**Heat-to-Heat Variations of Total Strain
(to 5%) at Discrete Stress Levels in
Types 316 and 304 Stainless Steel
from 24 to 316° C**

J. P. Hammond
V. K. Sikka

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METALS AND CERAMICS DIVISION

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HEAT-TO-HEAT VARIATIONS OF TOTAL STRAIN (TO 5%) AT DISCRETE STRESS LEVELS IN TYPES 316 AND 304 STAINLESS STEEL FROM 24 TO 316°C*

J. P. Hammond V. K. Sikka

ABSTRACT

Tensile tests were conducted on eight heats of randomly selected, mill-annealed type 316 stainless steel and seven heats of mill-annealed type 304 stainless steel at 24, 93, 204, and 316°C to establish the effects of heat-to-heat variations on total strain (to 5%) at discrete stress levels. Factors of difference were established between maximum and average strain (corresponding to minimum and nominal yield strength material respectively) for regulatory analysis applications. Loaded tests were conducted to show the effects of product form and material condition on total strain.

INTRODUCTION

In anticipation of accident-induced pressure transients without scram, as described for water-cooled power reactors in a recent report,¹ there is concern that operability of "active" valves and other components that maintain safety may be impaired by excessive deformation. Such parts usually are designed to stress allowables of the ASME Pressure Vessel Code,² values directly related to the yield and ultimate tensile strength of the structural material. Because recent studies³ indicate that yield strength of austenitic type stainless steels may vary substantially from heat to heat, concern was voiced¹ that parts fabricated of heats of low yield strength may deform prohibitively. Therefore, studies were performed to establish total strain (to 5%) at discrete stress levels as a function of yield strength. This was accomplished with tensile tests conducted on statistically selected heats of the materials from 24 to 316°C (75 to 600°F). Types 316 and 304 stainless steel in the mill-annealed condition were selected as test materials for the initial studies.

MATERIALS AND PROCEDURES

Production heats of mill-annealed types 316 and 304 stainless steel without regard for product form were obtained for testing. For type 304 stainless steel, seven heats were randomly selected from ones locally available. Materials from eight random heats of type 316 stainless steel were procured. The selected heats in each of the alloy types, with vendor, product form, and grain size, are given in Table 1. Chemical analyses of the heats are presented in Table 2.

Standard 0.250-in.-diam tensile specimens with gage-section dimensions recommended in ASTM E-8 were machined from the forms from midthickness locations at orientations parallel to the rolling or working direction. The reduced sections of the specimens were machined in a lathe and finally finished by machine turning. The tensile tests were conducted in air at 24, 93, 204, and 316°C (75, 200, 400, and 600°F) by using a 44.5-kN (10,000-lb) Instron machine. Engineering stress-strain curves were recorded on an x-y recorder employing a mechanical strain-averaging extensometer (fitted with dual linear variable

*Task 4 of project entitled "Fracture and Irradiation Effects."

1. Regulatory Staff, U.S. Atomic Energy Commission, *Technical Report on Anticipated Transients without SCRAM for Water-Cooled Power Reactors*, WASH-1270 (September 1973).

2. ASME *Boiler and Pressure Vessel Code*, Case 1592 (April 1975).

3. V. K. Sikka, H. F. McCoy, Jr., M. K. Booker, and C. R. Brinkman, "Heat-to-Heat Variation in Creep Properties of Type 304 and 316 Stainless Steels," *J. Pressure Vessel Technol.* 97: 243-51 (1975).

Table 1. List of heats

Heat	Heat symbol	Vendor	As-received form	Dimensions		Grain size ^a (intercept)			
				(in.)	(mm)	As-received		Reannealed ^b	
						ASTM	(μm)	ASTM	(μm)
Type 316									
327686	686	Allegheny Ludlum	Plate	0.5	12.7	10.0	8	10	8
500613	613	Carlson	Plate	0.5	12.7	6.0	39	6.4	34
2P3212	212	U.S.S.	Plate	0.5	12.7	6.5	33	4.8	60
30160	160	U.S.S.	Bar	2.06	52.4	9.0	14.5	6.8	29
91694	694	U.S.S.	Bar	2.06	52.4	7.4	24.0	5.4	48
91695	695	U.S.S.	Bar	2.06	52.4	7.5	23	5.3	50
915509	509	U.S.S.	Pipe	28 OD x 0.4 wall	710 x 9.5	4.0	78	4.8	60
8092297	297	Republic	Plate	0.63	16	5.3	50	3.6	90
Type 304									
544086	086	Carlson	Plate	1.00	25.4	5.8	42	4.6	64
60551	551	Carlson	Bar	5 x 7	127 x 178	4.0	78	3.7	87
346779	779	Allegheny Ludlum	Plate	2.50	63.5	4.1	76	4.4	68
G00414	414	Carlson	Plate	2.38	60.3	3.7	97	2.7	140
337330	330	Allegheny Ludlum	Plate	1.13	28.6	5.6	45	5.0	55
345866	866	Allegheny Ludlum	Plate	3.00	76.2	4.2	73	3.2	103
R22926	926	U.S.S.	Plate	2.00	50.8	3.6	90	3.5	94

^aMethod of J. E. Hillard, "Estimating Grain Size by the Intercept Method," *Mater. Prog.* 85(5): 99-102 (1964). Grain size excludes twin boundaries.

