{1 - [(2A_t/\epsilon_{tt}^2) - E_m]/(E - E_m)\}^{1/2}. \quad (6)$$

For calculating σ from Eq. 6, the area A_t (area OBQHO) is computed by means of numerical-integration procedures. From the symmetry of the hysteresis loop,* the bilinear yield stress for the i th loop σ_i is given by**

$$\sigma_i = 2\sigma + \epsilon_{tp}E_m. \quad (7)$$

The bilinear yield stress σ_i and the parameter k_i are related by

$$k_i = \frac{\sigma_i^2}{12} \quad (i = 1-10 \text{ and the saturation cycles}). \quad (8)$$

Thus,

$$k_s = \frac{\sigma_s^2}{12}.$$

*The analysis can also be applied to unsymmetrical loops.

** σ_i has the same meaning as $\Delta\sigma$ used in Ref. 2. In comparing σ_0 with σ_i , note that σ_i should be divided by 2, which is not done in the present report. However, there is no such inconsistency in the definition of k_0 and k_i .

RESULTS AND DISCUSSION

Table III lists the values for C and E_m at strains $\epsilon_{\max}$ between 0.1 and 0.4% ($\epsilon_{\max} = \Delta\epsilon_t/2$) and different temperatures. Figures 5-9 show the variation of C and E_m with $\epsilon_{\max}$ at temperatures from room temperature to 593°C (1100°F). Both C and E_m decrease markedly at $\epsilon_{\max}$ between 0.1 and 0.2%, beyond which the parameters are approximately independent of strain. (The apparent variation in C and E_m at $\epsilon_{\max}$ between 0.1 and 0.2% does not reflect the true material behavior, but results from the recommended procedure outlined in Refs. 2 and 3.)

TABLE III. Bilinear Stress-Strain Parameters E_m and C for Incoloy 800. Strain rate = $8.6 \times 10^{-5} \text{ s}^{-1}$.

Specimen Number	$\epsilon_{\max}$, %	E_m , 10^3 MPa (10^3 ksi)	C , 10^3 MPa (10^3 ksi)
<u>Room Temperature</u>			
H10	0.1	110.39 (16.01)	167.94 (24.36)
H22	0.2	15.90 (2.31)	11.53 (1.67)
H23	0.3	6.36 (0.922)	4.38 (0.635)
H20	0.4	6.22 (0.902)	4.28 (0.621)
<u>427 C</u>			
H5	0.1	41.77 (6.06)	36.95 (5.36)
H6	0.2	4.643 (0.673)	3.183 (0.462)
H11	0.3	3.775 (0.548)	2.574 (0.373)
H12	0.4	3.173 (0.46)	2.156 (0.313)
<u>538 C</u>			
H16	0.1	30.80 (4.468)	25.357 (3.678)
H18	0.2	4.472 (0.649)	3.066 (0.445)
H4	0.2	9.557 (1.386)	6.771 (0.982)
H14	0.3	3.624 (0.526)	2.472 (0.358)
H13	0.4	3.223 (0.467)	2.192 (0.318)
<u>593 C</u>			
H24	0.1	31.52 (4.57)	26.26 (3.81)
H1	0.1	35.79 (5.19)	30.84 (4.47)
H8	0.1	34.48 (5.0)	29.4 (4.26)
H9	0.2	11.5 (1.67)	8.27 (1.20)
H2	0.3	2.86 (0.415)	1.94 (0.282)
H3	0.4	2.16 (0.313)	1.46 (0.211)

Fig. 5. Variation of E_m with $\epsilon_{\max}$ at Room Temperature. ANI. Neg. No. 306-77-231.

Fig. 6. Variation of C with $\epsilon_{\max}$ at Room Temperature. ANI. Neg. No. 306-77-232.

Fig. 7. Variations of E_m and C with ϵ_{max} at 538°C (1000°F). ANL Neg. No. 306-77-233.

