ELEVATED TEMPERATURE PROPERTIES AS INFLUENCED BY NITROGEN ADDITIONS TO TYPES 304 AND 316 AUSTENITIC STAINLESS STEELS

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75TH ANNIVERSARY ASTM

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ELEVATED TEMPERATURE PROPERTIES AS INFLUENCED BY NITROGEN ADDITIONS TO TYPES 304 AND 316 AUSTENITIC STAINLESS STEELS

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J. J. Heger and G. V. Smith, co-chairmen

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Foreword

The Symposium on Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels was presented at an informal workshop session held at the 72nd Annual Meeting of the Society, in Atlantic City, N. J., 22–27 June 1969. The sponsors of this symposium included the Joint Committee on Effect of Temperature on the Properties of Metals, Metals Properties Council, American Society for Testing and Materials, and American Society of Mechanical Engineers. J. J. Heger, U. S. Steel Corporation, and G. V. Smith, consultant, served as co-chairmen.

Related ASTM Publications

Report on Elevated-Temperature Properties of Selected Superalloys, DS 7-S1 (1970), $11.00

Evaluation of the Elevated Temperature Tensile and Creep-Rupture Properties of C-Mo, Mn-Mo, and Mn-Mo-Ni Steels, DS 47 (1971), $6.50

Elevated Temperature Static Properties of Wrought Carbon Steel, STP 503 (1972), $3.00

Contents

Introduction

A plan for an informal workshop discussion session was organized during 1968 by The Joint Committee on Effect of Temperature on the Properties of Metals for the purpose of reviewing and clarifying differences in creep-rupture properties between the "regular" and the "H" grades of Types 304, 316, 321, and 347 austenitic stainless steels. The plan included consideration of the influence of carbon and nitrogen contents on the creep-rupture strengths plus preparation of a summary of short time elevated temperature properties.

As the plan developed, it became apparent that the paramount interest focussed on the nitrogen-bearing grades. The outcome was a jointly sponsored session held at the ASTM Annual Meeting at Atlantic City, N.J., June 1969, which presented a series of papers concerned with several aspects of the properties and uses of nitrogen-strengthened austenitic steels. Cosponsorship was contributed by The Metal Properties Council, The American Society for Testing and Materials and The American Society for Mechanical Engineers.

The session at the ASTM meeting was advertized as being restricted to informal verbal reporting and discussion of current data. At the completion of the session, however, it was apparent to all concerned that the presentations contained a sufficient wealth of excellent high temperature information to warrant publication. The Metal Properties Council, as a further means of fulfilling its function of service to the metals industry, undertook the task of inducing the speakers to prepare and submit for review written versions of their papers. This has been accomplished and the material is presented herewith.

The importance of the data contained in this Special Technical Publication lies in the needs of the design engineer which extend beyond the aids supplied by industry standards and codes. The basic function of the designer is to exercise an informed judgment in the selection of appropriate materials for safe design, which is achieved only through a thorough understanding of the behavior of metals under stress at elevated temperatures. The papers of this session offer a means of advancing this necessary understanding to an important degree now that they have been made available

by publication through the efforts of The Metal Properties Council and the American Society for Testing and Materials.

Special acknowledgments and thanks are due to the authors of the papers; also to Mr. J. J. Heger, U. S. Steel Corporation, Monroeville, Pa., to Dr. G. V. Smith, Consultant, Ithaca, N.Y., to Dr. M. Semchyshen, Climax Molybdenum Co. of Mich., Ann Arbor, Mich., and to J. A. Fellows, Shaker Heights, Ohio, for their effective joint activities in initiating and preparing the workshop program. Appreciation is also due Dr. Smith for his excellent service as session moderator.

E. J. Rozic, Jr.

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Philip Kadlecek[1]

Mechanical Property Data on Hot-Extruded 304N and 316N Stainless Steel Pipe

REFERENCE: Kadlecek, Philip, "**Mechanical Property Data on Hot-Extruded 304N and 316N Stainless Steel Pipe,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522*, American Society for Testing and Materials, 1973, pp. 3–34.

ABSTRACT: The effects of nitrogen in both Types 304 and 316 stainless steel were investigated on a production scale and the results are presented in this paper. The test program revealed that nitrogen had an affirmative strengthening effect on wrought austenitic stainless steels. A program establishing hot tensile, stress-rupture, creep, and fatigue data, plus welding experiments, are reported.

KEY WORDS: nitrogen, austenitic stainless steels, welding, tensile strength, piping, creep rupture strength, mechanical properties, tubing

A customer's request for nitrogen-bearing Type 304 stainless steel stimulated interest at Cameron Iron Works as to the overall effects of nitrogen in both Type 304 and 316 stainless steels. At that time, little production data on tubing were available, even though a search through literature published during the past 30 years revealed numerous references to the effects of nitrogen. The data which were available from laboratory scale investigations did show that nitrogen had a pronounced strengthening effect on wrought austenitic materials.

Test Program

In 1968, a program was initiated at Cameron Iron Works to evaluate the effect of a controlled nitrogen addition on a production basis. The heats analyzed in this study were either electric arc or vacuum induction melted or arc remelted (see Tables 1A and 1B for compositions and tensile data). The minimum heat size was 25 tons. All test material was in the form of hot-extruded seamless pipe in the following sizes representing the range in-

[1] Chief development engineer, Cameron Iron Works, Inc., Houston, Tex. 77001.

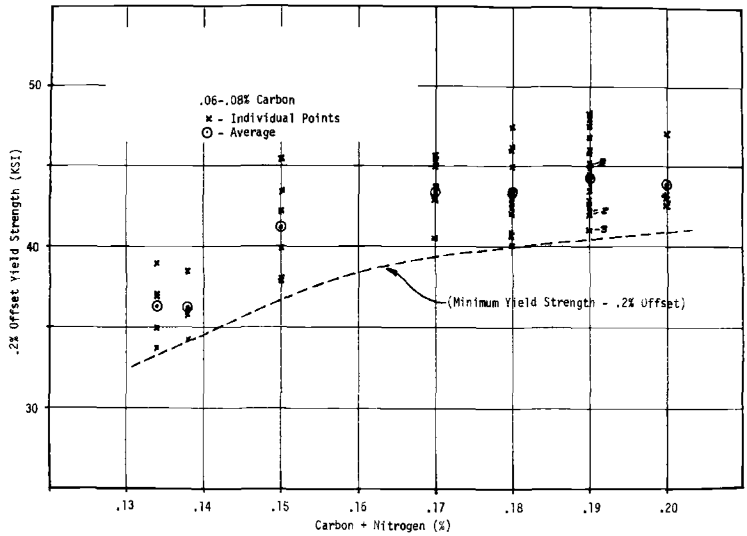

FIG. 1—*Effect of carbon and nitrogen on Type 316 stainless steel yield strength.*

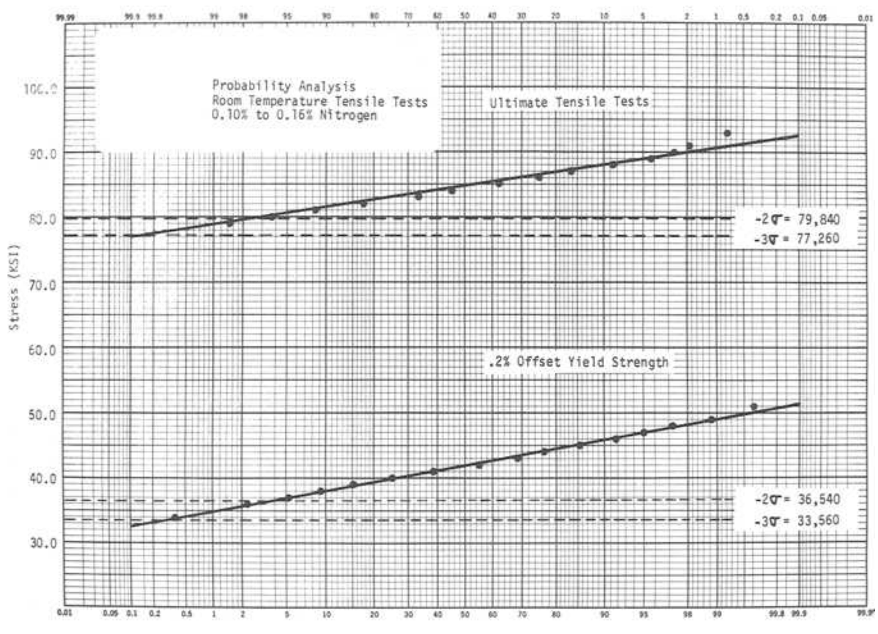

FIG. 2—*Type 304N stainless steel.*

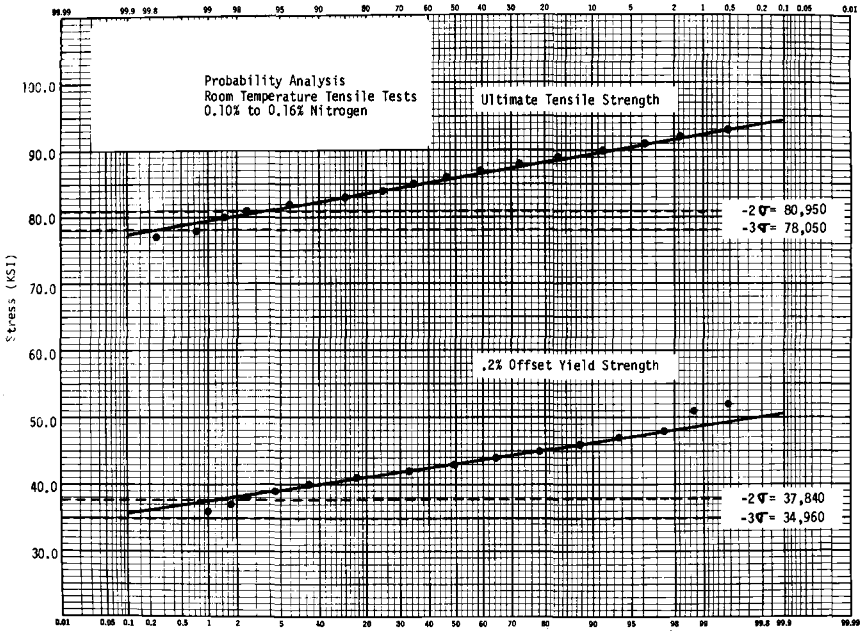

FIG. 3—*Type 316N stainless steel.*

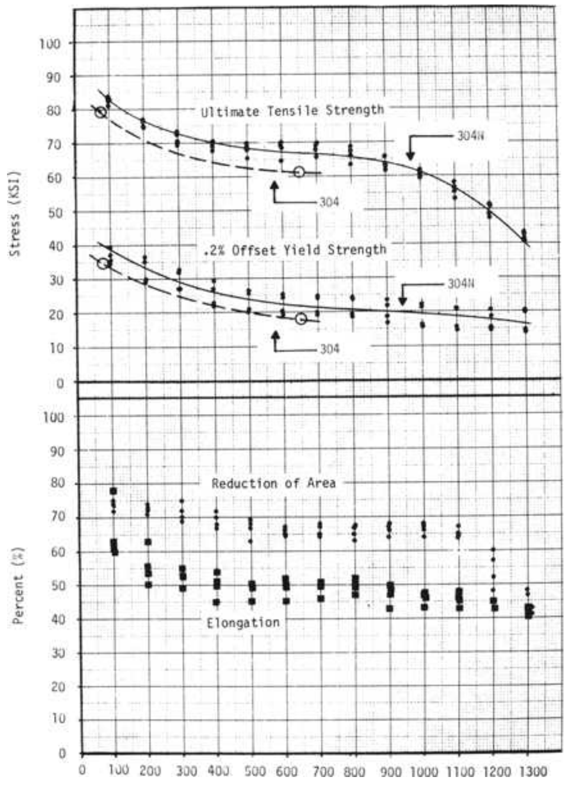

FIG. 4—*Type 304N stainless steel hot tensile data.*

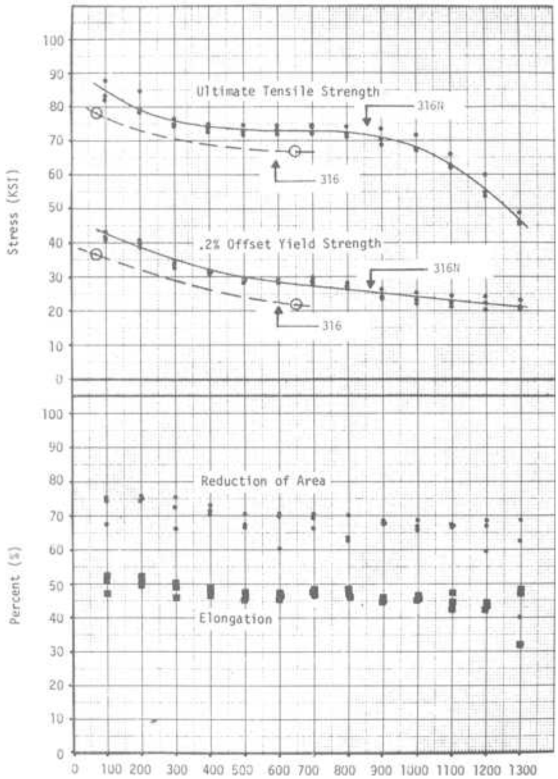

FIG. 5—*Type 316N stainless steel hot tensile data.*

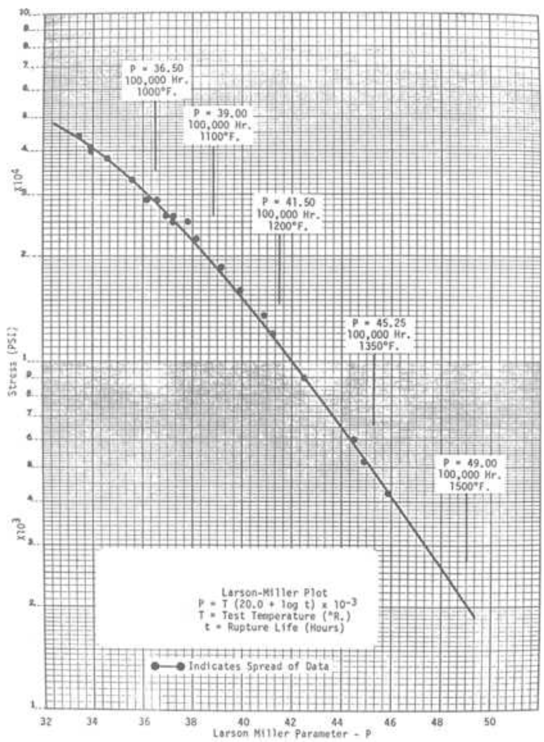

FIG. 6—*Type 304N stainless steel stress-rupture test data.*

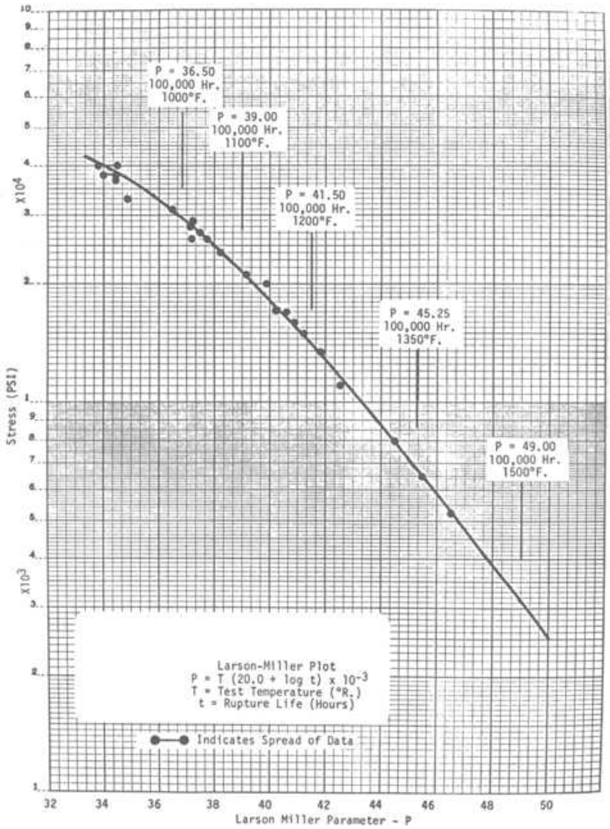

FIG. 7—*Type 316N stainless steel stress-rupture tests data.*

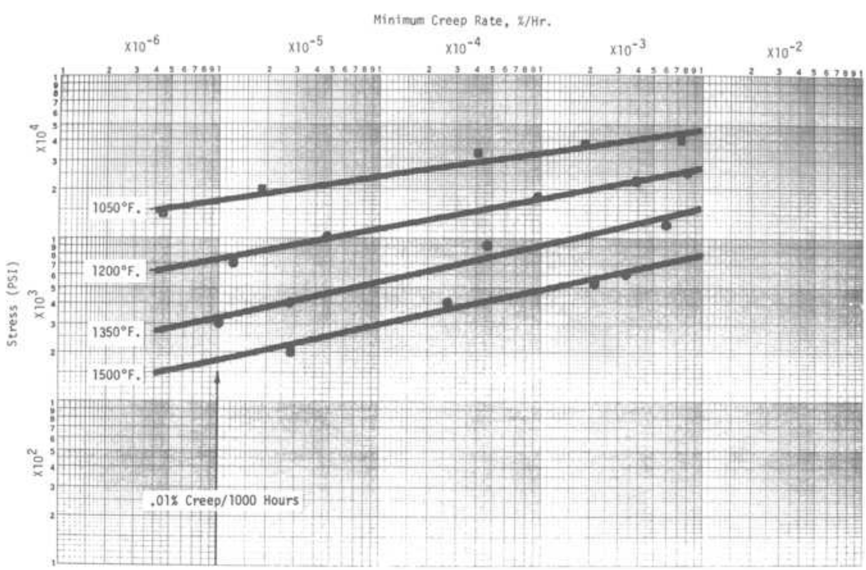

FIG. 8—*Minimum-creep rate data, Type 304N stainless steel.*

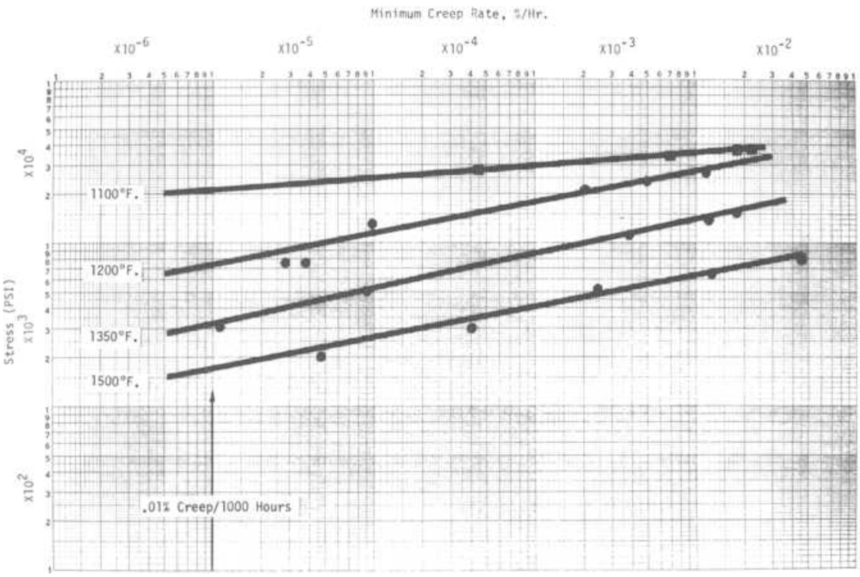

FIG. 9—*Minimum-creep rate data, Type 316N stainless steel.*

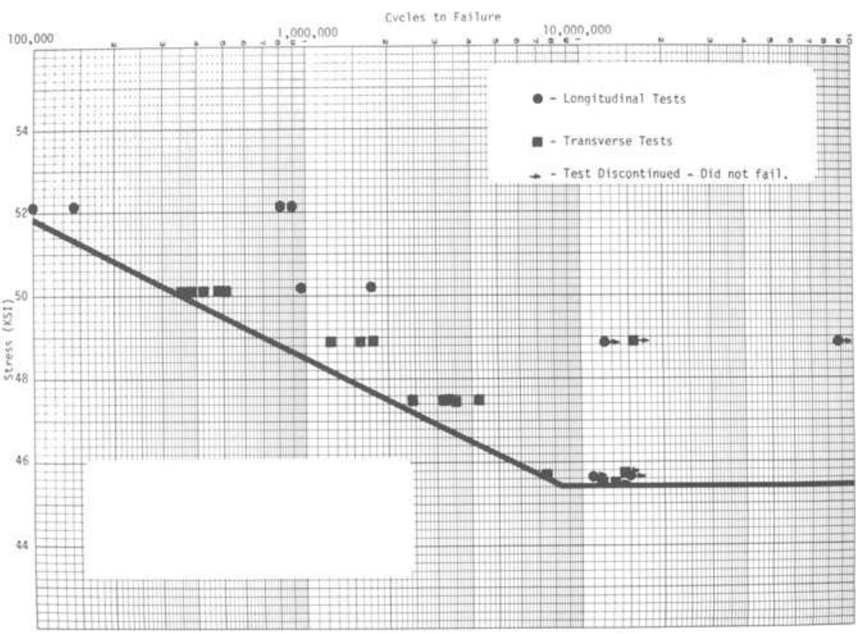

FIG. 10—*Fatigue data, Type 304N stainless steel.*

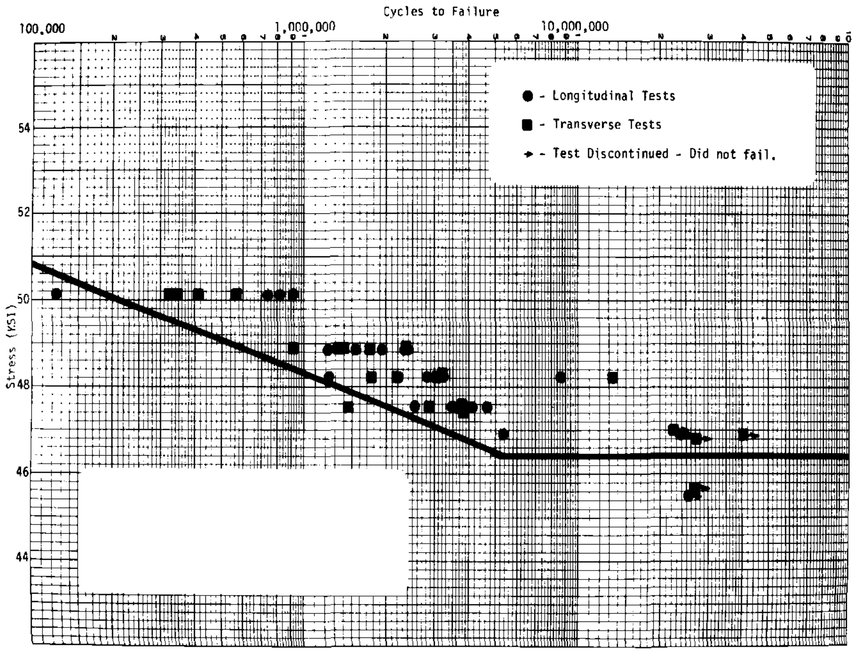

FIG. 11—*Fatigue data, Type 316N stainless steel.*

cluded in the test program: 8.75 in. (222 mm) inside diameter by 1.0 in. (24.4 mm) wall, 21.89 in. (556 mm) inside diameter by 3.30 in. (83.8 mm) wall, and 29.0 in. (736 mm) inside diameter by 2.50 in. (63.5 mm) wall.