^bReannealed for 0.5 hr at 1065°C (1950°F).

Table 2. Chemical analyses

Heat symbol	Chemical element, %														
	C	N	P	B	O	H	Fe	Mn	Cr	Si	Mo	S	Nb	V	Ti
Type 316 stainless steel															
686	0.053	0.079	0.023	0.001	0.0066	0.0005	13.3	1.60	17.2	0.55	2.2	0.007	0.15	0.037	0.0007
613	0.063	0.042	0.023	0.0002	0.015	0.0002	12.9	1.65	16.4	0.72	2.2	0.024	0.005	0.041	0.0001
212	0.055	0.053	0.026	0.0002	0.0076	0.0008	13.4	1.41	17.3	0.55	2.4	0.012	0.002	0.035	0.0001
160	0.041	0.021	0.019	0.0001	0.0032	0.0004	13.6	1.63	17.4	2.2	0.013	0.0020	0.0003	0.030	0.0003
694	0.043	0.021	0.018	0.0001	0.0008	0.0007	13.5	1.63	17.4	2.2	0.014	0.0020	0.0001	0.030	0.0001
695	0.039	0.019	0.019	0.0001	0.0036	0.0006	13.7	1.38	17.3	2.2	0.014	0.0020	0.0001	0.030	0.0001
509	0.053	0.074	0.022	0.0005	0.0030	0.0025	13.5	1.54	16.9	0.60	2.5	0.015	0.002	0.030	0.0001
297	0.065	0.031	0.022	0.0005	0.0043	0.0007	13.9	1.88	16.5	0.51	2.4	0.018	0.0004	0.030	0.0001
Type 304 stainless steel															
926	0.053	0.041	0.020	0.0002	0.0084	0.0007	9.79	1.16	19.0	0.68	0.10	0.075	0.0180	0.030	0.010
866	0.044	0.022	0.023	0.0002	0.0096	0.0010	8.98	1.51	18.5	0.47	0.2	0.007	0.010	0.007	0.01
330	0.068	0.031	0.018	0.0002	0.0042	0.0005	9.43	0.83	18.2	0.59	0.07	0.008	0.0100	0.0060	0.01
779	0.065	0.023	0.024	0.0002	0.0056	0.0008	9.46	0.94	18.1	0.47	0.20	0.005	0.0075	0.003	0.01
414	0.073	0.058	0.016	0.0001	0.0190	0.0004	9.52	0.94	18.7	0.69	0.10	0.018	0.0100	0.002	0.01
551	0.043	0.017	0.022	0.0010	0.0220	0.0013	9.40	1.20	18.5	0.59	0.30	0.018	0.0140	0.009	0.01
086	0.050	0.043	0.025	0.0001	0.0091	0.0005	9.46	1.21	18.4	0.53	0.20	0.016	0.0030	0.021	0.01

differential transformer transducers) and a strain-gage-type load cell. For tests at elevated temperatures, the specimen-extensometer assembly was heated by a vertically split, resistance-heated muffle furnace with an associated temperature controller of the current-adjustment type. Specimens were heated at test temperature about 30 min before testing and were controlled to $\pm 2^\circ\text{C}$.

Because the literature indicates that the plastic flow characteristics of type 304 stainless steel are relatively insensitive to strain rate (from 3×10^{-5} to 1×10^{-2} in. in. $^{-1}$ sec $^{-1}$) at temperatures up to 538°C (1000°F),⁴ a single comparatively low strain rate (6.6×10^{-4} sec crosshead) was employed for all tests. Single tests were run at each temperature for each of the materials from which true-stress-true-strain curves were derived from the load-extension graphs. The literature further indicates that the flow characteristics of type 304 stainless steel may vary with product form and metal condition (mill-anneal vs. reannealed).⁵ Consequently, in addition to evaluating the effects of heat-to-heat variations in some detail, the influence of product form and metal condition were examined in a cursory fashion. A mathematical model, with which to present the tensile results and aid the interpretation of data, was developed from the data on type 316 stainless steel.

EXPERIMENTAL RESULTS

The true-stress-true-strain diagrams established for the various heats of type 316 stainless steel at 24, 93, 204, and 316°C are given in Figs. 1 through 4, respectively, and those for type 304 stainless steel are given in Figs. 5 through 8.

The following general features are noted from the tensile graphs. The curves, without exception, pass through an early stage of strain that includes elastic strain followed by plastic flow of a hyperbolic form.⁶ Then, at about 0.004 total strain, the curves enter an extended stage of near linearity. The "linear" regions for the individual heats in each family of curves are approximately parallel. As expected, each family of curves for the individual alloys is displaced downward (to lower stress levels) with increasing test temperature, reflecting a diminution of strength.

A further analysis of the curves showed that the greatest factor of difference between strain for the heat of highest yield strength (upper bound material) and that of lowest yield strength (lower bound) occurred when the first-stage strain of the highest-strength material was most confined. Moreover, this factor of difference increased as the distance between the upper and lower bounds increased. Finally, the factor was observed to decrease as the slopes of the curves increased, and vice versa. These relationships are illustrated in the schematic graphs in Fig. 9.

