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BILINEAR CYCLIC STRESS-STRAIN PARAMETERS FOR TYPES 304 AND 316 STAINLESS STEEL

by

P. S. Maiya

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P. S. Maiya

Materials Science Division

July 1978

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BILINEAR CYCLIC STRESS-STRAIN PARAMETERS FOR TYPES 304 AND 316 STAINLESS STEEL

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ABSTRACT

This report describes the bilinear cyclic stress-strain parameters for Types 304 and 316 stainless steel. The bilinear properties of solution-annealed and aged Type 304 stainless steel (heat 9T2796) and solution-annealed Type 316 stainless steel (heat 8092297) under cyclic-loading conditions at a strain rate ($\dot{\epsilon}_t$) of 8.6×10^{-5} s^{-1}, total strain range ($\Delta\epsilon_t$) between 0.2 and 0.8%, and temperatures from 22 to 593°C have been determined. The dependence of bilinear parameters on maximum strain ϵ_{max} (= $\Delta\epsilon_t/2$) and temperature is discussed.

I. INTRODUCTION

Inelastic analyses of nuclear structural components subjected to creep and fatigue loadings are often required to establish the levels of stresses and strains in critical locations. Under the provisions of the ASME Boiler and Pressure Vessel Code Cases, both time-independent elastic-plastic and time-dependent creep behavior must be included in a detailed analysis of components operating at elevated temperatures. Generally, the elastic-plastic analysis is based on the von Mises or Tresca yield condition, the classical kinematic hardening rule, and the bilinear stress-strain relationships. The bilinear representation of the uniaxial stress-strain curve can be generalized to the multiaxial stress state using von Mises' yield criterion. Using the available procedures,[1,2] the bilinear yield parameters have been described[3,4] for Types 304 and 316 stainless steel and, more recently, for Incoloy alloy 800H.[5,6] The bilinear material-properties data for Types 304 and 316 stainless steel reported in Refs. 3 and 4 are applicable to some loading variables, but the present report describes properties determined under cyclic-loading conditions that are different from previous work and of interest to designers. In addition, improved analytical techniques have been used to establish bilinear cyclic-hardening parameters.

II. EXPERIMENTAL MATERIAL AND PROCEDURES

The chemical composition of Types 304 and 316 stainless steel is given in Table I. The hourglass-shape specimens (6.35-mm minimum diameter) were obtained from 15.5-mm-dia rod material of Type 304 stainless steel (heat 9T2796) and from 25.4-mm-dia rod material of Type 316 stainless steel (heat 8092297). The specimens of Type 304 stainless steel were solution-annealed at 1092°C for 0.5 h and aged at 593°C for 1000 h, and the Type 316 stainless steel specimens were solution-annealed at 1065°C for 0.5 h. The heat treatment of specimens (wrapped in tantalum foil) was carried out in evacuated quartz tubes that were backfilled with argon. The ASTM grain size of the heat-treated material is 2.5 for Type 304 stainless steel and 4.4 for Type 316 stainless steel, as determined by the intercept method.[7] The cyclic tests were performed in air under push-pull conditions in the axial strain-control mode (continuous cycling without hold time) until stress saturation was achieved. The experimental procedure used for fatigue testing is similar to that described by Slot et al.[8] The tests were conducted at a strain rate of $8.6 \times 10^{-5}\ s^{-1}$, total strain range of 0.2 to 0.8%, and temperatures of 22-593°C.

TABLE I. Chemical Composition of Types 304 and 316 Stainless Steel

Type of Steel[a]	Heat No.	C	P	S	B	N	Si	Mn	Cu	Al	Co	Mo	Ni	Cr	Fe
304	9T2796	0.059	0.033	0.016	-	-	0.44	1.26	0.25	-	-	0.35	9.50	18.60	Balance
316	8092297	0.06	0.024	0.019	0.005	0.032	0.58	1.85	0.09	0.023	0.02	2.35	13.70	17.10	Balance

[a]Material obtained from rod.

III. BILINEAR CYCLIC STRESS-STRAIN ANALYSIS

The bilinear stress-strain analysis of the monotonic initial-loading stress-strain curves and hysteresis loops was performed using the procedure summarized in Figs. 1-3. (This procedure has also been described in Refs. 1 and 2.) The bilinear representation of monotonic, initial-loading stress-strain curves is shown in Fig. 1. The elastic line (with a slope equal to Young's modulus) is drawn from the zero origin. The elastic-plastic segment of the bilinear curve is determined by a straight line that connects the stress at the maximum strain, ϵ_{max}, with the stress at strain $\epsilon_{max}/2$. The bilinear yield stress σ_0^y, defined by the intersection of the two straight lines OP and PQR, is related to the bilinear parameter κ_0 by[1,2]

$$\sigma_0^y = \sqrt{3\kappa_0}, \tag{1}$$

where κ_0 is a measure of the size of the yield surface for the first inelastic loading. Equation 1 is based on the von Mises yield condition; i.e., the second invariant of the deviatoric stress tensor at yield is equal to κ.

In the bilinear representation, C is defined as

$$C = \frac{2}{3}\frac{EE_m}{E - E_m}, \tag{2}$$

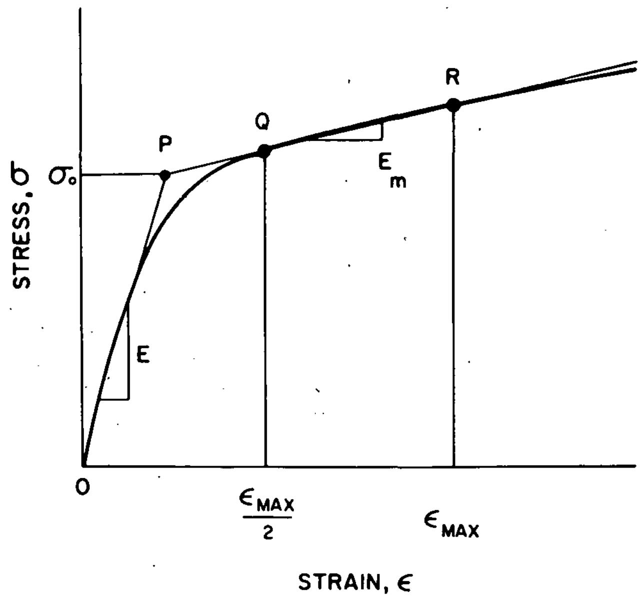

Fig. 1

Bilinear Representation of Monotonic, Initial-loading Stress-Strain Curve. Neg. No. MSD-64007.