The standard tensile requirements on the production parts provided sufficient room temperature test data. For supplementary information, a program was established to provide hot tensile, stress-rupture, creep, and fatigue data. Also, welding tests were performed using standard and nitrogen-bearing electrodes.

All test material received a standard production heat treatment of one hour per in. (per 25.4 mm) of wall thickness at 1925 F (1052 C), water quench. Since the test material was in the form of hot extruded pipe, the average "as-extruded" grain size varied from an ASTM 2 to 5 and was not altered by this heat treatment.

Test Results

Examination of room temperature tension test results indicated a reasonable correlation between the nitrogen content and the strength of the material. Although the ultimate tensile strength increased with higher nitrogen contents, the most significant improvement was in the yield strength. Figure 1 shows the effect of nitrogen on the yield strength of one size of Type 316 stainless steel pipe. (Since carbon is also an effective strengthener,

TABLE 1A—*Chemistry and room temperature mechanical properties of Type 304N stainless steel, 0.10 to 0.16 percent nitrogen.*

Heat Treatment: 1 h/in. at 1925 F, water quench

Heat No.	C	Mn	P	S	Si	Cr	Ni	N	Tensile Properties—Transverse Tests: Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
C9739	0.08	1.56	0.012	0.010	0.24	18.61	10.51	0.13	84.9	40.0	52.5	59.8
C9739	0.08	1.56	0.012	0.010	0.24	18.61	10.51	0.13	82.8	39.0	64.7	53.0
52390	0.08	1.68	0.015	0.010	0.18	18.73	10.67	0.11	84.3	40.4	53.5	72.7
									84.2	42.3	55.0	68.1
F0186	0.07	1.47	0.015	0.006	0.28	18.37	10.50	0.13	87.3	45.0	54.0	75.5
									87.8	47.0	53.0	73.5
F0186	0.07	1.47	0.015	0.006	0.28	18.37	10.50	0.13	86.3	41.2	52.0	68.4
									89.5	44.9	49.0	66.1
F0186	0.07	1.47	0.015	0.006	0.28	18.37	10.50	0.13	87.0	43.3	52.0	72.7
									87.1	44.0	52.0	70.1
F0186	0.07	1.47	0.015	0.006	0.28	18.37	10.50	0.13	83.3	38.7	51.0	71.4
									86.6	43.2	52.0	70.1
F0262	0.06	1.46	0.006	0.008	0.25	18.77	10.40	0.11	82.2	40.0	56.3	78.6
									86.1	43.5	55.5	54.7
F0262	0.06	1.46	0.006	0.008	0.25	18.77	10.40	0.11	87.3	42.6	54.0	70.0
									85.0	39.5	57.0	71.8
F0262	0.06	1.46	0.006	0.008	0.25	18.77	10.40	0.11	81.9	38.5	54.4	70.4
									84.4	43.6	55.0	69.7
F0262	0.06	1.46	0.006	0.008	0.25	18.77	10.40	0.11	83.8	39.0	53.5	68.8
									88.4	44.5	51.6	70.4
F0313	0.07	1.50	0.005	0.005	0.30	18.80	10.66	0.10	85.0	45.3	58.6	74.2
F0313	0.07	1.50	0.005	0.005	0.30	18.80	10.66	0.10	81.4	42.1	60.5	75.8
F0313	0.07	1.50	0.005	0.005	0.30	18.80	10.66	0.10	82.9	44.9	59.5	76.6
									79.5	39.7	61.0	74.2

F0316	0.06	1.50	0.015	0.005	0.35	18.73	10.57	0.10	80.2	43.1	61.5	75.8
									84.6	45.1	58.0	74.5
F0318	0.06	1.53	0.005	0.012	0.35	18.62	10.33	0.11	83.4	45.1	58.0	77.3
									87.0	44.9	55.7	75.1
F0314	0.07	1.53	0.009	0.008	0.29	18.54	10.69	0.12	81.4	42.0	60.0	76.2
									83.4	45.7	56.5	75.4
F0313	0.07	1.50	0.005	0.005	0.30	18.80	10.66	0.10	82.4	43.1	50.0	56.1
									85.9	43.9	54.0	75.1
F0315	0.08	1.58	0.017	0.005	0.31	18.65	10.89	0.10	89.7	44.9	53.7	73.3
F0315	0.08	1.58	0.017	0.005	0.31	18.65	10.89	0.10	89.4	45.2	53.5	74.7
F0316	0.06	1.50	0.015	0.005	0.35	18.73	10.57	0.10	88.9	42.4	55.0	72.5
									88.7	44.9	53.2	71.0
F0316	0.06	1.50	0.015	0.005	0.35	18.73	10.57	0.10	83.7	40.9	55.8	75.5
									88.6	45.9	56.6	73.3
F0316	0.06	1.50	0.015	0.005	0.35	18.73	10.57	0.10	83.0	46.1	58.0	76.6
									87.9	49.8	62.5	77.3
F0318	0.06	1.53	0.005	0.012	0.35	18.62	10.33	0.11	84.0	41.4	57.0	72.7
									85.9	41.7	56.1	73.0
F0318	0.06	1.53	0.005	0.012	0.35	18.62	10.33	0.11	86.2	46.1	55.5	78.4
									84.6	46.9	55.0	71.3
F0318	0.06	1.53	0.005	0.012	0.35	18.62	10.33	0.11	86.6	42.7	55.0	75.5
									85.9	42.7	56.2	74.7
F0317	0.07	1.45	0.015	0.008	0.35	18.54	10.49	0.10	85.0	47.1	57.5	75.4
									84.9	45.4	59.1	76.2
F0319	0.06	1.52	0.005	0.006	0.33	18.89	10.69	0.10	85.4	39.9	54.1	74.1
									85.0	41.4	53.5	73.5
F0319	0.06	1.52	0.005	0.006	0.33	18.89	10.69	0.10	86.2	48.8	50.9	59.7
									82.2	46.9	51.5	70.4
F0320	0.06	1.49	0.014	0.007	0.24	18.49	10.71	0.10	87.1	42.1	56.4	72.6
									86.2	45.5	55.0	73.4
F0314	0.07	1.53	0.009	0.008	0.29	18.54	10.69	0.12	81.0	43.9	55.0	73.4
									83.4	42.5	58.0	70.4
F0317	0.07	1.45	0.015	0.008	0.35	18.54	10.49	0.10	83.2	42.2	55.0	73.4
									85.6	47.3	55.0	74.2

TABLE 1A—*Chemistry and room temperature mechanical properties of Type 304N stainless steel, 0.10 to 0.16 percent nitrogen.—Continued*

Heat Treatment: 1 h/in. at 1925 F, water quench

									Tensile Properties—Transverse Tests			
Heat No.	C	Mn	P	S	Si	Cr	Ni	N	Ultimate . Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
F0353	0.06	1.55	0.005	0.007	0.38	18.34	10.52	0.10	79.1	38.7	59.4	73.9
									84.0	41.1	55.1	70.1
F0353	0.06	1.55	0.005	0.007	0.38	18.34	10.52	0.10	81.2	37.1	56.8	69.9
F0353	0.06	1.55	0.005	0.007	0.38	18.34	10.52	0.10	80.1	39.0	56.8	70.8
F0314	0.07	1.53	0.009	0.008	0.29	18.54	10.69	0.12	85.5	42.9	57.5	70.4
F0314	0.07	1.53	0.009	0.008	0.29	18.54	10.69	0.12	83.7	39.0	55.0	70.4
F0368	0.08	1.49	0.005	0.005	0.25	18.75	10.50	0.12	83.1	43.3	58.6	77.3
F0368	0.08	1.49	0.005	0.005	0.25	18.75	10.50	0.12	87.4	45.0	55.0	50.8
F0379	0.08	1.55	0.009	0.006	0.21	18.87	10.86	0.10	84.9	41.4	55.2	70.6
F0379	0.08	1.55	0.009	0.006	0.21	18.87	10.86	0.10	84.1	40.0	57.0	73.0
F0379	0.08	1.55	0.009	0.006	0.21	18.87	10.86	0.10	84.5	40.0	53.8	72.5
F0372	0.06	1.46	0.005	0.010	0.16	18.43	10.41	0.10	82.9	41.1	57.0	72.8
									84.8	41.2	55.3	68.9
F0372	0.06	1.46	0.005	0.010	0.16	18.43	10.41	0.10	85.5	41.2	55.2	72.6
F0380	0.07	1.55	0.008	0.005	0.35	18.04	10.74	0.10	82.0	40.4	56.5	72.5
F0380	0.07	1.55	0.008	0.005	0.35	18.04	10.74	0.10	85.4	36.4	68.0	76.6
F0380	0.07	1.55	0.008	0.005	0.35	18.04	10.74	0.10	83.9	41.3	56.2	73.5
F0372	0.06	1.46	0.005	0.010	0.16	18.43	10.41	0.10	82.5	42.5	53.5	71.4
E1463	0.07	1.44	0.007	0.007	0.28	18.91	10.47	0.10	83.2	40.0	56.6	73.0
E1463	0.07	1.44	0.007	0.007	0.28	18.91	10.47	0.10	83.7	42.5	55.0	73.0
E1463	0.07	1.44	0.007	0.007	0.28	18.91	10.47	0.10	82.2	40.4	56.4	72.7
E1462	0.07	1.40	0.008	0.008	0.23	18.77	10.41	0.10	82.5	42.0	53.3	71.4
F0391	0.08	1.76	0.008	0.005	0.22	18.79	10.85	0.12	79.6	39.6	59.5	71.4
F0392	0.08	1.85	0.010	0.005	0.21	18.95	10.50	0.11	87.8	44.6	53.7	73.5

E1466	0.07	1.45	0.014	0.005	0.28	18.70	10.64	0.10	84.6	42.8	55.5	76.9
E1466	0.07	1.45	0.014	0.005	0.28	18.70	10.64	0.10	84.1	44.6	55.5	72.5
E1466	0.07	1.45	0.014	0.005	0.28	18.70	10.64	0.10	81.2	36.1	59.0	72.5
E1467	0.07	1.38	0.005	0.005	0.21	18.55	10.71	0.11	83.4	37.4	57.5	72.5
E1467	0.07	1.38	0.005	0.005	0.21	18.55	10.71	0.11	83.8	43.6	53.5	71.4
E1462	0.07	1.40	0.008	0.008	0.23	18.77	10.41	0.10	85.9	40.5	56.7	66.8
E1467	0.07	1.38	0.005	0.005	0.21	18.55	10.71	0.11	85.4	40.1	54.2	70.1
E1465	0.06	1.47	0.005	0.005	0.31	18.76	10.49	0.10	82.9	38.9	58.0	72.7
E1465	0.06	1.47	0.005	0.005	0.31	18.76	10.49	0.10	84.6	36.7	57.5	73.0
E1465	0.06	1.47	0.005	0.005	0.31	18.76	10.49	0.10	81.8	41.2	56.0	72.7
53270	0.08	1.80	0.013	0.005	0.25	19.08	10.82	0.11	88.6	42.8	52.9	74.7
53270	0.08	1.80	0.013	0.005	0.25	19.08	10.82	0.11	84.7	41.5	51.3	74.7
53271	0.08	1.79	0.013	0.005	0.22	18.77	10.72	0.13	81.4	37.9	58.8	78.0
53271	0.08	1.79	0.013	0.005	0.22	18.77	10.72	0.13	85.0	41.4	56.5	74.3
53273	0.08	1.85	0.010	0.005	0.21	18.95	10.50	0.11	85.4	41.0	53.6	73.0
53273	0.08	1.85	0.010	0.005	0.21	18.95	10.50	0.11	83.0	41.9	56.5	76.7
E1499	0.07	1.47	0.014	0.005	0.27	18.62	10.51	0.12	79.2	38.0	58.0	73.5
E1499	0.07	1.47	0.014	0.005	0.27	18.62	10.51	0.12	83.0	40.0	58.0	73.3
E1499	0.07	1.47	0.014	0.005	0.27	18.62	10.51	0.12	85.1	42.7	56.6	75.4
									82.0	36.5	60.0	71.8
E1496	0.07	1.49	0.007	0.008	0.21	18.74	10.65	0.12	81.0	37.3	58.0	72.5
E1497	0.08	1.42	0.005	0.005	0.14	18.39	10.42	0.12	83.5	38.8	55.0	72.9
E1497	0.08	1.42	0.005	0.005	0.14	18.39	10.42	0.12	84.0	41.2	55.0	73.2
									82.4	40.1	57.6	76.3
E1497	0.08	1.42	0.005	0.005	0.14	18.39	10.42	0.12	81.6	42.3	57.0	75.6
									86.5	41.8	57.1	75.8
E1498	0.06	1.50	0.014	0.005	0.39	18.56	10.53	0.12	82.0	41.0	56.5	74.1
E1498	0.06	1.50	0.014	0.005	0.39	18.56	10.53	0.12	83.0	40.5	57.3	78.0
E1498	0.06	1.50	0.014	0.005	0.39	18.56	10.53	0.12	85.0	51.2	68.0	71.3
									93.4	48.5	62.5	75.8
E1497	0.08	1.42	0.005	0.005	0.14	18.39	10.42	0.12	85.9	42.4	57.8	75.0
									85.5	41.0	55.0	76.7
E1498	0.06	1.50	0.014	0.005	0.39	18.56	10.53	0.12	87.6	44.3	55.1	75.2
									90.3	45.0	53.7	78.6
E1462	0.07	1.40	0.008	0.008	0.23	18.77	10.41	0.10	86.4	44.0	55.4	73.9

TABLE 1A—*Chemistry and room temperature mechanical properties of Type 304N stainless steel, 0.10 to 0.16 percent nitrogen.—Continued*

Heat Treatment: 1 h/in. at 1925 F, water quench

Heat No.	C	Mn	P	S	Si	Cr	Ni	N	Tensile Properties—Transverse Tests: Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
F0390	0.08	1.79	0.013	0.005	0.22	18.77	10.72	0.13	91.3	48.3	53.4	73.0
F0389	0.08	1.80	0.013	0.005	0.25	19.08	10.82	0.11	85.9	40.5	53.7	73.5
F0134	0.07	1.53	0.009	0.008	0.29	18.54	10.69	0.12	85.2	39.8	54.0	73.5
									85.7	42.0	55.0	75.2
E1494	0.06	1.52	0.007	0.008	0.23	18.58	10.56	0.12	88.6	45.7	57.6	69.1
									88.2	46.5	58.2	81.6
E1496	0.07	1.49	0.007	0.008	0.21	18.74	10.65	0.12	86.2	42.5	61.5	75.0
									88.2	42.1	74.4	77.3
E1494	0.06	1.52	0.007	0.008	0.23	18.58	10.56	0.12	84.9	42.0	56.0	70.8
E1494	0.06	1.52	0.007	0.008	0.23	18.58	10.56	0.12	87.2	40.7	56.0	69.5
E1496	0.07	1.49	0.007	0.008	0.21	18.74	10.65	0.12	84.2	39.2	55.0	67.8
E1496	0.07	1.49	0.007	0.008	0.21	18.74	10.65	0.12	85.9	42.5	55.0	72.5
E1492	0.08	1.45	0.006	0.013	0.39	18.87	10.27	0.12	93.0	34.8	56.9	73.0
D8686	0.08	1.47	0.015	0.013	0.27	18.71	11.00	0.11	81.1	40.0	55.5	68.4
D8685	0.08	1.45	0.020	0.015	0.30	18.84	10.85	0.13	84.9	42.9	56.0	71.8
									Avg.	41.6		

[a] To convert ksi to megapascals, multiply by 6.894757.