Observe that the factor of difference is greater the more confined the first-stage strain, and, in the limiting case, is greatest where the stress-strain curve is represented by bilinearity (ob'p in Fig. 9). Accordingly, the maximum factor occurs at the stress level a' and is represented by the vector quotient

$$\frac{a'd'}{a'b'}$$

4. J. M. Steichen, "High Strain Rate Tensile Properties of AISI Type 304 Stainless Steel," *Trans. ASME* 95: 182-85 (1973).

5. H. E. McCoy, Jr., and R. D. Waddell, "Mechanical Properties of Several Products from a Single Heat of Type 304 Stainless Steel," *J. Eng. Mater. Technol.* 97: 343-49 (1975).

6. D. O. Hobson and M. K. Booker, *Materials Applications and Mathematical Properties of the Rational Polynomial Creep Equation*, ORNL report in preparation.

Fig. 1. True-stress-true-strain diagrams of randomly selected heats of type 316 stainless steel tested at 24°C (75°F).

Fig. 2. True-stress-true-strain diagrams of randomly selected heats of type 316 stainless steel tested at 93°C (200°F).

Fig. 3. True-stress-true-strain diagrams of randomly selected heats of type 316 stainless steel tested at 204°C (400°F).

Fig. 4. True-stress-true-strain diagrams of randomly selected heats of type 316 stainless steel tested at 316°C (600°F).

Fig. 5. True stress-true strain diagrams of randomly selected heats of type 304 stainless steel tested at 24°C (75°F).

Fig. 6. True stress-true strain diagrams of randomly selected heats of type 304 stainless steel tested at 93°C (200°F).

Fig. 7. True-stress-true-strain diagrams of randomly selected heats of type 304 stainless steel tested at 204°C (400°F).

Fig. 8. True-stress-true-strain diagrams of randomly selected heats of type 304 stainless steel tested at 316°C (600°F).

Fig. 9. Hypothetical true-stress-true-strain diagrams illustrating relationships of flow curves with factor of difference.

That the factor of difference increases with distance between the upper and lower bounds is indicated by

$$\frac{a'c'}{a'b'} > \frac{a'd'}{a'b'}$$

Finally, the factor of difference decreases with increasing curve slope since

$$\frac{a'c'}{a'h'} < \frac{a'd'}{a'b'}$$

For the type 316 stainless steels examined here (Figs. 1 through 4), the maximum factor of strain difference occurred at a stress slightly above the point of departure from the modulus line. At room temperature, this maximum factor of difference was about 15 (Fig. 1), and at 316°C the maximum was about 18 (Fig. 4).

Figure 10 illustrates how the true-stress-true-strain curves for mill-annealed type 316 stainless steel (reference heat No. 297) change with temperature between 24 and 316°C. The curve slopes (work hardening coefficients) are about equal. The rate of decrease in yield strength with temperature appears to be higher at just above room temperature than at just below 316°C.

Figure 11 shows the same family of mill-annealed curves together with curves for the reannealed conditions for comparison. The slopes of the reannealed curves also appear to be about equal and are approximately parallel to the mill-annealed ones at strains greater than about 0.004. Significantly, the reannealed curves fall below the mill-annealed ones for each of the respective temperatures. At room

Fig. 10. True-stress-true-strain diagrams of reference heat (297) of mill-annealed type 316 stainless steel as a function of temperature.

Fig. 11. Comparison of the effects of the mill-annealed and reannealed conditions on the true-stress-true-strain diagrams of reference heat (297) of type 316 stainless steel.

temperature, the maximum factor of difference between strains for these conditions is about 3; at higher temperatures, the maximum factor of difference varies around 2.

Figure 12 shows flow curves for a number of as-received product forms at room temperature for a single alloy of type 316 stainless steel (reference heat No. 297). The bar product forms were consistently stronger than the plate products, and accordingly, a factor of difference in total strain between these product forms is to be expected. It is apparent that product form also has a substantial effect on the extent of total strain with discrete stressing.

Fig. 12. Influence of product form on the true-stress-true-strain diagram of reference heat (297) of type 316 stainless steel at room temperature.

MODEL FOR PREDICTING TENSILE RESULTS

A number of models for representing true-stress-true-strain results of types 316 and 304 stainless steel in the temperature region and strain range of interest were examined. These included equations of the Ludwigson,⁷ Voce,⁸ and Blackburn⁹ types. Since each had limitations or did not adequately predict our results, we developed a model more suited to our specific requirements. This was done by using the tensile data for type 316 stainless steel.

The true-stress, true-plastic-strain curve, up to about 0.06 strain for type 316 stainless steel, has a shape similar to a classical creep curve before onset of tertiary creep. An accelerated initial hardening stage, similar to primary creep, blends into a steady-state strain hardening, similar to steady-state creep rate. The

7. D. C. Ludwigson, "Modified Stress-Strain Relation of FCC Metals and Alloys," *Metallurg. Trans.* 2: 2825-28 (1971).

8. E. Voce, "The Relationship Between Stress and Strain for Homogeneous Deformation," *J. Inst. Metals* 74: 537 (1948).

9. L. D. Blackburn, "Isochronous Stress-Strain Curves for Austenitic Steels," *The Generation of Isochronous Stress-Strain Curves*, ASME, New York, 1972, pp. 15-48.

classical creep behavior of several alloys can be described by a single rational polynomial.¹⁰⁻¹² The details of this equation were described by Booker.¹³ Our purpose here is to apply the single rational polynomial equation to approximate the true-stress, true-plastic-strain behavior of a reference heat of mill-annealed type 316 stainless steel.