Fig. 8. Variation of C with ϵ_{max} at 427°C (800°F) and 593°C (1100°F). Neg. No. MSD-64004.

Fig. 9

Variation of E_m with ϵ_{max} at 427°C (800°F) and 593°C (1100°F). Neg. No. MSD-64005.

Tables IV and V list the values of bilinear yield strengths σ_0 , σ_1 , σ_2 , and σ_8 and the corresponding k parameters at ϵ_{max} between 0.1 and 0.4% for different temperatures. Figures 10-17 describe the variation of both yield stress and the parameter k for the monotonic stress-strain curve, first cycle, tenth cycle, and the saturated hysteresis loop with ϵ_{max} . The parameters k_8 and σ_8 for the saturated hysteresis loop cannot be determined at $\epsilon_{max} = 0.1\%$ because the material has approximately elastic behavior in the cyclically hardened state near stress saturation.

Figures 18 and 19 show the variation of parameters C and E_m with temperature at different maximum strains (ϵ_{max}). In the range of maximum strain levels from 0.2 to 0.4%, the bilinear parameters C and E_m exhibit a weak dependence on temperature. At $\epsilon_{max} = 0.1\%$, C and E_m have significantly higher values than those determined at higher temperature. Figures 20-23 show the dependence of bilinear yield strengths σ_0 , σ_1 , σ_2 and σ_8 on temperature. At 427-593°C, the bilinear yield stresses σ_0 and σ_1 are approximately independent of temperature at ϵ_{max} between 0.1 and 0.4%. However, the bilinear yield stress determined for the 10th cycle, σ_2 , varies with temperature and strain in an anomalous but consistent manner, which may be attributed to aging effects associated with elevated temperature and cycling.

TABLE IV. Bilinear Yield Strengths σ_0 , σ_1 , σ_2 , and σ_s for Incoloy 800.
Strain rate = $8.6 \times 10^{-5} \text{ s}^{-1}$.

Specimen Number	$\epsilon_{\text{max.}}$ %	σ_0 , MPa (ksi)	σ_1 , MPa (ksi)	σ_2 , MPa (ksi)	σ_s , MPa (ksi)
<u>Room Temperature</u>					
H10	0.1	125.86 (18.25)	278.79 (40.43)	295.14 (42.81)	-
H22	0.2	164.58 (23.87)	293.86 (42.62)	327.73 (47.53)	344.92 (50.03)
H23	0.3	187.28 (27.16)	303.91 (44.08)	357.49 (51.85)	422.77 (61.32)
H20	0.4	181.44 (26.32)	347.47 (50.40)	419.02 (60.07)	469.58 (68.11)
<u>427°C</u>					
H5	0.1	84.51 (12.26)	160.25 (23.24)	204.80 (29.70)	-
H6	0.2	101.50 (14.72)	190.96 (27.70)	239.59 (34.75)	543.51 (78.83)
H11	0.3	108.66 (15.76)	191.66 (27.80)	269.79 (39.13)	562.97 (81.65)
H12	0.4	105.34 (15.28)	212.43 (30.81)	309.76 (44.93)	590.87 (85.70)
<u>538°C</u>					
H16	0.1	76.87 (11.15)	167.52 (24.30)	172.53 (25.02)	-
H18	0.2	104.91 (15.22)	159.37 (23.11)	246.90 (35.81)	-
H4	0.2	113.77 (16.50)	197.84 (28.69)	253.85 (36.82)	605.87 (87.87)
H14	0.3	91.77 (13.31)	201.12 (29.17)	313.48 (45.47)	546.33 (79.24)
H13	0.4	94.30 (13.68)	217.06 (31.48)	362.18 (52.53)	602.00 (87.31)
<u>593°C</u>					
H24	0.1	80.28 (11.64)	169.79 (24.62)	184.94 (26.82)	-
H1	0.1	79.07 (11.47)	169.84 (24.63)	187.46 (27.19)	-
H8	0.1	83.70 (12.14)	170.82 (24.77)	182.69 (26.50)	-
H9	0.2	86.56 (12.55)	185.06 (26.84)	243.09 (35.26)	479.79 (69.59)
H2	0.3	97.35 (14.12)	195.28 (28.32)	295.80 (42.90)	528.96 (76.72)
H3	0.4	96.51 (14.0)	210.26 (30.50)	401.40 (58.22)	560.46 (81.29)