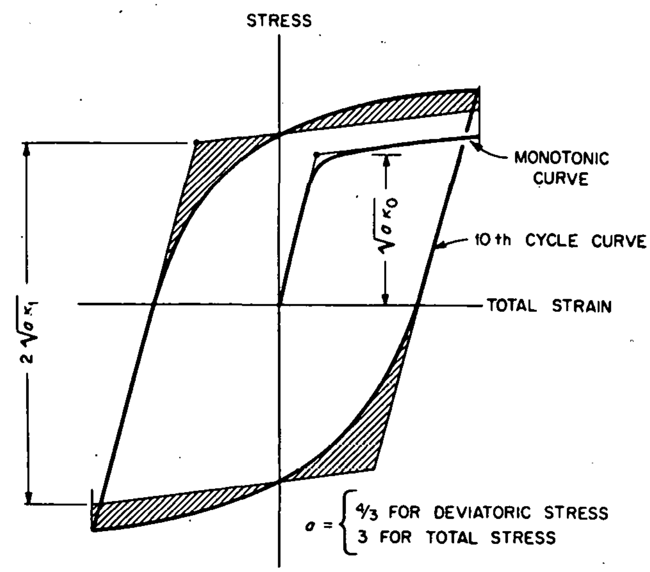

Fig. 2

Bilinear Representation of Initial and Tenth-cycle Stress-Strain Curves. Neg. No. MSD-64006.

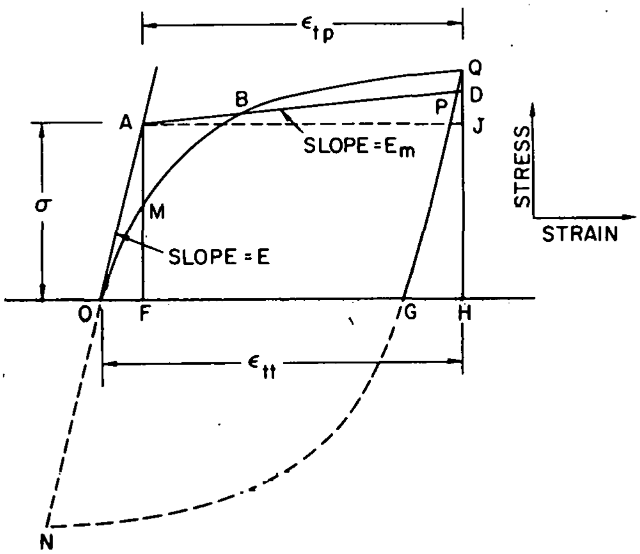

Fig. 3

Schematic Representation of a Hysteresis Loop Used in Bilinear Cyclic Stress-Strain Analysis. Neg. No. MSD-64794.

where E is Young's modulus and E_m is the slope of the elastic-plastic line (see Fig. 1). The parameter C is actually the slope of the elastic-plastic line in terms of deviatoric stress versus plastic strain ϵ_p (i.e., $C = d\sigma'/d\epsilon_p$, where σ' is the deviatoric stress). The bilinear parameters for the 10th cycle (κ_1) and the stress-saturation cycle (κ_s) 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. In design, K is assumed to reach a limiting value at the 10th cycle.[2] However, in Types 304 and 316 stainless steel, significant hardening occurs even beyond the 10th cycle.

The intersection of the elastic and elastic-plastic lines is located so that the shaded areas above and below the actual curve are equal for the tensile and compressive portions of the cyclic curve (see Fig. 2). This is accomplished by means of an analytical procedure described in Refs. 5 and 6 and briefly illustrated in Fig. 3, a schematic representation of a hysteresis loop. To determine the bilinear yield stress, a line ABPD with a slope equal to E_m must be drawn so that the area OABO is equal to area BQDB. This is done by equating area OAPDHO to area OBQHO. With reference to Fig. 3, defining $AF = \sigma$, $\epsilon_{tp} = \epsilon_{tt} - \sigma/E$, and $DJ = \epsilon_{tp}E_m$ and designating the area OBQHO by A_t, we can show that, for the hysteresis loop i, the bilinear yield stress σ_i^y is expressed as

$$\sigma_i^y = \epsilon_{tt}E - \epsilon_{tt}E\{1 - [(2A_t/\epsilon_{tt}^2) - E_m]/(E - E_m)\}^{1/2} + \epsilon_{tp}E_m/2. \qquad (3)$$

To determine σ_i^y, the value of A_t is required; this is obtained by means of conventional numerical-integration procedures. The parameters κ_1 and κ_s and the corresponding cyclic yield stresses σ_1^y and σ_s^y are related by

$$\sigma_1^y = \sqrt{3\kappa_1} \qquad (4)$$

and

$$\sigma_s^y = \sqrt{3\kappa_s}\,. \qquad (5)$$

For materials such as austenitic stainless steels that undergo cyclic hardening when cycled at constant strain ranges, $\kappa_0 < \kappa_1 < \kappa_s$.

IV. RESULTS AND DISCUSSION

The values for C and E_m at strains ϵ_{max} (= $\Delta\epsilon_t/2$) between 0.1 and 0.4% and four different temperatures are listed in Tables II and III for Types 304 and 316 stainless steel, and these parameters are plotted against ϵ_{max} in

TABLE II. Bilinear Stress-Strain Parameters E_m and C for Type 304 Stainless Steel. Strain rate = $8.6 \times 10^{-5}\ s^{-1}$.

Specimen Number	ϵ_{max}, %	E_m, 10^3 MPa (10^3 ksi)	C, 10^3 MPa (10^3 ksi)
		Room Temperature	
T407	0.1	139.4 (20.22)	331.8 (48.13)
T406	0.2	24.24 (3.515)	18.47 (2.679)
T405	0.3	11.42 (1.656)	8.091 (1.173)
T404	0.4	5.097 (0.739)	3.490 (0.506)
		427°C (800°F)	
T470	0.1	17.00 (2.465)	12.62 (1.831)
T466	0.2	2.431 (0.353)	1.645 (0.239)
T463	0.3	2.120 (0.307)	1.431 (0.208)
T461	0.4	7.106 (1.031)	4.950 (0.718)
		538°C (1000°F)	
T424	0.1	34.12 (4.949)	29.15 (4.228)
T384	0.2	10.58 (1.535)	7.571 (1.098)
T422	0.3	4.441 (0.644)	3.048 (0.442)
T415	0.4	4.203 (0.610)	2.880 (0.418)
		593°C (1100°F)	
T413	0.1	43.87 (6.363)	41.37 (6.000)
T412	0.2	13.90 (2.016)	10.22 (1.482)
T410	0.3	2.689 (0.390)	1.826 (0.265)
T408	0.4	4.881 (0.708)	3.364 (0.488)

TABLE III. Bilinear Stress-Strain Parameters E_m and C for Type 316 Stainless Steel. Strain rate = $8.6 \times 10^{-5}\ s^{-1}$.