The single rational equation for true-stress-true-strain behavior can be written as

$$\sigma - \sigma_{PL} = \frac{C\dot{\epsilon}_p}{1 + P\dot{\epsilon}_p} + \dot{H}\epsilon_p \quad (1)$$

where

C = a measure of strength level which, as shown later, is related to yield strength.

$\dot{H}$ = steady-state hardening,

P = parameter describing the shape of the stress-strain curve before reaching the steady-state hardening,

σ_{PL} = proportional limit or stress below which there is negligible plastic strain,

ϵ_p = true plastic strain.

The graphical technique suggested by Oding¹² and applied by Booker¹³ to creep data was used here to obtain the values of C , P , and $\dot{H}$. This method requires the use of three stress-strain points from the actual curve. The stress points selected in the present analysis were at strain values of 0.0004, 0.004, and 0.04. The stress-strain data^{14,15} used are on the reference heat (297) of type 316 stainless steel. Tests were performed at a crosshead speed of 0.004/min and at temperatures ranging from room temperature to 760°C (1400°F). Calculated values of $\dot{H}$ are plotted as a function of test temperature in Fig. 13 and least squares fitted to the following equations:

$$\begin{aligned} \dot{H}(\text{GPa}) &= 2.844 - 0.000431T, \\ \dot{H}(\text{ksi}) &= 412.5 - 0.0625T, \end{aligned} \quad (2)$$

where T is the temperature (°C).

Although Eqs. (2) shows a slight temperature dependence of $\dot{H}$, an average value of 2.76 GPa (400 ksi) independent of temperature was selected for the present analysis. It will be shown later that this assumption is reasonable, at least at test temperatures of 649°C (1200°F) and below.

10. M. K. Booker, T. L. Hebble, D. O. Hobson, and C. R. Brinkman, "Mechanical Property Correlations for 2% Cr-1 Mo Steel in Support of Nuclear Reactor Systems Design," paper F 8/9 in *Transactions of the 3rd International Conference on Structural Mechanics in Reactor Technology*, London, Sept. 1-5, 1975, vol. 2, Part F, Commission of the European Communities, Luxembourg.

11. W. E. Stillman, "Development of Creep Equation for Type 316 Stainless Steel," *Mechanical Properties Test Data for Structural Materials Q. Prog. Rep. Oct. 31, 1975*, ORNL-5107, pp. 81-93.

12. I. A. Oding, ed., *Creep and Stress Relaxation in Metals*, transl. E. Bishop, ed. A. J. Kennedy, Oliver and Boyd, London, 1959, pp. 78-82.

13. M. K. Booker, "Development of Creep Equation for Type 304 Stainless Steel," *Mechanical Properties Test Data for Structural Materials Q. Prog. Rep. Jan. 31, 1976*, ORNL-5112, pp. 67-74.

14. V. K. Sikka, "Mechanical Property Characterization of Type 316 Stainless Steel Reference Heat," *Mechanical Properties Test Data for Structural Materials Q. Prog. Rep. July 31, 1975*, ORNL-5106, pp. 50-64.

15. V. K. Sikka, "Mechanical Property Characterization of Type 316 Stainless Steel Reference Heat," *Mechanical Properties Test Data for Structural Materials Q. Prog. Rep. Oct. 31, 1975*, ORNL-5107, pp. 34-46.

Fig. 13. Steady-state hardening, H , as a function of test temperature for reference heat (mill-annealed condition) of type 316 stainless steel.

Figure 14 shows P as a function of C for the whole test temperature range. This figure shows that P and C are possibly related as

$$\begin{aligned} P(\text{MPa}) &= 72.5C, \\ P(\text{ksi}) &= 500C. \end{aligned} \quad (3)$$

For $\epsilon_p = 0.002$, $\sigma = \sigma_y$, (0.2% yield strength), and therefore Eq. (1) can be solved for values of C :

$$C = [(a - \sigma_{pL} - a) + \sqrt{(\sigma_{ys} - \sigma_{pL} - a)^2 + b(\sigma_{ys} - \sigma_{pL} - a)}] / 2. \quad (4)$$

where

$$a = 5.25 \text{ MPa} = 0.80 \text{ ksi},$$

$$b = 27.6 \text{ MPa} = 4.0 \text{ ksi}.$$

Values of σ_{pL} are generally very difficult to determine with any significant accuracy. Thus, in an attempt to eliminate σ_{pL} from Eqs. (1) and (4), it was plotted as a function of σ_y in Fig. 15. It will be noted that for the mill-annealed condition,

$$\sigma_{pL} = 0.5\sigma_{ys}. \quad (5)$$

and for the reannealed condition,

$$\sigma_{pL} = 0.76\sigma_{ys}. \quad (6)$$

Fig. 14. Parameter P as a function of parameter C for the reference heat (297) of type 316 stainless steel.

A comparison of the experimental and computed values for mill-annealed and reannealed conditions suggested that the equation $\sigma_{PL} = 0.5\sigma_{ys}$ is adequate for both conditions. Thus, instead of plastic strain being zero at the proportional limit, it may be assumed to be zero at $0.5\sigma_{ys}$.