TABLE 1B—*Chemistry and room temperature mechanical properties of Type 316N stainless steel, 0.10 to 0.16 percent nitrogen.*

Heat Treatment: 1 h/in. at 1925 F, water quench

Heat No.	C	Mn	P	S	Si	Cr	Ni	Mo	N	Tensile Properties—Transverse Tests: Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
E1472	0.07	1.69	0.017	0.009	0.35	16.92	13.51	2.21	0.10	85.0	43.3	54.0	71.3
										85.8	44.5	58.0	72.6
E1472	0.07	1.69	0.017	0.009	0.35	16.92	13.51	2.21	0.10	85.4	45.3	54.0	71.3
										87.0	47.7	54.0	72.6
E1472	0.07	1.69	0.017	0.009	0.35	16.92	13.51	2.21	0.10	86.2	47.3	54.0	71.3
										87.0	42.9	54.5	71.3
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	85.4	45.3	55.0	74.2
										87.8	47.3	52.0	66.9
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	86.6	46.1	54.0	75.9
										86.6	45.3	54.0	74.2
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	85.4	41.1	57.5	75.8
										89.0	44.9	55.0	69.1
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	85.0	43.7	55.2	75.4
										88.2	44.1	55.4	75.4
E1474	0.08	1.62	0.015	0.007	0.33	17.13	13.50	2.37	0.11	89.9	45.1	55.0	79.7
										88.2	44.9	55.0	71.3
E1474	0.08	1.62	0.015	0.007	0.33	17.13	13.50	2.37	0.11	87.8	43.1	55.5	75.4
										88.2	47.1	55.1	74.6
E1474	0.08	1.62	0.015	0.007	0.33	17.13	13.50	2.37	0.11	89.0	44.1	61.0	72.6
										89.2	39.3	56.5	73.4
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	87.8	42.5	57.3	72.6
										86.6	43.7	58.5	72.1
F0228	0.06	1.69	0.010	0.006	0.27	17.04	13.58	2.29	0.13	88.2	45.0	54.3	69.1
										87.4	42.9	53.0	70.4

TABLE 1B—*Chemistry and room temperature mechanical properties of Type 316N stainless steel, 0.10 to 0.16 percent nitrogen.*—*Continued*

Heat Treatment: 1 h/in. at 1925 F, water quench

										Tensile Properties—Transverse Tests			
Heat No.	C	Mn	P	S	Si	Cr	Ni	Mo	N	Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
F0220	0.07	1.65	0.014	0.012	0.38	16.96	13.58	2.35	0.12	85.5	42.6	57.3	71.8
										87.9	44.0	57.3	68.4
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	85.9	41.9	47.5	57.3
										89.9	45.9	48.4	67.5
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	87.7	43.2	50.5	71.4
										85.2	41.2	52.0	70.8
F0220	0.07	1.65	0.014	0.012	0.38	16.96	13.58	2.35	0.12	87.9	42.5	51.0	71.4
										83.4	41.9	49.1	67.0
F0220	0.07	1.65	0.014	0.012	0.38	16.96	13.58	2.35	0.12	88.3	45.0	49.7	65.9
										83.9	41.1	53.0	71.0
E1474	0.08	1.62	0.015	0.007	0.33	17.13	13.50	2.37	0.11	90.5	45.1	53.7	69.1
										90.3	45.1	56.5	66.9
E1474	0.08	1.62	0.015	0.007	0.33	17.13	13.50	2.37	0.11	87.3	45.1	57.6	66.4
										87.5	45.7	57.5	66.0
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	84.5	41.7	58.5	70.9
										82.3	41.5	59.6	71.3
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	83.3	43.7	60.0	74.2
										83.3	42.5	60.0	73.4
E1473	0.08	1.69	0.015	0.005	0.36	16.93	13.54	2.17	0.11	81.3	44.0	53.7	68.2
										86.0	45.1	60.0	71.3
F0162	0.07	1.84	0.016	0.010	0.34	16.92	13.35	20.0	0.11	83.1	43.7	52.5	71.4
										84.9	46.2	50.0	75.5
F0162	0.07	1.84	0.016	0.010	0.34	16.92	13.35	2.20	0.11	83.5	46.0	46.5	64.7
										87.9	52.5	47.5	70.2
F0162	0.07	1.84	0.016	0.010	0.34	16.92	13.35	2.20	0.11	83.9	43.7	53.0	62.0
										90.4	47.4	48.0	68.2

F0216	0.07	1.71	0.022	0.016	0.28	16.95	13.76	2.18	0.11	83.4	40.6	48.5	68.2
										80.5	40.0	50.7	69.3
F0216	0.07	1.71	0.022	0.016	0.28	16.95	13.76	2.18	0.11	83.0	40.9	50.2	65.9
										83.5	42.5	47.2	61.1
F0226	0.06	1.71	0.014	0.012	0.31	16.81	13.61	2.32	0.12	86.3	42.8	51.2	72.5
										87.5	45.0	52.4	69.3
F0226	0.06	1.71	0.014	0.012	0.31	16.81	13.61	2.32	0.12	85.0	43.0	55.0	71.4
										86.0	42.1	51.2	69.3
F0227	0.07	1.72	0.015	0.011	0.33	17.06	13.58	2.38	0.13	83.3	42.5	54.2	72.5
										87.1	43.2	52.2	69.3
F0228	0.06	1.69	0.010	0.006	0.27	17.04	13.58	2.29	0.13	89.9	45.0	50.7	72.5
										87.4	42.5	57.5	74.5
F0228	0.06	1.69	0.010	0.006	0.27	17.04	13.58	2.29	0.13	86.1	42.2	58.2	74.5
										89.9	45.0	54.2	73.9
F0229	0.08	1.79	0.006	0.013	0.42	17.15	13.98	2.38	0.11	85.7	41.0	53.0	71.6
										86.4	44.4	52.5	68.8
F0229	0.08	1.79	0.006	0.013	0.42	17.15	13.98	2.38	0.11	84.4	42.0	52.0	71.8
										86.8	44.5	52.0	70.4
F0229	0.08	1.79	0.006	0.013	0.42	17.15	13.98	2.38	0.11	83.4	39.7	52.8	73.5
										85.3	42.2	52.2	69.9
F0229	0.08	1.79	0.006	0.013	0.42	17.15	13.98	2.38	0.11	84.9	41.0	53.5	72.5
										86.2	45.0	52.4	71.4
										84.3	42.0	55.0	73.9
F0230	0.06	1.56	0.013	0.008	0.27	16.82	13.51	2.32	0.14	88.1	43.0	53.7	71.4
										90.9	47.0	49.2	69.3
F0229	0.08	1.79	0.006	0.013	0.42	17.15	13.98	2.38	0.11	82.2	41.0	52.5	71.4
										87.9	45.0	52.0	69.3
F0228	0.06	1.69	0.010	0.006	0.27	17.04	13.58	2.29	0.13	87.7	43.5	54.0	73.5
										89.9	45.0	52.5	73.5
F0228	0.06	1.69	0.010	0.006	0.27	17.04	13.58	2.29	0.13	87.4	43.9	51.0	72.7
										88.6	45.1	52.3	71.3
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	85.4	42.9	53.7	73.6
										88.1	47.5	50.2	71.4
										88.5	46.0	59.2	74.0

TABLE 1B—*Chemistry and room temperature mechanical properties of Type 316N stainless steel, 0.10 to 0.16 percent nitrogen.—Continued*

Heat Treatment: 1 h/in. at 1925 F, water quench

Heat No.	C	Mn	P	S	Si	Cr	Ni	Mo	N	Tensile Properties—Transverse Tests: Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reudction of Area, %
F0371	0.07	1.68	0.012	0.009	0.25	17.33	13.76	2.32	0.12	88.9	44.8	51.5	73.9
										93.2	48.3	51.0	71.4
F0371	0.07	1.68	0.012	0.009	0.25	17.33	13.76	2.32	0.12	78.7	46.8	49.3	68.4
										84.7	36.9	54.5	73.9
F0371	0.07	1.68	0.012	0.009	0.25	17.33	13.76	2.32	0.12	90.9	44.3	50.0	79.5
										92.7	48.0	47.1	72.5
F0371	0.07	1.68	0.012	0.009	0.25	17.33	13.76	2.32	0.12	88.7	47.2	52.9	75.5
										88.8	44.0	51.0	72.9
F0382	0.07	1.67	0.010	0.005	0.33	16.92	13.50	2.30	0.10	86.9	45.7	51.4	71.5
										90.5	45.0	52.5	73.3
F0382	0.07	1.67	0.010	0.005	0.33	16.92	13.50	2.30	0.10	85.3	43.0	56.3	72.3
										86.8	43.7	52.5	71.2
F0382	0.07	1.67	0.010	0.005	0.33	16.92	13.50	2.30	0.10	86.2	36.3	51.0	71.9
										90.7	45.2	51.0	71.0
F0373	0.07	1.74	0.005	0.006	0.27	17.19	13.55	2.28	0.11	86.1	41.5	52.9	71.4
										88.9	43.3	50.5	68.2
F0373	0.07	1.74	0.005	0.006	0.27	17.19	13.55	2.28	0.11	86.9	40.1	51.3	71.0
										91.9	45.5	50.3	69.3
F0373	0.07	1.74	0.005	0.006	0.27	17.19	13.55	2.28	0.11	87.1	44.2	50.7	73.9
										91.1	47.0	50.3	71.4
F0369	0.07	1.67	0.010	0.006	0.26	17.16	13.42	2.26	0.12	90.8	46.0	50.0	76.7
										91.0	46.7	48.8	74.5
F0373	0.07	1.74	0.005	0.006	0.27	17.19	13.55	2.28	0.11	85.8	41.4	55.0	74.1
										89.7	44.8	50.3	71.6
F0369	0.07	1.67	0.010	0.006	0.26	17.16	13.42	2.26	0.12	89.5	42.3	53.5	76.7
										89.8	43.7	51.3	73.9

F0369	0.07	1.67	0.010	0.006	0.26	17.16	13.42	2.26	0.12	89.1	43.0	51.5	75.9
										93.7	47.7	48.7	73.3
F0369	0.07	1.67	0.010	0.006	0.26	17.16	13.42	2.26	0.12	88.4	46.5	50.5	71.5
										91.5	48.4	50.5	74.8
F0382	0.07	1.67	0.010	0.005	0.33	16.92	13.50	2.38	0.10	92.3	51.1	52.3	76.6
										86.0	42.5	54.0	71.8
F0213	0.07	1.73	0.011	0.010	0.26	17.35	13.45	2.24	0.12	90.3	46.2	50.0	71.1
										88.4	44.0	62.5	73.9
F0188	0.07	1.72	0.011	0.009	0.43	16.83	13.70	2.22	0.13	84.0	38.9	52.0	75.5
										83.4	39.2	52.5	72.9
F0188	0.07	1.72	0.011	0.009	0.43	16.83	13.70	2.22	0.13	84.8	43.0	50.0	73.5
										85.8	40.9	58.0	77.3
F0188	0.07	1.72	0.011	0.009	0.43	16.83	13.70	2.22	0.13	87.4	46.0	50.0	71.9
										87.4	45.7	49.5	71.9
F0190	0.07	1.66	0.011	0.011	0.31	16.90	13.66	2.07	0.12	84.0	40.0	49.5	70.1
										86.3	42.9	42.5	66.5
F0190	0.07	1.66	0.011	0.011	0.31	16.90	13.66	2.07	0.12	86.0	43.0	50.0	71.4
										88.8	42.0	50.0	70.6
F0190	0.07	1.66	0.011	0.011	0.31	16.90	13.66	2.07	0.12	82.4	32.7	52.0	72.9
										85.0	43.3	50.0	71.9
F0214	0.07	1.74	0.009	0.012	0.35	16.97	13.78	2.39	0.10	83.3	52.0	53.0	73.5
										82.8	43.0	45.0	67.0
F0214	0.07	1.74	0.009	0.012	0.35	16.97	13.78	2.39	0.10	83.0	40.4	51.0	71.0
										84.5	41.0	52.0	69.3
F0214	0.07	1.74	0.009	0.012	0.35	16.97	13.78	2.39	0.10	82.3	42.5	55.0	71.4
										77.3	44.5	46.5	65.9
F0213	0.07	1.73	0.011	0.010	0.26	17.35	13.45	2.24	0.12	83.0	41.0	53.2	72.9
										86.0	44.0	50.0	64.7
F0221	0.07	1.65	0.012	0.009	0.33	17.00	13.60	2.29	0.12	83.9	44.0	49.0	69.3
										86.0	42.7	49.5	70.2
F0212	0.06	1.72	0.012	0.010	0.28	17.21	13.43	2.02	0.12	84.2	43.5	52.1	73.3
										82.5	43.9	50.0	69.3
F0189	0.07	1.67	0.012	0.010	0.38	16.84	13.70	2.29	0.12	80.6	37.7	56.0	73.3
										91.0	44.1	55.0	73.3

TABLE 1B—*Chemistry and room temperature mechanical properties of Type 316N stainless steel, 0.10 to 0.16 percent nitrogen.—Continued*

Heat Treatment: 1 h/in. at 1925 F, water quench

Heat No.	C	Mn	P	S	Si	Cr	Ni	Mo	N	Tensile Properties—Transverse Tests: Ultimate Yield Strength, ksi[a]	Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %
F0189	0.07	1.67	0.012	0.010	0.38	16.84	13.70	2.29	0.12	83.4	41.7	58.0	77.3
										92.2	45.3	54.0	75.7
F0189	0.07	1.67	0.012	0.010	0.38	16.84	13.70	2.29	0.12	82.2	41.3	58.0	74.1
										84.2	42.9	58.0	74.4
F0212	0.06	1.72	0.012	0.010	0.28	17.21	13.43	2.02	0.12	85.1	43.5	51.2	69.3
										88.0	43.2	47.7	72.0
F0215	0.06	1.64	0.014	0.011	0.34	16.88	13.63	2.30	0.11	84.8	40.0	52.8	71.2
										87.7	41.9	49.9	71.1
F0216	0.07	1.71	0.022	0.016	0.28	16.95	13.26	2.18	0.11	82.1	39.5	53.1	71.9
										86.7	43.7	49.5	67.9
F0221	0.07	1.65	0.012	0.009	0.33	17.00	13.60	2.29	0.12	82.6	39.3	53.2	71.4
										89.0	45.5	49.1	67.0
F0221	0.07	1.65	0.012	0.009	0.33	17.00	13.60	2.29	0.12	83.9	41.0	51.0	70.6
										83.0	41.5	51.5	71.0
F0213	0.07	1.73	0.011	0.010	0.26	17.35	13.45	2.24	0.12	82.5	41.9	52.5	71.4
										84.5	46.5	51.2	69.3
F0212	0.06	1.72	0.012	0.010	0.28	17.21	13.45	2.02	0.12	83.6	42.5	50.7	70.1
										81.6	38.5	52.1	71.6
F0215	0.06	1.64	0.014	0.011	0.34	16.88	13.63	2.30	0.11	83.0	43.0	52.5	71.4
										84.6	42.0	50.9	69.3
F0215	0.06	1.64	0.014	0.011	0.34	16.88	13.63	2.30	0.11	82.3	41.0	52.7	70.4
										83.7	46.9	56.0	67.0
F0227	0.07	1.72	0.015	0.011	0.33	17.06	13.58	2.38	0.13	85.5	42.5	49.7	70.6
										86.8	41.8	49.7	64.6
F0222	0.08	1.65	0.013	0.012	0.26	17.66	14.00	2.33	0.11	86.5	44.0	50.1	70.4
										83.2	41.5	52.0	73.5

F0222	0.08	1.65	0.013	0.012	0.26	17.66	14.00	2.33	0.11	82.7	41.0	50.1	70.4
										87.2	44.5	48.7	68.2
F0222	0.08	1.65	0.013	0.012	0.26	17.66	14.00	2.33	0.11	85.1	43.5	53.0	68.2
										85.6	44.3	47.7	67.0
F0227	0.07	1.72	0.015	0.011	0.33	17.06	13.58	2.38	0.13	86.0	44.5	48.2	68.2
										85.1	42.5	51.7	70.4
F0230	0.06	1.56	0.013	0.008	0.27	16.82	13.51	2.32	0.14	89.0	43.3	54.3	73.8
										89.5	47.2	50.0	70.4
F0230	0.06	1.56	0.013	0.008	0.27	16.82	13.51	2.32	0.14	88.6	42.5	55.6	73.0
										88.2	45.3	53.1	67.8
										87.8	40.9	55.1	72.1
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	87.8	48.9	56.0	70.9
										89.4	44.1	60.1	68.2
F0244	0.07	1.63	0.016	0.009	0.27	16.90	13.65	2.32	0.12	89.4	44.9	55.2	73.4
										88.2	43.8	55.0	74.2
F0220	0.07	1.65	0.014	0.012	0.38	16.96	13.58	2.35	0.12	87.0	42.9	57.6	73.0
										88.2	44.1	55.0	73.8
F0220	0.07	1.65	0.014	0.012	0.38	16.96	13.58	2.35	0.12	85.6	41.6	53.9	72.6
										89.4	44.9	57.7	74.6
E1468	0.07	1.71	0.006	0.007	0.36	16.71	13.55	2.23	0.12	89.9	42.7	54.7	76.7
										90.3	44.9	50.5	70.9
E1468	0.07	1.71	0.006	0.007	0.36	16.71	13.55	2.23	0.12	87.9	41.1	53.1	75.4
										90.3	42.7	53.0	73.4
E1468	0.07	1.71	0.006	0.007	0.36	16.71	13.55	2.23	0.12	90.3	42.1	53.0	75.4
										90.7	42.7	55.0	75.4
E1468	0.07	1.71	0.006	0.007	0.36	16.71	13.55	2.23	0.12	89.5	41.7	53.0	74.6
										89.9	41.7	55.0	73.4
E1468	0.07	1.71	0.006	0.007	0.36	16.71	13.55	2.23	0.12	88.3	39.7	55.0	78.8
										87.9	42.1	54.0	73.0
E1493	0.08	1.49	0.005	0.010	0.29	16.72	13.63	2.21	0.12	83.1	42.0	53.1	73.0
										84.5	42.6	50.7	72.3
									Avg.		43.5		

[a] To convert ksi to megapascals, multiply by 6.894757.

TABLE 2A—*Hot tensile results of Type 304N stainless steel, 0.10 to 0.16 percent nitrogen.*

Heat Treatment: 1 h/in. at 1925 F, Water Quench

Chemistry:

Heat No.	C	Mn	P	S	Si	Cr	Ni	N
J-1295[a]	0.07	1.36	0.012	0.006	0.43	18.33	10.41	0.10
E-1499[b]	0.08	1.49	0.014	0.010	0.23	18.93	10.53	0.12
E-1497[c]	0.08	1.44	0.013	0.005	0.15	18.60	10.33	0.12
F-0262[d]	0.08	1.46	0.005	0.008	0.29	18.70	10.42	0.11

	Heat J-1295				*Heat E-1499*			
Temperature, deg F	Ultimate Tensile Strength, ksi[e]	Yield Strength, ksi[e]	Elongation, %	Reduction of Area, %	Ultimate Tensile Strength, ksi[e]	Yield Strength, ksi[e]	Elongation, %	Reduction of Area, %
100	81.0	39.5	63	75	84.0	35.6	60	75
200	74.8	35.0	50	71	76.8	29.2	55	72
300	70.5	31.9	49	70	72.8	26.9	52	69
400	69.0	29.4	45	67	70.2	22.0	50	68
500	68.0	26.4	45	69	69.7	20.1	50	67
600	68.4	25.4	45	65	69.9	19.2	50	66
700	67.9	25.0	46	65	69.8	19.5	50	68
800	66.0	24.4	47	65	67.4	18.5	51	67
900	61.7	21.9	43	64	64.0	16.8	48	67
1000	60.1	21.4	43	64	60.6	15.3	46	67
1100	53.2	20.5	43	64	58.0	15.7	48	64
1200	47.3	18.5	43	57	51.9	14.9	43	52
1300	40.5	20.0	43	47	43.2	14.5	41	48

	Heat E-1497				*Heat F-0262*			
Temperature, deg F	Ultimate Tensile Strength, ksi[e]	Yield Strength, ksi[e]	Elongation, %	Reduction of Area, %	Ultimate Tensile Strength, ksi[e]	Yield Strength, ksi[e]	Elongation, %	Reduction of Area, %
100	82.8	34.8	60	72	83.7	37.2	78	74
200	77.0	29.6	54	74	76.7	36.5	63	73
300	73.5	25.9	52	72	69.1	32.9	55	75
400	70.3	23.0	51	70	67.5	27.0	54	72
500	69.3	20.9	50	63	65.2	26.2	50	68
600	70.0	20.4	50	65	64.6	24.6	52	67
700	69.8	19.1	50	67	65.9	24.7	50	64
800	68.8	19.1	49	63	63.6	24.6	52	67
900	65.8	18.2	48	68	63.1	24.4	50	66
1000	61.8	15.5	47	68	59.2	22.7	47	66
1100	55.9	14.7	45	67	56.3	20.8	46	64
1200	51.5	15.4	43	60	48.6	20.4	45	48
1300	42.9	14.0	40	43	40.8	20.2	41	41

[a] Heat J-1295 tested at strain rate of 0.01 in./in./min to yield, 0.05 in./in./min to fracture.

[b] Heat E-1499 tested at strain rate of 0.005 in./in./min to yield 0.05 in./in./min to fracture.

[c] Heat E-1497 tested at strain rate of 0.005 in./in./min to yield, 0.05 in./in./min to fracture.

[d] Heat F-0262 tested at strain rate of 0.05 in./in./min to yield, 0.1 in./in./min to fracture.

[e] To convert ksi to megapascals, multiply by 6.894757.