Specimen Number	ϵ_{max}, %	E_m, 10^3 MPa (10^3 ksi)	C, 10^3 MPa (10^3 ksi)
		Room Temperature	
P-30	0.2	50.76 (7.36)	45.86 (6.65)
P-29	0.3	6.43 (0.933)	4.44 (0.643)
P-28	0.4	3.40 (0.493)	2.31 (0.335)
		427°C (800°F)	
P-25	0.1	92.03 (13.35)	137.81 (19.99)
P-15	0.2	8.62 (1.25)	6.06 (0.879)
P-14	0.3	4.58 (0.664)	3.14 (0.455)
P-18	0.4	2.70 (0.391)	1.83 (0.265)
		538°C (1000°F)	
P-22	0.1	82.30 (11.94)	116.70 (16.93)
P-11	0.2	4.83 (0.700)	3.32 (0.482)
P-12	0.3	12.73 (1.85)	9.24 (1.34)
P-13	0.4	2.84 (0.412)	1.93 (0.280)
		593°C (1100°F)	
P-17	0.1	55.93 (8.11)	59.52 (8.63)
P-9	0.2	15.95 (2.31)	11.90 (1.73)
P-5	0.3	3.50 (0.508)	2.39 (0.347)
P-1	0.4	3.65 (0.529)	2.49 (0.362)
P-3	0.4	5.00 (0.725)	3.45 (0.500)

Figs. 4-7. In all cases, both C and E_m decrease markedly at ϵ_{max} between 0.1 and 0.2%; beyond ϵ_{max} = 0.2%, the parameters are approximately independent of strain. Also, Type 316 stainless steel has approximately elastic behavior at room temperature when cycled at a total strain range of 0.2% (i.e., ϵ_{max} = 0.1%).

The values of bilinear yield parameters σ_0^y, σ_1^y, and σ_s^y for the two types of steel, determined at ϵ_{max} between 0.1 and 0.4% and for different temperatures, are listed in Tables IV and V. The values of parameter κ_i corresponding to the bilinear yield strength σ_i^y were calculated from Eqs. 1, 4, and 5, and are given in Tables VI and VII for Types 304 and 316 stainless steel, respectively.

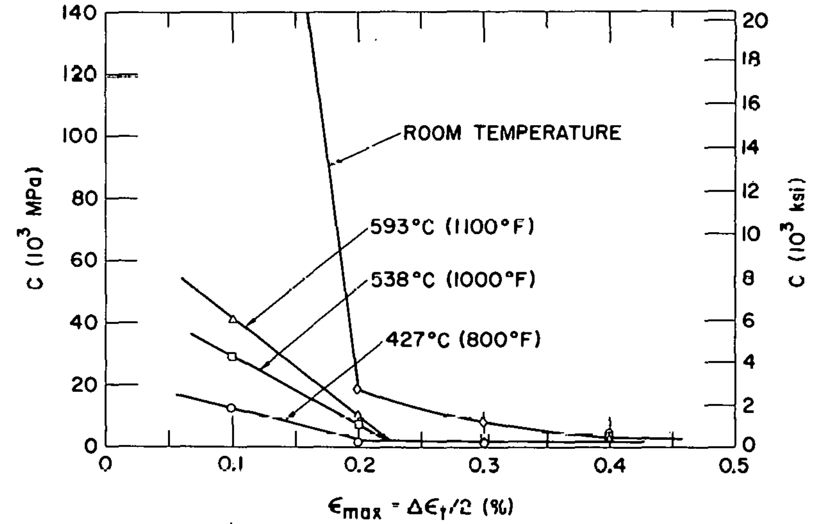

Fig. 4. Variation of C with ϵ_{max} at Different Temperatures for Type 304 Stainless Steel. ANL Neg. No. 306-78-264.

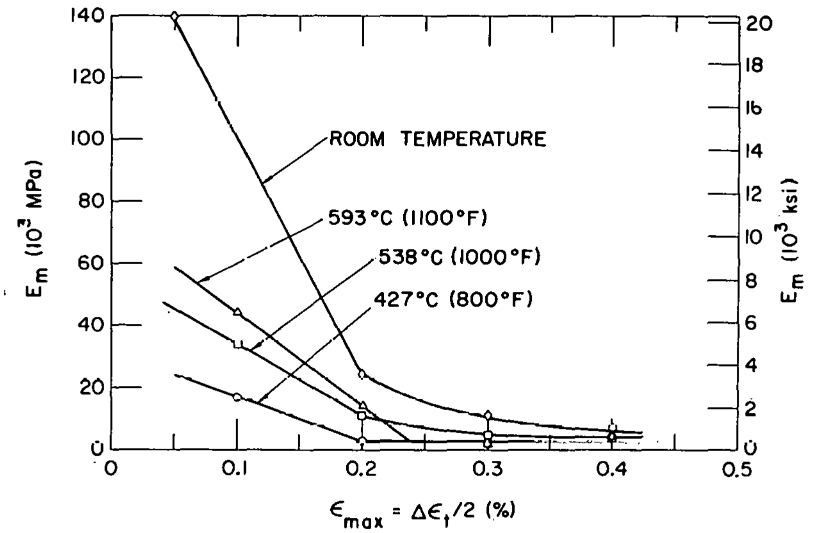

Fig. 5. Variation of E_m with ϵ_{max} at Different Temperatures for Type 304 Stainless Steel. ANL Neg. No. 306-78-265.