TABLE V. Bilinear Stress-Strain Parameters k_0 , k_1 , k_2 , and k_s for Incoloy 800.
Strain rate = $8.6 \times 10^{-5} \text{ s}^{-1}$.

Specimen Number	$\epsilon_{\text{max.}}$ %	k_0 , MPa ² (ksi ²)	k_1 , MPa ² (ksi ²)	k_2 , MPa ² (ksi ²)	k_s , MPa ² (ksi ²)
<u>Room Temperature</u>					
H10	0.1	5 280 (111)	6 477 (136)	7 259 (153)	-
H22	0.2	9 029 (190)	7 196 (151)	8 950 (188)	9 914 (209)
H23	0.3	11 691 (246)	7 697 (162)	10 650 (224)	14 895 (313)
H20	0.4	10 973 (231)	10 061 (212)	14 631 (308)	18 375 (387)
<u>427°C</u>					
H5	0.1	2 381 (50.1)	2 140 (45.0)	3 495 (73.5)	-
H6	0.2	3 434 (72.2)	3 039 (63.9)	4 784 (100.6)	24 617 (517.8)
H11	0.3	3 936 (82.8)	3 061 (64.4)	6 065 (127.6)	26 411 (555.6)
H12	0.4	3 699 (77.8)	3 760 (79.1)	7 996 (168.2)	29 094 (612.0)
<u>538°C</u>					
H16	0.1	1 970 (41.4)	2 338 (49.2)	2 480 (52.2)	-
H18	0.2	3 668 (77.2)	2 117 (44.5)	5 080 (106.9)	-
H4	0.2	4 314 (90.8)	3 262 (68.6)	5 370 (113.0)	30 589 (643.5)
H14	0.3	2 807 (59.1)	3 371 (70.9)	8 189 (172.3)	24 873 (523.2)
H13	0.4	2 964 (62.4)	3 926 (82.6)	10 931 (229.9)	30 200 (635.3)
<u>593°C</u>					
H24	0.1	2 148 (45.2)	2 402 (50.5)	2 850 (60.0)	-
H1	0.1	2 084 (43.8)	2 404 (50.6)	2 929 (61.6)	-
H8	0.1	2 335 (49.1)	2 431 (51.1)	2 781 (58.5)	-
H9	0.2	2 498 (52.5)	2 854 (60.0)	4 924 (103.6)	19 183 (403.5)
H2	0.3	3 159 (66.5)	3 178 (66.8)	7 292 (153.4)	23 317 (490.5)
H3	0.4	3 104 (65.3)	3 684 (77.5)	13 426 (282.4)	26 176 (550.6)

Fig. 10. Bilinear Yield Stress as a Function of $\epsilon_{\max}$ at Room Temperature. ANL Neg. No. 306-77-230.

Fig. 11. Variation of Parameter k with $\epsilon_{\max}$ at Room Temperature. ANL Neg. No. 306-77-217 Rev. 1.

Fig. 12. Bilinear Yield Stress as a Function of $\epsilon_{\max}$ at 427°C (800°F). ANL Neg. No. 306-77-216.

Fig. 13. Variation of Parameter k with $\epsilon_{\max}$ at 427°C (800°F). Neg. No. MSD-64001.

Fig. 14. Bilinear Yield Stress as a Function of $\epsilon_{\max}$ at 538°C (1000°F). ANL Neg. No. 306-77-223.