TABLE 2B—*Type 316N stainless steel, 0.10 to 0.16 percent nitrogen.*

Heat Treatment: 1 h/in. at 1925 F, Water Quench

Hot Tensile Results

Chemistry

Heat No.	C	Mn	P	S	Si	Cr	Ni	Mo	N
F0369	0.07	1.67	0.010	0.006	0.26	17.16	13.42	2.26	0.12
E1478	0.08	1.65	0.005	0.009	0.27	16.96	13.34	2.00	0.10
V0630	0.08	1.70	0.018	0.019	0.28	17.11	13.42	2.00	0.08[a]

	Heat F0369				*Heat E1478*				*Heat V0630*			
Temperature, deg F	Ultimate Tensile Strength, ksi[b]	Yield Strength, ksi[b]	Elongation, %	Reduction of Area, %	Ultimate Tensile Strength, ksi[b]	Yield Strength ksi[b]	Elongation, %	Reduction of Area, %	Ultimate Tensile Strength, ksi[b]	Yield Strength, ksi[b]	Elongation, %	Reduction of Area %
100	87.6	43.3	47.1	75.4	83.1	41.2	50.8	67.5	82.5	41.1	52.3	74.1
200	84.7	40.7	49.5	75.1	79.3	39.5	50.9	76.0	78.5	39.2	52.1	75.2
300	76.5	32.5	50.1	75.3	74.7	34.5	45.7	66.2	74.6	33.7	48.7	72.5
400	75.0	31.5	48.9	73.0	73.8	31.3	46.5	70.2	72.4	31.3	47.7	71.5
500	74.5	28.1	47.7	70.5	72.8	29.5	45.8	66.5	71.7	29.4	45.9	67.1
600	74.3	29.1	46.3	70.1	73.1	28.1	45.1	60.2	72.0	28.7	47.3	69.8
650	75.1	29.5	45.4	67.6	72.5	28.3	45.5	64.6	72.4	28.2	42.7	68.1
700	74.8	28.9	48.3	70.4	74.1	29.8	47.9	66.1	72.0	28.0	47.4	69.2
750	74.5	28.5	48.7	71.1	72.5	28.1	47.2	60.1	74.5	28.7	49.7	68.4
800	74.1	27.2	46.2	62.6	72.1	28.0	46.6	63.2	71.1	26.5	48.1	70.1
850	73.7	27.3	47.4	71.5	72.3	25.6	40.5	66.3	71.0	25.4	45.5	66.0
900	73.4	26.1	45.8	68.3	70.0	23.5	44.8	68.6	68.9	24.0	45.3	67.0
950	73.1	25.0	47.0	69.7	68.0	22.9	37.8	45.0	68.5	23.8	44.5	61.0
1000	71.5	25.2	45.4	68.8	67.0	22.5	46.2	66.9	67.0	22.9	44.8	65.9
1050	70.4	23.7	44.9	68.6	66.8	22.1	46.2	66.1	65.5	23.6	45.3	66.3
1100	66.0	24.2	47.1	67.0	62.8	21.7	42.2	67.7	62.0	22.2	44.3	67.0
1150	64.9	25.2	42.9	67.0	58.8	20.8	41.9	67.7	57.0	21.9	43.4	65.8
1200	59.9	24.3	42.4	59.8	54.8	20.0	43.3	68.8	53.4	22.5	43.9	67.0
1250	55.0	23.8	38.8	51.4	48.7	20.1	47.8	68.1	52.8	21.0	45.3	65.9
1300	48.8	23.1	31.8	40.0	45.3	21.0	47.0	62.5	45.3	20.7	47.7	68.6

[a] Included to show the gradual improvement with increasing nitrogen.
[b] To convert ksi to megapascals, multiply by 6.894757.

TABLE 3—*CIW stress-rupture data for smooth bars, transverse locations of Type 304N.*

Heat Treatment: 1 h/in. at 1925 F, Water Quench

Heat No.	Stress-Rupture Data: Temperature, deg F	Stress, ksi[a]	Life, h	Elongation, %	Larson-Miller Parameter C = 20.0
E1499	1050	44.0	129.2	20.2	33.38
E1499	1050	41.0	262.3	17.5	33.85
E1498	1050	40.0	275.4	20.0	33.88
E1498	1050	38.0	755.8	15.0	34.54
E1498	1050	33.0	3768.5	14.0	35.59
D8685	1200	29.0	57.2	13.7	36.11
D8685	1200	29.0	58.1	11.8	36.12
D8685	1200	29.0	68.7	12.7	36.24
D8685	1200	29.0	73.3	13.1	36.29
D8685	1200	29.0	78.3	13.2	36.34
D8685	1200	29.0	57.3	14.4	36.11
D8685	1200	29.0	64.2	17.5	36.20
D8685	1200	29.0	85.1	13.6	36.40
E1499	1200	29.0	106.8	13.7	36.56
D8686	1200	26.0	180.8	15.2	36.94
D8686	1200	26.0	255.0	12.3	37.19
D8686	1200	26.0	266.0	18.8	37.22
D8686	1200	26.0	189.2	12.5	36.97
D8686	1200	26.0	163.1	12.0	36.87
D8686	1200	26.0	175.9	15.2	36.92
F0262	1200	26.0	161.6	14.6	36.86
E1499	1200	25.0	277.9	10.7	37.25
E1498	1200	25.0	538.1	12.0	37.73
E1498	1200	22.5	952.8	10.0	38.14
E1498	1200	18.5	3836.9	6.0	39.15
E1497	1350	16.0	116.0	19.2	39.93
E1498	1350	13.5	310.9	11.0	40.71
E1498	1350	12.0	603.2	15.0	41.21
E1498	1350	9.0	2797.7	10.0	42.43
E1498	1500	6.0	526.1	10.0	44.53
E1498	1500	5.2	838.5	8.0	44.93
E1498	1500	4.2	2397.1	2.0	45.82

[a] To convert ksi to megapascals, multiply by 6.894757.

the combined effect of carbon plus nitrogen is shown. The carbon contents of these heats varied from 0.06 to 0.08 percent). By grouping heats according to various nitrogen ranges, it was possible to look at a series of probability analyses on both 304N and 316N material. The probability analyses shown in Figs. 2 and 3 indicate that with a 0.10 to 0.16 percent nitrogen addition either of these alloys in the form of heavy wall pipe would meet an 80 000 psi (552 MPa) ultimate tensile strength and a 35 000 psi (241 MPa) yield strength specification. The probability data were determined by first tabulating a frequency distribution of all data points, and then

TABLE 4—*CIW stress-rupture data for smooth bars, transverse locations of Type 316N.*

Heat Treatment: 1 h/in. at 1925 F, Water Quench

	Stress-Rupture Data				
Heat No.	Temperature, deg F	Stress, ksi[a]	Life, h	Elongation, %	Larson-Miller Parameter $C = 20.0$
F0244	1100	38.0	104.2	18.0	34.34
F0244	1100	38.0	88.8	18.0	34.23
F0230	1100	38.0	110.2	10.2	34.38
E1493	1100	38.0	67.9	16.1	34.05
F0244	1100	40.0	42.9	20.0	33.74
F0230	1100	40.0	105.2	15.5	34.35
F0244	1100	40.0	62.8	19.7	34.00
F0244	1100	37.0	128.5	17.6	34.48
E1493	1100	33.0	235.8	11.5	34.90
F0244	1100	28.0	7055.8	9.0	37.20
F0230	1200	29.0	289.8	27.8	37.28
E1493	1200	31.0	94.1	13.3	36.47
F0230	1200	26.0	501.0	27.2	37.68
F0244	1200	26.0	260.5	14.1	37.21
E1493	1200	27.0	388.7	14.2	37.49
F0244	1200	27.0	416.0	18.0	37.54
F0244	1200	24.0	1105.0	21.0	38.25
F0244	1200	21.0	3552.6	21.0	39.09
F0225	1200	17.0	15791.0	31.6	40.16
F0244	1350	17.0	295.3	31.2	40.65
E1493	1350	20.0	110.8	41.2	39.90
E1493	1350	16.0	385.7	54.4	40.88
F0244	1350	15.0	618.3	60.0	41.25
F0244	1350	13.5	1172.7	58.0	41.75
F0244	1350	11.0	2863.1	65.0	42.45
F0244	1500	8.0	486.4	59.0	44.46
F0244	1500	6.5	1482.8	56.0	45.41
F0244	1500	5.2	4648.5	33.0	46.38

[a] To convert ksi to megapascals, multiply by 6.894757.

calculating the cumulative percentage through each frequency interval. The cumulative percentages are then plotted on the probability paper [*1*].[2]

A series of hot tension tests was completed on four heats of 304N and three heats of 316N stainless steel. The test results along with "least squares" regression curves of the ultimate tensile and yield strengths are plotted in Figs. 4 and 5. The actual data are tabulated in Tables 2A and 2B. Strengthwise, these results are consistently higher than for the standard material without nitrogen in the same product form. (Average data for 304 and 316 without nitrogen are shown as dashed lines on the figures.)

Stress-rupture results for both materials are tabulated in Tables 3 and 4.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 5—*Creep data for Type 304N stainless steel, Heat E-1498.*

			Heat Treatment: 1 h/in. at 1925 F, Water Quench							
			Time h to							
Specimen No.	Temperature, deg F	Stress, ksi[a]	0.01%	0.05%	0.1%	0.2%	0.5%	1.0%	Rupture	Minimum-Creep Rate, 10^{-4} %/h
5	1050	40.0	...	...	5	10	31	93	275.4	72
18	1050	38.0	...	3.2	7.5	18	45	273	755.8	18
17	1050	33.0	...	...	15	42	225	...	...	4.0
23	1050	20.0	35	730		discontinued at 978.8 h				0.18
11	1050	14.0	60	...		discontinued at 1565.0 h				0.045
22	1100	15.0	130			discontinued at 815 h				0.13
8	1200	25.0	...	...	0.8	2.6	19	77	538.1	80
19	1200	22.5	...	...	2.5	12	72	182	952.8	38
21	1200	18.5	...	...	40	150	465	1025	...	9.5
7	1200	10.0	34	815		discontinued at 985 h				0.46
20	1200	7.0	25	...		discontinued at 965.6 h				0.12
4	1300	7.5	6	115	395		discontinued at 648 h			1.5
3	1350	13.5	...	...	...	...	...	...	310.9	...
16	1350	12.0	...	3.0	8.8	23	76	144	603.2	58
15	1350	9.0	1.0	18	63	255	785	1177	2797.7	4.6
10	1350	4.0	38			discontinued at 965.3 h				0.27
2	1350	3.0	100	450		discontinued at 983.3 h				0.10
9	1500	6.0	...	...	...	...	...	...	526.1	33
24	1500	5.2	...	4.5	16	56	195	358	838.5	22
14	1500	4.0	2.5	60	245	615	...	...	...	2.6
12	1500	2.0	20	75		discontinued at 1246.9 h				0.28

[a] To convert ksi to megapascals, multiply by 6.894757.

TABLE 6—*Creep data for Type 316N stainless steel, Heat F-0244.*

Specimen No.	Temperature, deg F	Stress, ksi[a]	Time, h to 0.01%	0.05%	0.1%	0.2%	0.5%	1.0%	Rupture	Minimum-Creep Rate, 10^{-4} %/h
			Heat Treatment: 1 h/in. at 1925 F, Water Quench							
28	1100	38.0	...	0.5	1.7	5.8	25	45	140.2	180
13	1100	38.0	...	...	2.8	7.3	22	44	88.8	218
8	1100	34.0	...	...	4.2	13	42	93	247.7	69
24	1100	28.0	...	0.7	3.0	19	115	720		4.4
4	1200	27.0	...	...	0.55	1.5	5.7	26	416.0	115
22	1200	24.0	...	1.2	2.7	5.7	17	56	1105.0	49
15	1200	21.0	...	...	5.0	10	85	328		20
18	1200	12.5	5	300		discontinued at 694.1 h				0.96
23	1200	7.5	10	280		discontinued at 932.4 h				0.37
17	1200	7.5	6.3	350		discontinued at 989.0 h				0.28
10	1350	15.0	...	...	5.4	11	23	44	618.3	175
26	1350	13.5	0.7	4.2	8.7	18	42	83	1172.7	120
14	1350	11.0	2.5	17	28	54	132	250		38
12	1350	5.0	14	310	880		discontinued at 864.6 h			0.90
11	1350	3.0	30				discontinued at 1092.5 h			0.11
19	1500	8.0	...	...	1.9	4.1	11	22	486.4	450
16	1500	6.5	...	3.5	7.5	17	39	68	1482.8	126
9	1500	5.2	0.5	8.0	25	65	190	330		24
25	1500	3.0	50	140	265	460	discontinued at 478.6 h			4.0
21	1500	2.0	5	48	180		discontinued at 1295.6 h			0.46

[a] To convert ksi to megapascals, multiply by 6.894757.

TABLE 7—*304N and 316N stainless steel weld tests. Chemical analysis of 304N pipe and 308N filler metal.*

Material	Type of Weld	Test Lab	Chemistry									
			C	Mn	Si	S	P	Cr	Ni	N	Cu	Co
304N base metal	...	CIW	0.07	1.45	0.26	0.006	0.015	18.36	9.85	0.13	0.08	0.06
T-7746 weld	manual	Arcos	0.036	2.32	0.65	0.011	0.008	19.81	10.44	0.15	...	...
	electric arc	CIW	0.04	2.25	0.64	0.011	0.008	20.35	9.94	0.153	...	...
T-7726 weld	manual	Arcos	0.038	2.29	0.62	0.018	0.009	20.41	10.33	0.164	...	...
	electric arc	CIW	0.030	2.23	0.66	0.018	0.008	21.00	9.70	0.171	...	...
T-7730	automatic	Arcos	0.058	1.77	0.85	NA[a]	NA[a]	20.20	10.25	0.109	...	...
	sub-arc	CIW	0.06	1.70	0.69	0.012	0.018	20.09	9.58	0.113	...	...
304N composition range		...	0.08 max	2.0 max	0.75 max	0.03 max	0.03 max	18.0 to 20.0	8.0 to 11.0	0.10 to 0.16	... ...	... ...
308 Filler metal composition range			0.08 max	2.50 max	0.90 max	0.03 max	0.04 max	18.0 to 21.0	9.0 to 11.0	NA ...	... ...	... ...

[a] NA = not available.

TABLE 8—*304N and 316N stainless steel weld tests. Chemical analysis of 316N pipe and 316N filler metal.*

Material	Type of Weld	Test Lab	Chemistry										
			C	Mn	Si	S	P	Cr	Ni	N	Mo	Cu	Co
316N Base metal	...	CIW	0.07	1.64	0.41	0.009	0.005	16.92	13.58	0.12	2.34	0.08	0.06
T-7745 Weld	manual	Arcos	0.036	1.98	0.32	0.013	0.011	18.15	12.71	0.150	2.40	...	...
	electric arc	CIW	0.05	2.15	0.43	0.016	0.010	17.70	12.50	0.133	2.65	...	...
T-7727 Weld	manual	Arcos	0.031	2.35	0.63	0.015	0.013	19.75	11.64	0.170	2.16	...	...
	electric arc	CIW	0.06	1.89	0.94	0.010	0.013	19.39	13.13	0.210	2.22	...	...
T-7710 Weld	automatic	Arcos	0.048	1.99	0.82	0.011	0.019	19.46	12.85	0.111	2.22	...	...
	sub-arc	CIW	0.05	1.85	0.95	0.013	0.018	19.32	13.27	0.112	2.24	...	...
316N Composition range		...	0.08 max	2.00 max	0.75 max	0.03 max	0.03 max	16.0 to 18.0	11.0 to 14.0	0.10 to 0.16	2.0 to 3.0	...	...
316 Filler metal *composition range*			0.08 max	2.5 max	0.90 max	0.03 max	0.04 max	17.0 to 20.0	11.0 to 14.0	...	2.0	...	...
										...	2.5	...	...

TABLE 9—*304N and 316N stainless steel weld tests. Tensile results on welded 304N pipe (weld base metal interface is at approximately midgage length on test specimens).*

Weld No.	Test Temperature, deg F	Ultimate Tensile Strength, ksi[a]	0.2% Offset Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %	Failure Location	Weld Metal Data: Ferrite Content, CIW	Ferrite Content, Arcos	Nitrogen Content, CIW	Nitrogen Content, Arcos	Carbon Content
T-7746	75	94.6	53.7	40.0	75.4	base metal	1.8	0.0	0.153	0.15	0.04
T-7746	75	95.2	53.4	42.0	79.2	base metal	1.8	0.0	0.153	0.15	0.04
T-7726	75	97.3	60.2	39.5	76.6	base metal	3.4	4.2	0.171	0.164	0.03
T-7726	75	95.9	61.6	40.0	76.6	base metal	3.4	4.2	0.171	0.164	0.03
T-7730	75	97.9	60.2	46.5	77.3	base metal	3.4	3.9	0.113	0.109	0.06
T-7730	75	98.3	58.2	44.3	76.2	base metal	3.4	3.9	0.113	0.109	0.06
T-7746	600	70.8	36.1	25.5	54.5	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	600	72.8	34.5	31.9	71.3	base metal	3.4	4.2	0.171	0.164	0.03
T-7730	600	74.4	38.7	33.8	72.9	base metal	3.4	3.9	0.113	0.109	0.06
T-7746	800	69.4	33.5	27.0	47.8	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	800	68.2	30.9	26.5	43.2	weld metal	3.4	4.2	0.171	0.164	0.03
T-7730	800	72.4	32.1	30.5	37.0	weld metal	3.4	3.9	0.113	0.109	0.06
T-7746	1000	63.0	28.7	19.0	59.7	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	1000	64.4	31.1	31.5	73.4	weld metal	3.4	4.2	0.171	0.164	0.03
T-7730	1000	65.2	26.9	21.6	33.8	weld metal	3.4	3.9	0.113	0.109	0.06
T-7746	1100	56.5	31.7	21.9	49.0	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	1100	60.2	28.6	30.5	40.1	weld metal	3.4	4.2	0.171	0.164	0.03
T-7730	1100	60.2	27.6	24.5	39.0	weld metal	3.4	3.9	0.113	0.109	0.06

[a] To convert ksi to megapascals, multiply by 6.894757.

TABLE 10—*304N and 316N stainless steel weld tests. Tensile results on welded 316N pipe (weld base metal interface is at approximately midgage length on test specimens).*

Weld No.	Test Temperature, deg F	Ultimate Tensile Strength, ksi[a]	0.2% Offset Yield Strength, ksi[a]	Elongation, %	Reduction of Area, %	Failure Location	Weld Metal Data: Ferrite Content		Nitrogen Content		Carbon Content
							CIW	Arcos	CIW	Arcos	
T-7727	75	92.2	54.5	34.5	79.9	base metal	5.4	3.4	0.210	0.170	0.06
T-7727	75	90.2	57.3	29.0	79.5	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	75	90.2	54.1	35.5	79.2	base metal	1.2	0.0	0.133	0.150	0.05
T-7745	75	91.4	57.8	33.8	79.2	base metal	1.2	0.0	0.133	0.150	0.05
T-7710	75	90.6	58.6	24.0	30.6	weld metal	1.8	3.4	0.112	0.111	0.05
T-7710	75	89.8	58.2	26.9	30.6	weld metal	1.8	3.4	0.112	0.111	0.05
T-7727	600	71.9	40.1	31.1	71.7	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	600	72.2	35.7	24.0	49.0	weld metal	1.2	0.0	0.133	0.150	0.05
T-7710	600	63.2	37.6	17.0	20.3	weld metal[b]	1.8	3.4	0.112	0.111	0.05
T-7727	800	70.8	32.9	29.8	69.1	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	800	71.2	34.1	24.0	43.2	weld metal	1.2	0.0	0.133	0.150	0.05
T-7710	800	69.2	36.7	21.5	40.1	weld metal	1.8	3.4	0.112	0.111	0.05
T-7727	1000	68.3	30.6	30.0	66.4	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	1000	65.6	33.6	33.1	71.3	base metal	1.2	0.0	0.133	0.150	0.05
T-7710	1000	59.3	34.4	15.0	21.6	weld metal[b]	1.8	3.4	0.112	0.111	0.05
T-7727	1100	63.8	30.1	30.0	71.3	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	1100	61.2	28.1	23.5	43.2	weld metal	1.2	0.0	0.133	0.150	0.05
T-7710	1100	62.2	33.6	33.5	69.1	base metal	1.8	3.4	0.112	0.111	0.05

[a] To convert ksi to megapascals, multiply by 6.894757.
[b] Fractured through weld defect.

TABLE 11—*304N and 316N stainless steel weld tests. Stress-rupture results on welded 304N pipe (weld base metal interface is at approximately midgage length on test specimens).*

Weld No.	Test Temperature, deg F	Stress, ksi[a]	Life, h	Elongation, %	Failure Location	Weld Metal Data: Ferrite Content CIW	Ferrite Content Arcos	Nitrogen Content CIW	Nitrogen Content Arcos	Carbon Content
T-7746	1050	40.0	232.9	8.6	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	1050	40.0	540.3	3.4	base metal	3.4	4.2	0.171	0.164	0.03
T-7730	1050	40.0	405.1	6.1	weld metal	3.4	3.9	0.113	0.109	0.06
T-7746	1200	25.0	408.3	6.1	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	1200	25.0	364.3	5.0	weld metal	3.4	4.2	0.171	0.164	0.03
T-7730	1200	25.0	478.3	9.4	weld interface	3.4	3.9	0.113	0.109	0.06
T-7746	1350	13.5	177.8	5.6	weld metal	1.8	0.0	0.153	0.15	0.04
T-7726	1350	13.5	76.3	5.6	weld metal[b]	3.4	4.2	0.171	0.164	0.03
T-7730	1350	13.5	270.2	[c]	weld metal	3.4	3.9	0.113	0.109	0.06

[a] To convert ksi to megapascals, multiply by 6.894757.
[b] Possible weld defect.
[c] Cannot measure elongation due to irregular type fracture.