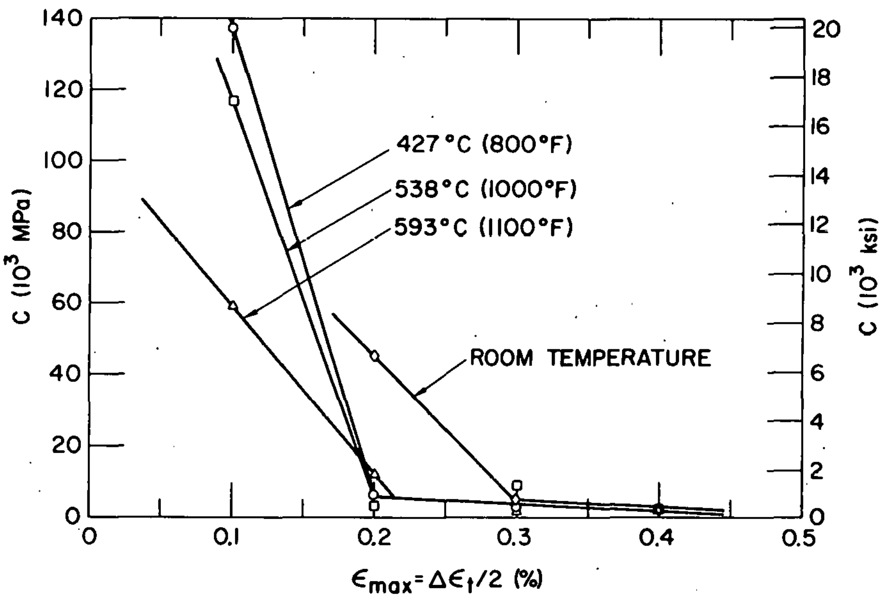

Fig. 6. Variation of C with ε_{max} at Different Temperatures for Type 316 Stainless Steel. ANL Neg. No. 306-78-240.

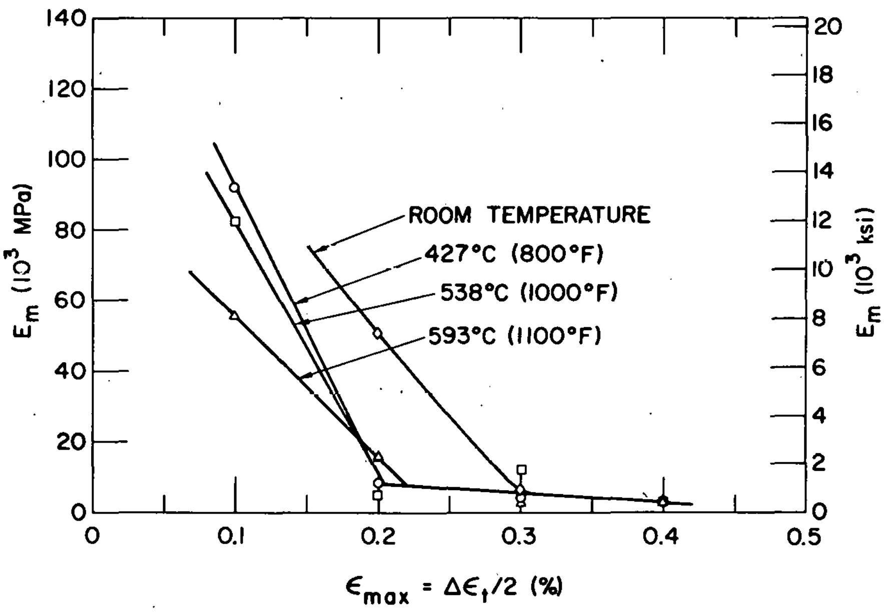

Fig. 7. Variation of E_m with ε_{max} at Different Temperatures for Type 316 Stainless Steel. ANL Neg. No. 306-78-241.

TABLE IV. Bilinear Yield Strengths σ_0^y, σ_1^y, and σ_s^y for Type 304 Stainless Steel. Strain rate = 8.6×10^{-5} s^{-1}.

Specimen Number	ϵ_{max}, %	σ_0^y, MPa (ksi)	σ_1^y, MPa (ksi)	σ_s^y, MPa (ksi)
		Room Temperature		
T407	0.1	75.51 (10.95)	119.7 (17.36)	119.7 (17.36)
T406	0.2	171.3 (24.85)	159.0 (23.05)	158.4 (22.98)
T405	0.3	189.8 (27.53)	180.9 (26.24)	182.7 (26.49)
T404	0.4	187.9 (27.25)	187.2 (27.15)	187.8 (27.2)
		427°C (800°F)		
T470	0.1	51.86 (7.522)	53.42 (7.748)	70.08 (10.16)
T466	0.2	69.80 (10.12)	79.90 (11.59)	138.1 (20.03)
T463	0.3	70.90 (10.28)	95.60 (13.87)	161.3 (23.40)
T461	0.4	70.90 (10.28)	114.3 (16.58)	164.0 (23.79)
		538°C (1000°F)		
T424	0.1	49.30 (7.150)	57.81 (8.384)	88.16 (12.79)
T384	0.2	76.96 (11.16)	82.43 (11.96)	115.2 (16.71)
T422	0.3	64.60 (9.370)	102.7 (14.90)	160.0 (23.21)
T415	0.4	95.04 (13.78)	136.2 (19.75)	193.3 (28.04)
		593°C (1100°F)		
T413	0.1	56.18 (8.148)	72.79 (10.56)	95.51 (13.85)
T412	0.2	48.81 (7.079)	94.11 (13.65)	131.4 (19.06)
T410	0.3	55.63 (8.068)	108.8 (15.78)	156.7 (22.72)
T408	0.4	92.69 (13.44)	153.5 (22.26)	175.5 (25.45)

TABLE V. Bilinear Yield Strengths σ_0^y, σ_1^y, and σ_s^y for Type 316 Stainless Steel. Strain rate = 8.6×10^{-5} s^{-1}.