Fig. 15. Variation of Parameter k with $\epsilon_{\max}$ at 538°C (1000°F). ANL Neg. No. 306-77-227.

Fig. 16. Bilinear Yield Stress as a Function of $\epsilon_{\max}$ at 593°C (1100°F). ANL Neg. No. 306-77-229.

Fig. 17. Variation of Parameter k with $\epsilon_{\max}$ at 593°C (1100°F). Neg. No. MSD-64002.

Fig. 18. Variation of C with Temperature. ANL Neg. No. 306-77-225.

Fig. 19. Variation of E_m with Temperature. ANL Neg. No. 306-77-235.

Fig. 20. Variation of σ_0 with Temperature. ANL Neg. No. 306-77-218.

Fig. 21. Variation of σ_1 with Temperature. ANL Neg. No. 306-77-226.

Fig. 22. Variation of σ_2 with Temperature.
ANL Neg. No. 306-77-219.

Fig. 23. Variation of σ_s with Temperature.
ANL Neg. No. 306-77-220.

The precipitated phases in Incoloy 800 are usually titanium nitrides, titanium carbides, and chromium carbides. In addition to the above phases, a gamma-prime type of precipitate (face-centered-cubic structure rich in nickel, aluminum, and titanium) may form upon long-time (over 100 h) exposure to temperatures of 565-630°C. The bilinear yield stress at saturation σ_s also shows anomalous behavior between 427 and 593°C. These observations suggest that it is not very realistic to assume smooth variation of bilinear cyclic parameters with temperature in the region where experimental data are not available.

Finally, it is required to change the bilinear yield parameter from k_0 to k in many design situations in which accurate representation of bilinear cyclic hardening behavior for the initial few cycles (e.g., first 10 cycles) may be important. Corum and Pugh have recommended* that such k change be made on the basis of accumulated plastic strain. Tables VI-XVII contain the bilinear yield stress, the parameter k , and accumulated plastic strain (assumed without regard to sign). Figures 24-27 are plots of bilinear yield

TABLE VI. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at Room Temperature:
 $\Delta\epsilon_f = 0.4\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	293.86 (42.62)	7196 (151.4)	0.420
2	306.22 (44.41)	7814 (164.4)	0.827
3	312.78 (45.36)	8153 (171.5)	1.222
4	315.03 (45.69)	8270 (174.0)	1.614
5	318.87 (46.25)	8473 (178.2)	1.998
6	321.09 (46.57)	8592 (180.7)	2.378
7	322.84 (46.82)	8685 (182.7)	2.755
8	324.87 (47.12)	8795 (185.0)	3.128
9	326.46 (47.35)	8881 (186.8)	3.498
10	327.73 (47.53)	8950 (188.3)	3.864

*J. M. Corum and C. E. Pugh, Oak Ridge National Laboratory, private communication (1976).

TABLE VII. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at Room Temperature:
 $\Delta\epsilon_t = 0.6\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	303.91 (44.08)	7 697 (161.9)	0.814
2	319.66 (46.36)	8 515 (179.1)	1.606
3	331.75 (48.12)	9 172 (192.9)	2.382
4	339.65 (49.26)	9 614 (202.2)	3.145
5	342.55 (49.68)	9 778 (205.7)	3.904
6	347.40 (50.39)	10 057 (211.6)	4.649
7	349.98 (50.76)	10 207 (214.7)	5.391
8	352.50 (51.13)	10 355 (217.8)	6.130
9	354.68 (51.44)	10 483 (220.5)	6.862
10	357.49 (51.85)	10 650 (224.0)	7.591