TABLE 12—*304N and 316N stainless steel weld tests. Stress-rupture results on welded 316N pipe (weld base metal interface is at approximately midgage length on test specimens).*

						Weld Metal Data				
						Ferrite Content		Nitrogen Content		
Weld No.	Test Temperature, deg F	Stress, ksi[a]	Life, h	Elongation, %	Failure Location	CIW	Arcos	CIW	Arcos	Carbon Content
T-7727	1100	35.0	613.1	2.5	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	1100	35.0	739.2	2.2	base metal	1.2	0.0	0.133	0.150	0.05
T-7710	1100	35.0	365.4	13.0	weld interface	1.8	3.4	0.112	0.111	0.05
T-7727	1200	27.0	492.0	19.8	base metal	5.4	3.4	0.210	0.170	0.06
T-7745	1200	27.0	687.9	14.5	base metal	1.2	0.0	0.133	0.150	0.05
T-7710	1200	27.0	95.2	7.1	weld interface	1.8	3.4	0.112	0.111	0.05
T-7727	1350	16.0	107.4	7.7	weld metal	5.4	3.4	0.210	0.170	0.06
T-7745	1350	16.0	264.0	42.5	base metal	1.2	0.0	0.133	0.150	0.05
T-7710	1350	16.0	36.9	13.0	weld metal[b]	1.8	3.4	0.112	0.111	0.05

[a] To convert ksi to megapascals, multiply by 6.894757.
[b] Possible weld defect.

The Larson-Miller plots of each set of data are shown in Figs. 6 and 7. Minimum-creep rate data were obtained on single heats of 304N and 316N stainless steel. These data are tabulated and plotted in Tables 5 and 6 and Figs. 8 and 9, respectively.

Welding programs were conducted at Cameron Iron Works as well as under a joint program with the Arcos Corporation. Both manual electric arc and semiautomatic submerged arc welding processes were used in weldability experiments. Some welds were completed using the standard electrodes for 304 and 316 stainless steels. Others were made using electrodes and wire specially prepared to produce a weld deposit containing the same amount of nitrogen as the base metal. In all cases, both 304N and 316N material displayed excellent weldability. If one considers only the tensile strength, the standard E308 and E316 electrodes are adequate. However, for service applications of 1000 F (538 C) or higher, stress rupture and creep properties become very important. The addition of nitrogen to the weld metal significantly increases the stress-rupture strength within the temperature range of 1000 to 1200 F (538 to 649 C). Above 1200 F (649 C), as is the case with wrought material, the benefits of nitrogen diminish. Tables 7 through 12 list the welding test results. (The weld defect mentioned in notes to the tables was the result of an equipment problem rather than material weldability.)

Rotating cantilever beam fatigue tests at room temperature were performed on both 304N and 316N grades, and the data are plotted in the S-N graphs of Figs. 10 and 11, respectively. The fatigue strengths are indicated to be approximately 44.5 and 46.5 ksi, respectively. These values are about 3 ksi above their average yield strengths, suggesting that the early cycles of fatigue testing must have accomplished measurable work hardening.

Conclusion

The data resulting from this testing program have demonstrated, on a production basis, that a controlled addition of nitrogen to both 304 and 316 stainless steels produces a consistent improvement in mechanical properties.

The various specification groups have recognized the importance of the nitrogen-bearing materials and have recently established design stresses for the new Grades 304N and 316N stainless steels.

Acknowledgments

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Reference

[1] Lewis, C. F., "Graphical Statistics," *Slide Rule*, Houston Engineers Club, June 1951.

C. E. Spaeder,[1] *W. F. Domis,*[1] *and K. G. Brickner*[1]

High-Nitrogen Austenitic Stainless Steels

REFERENCE: Spaeder, C. E., Domis, W. F., and Brickner, K. G., "**High-Nitrogen Austenitic Stainless Steels,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522*, American Society for Testing and Materials, 1973, pp. 35–45.

ABSTRACT: The present paper summarizes the results of a number of investigations in which the effects of nitrogen on the mechanical properties of an austenitic stainless steel were evaluated. The results of studies on commercially produced plate indicated that increasing the nitrogen content of Type 304L steel to the range 0.10 to 0.13 percent increased the room and elevated temperature strength of this steel such that its strength was equivalent to that of Type 304 steel in both the welded and unwelded condition.

The results of room and elevated temperature tension tests on product from four commercial heats of high-nitrogen (0.12 to 0.16 percent) Type 304 steel indicated that the yield and tensile strength of this steel was significantly increased. Creep-rupture tests were too limited to assess the effect of nitrogen on the creep-rupture strength of the steel. Some failures on punch marks of the creep-rupture test specimens were observed suggesting the possibility of some notch sensitivity in this steel.

The results of a limited study on laboratory heats of Type 316L containing nitrogen in the range 0.02 to 0.19 percent indicated a significant increase in the elevated temperature yield and tensile strength of this steel. The creep-rupture strength at 1300 F also increased with increasing nitrogen content.

KEY WORDS: nitrogen, creep rupture strength, austenitic stainless steel, tensile strength, welding, stresses

The results of many investigations reported in the literature indicate that nitrogen in solid solution markedly increases the strength of austenitic stainless steels. Accordingly, as part of an extensive program to develop high strength steels, the U. S. Steel Research Laboratory has studied the effect of nitrogen on the mechanical properties of austenitic stainless steels, such as AISI Types 304 and 304L stainless steels. The initial studies were concerned with the development of a Type 304L steel with a strength equiv-

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TABLE 1—*Compositions of stainless steels investigated, percent (Check Analyses).*

Steel	Heat No.	C	Mn	P	S	Si	Ni	Cr	N
				High-nitrogen Type 304L					
A	X18338	0.030	1.47	0.022	0.024	0.64	9.72	19.13	0.10
B	X18342	0.025	1.63	0.026	0.025	0.55	9.87	18.87	0.13
				Regular Type 304					
C	X20792	0.070	1.62	0.026	0.026	0.79	9.51	18.66	0.04

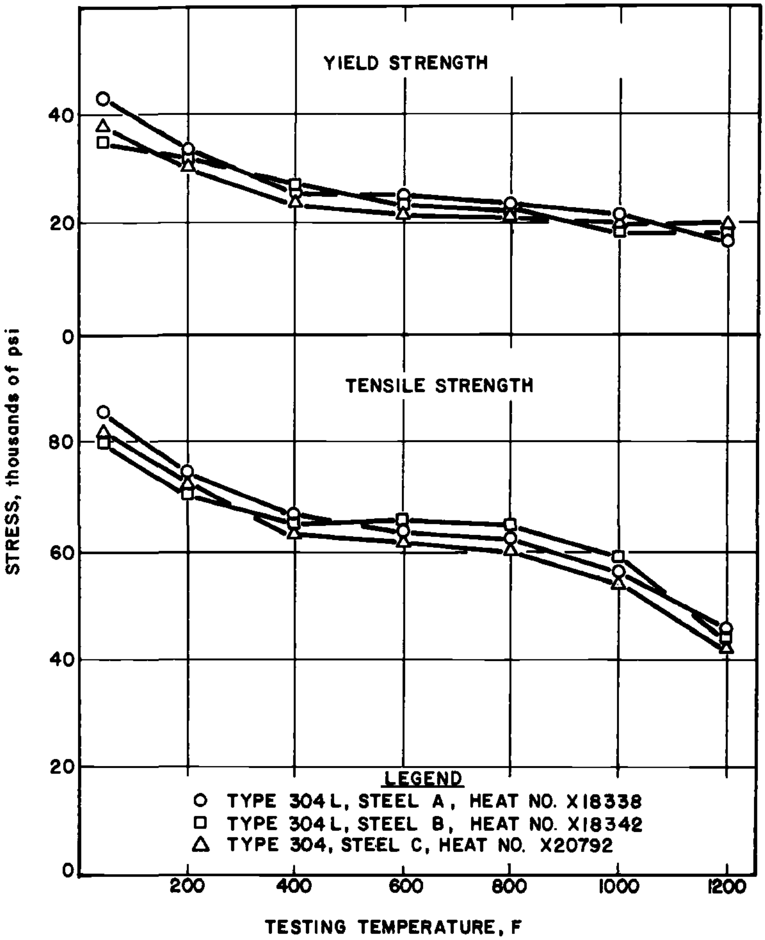

FIG. 1—*Effect of temperature on the yield and tensile strengths of annealed high-nitrogen Type 304L and regular Type 304 steels. (To convert ksi to megapascals, multiply by 6.894757).*

TABLE 2—*Creep-rupture strength of Types 304LN and 304 stainless steels* [1].

Steel	1000-h Rupture Strength, at Test Temperature			
	900 F (482 C)	1100 F (593 C)	1300 F (704 C)	1500 F (816 C)
	Type 304LN			
	ksi (MPa)	ksi (MPa)	ksi (MPa)	ksi (MPa)
A	52.0 (359)	27.0 (186)	11.5 (79.3)	4.6 (31.7)
B	52.0 (359)	26.0 (179)	11.0 (75.8)	4.7 (32.4)
	Type 304			
C	54.0 (372)	27.5 (190)	11.5 (79.3)	5.6 (38.6)

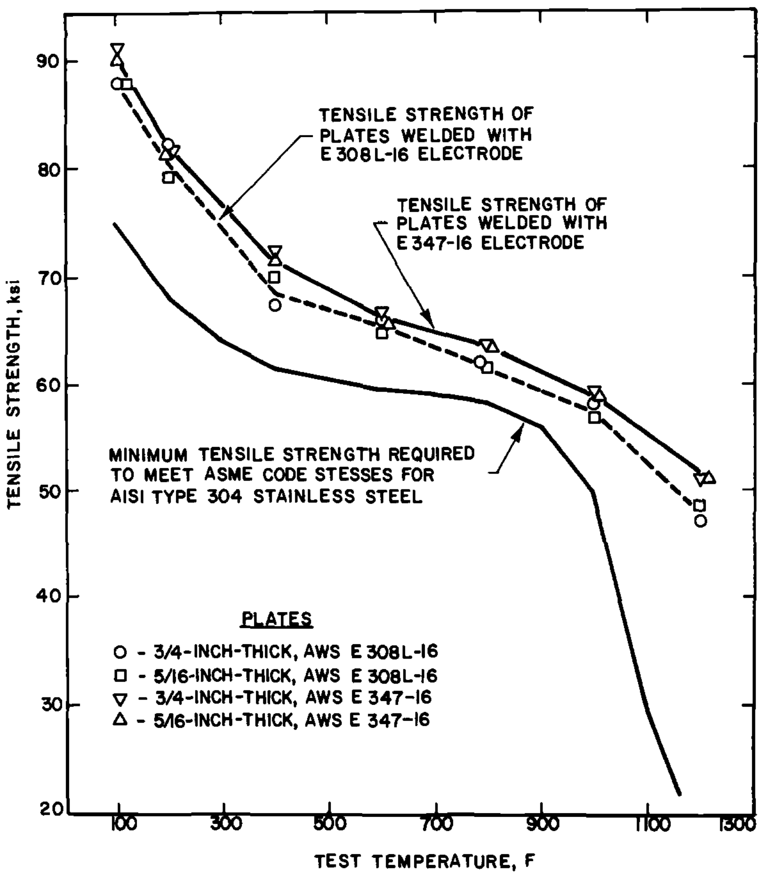

FIG. 2—*Comparison of tensile strength of welded high-nitrogen Type 304L stainless steel plates with that required to meet ASME code stresses for AISI 304 stainless steel. (To convert ksi to megapascals, multiply by 6.894757).*

TABLE 3—*Chemical compositions of the commercial stainless steels investigated, percent.*

Steel	Heat No.	C	Mn	P	S	Si	Cu	Ni	Cr	N
D	X24189	0.05	1.53	0.025	0.015	0.52	0.09	9.40	18.77	0.16
E	X24191	0.05	1.46	0.025	0.011	0.48	0.10	9.30	18.48	0.13
F	X24216	0.04	1.45	0.025	0.017	0.62	0.10	9.40	18.52	0.14
G	X24225	0.04	1.63	0.025	0.012	0.50	0.09	9.60	18.18	0.12

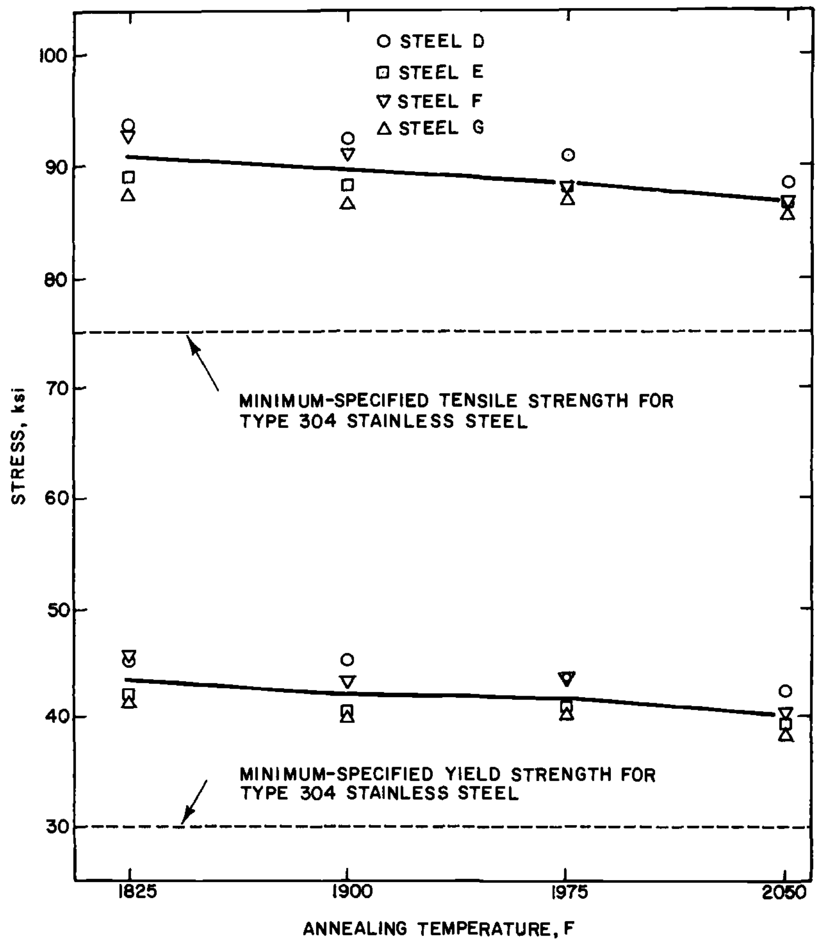

FIG. 3—*Effect of annealing temperature on the room temperature yield and tensile strengths of Type 304N stainless steel. (To convert from ksi to megapascals, multiply by 6.894757).*

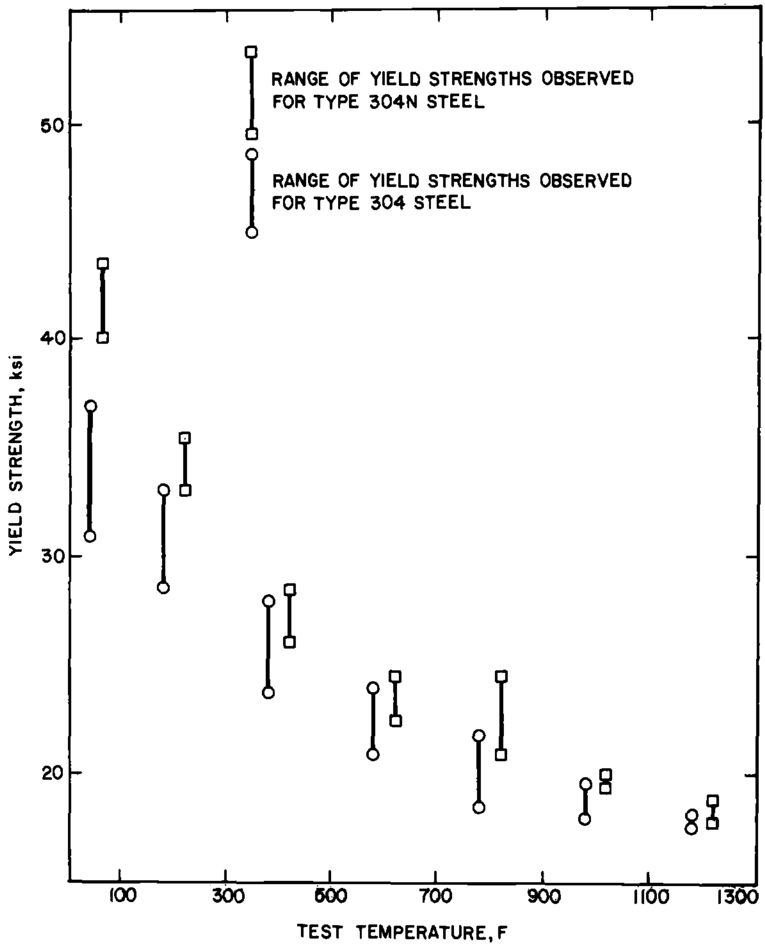

FIG. 4—*Comparison of the room and elevated temperature yield strengths of Types 304N and Type 304 stainless steels. (To convert from ksi to megapascals, multiply by 6.894757).*

alent to that of the regular grade Type 304 steel. In these studies [*1*][2], three 3-in. thick plates from commercial heats (compositions shown in Table 1) were investigated. Note that the steels differ significantly only with respect to carbon and nitrogen. Type 304LN steel contained 0.10 to 0.13 percent nitrogen compared with 0.04 percent for the Type 304 steel, and Type 304LN steel contained 0.03 and 0.025 percent carbon compared with 0.07 percent for the Type 304 steel.

A comparison of the yield and tensile strengths of the three steel plates is shown in Fig. 1. Over the temperature range investigated from room

[2] The italic numbers in brackets refer to the list of references appended to this paper.

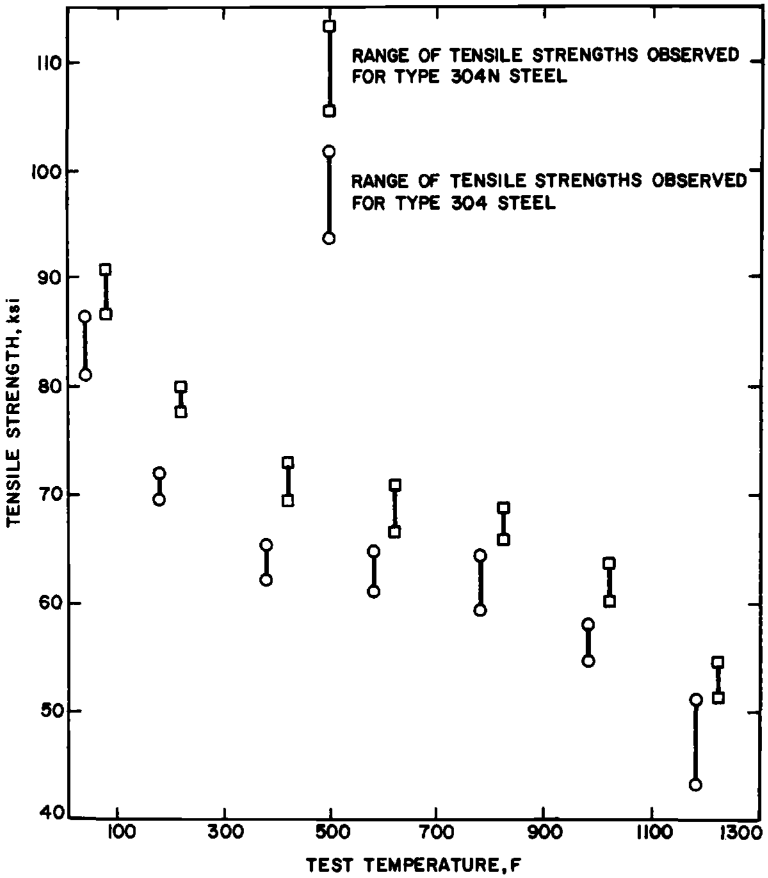

FIG. 5—*Comparison of the room and elevated temperature tensile strengths of Types 304N and 304 stainless steels. (To convert from ksi to megapascals, multiply by 6.894757).*

temperature through 1200 F (649 C), the strength of the Type 304LN steel is about the same as that of the Type 304 Steel.

Table 2 presents a comparison of the 1000-h rupture strength of the three steels at 900, 1100, 1300, and 1500 F (482, 593, 704 and 816 C) [*1*]. These data indicate that in the range 900 to 1300 F (482 to 704 C) the 1000-h rupture strength of the steels is about the same. However, at 1500 F (816 C), Type 304 steel is stronger than Type 304LN steel. This is consistent with results in the literature, which indicate that the strengthening effect of nitrogen decreases with increasing temperature.