Specimen Number	ϵ_{max}, %	σ_0^y, MPa (ksi)	σ_1^y, MPa (ksi)	σ_s^y, MPa (ksi)
		Room Temperature		
P-30	0.2	178.2 (25.84)	172.6 (25.04)	173.0 (25.09)
P-29	0.3	218.0 (31.62)	195.6 (28.37)	190.8 (27.68)
P-28	0.4	231.2 (33.53)	213.4 (30.95)	214.3 (31.09)
		427°C (800°F)		
P-25	0.1	59.99 (8.70)	62.31 (11.94)	-
P-15	0.2	118.3 (17.16)	105.2 (15.26)	146.2 (21.21)
P-14	0.3	125.9 (18.25)	131.8 (19.12)	182.8 (26.51)
P-18	0.4	125.5 (18.20)	145.3 (21.08)	205.7 (29.84)
		538°C (1000°F)		
P-22	0.1	60.48 (8.77)	75.45 (10.95)	-
P-11	0.2	109.4 (15.86)	107.2 (15.55)	179.6 (26.05)
P-12	0.3	85.76 (12.44)	134.9 (19.56)	220.5 (31.99)
P-13	0.4	109.41 (15.87)	157.6 (22.86)	245.2 (35.57)
		593°C (1100°F)		
P-17	0.1	63.53 (9.21)	85.87 (12.46)	-
P-9	0.2	84.32 (12.23)	115.6 (16.77)	182.7 (26.49)
P-5	0.3	106.3 (15.41)	151.0 (21.91)	213.0 (30.90)
P-1	0.4	111.3 (16.14)	177.2 (25.71)	261.2 (37.88)

TABLE VI. Bilinear Cyclic Parameters κ_0, κ_1, and κ_s for Type 304 Stainless Steel. Strain rate = 8.6×10^{-5} s^{-1}.

Specimen Number	ϵ_{max}, %	κ_0, MPa^2 (ksi^2)	κ_1, MPa^2 (ksi^2)	κ_s, MPa^2 (ksi^2)
		Room Temperature		
T407	0.1	1 901 (40.0)	4 774 (100.4)	4 774 (100.4)
T406	0.2	9 782 (205.8)	8 421 (177.2)	8 366 (176.0)
T405	0.3	12 010 (252.6)	10 910 (229.5)	11 120 (234.0)
T404	0.4	11 770 (247.6)	11 680 (245.7)	11 760 (247.4)
		427°C (800°F)		
T470	0.1	896.5 (18.9)	951.2 (20.0)	1 637 (34.4)
T466	0.2	1 624 (34.2)	2 128 (44.8)	6 356 (133.7)
T463	0.3	1 675 (35.2)	3 046 (64.1)	8 678 (182.5)
T461	0.4	1 675 (35.2)	4 358 (91.7)	8 965 (188.6)
		538°C (1000°F)		
T424	0.1	810.1 (17.0)	1 114 (23.4)	2 591 (54.5)
T384	0.2	1 974 (41.5)	2 265 (47.6)	4 425 (93.1)
T422	0.3	1 800 (29.3)	3 519 (74.0)	8 535 (179.6)
T415	0.4	3 011 (63.3)	6 181 (130.0)	12 460 (262.1)
		593°C (1100°F)		
T413	0.1	1 052 (22.1)	1 766 (37.2)	3 040 (64.0)
T412	0.2	794.1 (16.7)	2 952 (62.1)	5 754 (121.0)
T410	0.3	1 031 (21.7)	3 948 (83.0)	8 182 (172.1)
T408	0.4	2 864 (60.2)	7 854 (165.2)	10 260 (215.9)

TABLE VII. Bilinear Cyclic Parameters κ_0, κ_1, and κ_s for Type 316 Stainless Steel. Strain rate = 8.6×10^{-5} s^{-1}.

Specimen Number	ϵ_{max}, %	κ_0, MPa^2 (ksi^2)	κ_1, MPa^2 (ksi^2)	κ_s, MPa^2 (ksi^2)
		Room Temperature		
P-30	0.2	10 581 (223)	9 930 (209)	9 976 (210)
P-29	0.3	15 838 (333)	12 753 (268)	12 135 (255)
P-28	0.4	17 811 (375)	15 179 (319)	15 311 (322)
		427°C (800°F)		
P-25	0.1	1 200 (25.2)	2 258 (47.5)	-
P-15	0.2	4 666 (98.2)	3 688 (77.6)	7 126 (150)
P-14	0.3	5 279 (111)	5 794 (122)	11 137 (234)
P-18	0.4	5 251 (110)	7 037 (148)	14 110 (297)
		538°C (1000°F)		
P-22	0.1	1 219 (25.6)	1 898 (39.9)	-
P-11	0.2	3 987 (83.9)	3 831 (80.6)	10 750 (226)
P-12	0.3	2 452 (51.6)	6 062 (128)	16 209 (341)
P-13	0.4	3 990 (83.9)	8 276 (174)	20 047 (422)
		593°C (1100°F)		
P-17	0.1	1 345 (28.3)	2 458 (51.7)	-
P-9	0.2	2 370 (49.8)	4 454 (93.7)	11 121 (234)
P-5	0.3	3 764 (79.2)	7 605 (160.0)	15 125 (318)
P-1	0.4	4 128 (86.8)	10 471 (220)	22 739 (478)

The variation of parameter $\varkappa$ with ϵ_{max} for the monotonic stress-strain curve ($\varkappa_0$), the 10th cycle ($\varkappa_1$), and the saturated hysteresis loop ($\varkappa_s$) is described for Type 304 stainless steel in Figs. 8-11 and for Type 316 stainless steel in Figs. 12-15. In general, parameter $\varkappa$ increases with an increase in ϵ_{max}. Figures 8 and 12 show that, at room temperature, cyclic softening occurs ($\varkappa_0 > \varkappa_1$ and $\varkappa_s$) at $\epsilon_{max} > 0.2\%$. Also, the parameters $\varkappa_1$ and $\varkappa_s$ appear to reach a saturation limit at $\epsilon_{max} = 0.4\%$ in Type 304 stainless steel, but they appear to increase continuously with strain in Type 316 stainless steel. This may be associated with the difference in heat treatment received by the two types of steels prior to fatigue tests. (Type 304 stainless steel is solution-annealed and aged, whereas Type 316 is solution-annealed only.)

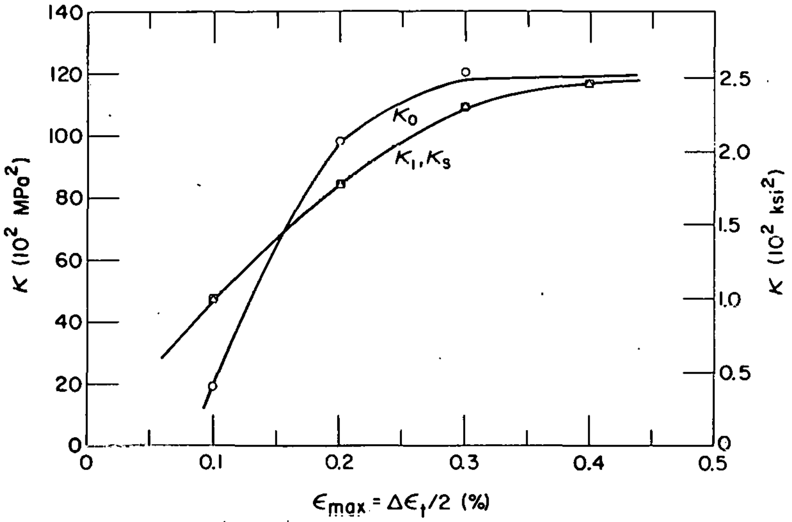

Fig. 8. Variation of Parameter $\varkappa$ with ϵ_{max} at Room Temperature for Type 304 Stainless Steel. ANL Neg. No. 306-78-262.