Substituting Eq. (5) in Eqs. (4) and (1) results in

$$C = [(0.5\sigma_{ys} - \alpha) + \sqrt{(0.5\sigma_{ys} - \alpha)^2 + b(0.5\sigma_{ys} - \alpha)}] / 2, \quad (7)$$

$$\sigma(\text{MPa}) = 0.5\sigma_{ys} + \frac{72.5C^2\epsilon_p}{1 + 72.5C\epsilon_p} + 2760\epsilon_p, \quad (8)$$

$$\sigma(\text{MPa}) = 0.5\sigma_{ys} + \frac{500C^2\epsilon_p}{1 + 500C\epsilon_p} + 400\epsilon_p.$$

Values of C in Eqs. (8) are given in Eq. (7). Thus, Eqs. (7) and (8) can be used to predict true-stress, true-plastic-strain behavior if the yield strength is known. The temperature dependence of true-stress and true-plastic-strain behavior can be obtained by substituting σ_{ys} at the desired temperatures. Figures 16 and 17 compare the experimental and predicted values for the data on the reference heat of mill-annealed type 316 stainless steel. The agreement is reasonable. Furthermore, by definition, predicted values always go through the 0.2% yield strength value.

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Fig. 15. Proportional limit as a function of 0.2% yield strength for the reference heat (297) of type 316 stainless steel.

Fig. 16. Comparison between experimental data and predicted values for mill-annealed reference heat (297) of type 316 stainless steel, 25 to 482°C (77 to 908°F).

Fig. 7. Comparison between experimental data and predicted values for mill-annealed reference heat (297) of type 316 stainless steel, 583 to 704°C (1080 to 1300°F).

ANALYSIS OF RESULTS

True-stress-true-strain data were calculated from Eqs. (8) for types 316 and 304 stainless steel to compare with experimental values of these materials in Figs. 1 through 8. The predicted flow curves are given for type 316 stainless steel at 24, 93, 204, and 316°C in Figs. 18 through 21, respectively, and for type 304 stainless steel in Figs. 22 through 25 respectively. These graphs show maximum, minimum, and average flow curves. The maximum and minimum curves were calculated with Eqs. (8), using yield strength

Fig. 18. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 316 stainless steel at 24°C (75°F).

Fig. 19. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 316 stainless steel at 93°C (200°F).

values of the heats of highest and lowest strengths respectively. The average flow curves were established by arbitrarily placing them midway between the maximum and minimum curves.

To compare the predicted with the experimental results, Tables 3 through 6 give the minimum and maximum amounts of true strain as a function of true stress obtained for type 316 stainless steel at 24, 93, 204, and 316°C respectively; the predicted results were determined from Figs. 18 through 21 and the actual results from Figs. 1 through 4. Similarly, Tables 7 through 10 give the minimum and maximum strains as a function of stress obtained for type 304 stainless steel at 24, 93, 204, and 316°C, respectively, the predicted results being obtained from Figs. 22 through 25 and the actual from Figs. 5 through 8. Tables 7

Fig. 20. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 316 stainless steel at 204°C (400°F).

Fig. 21. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 316 stainless steel at 316°C (600°F).

through 10 also give factors of difference between the maximum and minimum amounts of strain for the respective stress levels. The last two columns in Tables 3 through 10 give the actual and predicted factors of difference between the maximum and the average strain. The latter data on types 316 and 304 stainless steel are combined in Tables 11 and 12, respectively, for comparing results at different temperatures. This category of information has direct use in analytical applications because strain or plastic set established for a material of average (or any) yield strength could be compared with the maximum strain for a material of lower-bound yield strength by multiplying by the difference factor.

Fig. 22. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 304 stainless steel at 24°C (75°F).

Fig. 23. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 304 stainless steel at 93°C (200°F).

Fig. 24. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 304 stainless steel at 204°C (400°F).

Fig. 25. Predicted maximum, average, and minimum true-stress-true-strain diagrams of type 304 stainless steel at 316°C (600°F).

In establishing the latter information, average strain curves were determined for the experimental graphs (Figs. 1 through 8) by locating them midway between the curves of highest and lowest yield strength. Because heat 551 had a flow curve of considerably higher yield strength and strain hardening coefficient when tested at 204°C than was expected (Fig. 7), its result is questionable and it was arbitrarily discounted.

Overall, a comparison of the predicted factors of difference between maximum and minimum strains with their corresponding actual factors for the respective alloys at the different temperatures will show that the rational polynomial derived for predicting results (Eqs. 8) is reasonably good. In all instances, the

Table 3. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 316 stainless steel at 24°C (75°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15								
138	20	0.08	0.08	1.0	0.08	0.08	1.0	1.0	1.0
172	25	0.09	0.12	1.3	0.09	0.09	1.0	1.0	1.0
207	30	0.11	0.20	1.8	0.11	0.15	1.4	1.5	1.4
241	35	0.13	1.06	8.1	0.13	0.67	5.2	6.2	5.2
276	40	0.16	2.31	14.4	0.16	1.88	11.8	6.4	9.4
310	45	0.24	3.53	14.7	0.19	3.15	16.6	2.4	3.5
345	50	0.67	4.82	7.2	0.22	4.52	20.5	1.7	2.1
379	55	2.02	6.05	3.0	0.71	5.87	8.2	1.4	1.5
414	60	3.51	7.25	2.1	1.83	7.23	3.9	1.3	1.5