Because of the importance of weldability of these high-nitrogen steels in pressure vessel applications, plate specimens of the Type 304LN steel were welded by the manual metal-arc process with AWS E308L-16 and E347-16 electrodes. The plates were welded and evaluated in accordance with

TABLE 4—*Results of creep and creep-rupture tests on Type 304N stainless steel.*

Test Temperature, deg F (deg C)	Stress, ksi (MPa)	Time to Rupture, h	Elongation in 1 in. (25.4 mm), %	Reduction of Area, %	Minimum-Creep Rate, %/h
			Steel F		
1200 (649)	35.0 (241)	99.0	13[a]	28.8	ND[b]
	30.0 (207)	443.1	13[a]	26.0	0.00688
	27.5 (190)	902.5	10[a]	20.0	0.00350
	25.0 (172)	1411.9	9[a]	18.4	0.00152
	22.5 (155)	3197.5	10[a]	16.0	0.00113
	20.0 (138)	5197.0	10[a]	21.1	0.00069
1300 (704)	25.0 (172)	76.5	14[a]	30.8	ND
	20.0 (138)	360.7	21[a]	30.8	0.0218
	17.5 (121)	799.6	31	34.1	0.0128
	15.0 (103)	1849.4	27[a]	33.4	0.00502

[a] Failed at gage marks.
[b] ND = not determined.

TABLE 5—*Chemical compositions of stainless steels investigated, percent.*

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	N
					Type 316L				
H	0.03	1.45	0.01	0.014	0.63	12.5	17.0	2.44	0.02
					Type 316LN				
I	0.02	1.46	0.008	0.013	0.57	12.3	16.6	2.50	0.10
J	0.02	1.51	0.008	0.007	0.58	12.2	16.8	2.48	0.14
K	0.02	1.49	0.008	0.011	0.56	12.0	17.0	2.47	0.19

TABLE 6—*Effect of nitrogen on the 1300 F (704 C) creep-rupture properties of Type 316L stainless steel.*

Nitrogen Content, %	Stress, for Rupture in 1000 h	Stress, for Rupture in 10 000[a] h
	ksi (MPa)	ksi (MPa)
0.02	12.0 (82.7)	9.4 (64.8)
0.10	15.0 (103)	10.0 (68.9)
0.19	17.0 (117)	11.0 (75.8)

[a] Extrapolated values.

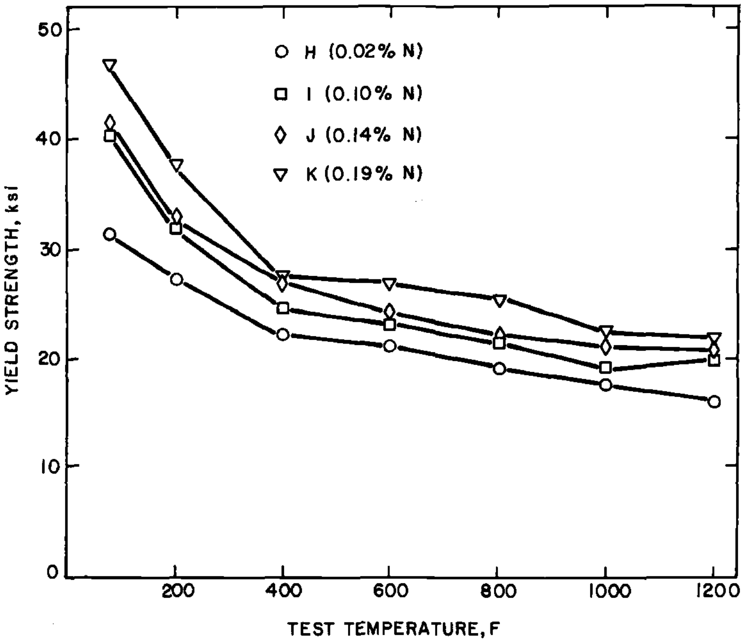

FIG. 6—*Effect of test temperature on the yield strength of Type 316L stainless steel containing nitrogen. (To convert from ksi to megapascals, multiply by 6.894757).*

American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section IX, Welding Qualification. All the welds were sound and exhibited room temperature tensile strengths in the range 88 to 91 ksi (607 to 627 MPa). Shown in Fig. 2 are the results of room and elevated temperature tension tests on specimens machined from the welded plates. Also shown in this figure are the tensile properties required to meet the present ASME code stresses for Type 304 steel. The results of these tests indicate that the strength of the welded Type 304LN plates exceeds the ASME strength requirements for Type 304 steel. Thus, it is concluded that the addition of a small amount of nitrogen to Type 304L steel generally increases its yield and tensile strengths to about the same level as regular Type 304 steel.

Additional studies were conducted to compare the properties of Type 304N steel with Type 304 steel. The chemical compositions of four commercial heats of Type 304N steel that were used in these studies are presented in Table 3. The compositions are typical of regular Type 304 steel except for the nitrogen content, which was 0.12 to 0.16 percent.

The effect of annealing temperature on the room temperature yield and tensile strengths of these Type 304N steels is shown in Fig. 3. Note that the yield and tensile strengths decrease slightly with increasing annealing tem-

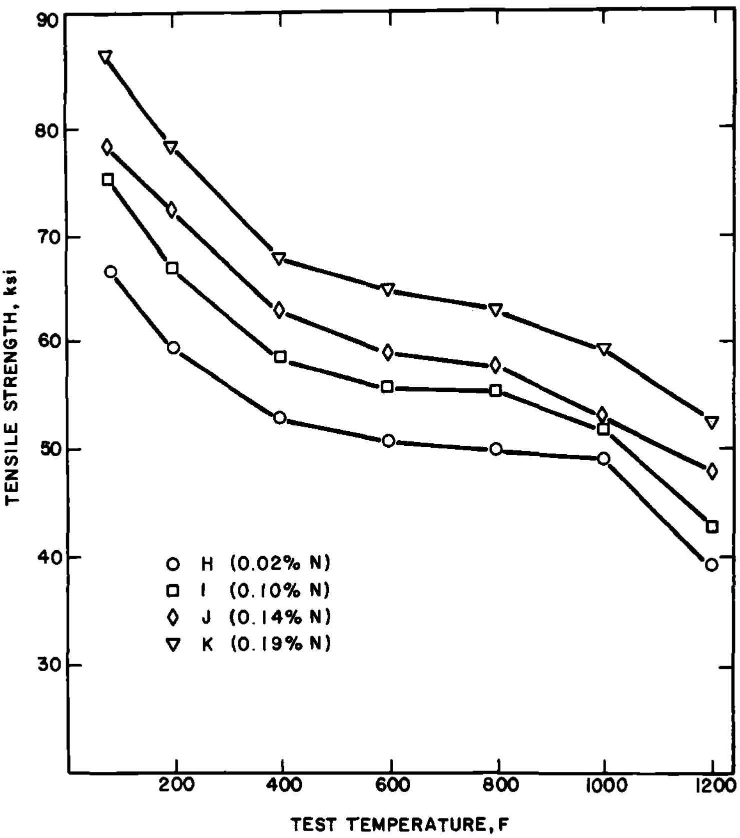

FIG. 7—*Effect of test temperature on the tensile strength of Type 316L stainless steel containing nitrogen. (To convert ksi to megapascals, multiply by 6.894757).*

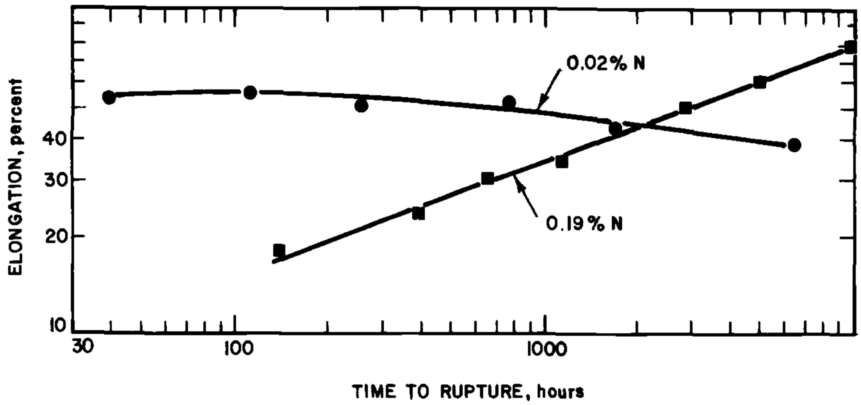

FIG. 8—*Creep-rupture elongation at 1300 F (704 C) for Type 316L stainless steel containing 0.02 and 0.19 percent nitrogen.*

perature, but that the strengths at all annealing temperatures are considerably above the strength requirements of the current American Society for Testing and Materials (ASTM) specifications for Type 304 steel.

A comparison of the yield strength of Type 304N steel with the yield strengths reported in the literature [2] for seven heats of Type 304 steel is shown in Fig. 4. The Type 304 data were obtained on annealed bar, plate, tubing, and pipe that, insofar as could be determined, had not been subjected to significant amounts of cold work after the final anneal. Cold work introduced by straightening operations can markedly affect the yield strength of Type 304 steel.

As shown in Fig. 4, the range of yield strengths observed for the Type 304N steel is above the top of the range observed for Type 304 steel at room temperature and 200 F (93 C). For example, at room temperature the range for Type 304N steel is 40.1 to 43.6 ksi (276 to 301 MPa) compared with the range of 31 to 36.9 ksi (214 to 254 MPa) for Type 304 steel. Between 400 and 1200 F (204 to 649 C), the range of yield strengths observed for the Type 304N steel overlaps the high side of the range of yield strengths observed for the Type 304 steel. A similar comparison for tensile strength is shown in Fig. 5. The range of tensile strengths for Type 304N steel is considerably above the top of the range observed for Type 304 steel at all temperatures in the range between room temperature and 1200 F (649 C). Therefore, these data indicate that the addition of nitrogen significantly increases the yield and tensile strengths of Type 304 steel.

Creep-rupture test data at 1200 and 1300 F (649 and 704 C) for one of the Type 304N steels are presented in Table 4 [1]. Note that most of the failures occurred on the punch marks. Because failure on punch marks is also indicative of low notched-bar creep-rupture strength, the effect of nitrogen on the elevated temperature ductility requires additional study. With regard to the effect of nitrogen on the creep-rupture strength, an assessment of the effect has been deferred until the results of additional testing are completed.

Studies also have been made on the effect of nitrogen on the elevated temperature properties of laboratory heats of Type 316L steel. The compositions of the steels investigated are shown in Table 5. Note that the nitrogen content of the four steels varies from 0.02 to 0.19 percent. A plot of the yield strength versus test temperature for the four steels is shown in Fig. 6. Between room temperature and 1200 F (649 C) the yield strength increased with increasing nitrogen content. Likewise, as shown in Fig. 7, the tensile strength increased with increasing nitrogen content.

Given in Table 6 are 1000 and 10 000-h rupture strengths at 1300 F (704 C) of the 0.02, 0.10, and 0.19 percent nitrogen Type 316L steels. These data indicate a beneficial effect of nitrogen on the creep-rupture strength. As shown in Fig. 8, the elongation of 0.19 percent nitrogen steel is initially lower than the elongation of the 0.02 percent nitrogen steel. However, the elongation of the 0.19 percent nitrogen steel increased with time, whereas the elongation of the 0.02 percent nitrogen steel decreased slightly with time, such that for times greater than about 2200 h at 1300 F (704 C), the steel with the 0.19 percent nitrogen content exhibited higher elongation compared with the 0.02 percent nitrogen steel. The reason for this divergent behavior is not understood.

In summation, the results of these studies indicate a general beneficial effect of nitrogen on the elevated temperature strength of the austenitic steels. However, failure on punch marks in some of the creep-rupture tests suggest the possibility of some notch sensitivity in Type 304N steel.

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P. D. Goodell[1] *and J. W. Freeman*[2]

Elevated Temperature Properties of Nitrogen-Containing Type 304L Austenitic Stainless Steel

REFERENCE: Goodell, P. D. and Feeman, J. W., "**Elevated Temperature Properties of Nitrogen-Containing Type 304L Austenitic Stainless Steel,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522,* American Society for Testing and Materials, 1973, pp. 46–59.

ABSTRACT: Experimental heats of Type 304L steel, compositionally balanced to be wholly austenitic, were prepared to determine the influence of nitrogen on elevated temperature properties of this steel. Nitrogen is shown to increase the 1200 F (649 C) and 1350 F (732 C) yield strength slightly and to increase markedly the creep and rupture strength at 1200 F (649 C). The effect of nitrogen on creep and rupture strengths at 1350 F (732 C) and 1500 F (816 C), however, is less pronounced. A beneficial effect of nitrogen on creep and rupture properties at 1200 F (649 C) is attainable from a considerable range of heat treatments and grain sizes.

KEY WORDS: nitrogen, austenitic stainless steel, creep properties, yield, high temperature, grain size, heat treatment, rupture strength

The elevated temperature properties of the nonstabilized 300 Series stainless steels can be affected by several major and minor element compositional factors. Among these, nitrogen has been considered by numerous investigators and, at temperatures of about 1200 F (649 C), has been reported to improve creep-rupture strength [*1–12*].[3] The magnitude of this strengthening, however, varies for the different circumstances considered. When expressed, for example, using the 1000-h rupture strength at 1200 F

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[3] The italic numbers in brackets refer to the list of references appended to this paper.

(649 C) as a common basis for comparison, the estimated increment of strengthening per 0.01 percent nitrogen ranges from 250 to 1000 psi (1.72 to 6.89 MPa). Additionally, various reports indicate comparisons of less, equal, and greater strengthening due to nitrogen than carbon.

In a previous paper by the present authors and T. M. Cullen, nitrogen was considered along with several other elements influencing the creep-rupture properties of Type 304 steel [*10*]. The magnitude of increase of the 1000-h rupture strength at 1200 F (649 C) was found to be 950 psi (6.55 MPa) per 0.01 percent nitrogen up to about 0.14 percent; this was determined independently of the influence of carbon which was approximately 25 percent less effective. The alloy examined was balanced to be wholly austenitic and, except for the low carbon content, was representative in base alloy chemistry of compositions used in the manufacture of seamless tubing for elevated temperature service.

The preceding results represent behavior particular to nitrogen in the absence of such other factors as austenite/ferrite balance, manganese level, and carbon effects. In light of this rather substantial strengthening influence, further work was undertaken to characterize more fully the behavior and to determine the manner in which nitrogen was operative [*13*]. The present paper considers the results indicating the influence of nitrogen on yield strength and minimum creep rate, as well as creep-rupture characteristics. Properties were evaluated at 1200 (649 C), 1350 (732 C), and 1500 F (816 C), and effects of grain size and temperature of heat treatment are included.

Experimental Procedure

The nominal composition (in weight percent) of the alloy base used in this investigation is as follows:

Cr	Ni	Mn	Si	C
18.5	10.5	1.5	0.5	0.03

This analysis was selected to provide a wholly austenitic structure and is typical (except for carbon) of Type 304 steel as usually balanced for elevated temperature service for seamless tubing. Heats of this base composition were prepared in which the nitrogen content was systematically varied from 0.01 to 0.22 percent. These limits were dictated, respectively, by the residual nitrogen of the melt stock and by the solubility limit of nitrogen in the liquid alloy during melting. The actual compositions are given in Table 1.

The alloys were prepared as 10-lb, (4.54-kg) carbon deoxidized, vacuum induction melts which were poured into 5-lb (2.27-kg) ingot molds approximately 2 in. (51 mm) in diameter. The ingots were 5 in. in length after discard of the hot top. Virgin melt stock was used consisting of electrolytic

TABLE 1—*Composition of the experimental heats.*

Heat No	Chemical Composition[a] (weight percent)					
	C	N	Mn	Ni	Cr	Si
1310A	0.01	0.01[b]	1.42	10.38	18.46	0.46
1470A	0.02[c]	0.023	1.5[c]	10.5[c]	18.5[c]	0.5[c]
1468A	0.02	0.037	1.5	10.70	18.40	0.44
1470B	0.02	0.038	1.48	10.60	18.42	0.42
1361A	0.03	0.051	1.56	10.95	18.06	0.5[c]
1470C	0.02[c]	0.087	1.5[c]	10.5[c]	18.5[c]	0.5[c]
1423A	0.03	0.115	1.72	10.60	18.60	0.46
1410A	0.03	0.14	1.60	11.00	18.57	0.52
1411A	0.03	0.14	1.5[c]	10.5[c]	18.5[c]	0.53
1343A	0.03[c]	0.145	1.5[c]	10.3[c]	18.3[c]	0.5[c]
1412A	0.03	0.17	1.66	10.85	18.37	0.51
1343B	0.02	0.18	1.62	10.00	17.92	0.48
1412B	0.03[c]	0.22	1.5[c]	10.5[c]	18.5[c]	0.5[c]

[a] In addition to the elements shown, the alloys contain residual amounts of phosphorus sulphur, and molybdenum which are typically less than 0.005, 0.007, and 0.03 percent, respectively.
[b] No intentional addition.
[c] Estimated values based on the aim analysis, comparison to other half of split heat, comparison to similar heats, and melting experience.

iron, nickel and manganese, aluminum-reduced chromium, and ferrosilicon. Nitrogen additions were made during the latter stages of melting by adding chromium-nitride powder or by way of pickup from a nitrogen atmosphere introduced into the furnace chamber or both.

The ingots were hot rolled at 2150 F (1177 C) to 1-in. (25-mm) square bars. After hot rolling and sampling for chemical analyses, the bars were cold rolled to 0.7-in. (18-mm) square bars, heat treated for ½ h at 2050 F (1121 C) and water quenched. These bars were given a final cold reduction of 50 percent in cross-sectional area to produce ½-in. (12.7-mm) square bar. Specimen blanks were cut from this bar, given a final heat treatment, and water quenched; unless specified otherwise, this heat treatment was for ½ h at 2050 F (1121 C) with water quench. Grain sizes following this treatment were between ASTM 5 and 4. These final procedures approximate the production of seamless tubing.

Creep-rupture tests were conducted using specimens having a 1-in. (25-mm) reduced section gage length of 0.250 in. (6.35 mm) diameter. Tests were of the constant load type and were conducted in simple beam or direct loaded individual test units. Elongation measurements were made using a modified Martens-type rotating mirror extensometer affixed to the specimen shoulder. Strain was corrected to that of the reduced section gage length.

Creep-rupture tests at 1200 F (649 C) were conducted at stress levels corresponding to rupture times ranging from about 50 to 2000 h. Additional, though less extensive, tests were carried out at 1350 F (732 C) and 1500 F (816 C). Stress-strain measurements on loading the creep tests were used to indicate the 0.2 percent offset yield strengths and work hardening trends. The minimum creep rate and time to rupture were the principal quantities determined from the creep-rupture tests; from these, 1000-h rupture strengths and 0.01 percent per hour creep strengths were derived for each alloy.

Results and Discussion

Yield Behavior

At 1200 F (649 C) the yield strength was found to be controlled by nitrogen content and grain size but was not independently influenced by the temperature of heat treatment. This is shown by the results in Fig. 1 which combines the loading results from numerous creep-rupture tests of several alloys. These data also indicate no discernible influence of nitrogen on the work hardening characteristics of this alloy; this fact was also confirmed by the stress dependence of the initial strain of the creep tests.

The magnitude of the influence of nitrogen on yield strength was similar at both 1200 F (649 C) and 1350 F (732 C), corresponding to an increase of 250 psi (1.72 MPa) per 0.01 percent nitrogen; the effect of nitrogen was considerably less at 1500 F (816 C). These effects are indicated by the results in Fig. 2. Recognizing slight variations in the grain sizes of various alloys, the yield strengths have been corrected to a common grain size. This correction was of the conventional Petch-Hall form, and the constants were determined from among the experimental data.

Creep and Rupture Strengths

Creep resistance at 1200 F (649 C) was markedly improved by increasing nitrogen content in the base alloy considered. Figure 3 illustrates the strengthening in terms of the stress to produce a minimum creep rate of 0.01 percent per hour.[4] This creep strength was increased by 950 psi (6.55 MPa) for each 0.01 percent nitrogen up to about 0.14 percent nitrogen; at higher nitrogen levels the effect was less pronounced. In contrast to the behavior at 1200 F (649 C), the effect of nitrogen was considerably less at 1350 F (732 C) and 1500 F (816 C). The stress sensitivity of the minimum creep rate was also found to depend on nitrogen content. Values for a power

[4] This value is within the measured range of data and does not require extrapolation. Examples of several typical creep curves, as well as minimum creep rate and rupture time data, will be presented in Figs. 6 and 7, in conjunction with heat treatment and grain size effects.