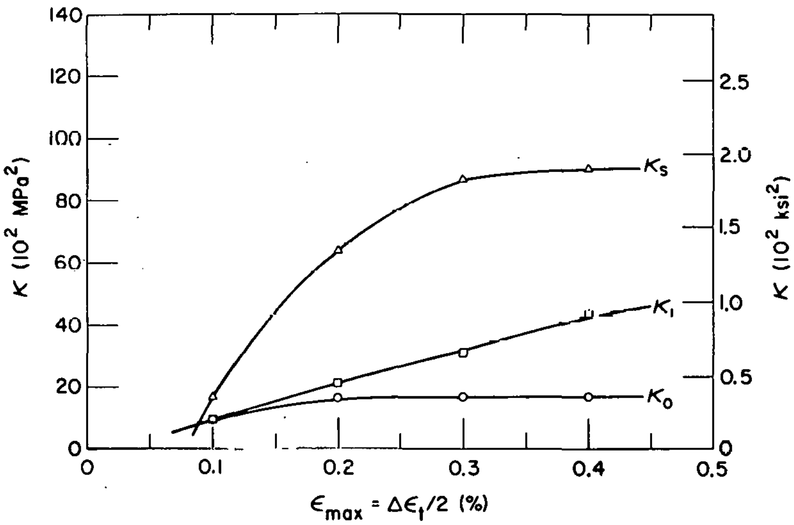

Fig. 9. Variation of Parameter $\varkappa$ with ϵ_{max} at 427°C (800°F) for Type 304 Stainless Steel. ANL Neg. No. 306-78-263.

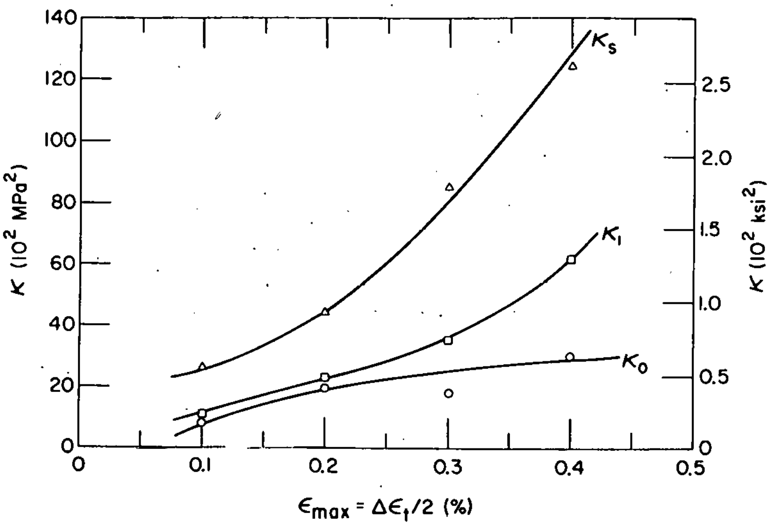

Fig. 10

Variation of Parameter $\varkappa$ with ε_{max} at 538°C (1000°F) for Type 304 Stainless Steel. ANL Neg. No. 306-78-267.

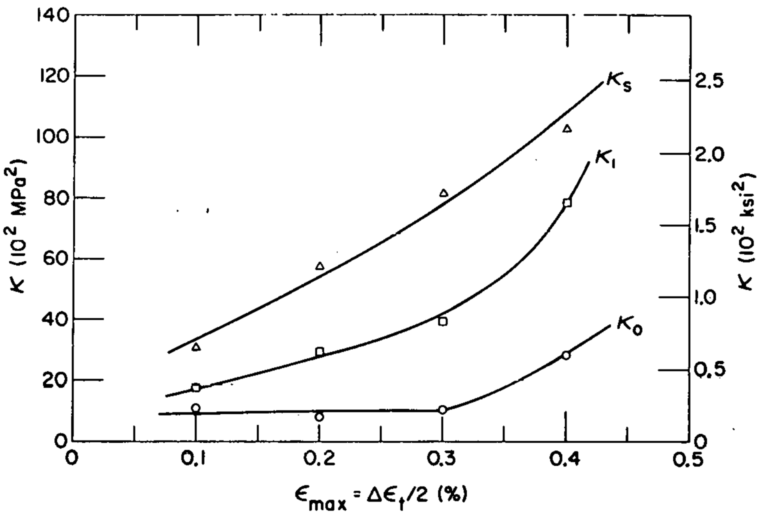

Fig. 11

Variation of Parameter $\varkappa$ with ε_{max} at 593°C (1100°F) for Type 304 Stainless Steel. ANL Neg. No. 306-78-275.

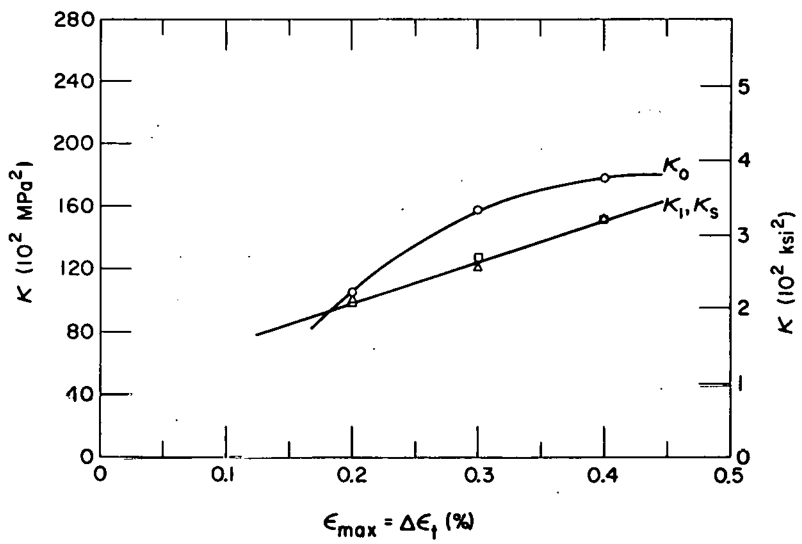

Fig. 12

Variation of Parameter $\varkappa$ with ε_{max} at Room Temperature for Type 316 Stainless Steel. ANL Neg. No. 306-78-243.