TABLE VIII. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at Room Temperature:
 $\Delta\epsilon_t = 0.8\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	347.47 (50.40)	10 061 (211.6)	1.242
2	371.13 (53.83)	11 478 (241.4)	2.452
3	383.25 (55.59)	12 240 (257.5)	3.642
4	394.62 (57.23)	12 977 (273.0)	4.817
5	403.18 (58.48)	13 546 (285.0)	5.98
6	404.55 (58.67)	13 638 (286.9)	7.134
7	407.15 (59.05)	13 814 (290.6)	8.280
8	412.40 (59.81)	14 173 (298.1)	9.418
9	416.53 (60.41)	14 458 (304.1)	10.551
10	419.02 (60.77)	14 631 (307.8)	11.679

TABLE IX. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 427°C (800°F), $\Delta\epsilon_t = 0.4\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	190.96 (27.7)	3039 (63.9)	0.501
2	202.62 (29.39)	3421 (72.0)	1.000
3	210.19 (30.49)	3682 (77.4)	1.470
4	215.06 (31.19)	3854 (81.1)	1.932
5	223.48 (32.41)	4162 (87.5)	2.38
6	225.56 (32.71)	4240 (89.4)	2.824
7	229.10 (33.22)	4374 (92.0)	3.260
8	233.03 (33.80)	4525 (95.7)	3.691
9	235.95 (34.22)	4639 (97.6)	4.118
10	239.59 (34.75)	4784 (100.6)	4.539

TABLE X. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 427°C (800°F): $\Delta\epsilon_t = 0.6\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	191.66 (27.80)	3061 (64.4)	0.923
2	210.59 (30.54)	3696 (77.7)	1.818
3	226.34 (32.83)	4269 (89.8)	2.693
4	236.30 (34.27)	4653 (97.9)	3.548
5	244.11 (35.41)	4966 (104.5)	4.390
6	248.83 (36.09)	5160 (108.5)	5.221
7	254.58 (36.92)	5401 (113.6)	6.047
8	258.12 (37.44)	5552 (116.8)	6.867
9	260.81 (37.83)	5669 (119.2)	7.679
10	269.79 (39.13)	6065 (127.6)	8.482

TABLE XI. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 427°C (800°F): $\Delta\epsilon_t = 0.8\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	212.43 (30.81)	3760 (79.1)	1.289
2	243.50 (35.32)	4941 (103.9)	2.531
3	261.12 (37.87)	5682 (119.5)	3.744
4	271.95 (39.44)	6163 (129.6)	4.944
5	284.96 (41.33)	6767 (142.3)	6.120
6	292.66 (42.45)	7137 (150.1)	7.288
7	298.90 (43.35)	7445 (156.6)	8.443
8	304.81 (44.21)	7743 (162.9)	9.587
9	307.11 (44.54)	7859 (165.3)	10.72
10	309.76 (44.93)	7996 (168.2)	11.85

TABLE XII. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 538°C (1000°F): $\Delta\epsilon_t = 0.4\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	197.84 (28.69)	3262 (68.6)	0.504
2	211.60 (30.69)	3731 (78.5)	0.989
3	221.83 (32.17)	4101 (86.3)	1.464
4	231.99 (33.65)	4485 (94.3)	1.924
5	237.48 (34.44)	4700 (98.9)	2.373
6	240.95 (34.95)	4838 (101.8)	2.815
7	242.82 (35.22)	4913 (103.4)	3.249
8	247.70 (35.93)	5113 (107.6)	3.676
9	250.67 (36.36)	5236 (110.2)	4.094
10	253.85 (36.82)	5370 (113.0)	4.509

TABLE XIII. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 538°C (1000°F): $\Delta\epsilon_t = 0.6\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	201.12 (29.17)	3371 (70.9)	0.958
2	229.77 (33.32)	4399 (92.5)	1.885
3	249.99 (36.26)	5208 (109.6)	2.782
4	270.01 (39.16)	6076 (127.8)	3.655
5	280.57 (40.69)	6560 (138.0)	4.503
6	289.04 (41.92)	6962 (146.5)	5.340
7	298.89 (43.35)	7444 (156.6)	6.156
8	302.50 (43.87)	7626 (160.0)	6.963
9	304.17 (44.12)	7710 (162.2)	7.758
10	313.48 (45.47)	8189 (172.3)	8.549