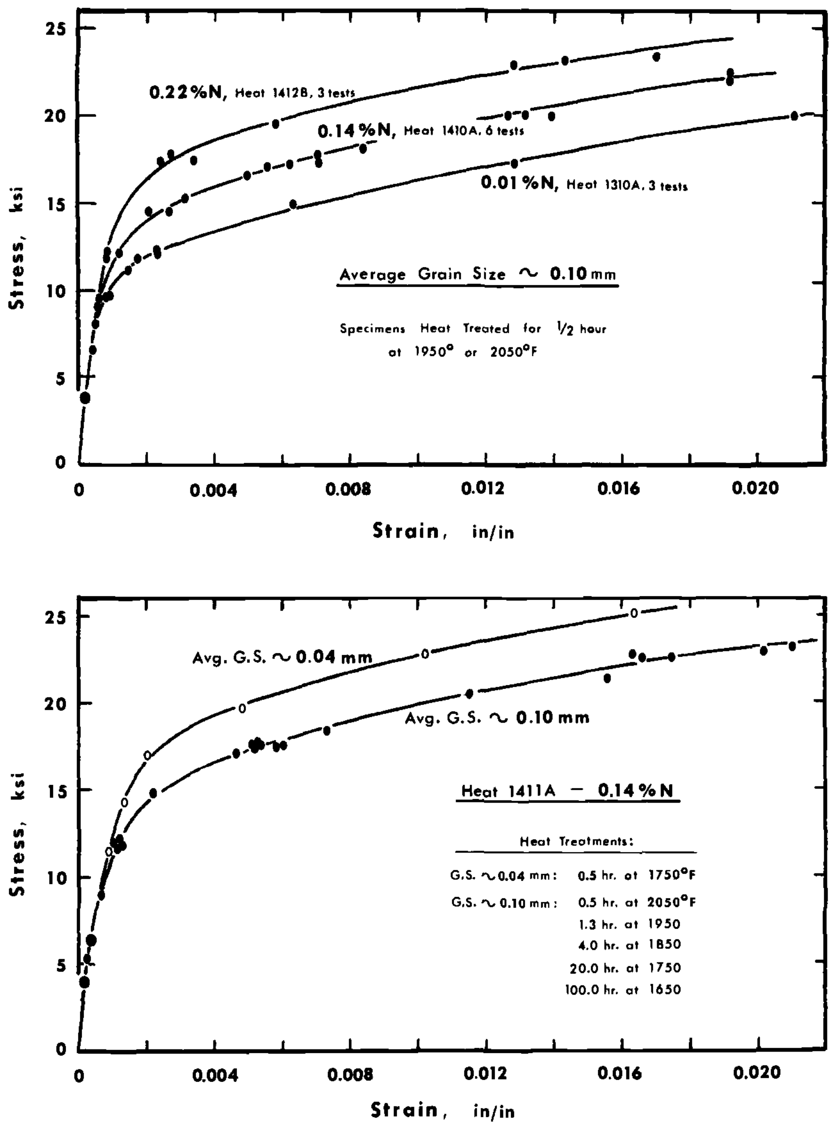


FIG. 1—*Influence of nitrogen content and grain size on the 1200 F (649 C) stress-strain characteristics of several heats. These data are taken from loading of the creep-rupture tests. (To convert ksi to megapascals, multiply by 6.894757).*

law stress exponent are included in Fig. 3. These data indicate a maximum stress sensitivity at between 0.09 and 0.14 percent nitrogen at 1200 F (649 C). A significant consequence of this maximum is that at lower creep rates a more pronounced inflection would be apparent at about 0.14 percent

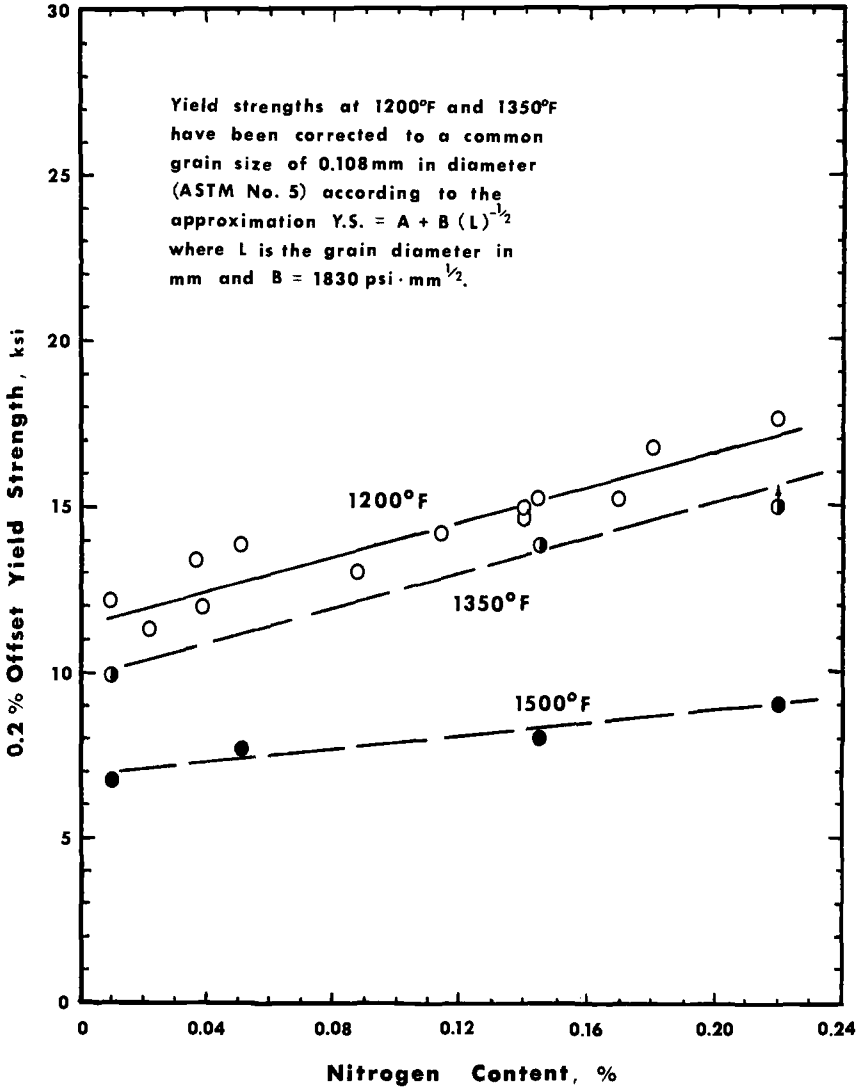


FIG. 2—*Influence of nitrogen on the 0.2 percent offset yield strength of the nitrogen series heats at 1200, 1350, and 1500 F (649, 732, and 816 C). (To convert ksi to megapascals, multiply by 6.894757).*

nitrogen than is indicated in Fig. 3.[5] Thus, optimum long time creep resistance for this particular alloy base would probably fall within this intermediate range of nitrogen content.

[5] Stress sensitivity of the minimum creep rate was based on engineering stress and strain relative to the initial dimension of the test specimen and applied load which was constant. Expressed in terms of true instantaneous stress and strain rates, the absolute values for stress sensitivity were lower than when expressed in engineering terms, but also decreased as nitrogen was increased above 0.14 percent.

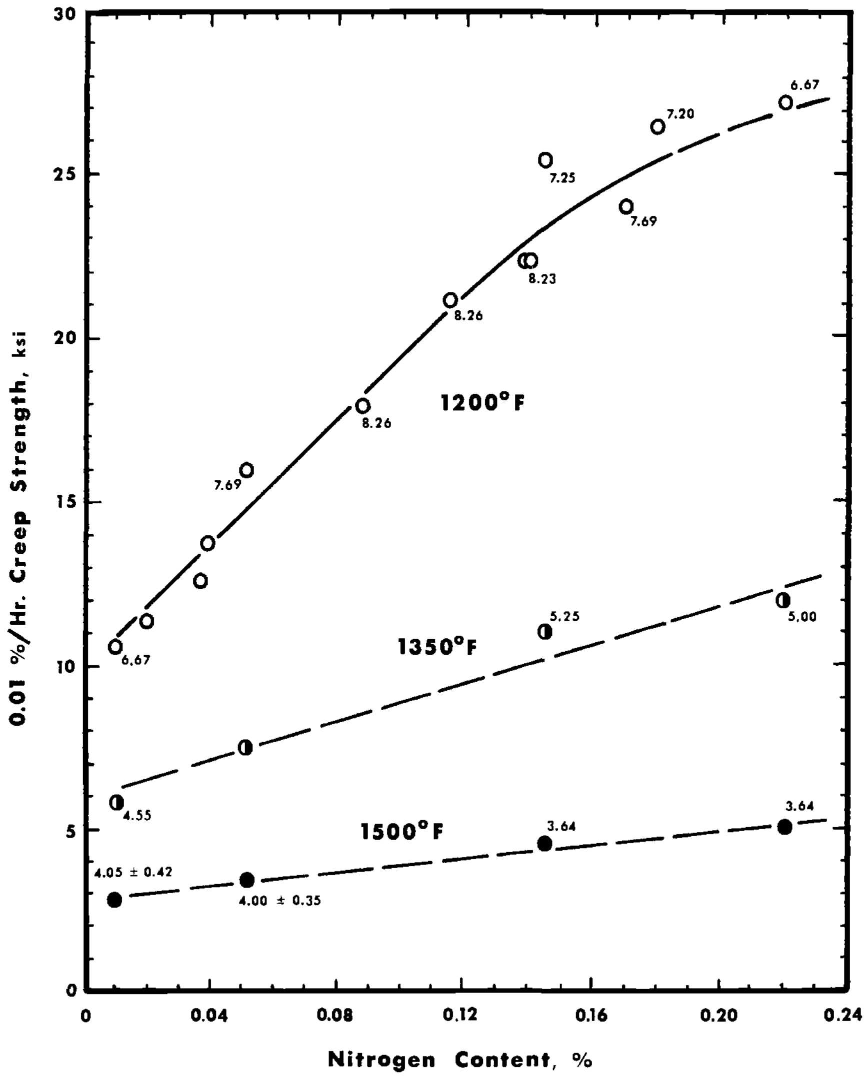


FIG. 3—*Influence of nitrogen on the 0.01 percent per hour creep strength (based on minimum creep rate) of the nitrogen series heats at 1200, 1350, and 1500 F (649, 732, and 816 C). The numbers adjacent to the symbols are the stress exponent n for the relation* $e = A\sigma^n$ *at a minimum creep rate of 0.01 percent per hour. (To convert ksi to megapascals, multiply by 6.894757).*

The influence of nitrogen on the 1000-h rupture strength appears, in Fig. 4, to be similar to that on the 0.01 percent per hour creep strength (Fig. 3). At 1200 F (649 C) the 1000-h rupture strength increased by 950 psi (6.55 MPa) for each 0.01 percent nitrogen up to about 0.14 percent; thereafter the effect of increasing nitrogen was much less. At 1350 F (732 C) and 1500 F

(816 C), the effect of nitrogen over the entire composition range was considerably less pronounced than at 1200 F (649 C). Smith et al [*4*] and Kawabe et al [*11*] have also reported a decrease in strengthening influence of nitrogen with increasing temperature. In each of these cases, however, the behavior was at least partially associated with interrelated effects of high carbon levels.

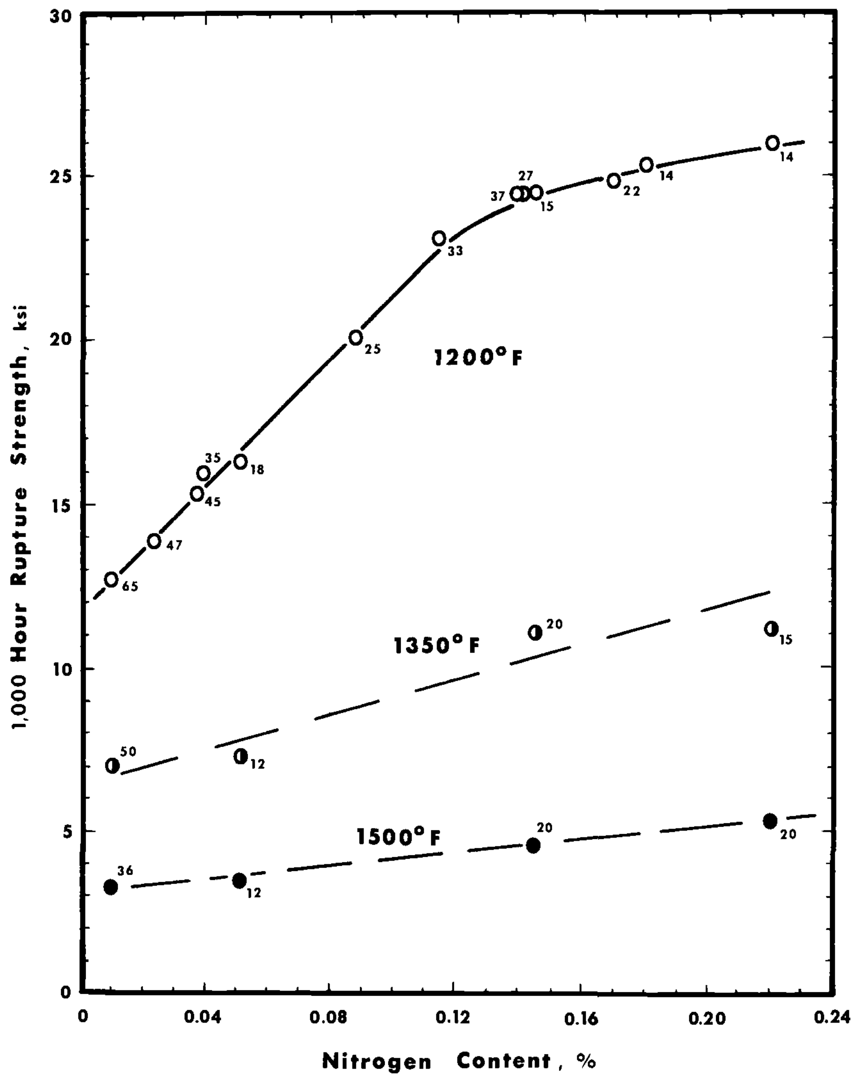


FIG. 4—*Influence of nitrogen on the 1000-h rupture strength of the nitrogen series heats at 1200, 1350, and 1500 F (649, 732, and 816 C). The numbers adjacent to the symbols are the estimated elongation for rupture in 1000 h. (To convert ksi to megapascals, multiply by 6.894757).*

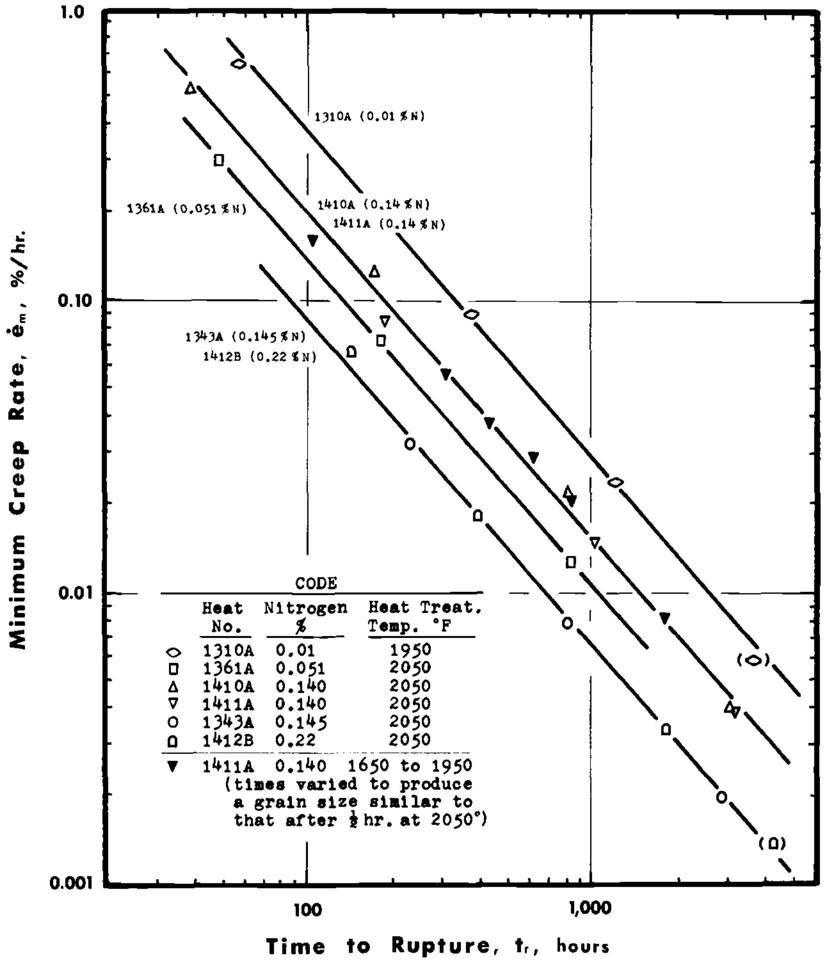


FIG. 5—*Examples illustrating the type of relationship between minimum creep rate and time to rupture of tests of the nitrogen series heats at 1200 F (649 C).*

Figure 4 also indicates the percent elongation on rupture in 1000 h. These values exhibit a generally decreasing trend with increasing nitrogen content. Despite this trend, the elongation remains quite high within the regime of 1200 F (649 C) for which the strengthening influence of nitrogen is greatest; only one anomalously low value was noted at less than 0.14 percent nitrogen. At nitrogen levels above about 0.14 percent, elongation was generally lower.

Stress exponents at 1000 h for a power function relation between rupture life and stress were slightly less than those given for the minimum creep rate in Fig. 3, but they exhibited a similar maximum in the intermediate range of nitrogen contents. A direct comparison between minimum creep rate and rupture life is presented in Fig. 5, which is based on data over a wide range of stress and nitrogen levels. A power function correlation is indicated with creep rate proportional to rupture life to the −1.15 power for all material examined. The proportionality factor appears primarily dependent on nitrogen content and slightly dependent on grain size (see following section). Thus, Fig. 5 corroborates that creep and rupture processes under these conditions are closely related and similarly affected by nitrogen content.

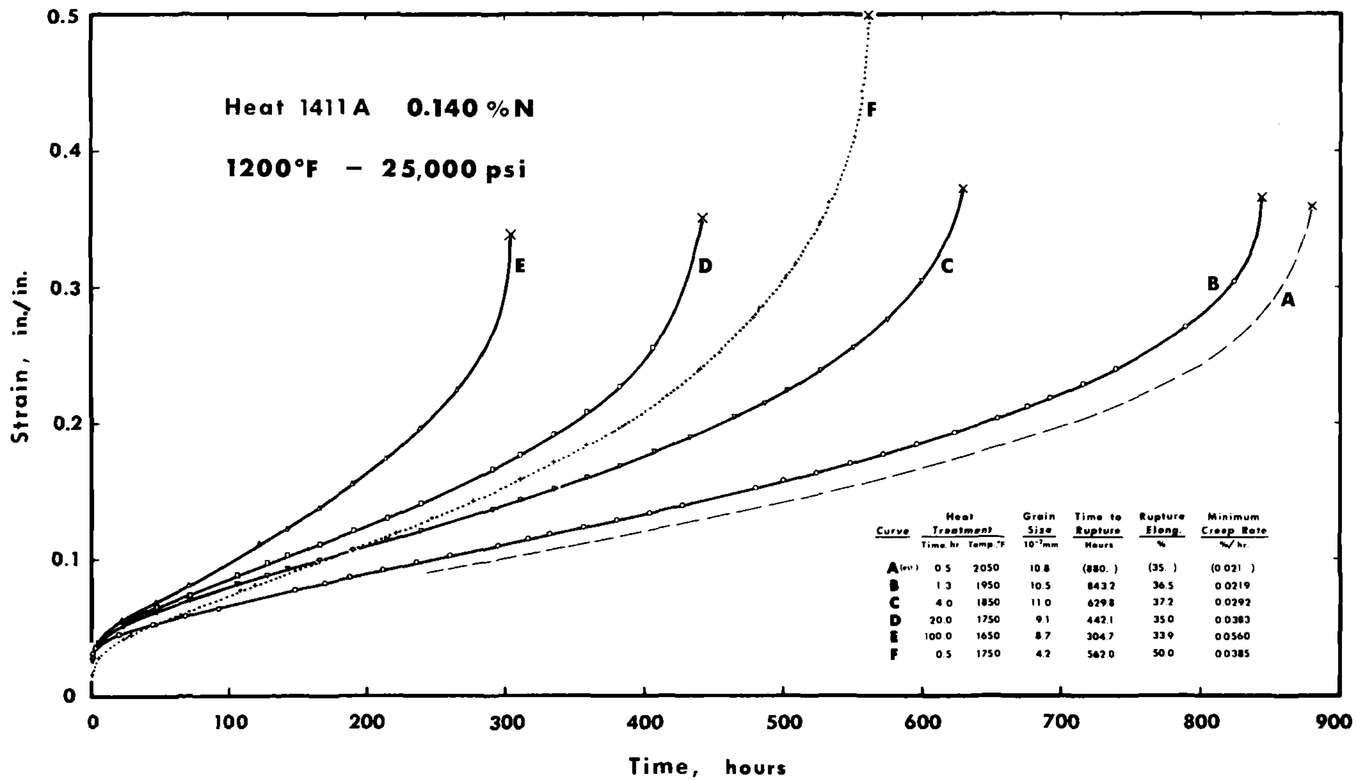
Taken together, the characteristics illustrated in Figs. 3, 4, and 5 indicate the influence of nitrogen at 1200 F (649 C) to be characterized by two regimes of behavior. These are distinguished by strengthening magnitude, ductility and stress sensitivity of creep rate, and rupture life. The most advantageous combination of these characteristics pursuant to long time strength and ductility can be derived from the present results to be attained at about 0.14 percent nitrogen. Note, however, that alloys containing less than 0.10 percent manganese exhibited a lower strength and nitrogen level for this optimum combination of properties [*10*].[6] Hence the influence of nitrogen can be affected to some extent by base alloy chemistry and warrants further consideration.