Table 4. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 316 stainless steel at 93°C (200°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15	0.05	0.05	1.0	0.05	0.05	1.0	1.0	1.0
138	20	0.07	0.09	1.3	0.07	0.07	1.0	1.3	1.0
172	25	0.09	0.18	2.0	0.09	0.15	1.7	1.7	1.7
207	30	0.11	0.56	5.1	0.11	0.72	6.5	4.3	6.5
241	35	0.13	1.56	12.0	0.13	1.96	15.1	7.4	8.5
276	40	0.16	2.92	18.2	0.17	3.20	18.8	5.8	3.1
310	45	0.24	4.30	17.9	0.25	4.47	17.9	3.4	2.0
345	50	0.44	5.80	13.2	1.04	5.72	5.5	2.3	1.5
379	55	1.08	7.20	6.7	2.30	6.95	3.0	1.9	1.4
414	60								

Table 5. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 316 stainless steel at 204°C (400°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15	0.06	0.06	1.0	0.06	0.06	1.0	1.0	1.0
138	20	0.08	0.15	1.9	0.08	0.13	1.6	1.9	1.6
172	25	0.10	0.60	6.0	0.10	0.74	7.4	4.6	7.4
207	30	0.12	1.64	13.7	0.12	1.98	16.5	6.3	11.0
241	35	0.18	3.06	17.0	0.14	3.20	22.9	4.4	3.8
276	40	0.33	4.54	13.6	0.26	4.50	17.3	2.8	2.2
310	45	0.72	5.98	8.3	1.16	5.66	4.9	2.0	1.7
345	50	1.60	7.40	4.6	2.40	6.84	2.9	1.7	1.5
379	55								
414	60								

Table 6. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 316 stainless steel at 316°C (600°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10	0.04	0.04	1.0	0.04	0.04	1.0	1.0	1.0
103	15	0.06	0.06	1.0	0.06	0.06	1.0	1.0	1.0
138	20	0.07	0.20	2.0	0.08	0.20	2.7	2.9	2.7
172	25	0.09	0.92	10.2	0.10	1.10	11.0	7.7	9.2
207	30	0.12	2.13	17.8	0.13	2.39	18.4	5.3	6.0
241	35	0.19	3.42	18.0	0.18	3.68	20.4	2.5	2.3
276	40	0.58	4.72	8.1	0.66	5.00	7.6	1.8	1.8
310	45	1.78	5.97	3.4	1.94	6.20	3.6	1.5	1.5
345	50								
379	55								

Table 7. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 304 stainless steel at 24°C (75°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15								
138	20	0.08	0.08	1.0	0.07	0.07	1.0	1.0	1.0
172	25	0.09	0.11	1.2	0.09	0.09	1.0	1.2	1.0
207	30	0.12	0.17	1.4	0.11	0.14	1.3	1.2	1.3
241	35	0.18	0.30	1.7	0.15	0.67	4.5	1.3	3.5
276	40	0.32	1.20	3.7	0.25	2.10	8.4	2.5	2.0
310	45	0.83	2.84	3.4	1.31	3.52	2.7	1.6	1.4
345	50	2.25	4.61	2.0	2.73	4.85	1.8	1.4	1.3
379	55	3.98	6.43	1.6	4.10	6.25	1.5	1.3	1.2
414	60								

Table 8. Actual and predicted maximum and minimum true strain as a function of true stress for sample of heats in mill-annealed type 304 stainless steel at 93°C (200°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15	0.06	0.06	1.0	0.06	0.06	1.0	1.0	1.0
138	20	0.08	0.08	1.0	0.08	0.08	1.0	1.0	1.0
172	25	0.10	0.15	1.5	0.10	0.14	1.4	1.2	1.3
207	30	0.17	0.51	3.0	0.14	0.79	5.6	2.1	3.0
241	35	0.40	1.40	3.5	0.50	2.21	4.4	1.7	1.6
276	40	1.49	3.16	2.1	1.87	3.67	2.0	1.3	1.3
310	45	3.20	4.88	1.5	3.31	5.01	1.5	1.2	1.2
345	50	4.80	6.67	1.4	4.70	6.41	1.4	1.2	1.2
379	55								
414	60								

Table 9. Actual and predicted maximum and minimum true strain as a function of true stress for sample heats in mill-annealed type 304 stainless steel at 204°C (400°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10								
103	15	0.06	0.06	1.0	0.06	0.06	1.0	1.0	1.0
138	20	0.08	0.08	2.2	0.08	0.14	1.7	1.6	1.4
172	25	0.15	0.57	3.8	0.16	0.93	5.8	2.0	3.6
207	30	0.52	1.93	3.7	0.48	2.33	4.9	1.9	1.6
241	35	1.79	3.60	2.0	1.80	3.71	2.1	1.3	1.3
276	40	3.33	5.20	1.6	3.25	4.98	1.5	1.2	1.2
310	45	4.75	6.90	1.5	4.51	6.34	1.4	1.2	1.2
345	50	6.28	8.30	1.3	5.88	7.72	1.3	1.1	1.2
379	55								
414	60								