TABLE XIV. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 538°C (1000°F): $\Delta\epsilon_t = 0.8\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	217.06 (31.48)	3 926 (82.6)	1.303
2	267.34 (38.77)	5 956 (125.3)	2.545
3	294.41 (42.70)	7 223 (151.9)	3.749
4	300.96 (43.65)	7 548 (158.8)	4.927
5	314.40 (45.60)	8 237 (173.3)	6.082
6	329.25 (47.75)	9 034 (190.0)	7.216
7	337.50 (48.95)	9 492 (199.7)	8.330
8	347.91 (50.46)	10 087 (212.2)	9.431
9	351.38 (50.96)	10 289 (216.4)	10.53
10	362.18 (52.53)	10 931 (229.9)	11.613

TABLE XV. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 593°C (1100°F): $\Delta\epsilon_t = 0.4\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	185.06 (26.84)	2854 (60.0)	0.526
2	197.84 (28.69)	3262 (68.6)	1.036
3	206.86 (30.00)	3566 (75.0)	1.528
4	213.33 (30.94)	3792 (79.8)	2.009
5	222.01 (32.20)	4108 (86.2)	2.478
6	229.30 (33.26)	4382 (92.2)	2.933
7	232.50 (33.72)	4505 (94.8)	3.386
8	234.84 (34.06)	4596 (96.7)	3.833
9	238.0 (34.52)	4720 (99.3)	4.274
10	243.09 (35.26)	4924 (103.6)	4.708

TABLE XVI. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 593°C (1100°F): $\Delta\epsilon_t = 0.6\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	195.28 (28.32)	3178 (66.8)	0.914
2	223.22 (32.38)	4152 (87.3)	1.792
3	240.63 (34.90)	4825 (101.5)	2.640
4	253.71 (36.80)	5364 (112.8)	3.462
5	264.25 (38.33)	5819 (122.4)	4.265
6	273.63 (39.69)	6240 (131.3)	5.054
7	278.59 (40.41)	6468 (136.1)	5.831
8	282.52 (40.98)	6651 (139.9)	6.597
9	288.73 (41.88)	6947 (146.1)	7.350
10	295.80 (42.903)	7292 (153.4)	8.096

TABLE XVII. Bilinear Yield Stress, Parameter k , and Accumulated Plastic Strain for Incoloy 800 at 593 C (1100°F): $\Delta\epsilon_t = 0.8\%$ and Strain Rate = $8.6 \times 10^{-5} \text{ s}^{-1}$

Cycle Number	Bilinear Yield Stress, MPa (ksi)	Parameter k , MPa ² (ksi ²)	Accumulated Plastic Strain, %
1	210.26 (30.5)	3 684 (77.5)	1.305
2	256.27 (37.17)	5 473 (115.1)	2.561
3	289.10 (41.93)	6 965 (146.5)	3.775
4	313.57 (45.48)	8 194 (172.4)	4.958
5	333.51 (48.37)	9 269 (195.0)	6.116
6	350.14 (50.78)	10 216 (214.9)	7.256
7	367.49 (53.30)	11 254 (236.7)	8.374
8	376.37 (54.59)	11 804 (248.3)	9.478
9	390.74 (56.67)	12 723 (267.6)	10.566
10	401.39 (58.22)	13 426 (282.4)	11.641

Fig. 24

Variation of Bilinear Yield Stress Range with Accumulated Plastic Strain at Room Temperature. ANL Neg. No. 306-77-224.

Fig. 25

Variation of Bilinear Yield Stress Range with Accumulated Plastic Strain at 427°C (800°F). Neg. No. MST-64009.