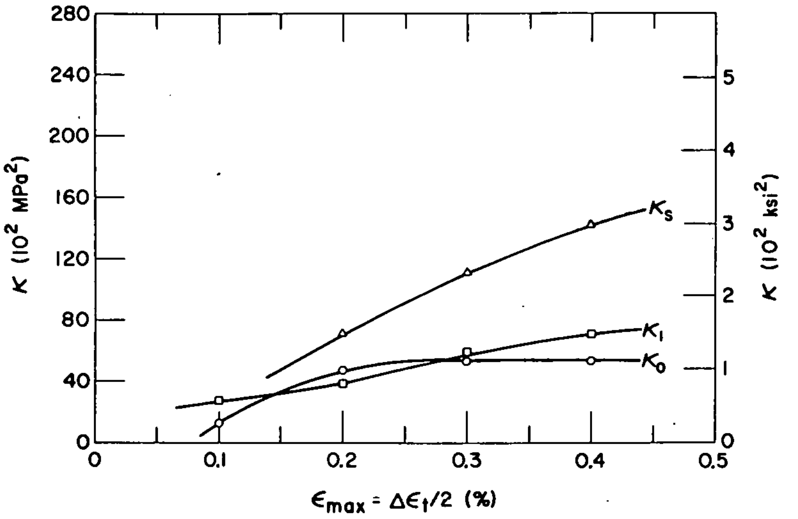

Fig. 13

Variation of Parameter κ with ε_{max} at 427°C (800°F) for Type 316 Stainless Steel. ANL Neg. No. 306-78-242.

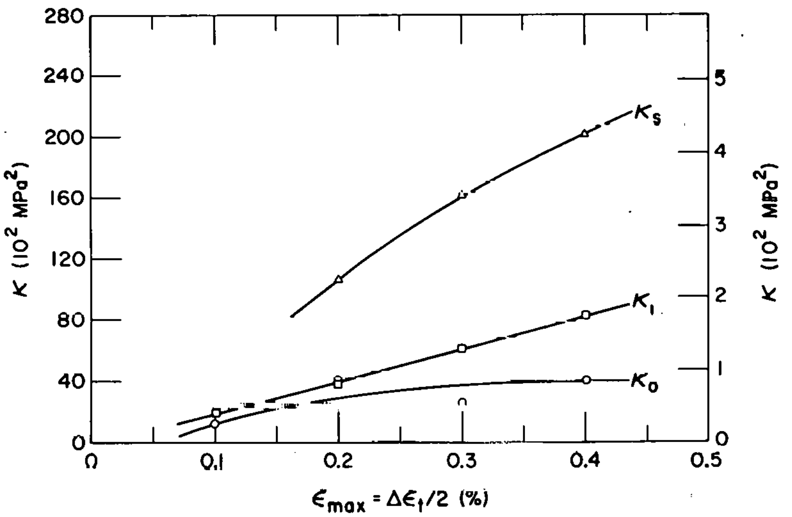

Fig. 14

Variation of Parameter κ with ε_{max} at 538°C (1000°F) for Type 316 Stainless Steel. ANL Neg. No. 306-78-245 Rev.

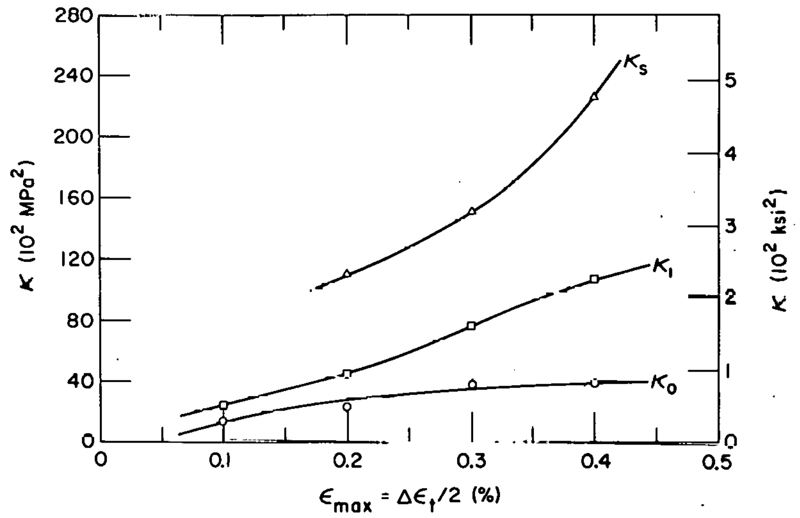

Fig. 15

Variation of Parameter κ with ε_{max} at 593°C (1100°F) for Type 316 Stainless Steel. ANL Neg. No. 306-78-244.

The variation of κ_0, κ_1, and κ_s with temperature for Type 304 stainless steel is shown in Figs. 16-18, respectively; κ_0 is less sensitive to temperature than κ_1 and κ_s. In the temperature range of 427-593°C, there is a trend to suggest that κ_1 increases with temperature with a more rapid increase at higher strains. The variation of κ_s with temperature, however, is not systematically related to strain. Figures 19-21, which show the variation of κ with temperature for Type 316 stainless steel, indicate that the temperature dependence of

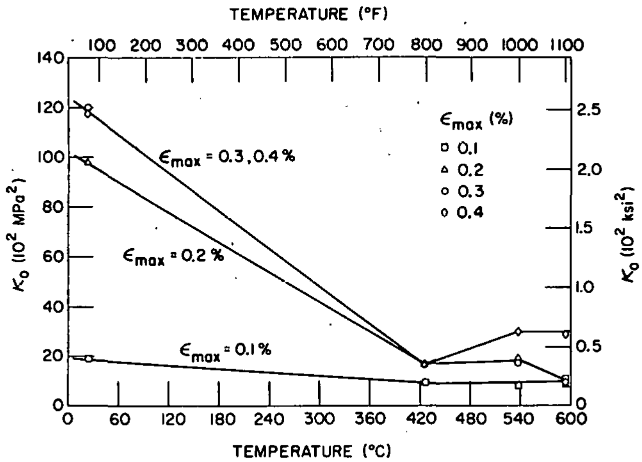

Fig. 16

Variation of Parameter κ_0 with Temperature and Strain for Type 304 Stainless Steel. ANL Neg. No. 306-78-266.