Table 10. Actual and predicted maximum and minimum true strain as a function of true stress for sample heats of mill-annealed type 304 stainless steel at 316°C (600°F)

True stress		Actual total true strain			Predicted total true strain			Factor of difference between average and maximum	
(MPa)	(ksi)	Min. (%)	Max. (%)	Factor of diff.	Min. (%)	Max. (%)	Factor of diff.	Actual	Predicted
69	10	0.04	0.04	1.0	0.04	0.04	1.0	1.0	1.0
103	15	0.06	0.06	1.6	0.06	0.06	1.0	1.0	1.0
138	20	0.08	0.20	2.5	0.10	0.20	2.0	1.4	1.7
172	25	0.22	0.89	4.0	0.22	1.32	6.0	2.1	2.4
207	30	1.03	2.42	2.3	1.20	2.75	2.3	1.4	1.4
241	35	2.60	4.15	1.6	2.60	4.51	1.7	1.2	1.3
276	40	4.14	5.94	1.4	4.40	5.54	1.3	1.2	1.2
310	45								
345	50								
379	55								
414	60								

Table 11. Comparisons of actual and predicted factors of difference between maximum and average true strain as a function of true stress and temperature for sample heats in mill-annealed type 316 stainless steel

True stress		24°C (75°F)		93°C (200°F)		204°C (400°F)		316°C (600°F)	
(MPa)	(ksi)	Act.	Pred.	Act.	Pred.	Act.	Pred.	Act.	Pred.
69	10							1.0	1.0
103	15			1.0	1.0	1.0	1.0	1.0	1.0
138	20	1.0	1.0	1.3	0.0	1.9	1.6	2.9	2.7
172	25	1.0	1.0	1.7	1.7	4.6	7.4	7.7	9.2
207	30	1.5	1.4	4.3	6.5	6.3	11.0	5.3	6.0
241	35	6.2	5.2	7.4	8.5	4.4	3.8	2.5	2.3
276	40	6.4	9.4	5.8	3.1	2.8	2.2	1.8	1.8
310	45	2.4	3.5	3.4	2.0	2.0	1.7	1.5	1.5
345	50	1.7	2.1	2.3	1.5	1.7	1.5		
379	55	1.4	1.5	1.9	1.4				
414	60	1.3	1.5						

maximum factors of difference for the predicted results are somewhat higher than for the experimental results and thus are more conservative for analytical use. This resulted, in part, because the predicted curves displayed a narrower first stage of strain (see Fig. 9) than did the experimental curves. Because the actual results were based on single tests conducted on each of the heats, the actual factors of difference sometimes suffer from a perturbation in a single test curve. The predicted results, on the other hand, appear to show more consistent trends.

The predicted factors of difference between maximum and minimum strains were substantially greater for type 316 stainless steel than for type 304, a characteristic observed earlier for the experimental curves. The maximum factors for the experimental data varied between 14.7 and 18.2 (from 24 to 316°C) for type 316 stainless steel, but only between 3.4 and 4.0 for type 304 stainless steel (Tables 3 through 10). Correspondingly, the maximum predicted factors for type 316 stainless steel varied between 18.8 and 22.9, and those for type 304 varied between 5.6 and 8.4 (Tables 3 through 10).

The factors of difference between the maximum and average strains appeared to be more consistent than those between maximum and minimum, both for actual and predicted results. Pertinent data on factors of difference between maximum and average strains are reproduced in Table 13 for analysis.

Table 12. Comparison of actual and predicted factors of difference between maximum and average true strain as a function of true stress and temperature for sample heats in well-annealed type 304 stainless steel

True stress		24°C (75°F)		93°C (200°F)		204°C (400°F)		316°C (600°F)	
(MPa)	(ksi)	Act.	Pred.	Act.	Pred.	Act.	Pred.	Act.	Pred.
69	10							1.0	1.0
103	15			1.0	1.0	1.0	1.0	1.0	1.0
138	20	1.0	1.0	1.0	1.0	1.6	1.4	1.4	1.7
172	25	1.2	1.0	1.2	1.3	2.0	3.6	2.1	2.4
207	30	1.2	1.3	2.1	3.0	1.9	1.6	1.4	1.4
241	35	1.3	3.5	1.7	1.6	1.3	1.3	1.2	1.3
276	40	2.5	2.0	1.3	1.3	1.2	1.2	1.2	1.2
310	45	1.6	1.4	1.2	1.2	1.2	1.2		
345	50	1.4	1.3	1.2	1.2	1.1	1.1		
379	55	1.3	1.2						

Table 13. Actual and predicted factors^a of difference between maximum and average true strain of types 316 and 304 stainless steel at the various temperatures

True stress		24°C (75°F)		93°C (200°F)		204°C (400°F)		316°C (600°F)	
(MPa)	(ksi)	Act.	Pred.	Act.	Pred.	Act.	Pred.	Act.	Pred.
Type 316 stainless steel									
172	25	1.0	1.0	1.7	1.7	4.6	7.4	<u>7.7</u>	<u>9.2</u>
207	30	1.5	1.4	4.3	6.5	<u>6.3</u>	<u>11.0</u>	5.3	6.0
241	35	6.2	5.2	7.4	<u>8.5</u>	4.4	3.8	2.5	2.3
276	40	<u>6.4</u>	<u>9.4</u>	<u>5.8</u>	3.1	2.8	2.2	1.8	1.8
Type 304 stainless steel									
172	25	1.2	1.0	1.2	1.3	2.0	3.6	2.1	2.4
207	30	1.2	1.3	<u>2.1</u>	<u>3.0</u>	1.9	1.6	1.4	1.4
241	35	1.3	<u>3.5</u>	1.7	1.6	1.3	1.3	1.2	1.3
276	40	<u>2.5</u>	<u>2.0</u>	1.3	1.3	1.2	1.2	1.2	1.2

^aMaximum factors are underlined.