Fig. 26

Variation of Bilinear Yield Stress Range with Accumulated Plastic Strain at 538°C (1000°F).
ANL Neg. No. 306-77-236.

Fig. 27

Variation of Bilinear Yield Stress Range with Accumulated Plastic Strain at 593°C (1100°F).
ANL Neg. No. 306-77-234.

stress versus accumulated plastic strain for the three strains. The symbols on Figs. 24-27 represent the bilinear yield stress for each individual cycle up to ten cycles.

The bilinear cyclic hardening curves can be empirically described by using a modified Voce-type equation.⁷ The present study shows that good correlation is obtained by using the bilinear parameter k instead of bilinear yield stress. The experimental data obtained in the range of 427-593°C were considered and fit to the following modified Voce-type equation:

$$\frac{k_{SV} - k}{k_{SV} - k_{0V}} = \exp(-k_e \sum |\epsilon_p|), \quad (9)$$

where $\sum |\epsilon_p|$ is the accumulated plastic strain, and k_{SV} , k_{0V} , and k_e are empirical parameters, which depend on material, temperature, ϵ_{max} , and strain rate.

The parameters k_{SV} , k_{0V} , and k_e in Eq. 9 were determined from a computer fit of the data by means of a variable-metric minimization program and are listed in Table XVIII. These parameters describe the bilinear hardening behavior satisfactorily, as can be seen from Figs. 28-30, where the symbols represent the experimental points. Furthermore, the constants k_{SV} and k_{0V} normalized by the shear modulus μ and k_e appear to be interdependent in a manner analogous to that established for the description of monotonic stress-strain curves by the Voce equation.⁸ For example, as shown in

Figs. 31 and 32, k_{SV} and k_{0V} normalized by the temperature-dependent shear modulus and k_ϵ are interrelated by the relations

$$\frac{k_{SV}}{\mu^2} = \alpha(k_\epsilon)^\beta \quad (10)$$

and

$$(k_{SV} - k_{0V})/\mu^2 = a\left(\frac{k_{SV}}{\mu^2}\right)^b \quad (11)$$

The values of α , β , a , and b in Eqs. 10 and 11 are 3.79×10^{-5} , -0.905 , 112.6 , and 1.39 , respectively.

Thus, changing k from k_0 during continuous fixed-strain-range cycling correlates well with the accumulated plastic strain by using a modified Voce-type equation, and the correlation is expected to be useful in the analysis of structural components.

TABLE XVIII. Empirical Parameters of Modified Voce-type Equations for Incoloy 800

$\epsilon_{\max}$, %	$k_{SV} \cdot 10^2$ MPa ²	$k_{0V} \cdot 10^2$ MPa ²	k_ϵ
<u>427°C</u>			
0.2	54.82	26.76	29.54
0.3	65.67	23.11	21.89
0.4	86.17	24.11	19.72
<u>538°C</u>			
0.2	57.35	26.42	44.47
0.3	91.10	19.25	22.81
0.4	122.52	23.64	15.88
<u>593°C</u>			
0.2	57.94	23.81	28.21
0.3	81.69	21.10	22.22
0.4	198.50	18.04	8.76

Fig. 28

Fit of Bilinear Cyclic Hardening Parameters to Modified Voce-type Equation at 427°C (800°F).
ANL Neg. No. 306-77-240 Rev. 1.

Fig. 29. Fit of Bilinear Cyclic Hardening Parameters to Modified Voce-type Equation at 538°C (1000°F). ANL Neg. No. 306-77-242.

Fig. 30. Fit of Bilinear Cyclic Hardening Parameters to Modified Voce-type Equation at 593°C (1100°F). ANL Neg. No. 306-77-239 Rev. 1.

Fig. 31. Dependence of Modified Voce Constant k_{sv} on k_v . ANL Neg. No. 306-77-244.

Fig. 32. Interdependence of Modified Voce Constants k_{sv} and k_{0v} . ANL Neg. No. 306-77-243.

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