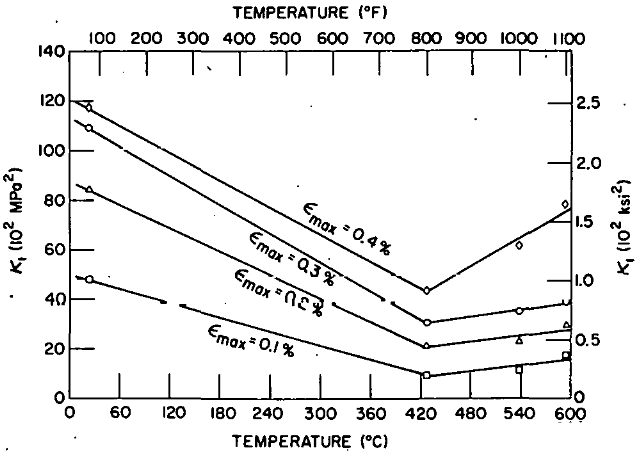

Fig. 17

Variation of Parameter κ_1 with Temperature and Strain for Type 304 Stainless Steel. ANL Neg. No. 306-78-269.

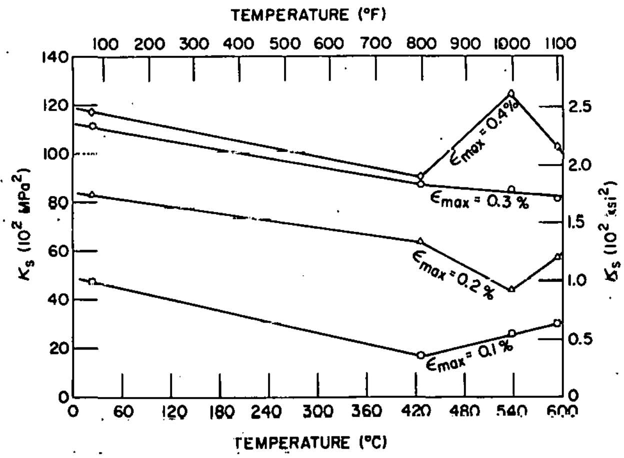

Fig. 18

Variation of Parameter κ_s with Temperature and Strain for Type 304 Stainless Steel. ANL Neg. No. 306-78-270.

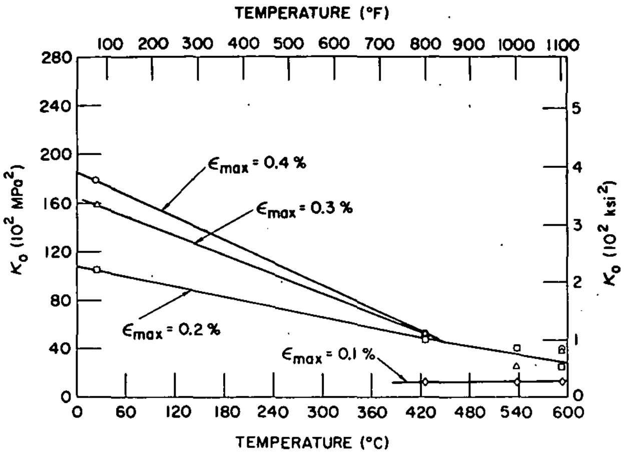

Fig. 19

Variation of Parameter κ_0 with Temperature and Strain for Type 316 Stainless Steel. ANL Neg. No. 306-78-252.

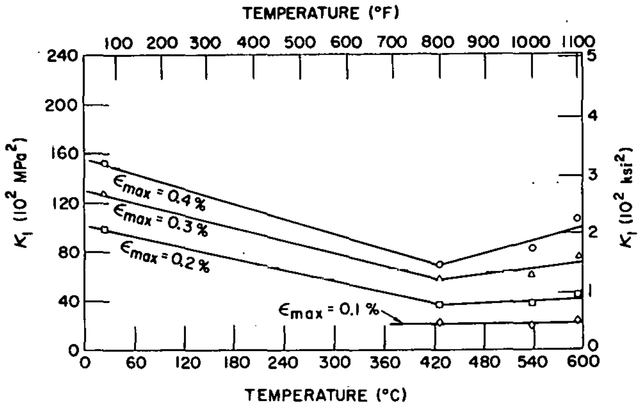

Fig. 20

Variation of Parameter κ_1 with Temperature and Strain for Type 316 Stainless Steel. ANL Neg. No. 306-78-246.

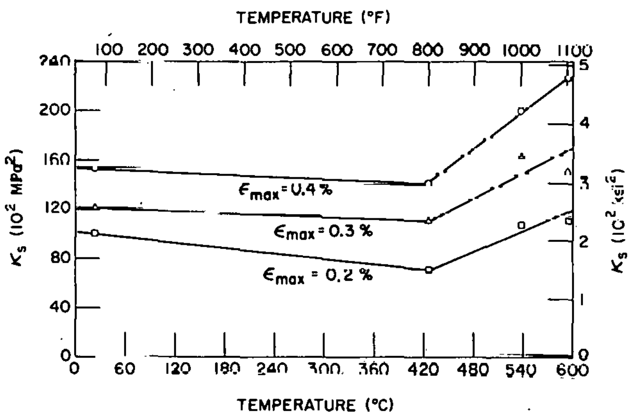

Fig. 21

Variation of Parameter κ_s with Temperature and Strain for Type 316 Stainless Steel. ANL Neg. No. 306-78-258.

κ at different strains is more consistent for Type 316 than for Type 304 stainless steel. The bilinear parameters κ_0 and κ_1 for Type 316 stainless steel are not significantly affected by temperature in the range 427-593°C, but κ_s shows a definite trend suggesting an increase with temperature at ϵ_{max} values between 0.2 and 0.4%; this is probably associated with precipitation of carbides at higher temperature and strain.

V. CONCLUSIONS

The bilinear cyclic stress-strain parameters for Types 304 and 316 stainless steel given in this report are of interest to designers concerned with inelastic analyses of structural components. These materials-property data are appropriate for incorporation into the Nuclear Systems Materials Handbook.

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