The maximum predicted factors are higher than the maximum actual factors for type 316 stainless steel at the consecutive temperatures of 24, 93, 204, and 316°C by 47, 47, 75, and 19% respectively. For type 304 stainless steel, they are higher by 40, 43, 80, and 14%. The stress range over which maximum factors of difference prevail is from 172 to 276 MPa (25 to 40 ksi) for both alloy types. On an average, the predicted factors are about 45% higher than the experimental ones.

SUMMARY AND CONCLUSIONS

For "ATWS" transients such as those described in WASH-1270, there is concern that operability of "active" valves and other components that must maintain safety during transients will be impaired by excessive deformation. Because extent of deformation may vary significantly with yield strength for a particular alloy, studies were instituted to establish tensile properties in relation to statistical variance of yield strength for mill-annealed types 304 and 316 stainless steel in the 24 to 316°C (75 to 600°F) temperature range. Total strain to a level of about 5% is of concern.

Tensile tests were conducted on eight randomly selected heats of type 316 stainless steel and seven random heats of type 304 stainless steel at 24, 93, 204, and 316°C to disclose the effects of yield strength on extent of total strain at discrete stress levels. Other limited tests on type 316 stainless steel were conducted to show the effects of material condition (mill-annealed vs reannealed) and product form on the extent of total strain.

To enable prediction of total strains, a rational polynomial was developed for establishing true-stress true-strain curves up to 0.06 strain for types 316 and 304 stainless steel. This equation incorporates three constants that characterize the flow curve: a strength parameter related to yield strength (C), the steady-state strain hardening coefficient (H), and a parameter describing the shape of the stress-strain curve before reaching the steady-state stage (P). For approximate results, predictive data were obtainable solely with knowledge of the material's yield strength (0.2% offset) at the test temperature. For the temperature range of interest, the parameter P appeared to be linearly related to C , which, in turn, was obtained simply from yield strength values. The hardening coefficient (H) varied only very slightly with temperature and was taken as constant. Comparisons of predicted true-stress true-strain curves with experimental ones gave reasonably good conformity.

Examination of the experimental tensile results revealed that the extent of deformation for discrete levels of stress varied substantially from heat to heat, depending upon the yield strength. Type 316 stainless steel had a much higher variation in total straining between heats with constant stressing than did type 304 stainless steel. For tests at 24°C on type 316 stainless steel, the maximum factor of difference between the heats of highest and lowest yield strength was around 14.5; this occurred at 276 to 310 MPa (40 to 45 ksi). At 316°C this maximum factor was about 18.0 and occurred at 207 to 241 MPa (30 to 35 ksi). For tests on type 304 stainless steel at 24°C, the maximum factor of difference between the heats of highest and lowest yield strength was around 3.5 and occurred at 276 to 310 MPa (40 to 45 ksi). At 316°C this factor was 4.0 and occurred at 172 MPa (25 ksi).

Because structural components are frequently designed on the basis of the constructional material's nominal yield strength, a useful design parameter is the factor of difference between the maximum strain (established from minimum yield strength) and nominal strain (determined from average yield strength). Such a factor has direct use since plastic strain determined for a material of average yield strength can be used to compute the maximum strain representative of the lower-bound yield strength simply by multiplying it by the difference factor.

Factors of difference between maximum and nominal strain were determined both with strains calculated from a rational polynomial equation and with data obtained experimentally. For type 316 stainless steel, the maximum experimental factors were 6.4, 5.8, 6.3, and 7.7, respectively, for the test temperatures 24, 93, 204, and 316°C. For type 304 stainless steel, the maximum experimental factors were 2.5, 2.1, 2.0, and 2.1 for the same temperatures. On an average, the predicted maximum factors of difference between maximum and average strain were higher than the experimental factors by about 45%. That the predicted factors were higher was attributed mainly to the fact that the first-stage strain of the flow curves was more confined in the predicted graphs than it was in the experimental graphs. Recommendations for future work include corroborating the experimental data and refining the model for predicting results.

RECOMMENDATIONS

We recommend that the investigation of the effects of heat-to-heat variations on the extent of total strain with constant stressing in wrought forms (plates, bars, and pipes) of types 316 and 304 stainless steel be extended to improve the model for predicting total strains. Factors of strain difference will be based on the statistically defined mean and bound values of yield strength rather than on the average, maximum, and minimum values. This will require a moderate amount of supplemental testing to define the needed statistical parameters.

Factors of strain difference between heats in castings of types 316 and 304 stainless steel should be examined to supplement the information on wrought forms. Suitable samples of test castings in these alloys are available from the Metals Properties Council and will be used.

Improved graphical means for portraying strain information on the foregoing materials for design and regulatory application will be explored.

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