Heat Treatment and Grain Size

Tests were performed to determine trends resulting from variations in alloy heat treatment. Figure 6 illustrates aspects of both temperature and grain size as evident in an alloy of intermediate nitrogen content. These results indicate that at nearly constant grain size, decreasing the temperature of heat treatment reduced the rupture life and increased the minimum creep rate (curves B, C, D, and E). At a fixed temperature of heat treatment (1750 F (954 C) in Fig. 6, curves D and F), the minimum creep rate was unaffected as the grain size was reduced by about one half, whereas rupture elongation and life were extended. Figure 7 provides further illustration of the effect of heat treatment and indicates essentially similar behavior in alloys of both low and intermediate nitrogen content. Consequently, the effects of temperature of heat treatment and grain size are not viewed as being characteristically related to any influence of nitrogen but, rather, are associated with behavior of the base alloy.

In contrast, alloys subject to precipitation, such as of chromium carbide in Type 304 steel [*10*] or titanium carbide in Type 321 steel [*14*], exhibit much greater sensitivity to heat treatment conditions than do the nitrogen strengthened alloys illustrated in Figs. 5 and 7. The relative independence of the influence of nitrogen from effects of heat treatment appears consistent

[6] Decreasing manganese would be expected to increase nitrogen activity, thus lowering solubility. This suggests, therefore, that the transition between the two regimes of behavior is in some way influenced by nitrogen activity. This and further relations of properties to nitrogen solubility will be considered in a subsequent publication.



Curve	Heat Treatment Time, hr	Heat Treatment Temp., °F	Grain Size 10^{-2}mm	Time to Rupture Hours	Rupture Elong. %	Minimum Creep Rate %/hr.
A(est)	0.5	2050	10.8	(880.)	(35.)	(0.021)
B	1.3	1950	10.5	843.2	36.5	0.0219
C	4.0	1850	11.0	629.8	37.2	0.0292
D	20.0	1750	9.1	442.1	35.0	0.0383
E	100.0	1650	8.7	304.7	33.9	0.0560
F	0.5	1750	4.2	562.0	50.0	0.0385

FIG. 6—*Comparison of the effect of heat treatment and grain size on the creep curves at 1200 F (649 C) and 25 000 psi (172 MPa) of a 0.140 percent nitrogen heat (Heat 1411A).*

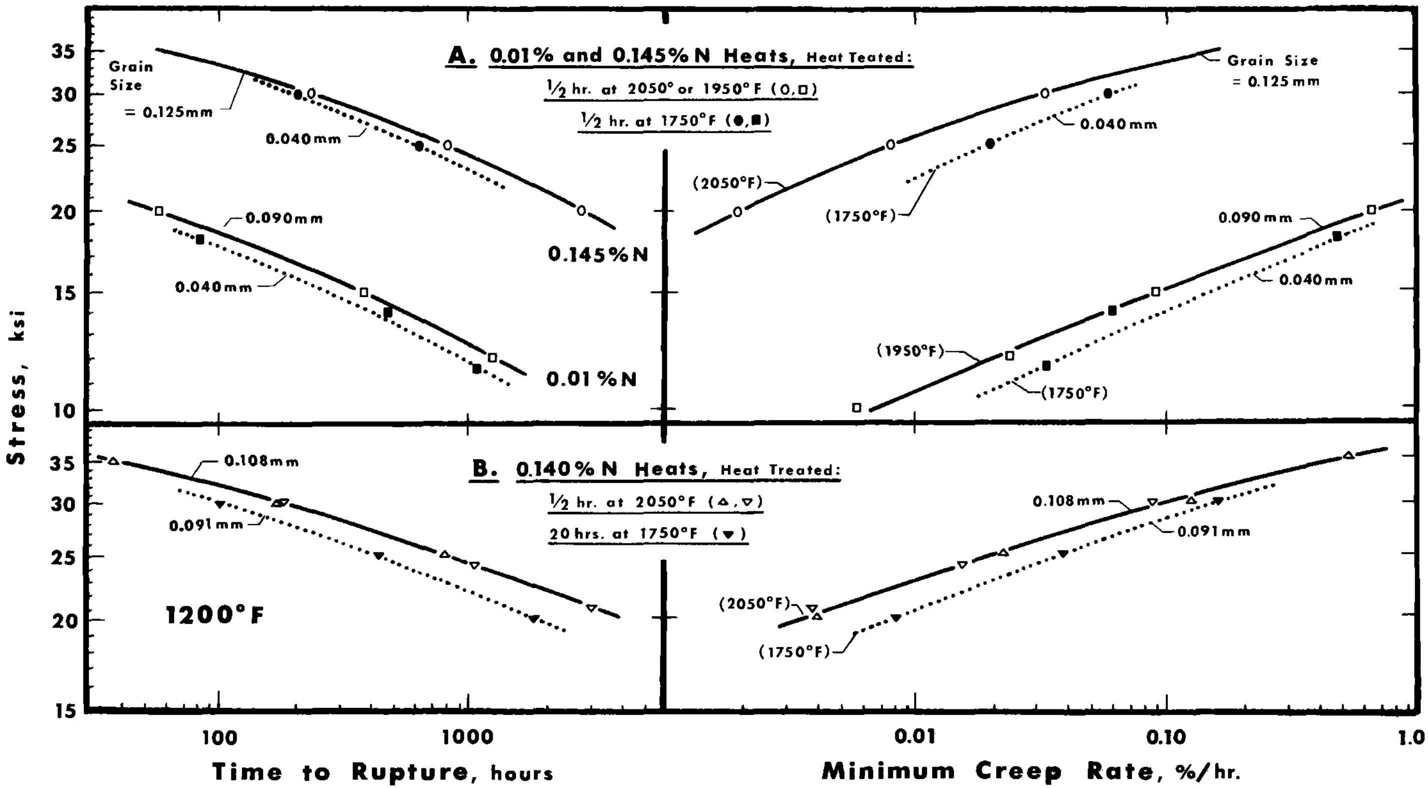


FIG. 7—*Comparison of the effects of heat treatment and grain size on creep and rupture characteristics at 1200 F (649 C) of heats of two nitrogen levels (Heats 1310A, 1411A, and 1343A). (To convert ksi to megapascals, multiply by 6.894757).*

with the reported high solubility of nitrogen [*15, 16*] at the heat treating temperatures employed. As a result, a strengthening influence of nitrogen may be attainable with a wide range of processing conditions.

Summary

The influence of nitrogen on elevated temperature mechanical properties has been examined in a wholly austenitic stainless steel alloy base of 18.5Cr–10.5Ni–1.5Mn–0.5Si–0.02C. The following conclusions are drawn:

1. The effect of nitrogen on creep and rupture properties at 1200 F (649 C) resulted in two regimes of behavior with the strengthening effect of nitrogen being quite pronounced at levels below 0.14 percent nitrogen. For this alloy base, optimum long time properties are expected at nitrogen levels of about this value, or slightly less.
2. Nitrogen has only a small strengthening effect on high temperature yield strength.
3. Nitrogen offers only limited benefit to creep and rupture properties at 1350 F (732 C) and 1500 F (816 C).
4. Low carbon, nitrogen-strengthened heats exhibited relative freedom from deleterious effects of heat treatment and grain size variation.

Acknowledgment

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T. M. Cullen[1] *and M. W. Davis*[1]

Influence of Nitrogen on the Creep-Rupture Properties of Type 316 Steel

REFERENCE: Cullen, T. M. and Davis, M. W., "**Influence of Nitrogen on the Creep-Rupture Properties of Type 316 Steel,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522*, American Society for Testing and Materials, 1973, pp. 60–78.

ABSTRACT: An experimental program has been conducted to determine the influence of nitrogen on the creep and rupture properties of Type 316 stainless steel. A series of commercial and laboratory heats with similar base composition but varying nitrogen contents were utilized in the study. The nitrogen content of the heats ranged from 0.039 to 0.15 percent.

The creep and rupture strengths of the steel at 1200 F increased with increasing nitrogen level. The stress for rupture in 1000 and 10 000 h was approximately 40 percent higher for the 0.15 percent nitrogen heat than for the 0.039 percent nitrogen alloy. The stress to produce a minimum creep rate of 0.01 percent per 1000 h increased by 50 percent over the same nitrogen range.

A ferrite containing heat was also tested in the program. Ferrite was shown to decrease creep resistance and increase rupture ductility. No significant influence of this phase was noted with respect to rupture strength.

Various parameter extrapolation methods were compared in their ability to predict the location of a break in the rupture curve of one of the nitrogen containing heats. Long time rupture tests were conducted to pinpoint the exact position of this change in slope.

KEY WORDS: nitrogen, creep strength, austenitic stainless steels, creep rupture strength, ferrite, microstructure, extrapolations, creep rate

As part of an effort to determine the influence of residual elements on the strength characteristics of the austenitic steels, a detailed evaluation has been made of the variation of creep-rupture properties of wrought Type 316 stainless steel with nitrogen content. Both laboratory and commercially produced materials were used in this study. Heats were selected on the

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basis of similarity of chemical composition, mechanical processing, and thermal history. The nitrogen content of the five heats used in this investigation ranged from 0.039 to 0.15 percent.

This investigation received added impetus from an American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Case to permit higher allowable stresses for nitrogen-containing grades of Types 304 and 316 steel at temperatures up to 1000 F (538 C). This case was based on improved tensile properties in steels which contain 0.10 to 0.16 percent nitrogen.

One heat of a duplex austenitic ferritic Type 316 steel was also tested in the research program. This material contained approximately 16 percent ferrite by volume. The objective of this phase of the study was to determine the influence of ferrite on long time elevated temperature strength and ductility.

Experimental Material

The alloys used in this research program, with one exception, consisted of sections of seamless superheater tubing made from centrifugally cast and tube reduced hollows. The exception was the ferrite-containing material, Heat F, which was air induction melted in the laboratory and statically cast. The resultant ingot was hot forged from 2100 F (1149 C) to a ½-in. (0.0127-m) thick slab.

The chemical compositions (in percentages by weight) of the test materials are given in Table 1. With the exception of the ferrite-containing material, the base compositions of all the materials were similar. In fact, nitrogen was the only significant variable among the first five heats listed.

All alloys evaluated in this study were heat treated in the same manner; 15 min at 1975 F (1079 C), air cooled. Following heat treatment, specimen blanks were cut from the test samples. Standard 0.252-in. (6.40-mm) uniaxial tension specimens were machined from these coupons and used for both the tensile and the creep-rupture tests.

TABLE 1—*Chemical composition of experimental materials.*

Heat	C	Mn	Si	Cr	Ni	Mo	N
A	0.042	1.55	0.50	16.25	12.55	2.62	0.039
B	0.041	1.18	0.39	16.00	11.80	2.28	0.044
C	0.042	1.47	0.50	16.20	12.05	2.43	0.070
D	0.058	1.50	0.47	16.75	12.95	2.55	0.099
E	0.041	1.55	0.36	16.71	14.25	2.58	0.15
F	0.040	1.56	0.42	19.86	8.24	2.90	0.11

TABLE 2—*Tensile properties of experimental materials.*

Test Temperature, deg F (deg C)	Ultimate Strength, ksi (MPa)	0.2% Offset Yield Strength, ksi (MPa)	Elongation in 1 in., %, (25 mm)	Reduction of Area, %
		Heat A, 0.039 percent nitrogen		
RT[a]	85.0 (586)	32.4 (223)	62	78
200 (93)	76.5 (527)	26.9 (185)	52	79
400 (204)	69.0 (476)	31.2 (214)	45	73
600 (316)	67.4 (465)	18.0 (124)	42	73
800 (427)	66.4 (458)	16.8 (116)	42	69
1000 (538)	64.3 (443)	13.8 (95.1)	45	69
1200 (649)	52.4 (361)	14.7 (101)	48	70
		Heat B, 0.044 percent nitrogen		
1200 (649)	50.0 (348)	15.6 (108)	44	72
		Heat C 0.070 percent nitrogen		
RT	86.0 (593)	37.2 (256)	63	78
200 (93)	76.3 (526)	28.8 (199)	50	80
400 (204)	71.0 (490)	24.0 (165)	47	75
600 (316)	68.8 (474)	18.0 (124)	44	73
800 (427)	67.8 (467)	16.8 (116)	45	72
1000 (538)	65.2 (450)	15.0 (103)	43	69
1200 (649)	54.6 (376)	13.8 (95.1)	44	70
		Heat D, 0.099 percent nitrogen		
RT	91.8 (633)	41.6 (287)	62	78
RT	94.0 (648)	37.2 (256)	57	78
200 (93)	83.6 (576)	31.8 (219)	54	78
400 (204)	77.6 (535)	26.4 (182)	49	75
600 (316)	76.4 (527)	21.6 (149)	47	72
800 (427)	75.2 (518)	20.8 (143)	43	68
1000 (538)	71.0 (490)	18.0 (124)	45	69
1200 (649)	58.8 (405)	16.8 (116)	47	67
		Heat E, 0.15 percent nitrogen		
RT	92.2 (636)	40.8 (281)	52	70
200 (93)	83.0 (512)	33.0 (228)	48	75
400 (204)	76.4 (527)	27.6 (190)	48	75
600 (316)	74.0 (510)	22.8 (157)	43	69
800 (427)	72.6 (501)	20.4 (141)	47	69
1000 (538)	68.0 (469)	19.0 (131)	44	66
1200 (649)	58.4 (403)	18.8 (130)	48	65
		Heat F, 16 percent ferrite		
RT	104.4 (720)	50.0 (345)	50	73
1200 (649)	55.6 (383)	27.6 (190)	50	70

[a] RT = room temperature.

Experimental Results

Varying Nitrogen Series

The results of the tension tests conducted on the various experimental alloys are shown in Table 2. Four of the five alloys which made up the nitrogen series were tested, at 200 F (111 C) increments, over a range from room temperature up to 1200 F (649 C). The results of these tests are plotted in Fig. 1. In general, both yield strength and ultimate strength at each temperature increment increased as nitrogen content increased. The differences, however, were not as great as might have been expected.

The creep-rupture test data obtained from these materials are shown in Table 3. An extensive test program was conducted on the five alloys. In each case the alloy was tested at 1200 F (649 C), and the rupture curve established out to at least 2500 h. In addition, Heat C was tested at 1300,

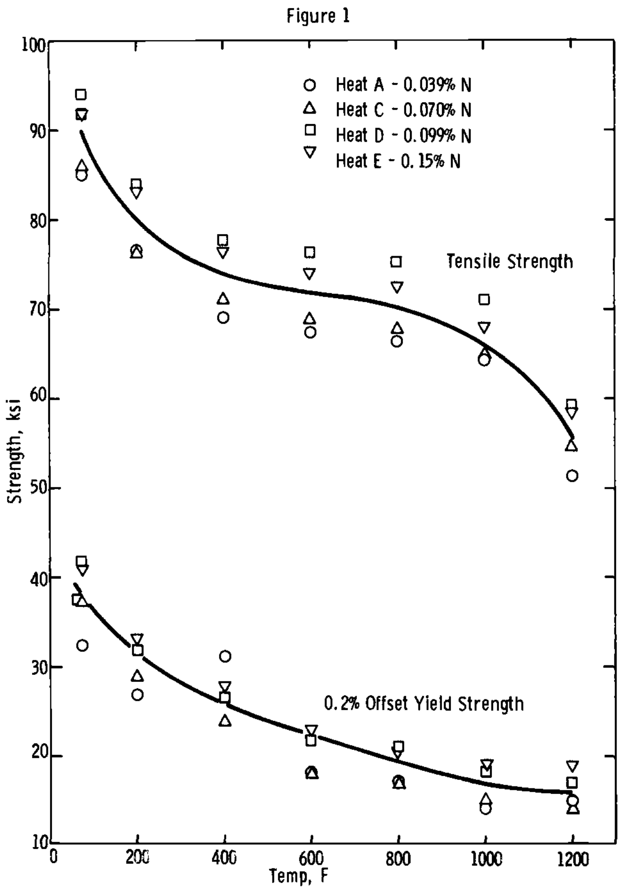

FIG. 1—*Tensile and yield strengths of varying nitrogen alloys as a function of test temperature.*

TABLE 3—*Creep-rupture properties of test materials.*

Stress, ksi (MPa)	Temperature, deg F (deg C)	Rupture, Time, h	Elongation, %	Reduction of Area, %	Minimum-Creep Rate, %/1000 h
Heat A, 0.039 percent nitrogen					
30 (207)	1200 (649)	68.4	41	39	...
28 (193)	1200 (649)	163.9	43	43	128
25 (172)	1200 (649)	450.8	55	54	50
23 (159)	1200 (649)	994.5	72	60	30
21 (145)	1200 (649)	3309.2	81	69	9.8
20 (138)	1200 (649)	4394.2	70	72	6.6
Heat B, 0.044 percent nitrogen					
30 (207)	1200 (649)	32.5	32	36	620
28 (193)	1200 (649)	67.7	68	39	308
24 (165)	1200 (649)	250.3	37	39	108
22 (152)	1200 (649)	753.2	54	48	32
20 (138)	1200 (649)	2575.0	47	51	9.6
Heat C, 0.070 percent nitrogen					
30 (207)	1200 (649)	74.6	26	32	209
28 (193)	1200 (649)	213.0	24	28	59
25 (172)	1200 (649)	656.2	32	41	22
22 (152)	1200 (649)	3476.1	51	54	7.2
20 (138)	1200 (649)	6825.3	74	64	2.3
18.5 (128)	1200 (649)	10076.5	64	71	1.06
17 (117)	1200 (649)	15790.8	59	70	0.189
25 (172)	1300 (704)	36.5	50	53	1280
22 (152)	1300 (704)	104.1	85	66	363
20 (138)	1300 (704)	228.1	60	60	136
19 (131)	1300 (704)	258.1	74	63	152
18 (124)	1300 (704)	319.0	70	68	100
17 (117)	1300 (704)	377.5	97	72	95
16.5 (114)	1300 (704)	785.3	91	76	51
16 (110)	1300 (704)	753.7	100	75	60
15 (103)	1300 (704)	1232.5	112	76	41
13.8 (95.1)	1300 (704)	1854.6	81	74	22
13 (89.6)	1300 (704)	2421.0	110	71	19
12 (82.7)	1300 (704)	4078.3	86	80	10.8
11 (75.8)	1300 (704)	6258.1	90	75	8.54
25 (172)	1400 (760)	2.7	75	60	...
15 (103)	1400 (760)	83.3	90	76	563
12.5 (86.2)	1400 (760)	251.2	105	75	236
10 (68.9)	1400 (760)	921.0	115	89	66
15 (103)	1450 (788)	27.9	108	71	...
12.5 (86.2)	1450 (788)	75.2	97	72	390
16.4 (113)	1500 (816)	5.0	111	78	...
12.5 (86.2)	1500 (816)	40.6	126	75	...
10 (68.9)	1500 (816)	87.9	97	73	562
9 (62.1)	1500 (816)	170.9	101	73	398
7 (48.3)	1500 (816)	614.9	89	66	87
5 (34.5)	1500 (816)	2892.3	70	42	16

TABLE 3—*Continued.*

Stress, ksi (MPa)	Temperature, deg F (deg C)	Rupture Time, h	Elonga-tion, %	Reduction of Area, %	Minimum-Creep Rate, %/1000 h
		Heat C, 0.070 percent nitrogen—Continued.			
25 (172)	1175 (635)	3142.9	34	47	5.1
25 (172)	1225 (663)	290.9	39	39	85
45 (172)	1250 (677)	186.5	47	46	205
25 (172)	1275 (691)	81.5	40	42	...
25 (172)	1325 (718)	21.5	80	55	...
25 (172)	1350 (732)	9.9	54	50	...
		Heat D, 0.099 percent nitrogen			
36 (248)	1200 (649)	71.1	13	15	...
35 (241)	1200 (649)	103.0	14	14	67
32 (221)	1200 (649)	248.8	15	15	25
31 (214)	1200 (649)	400.4	16	20	14.5
30 (207)	1200 (649)	935.3	20	30	7.6
29 (200)	1200 (649)	1162.0	30	34	8.3
28 (193)	1200 (649)	1565.0	40	43	7.0
26 (179)	1200 (649)	2967.5	42	51	3.55
22.5 (155)	1200 (649)	7427.0	75	64	1.2
28 (193)	1300 (704)	43.1	33	37	380
25 (172)	1300 (704)	227.0	58	52	80
22 (152)	1300 (704)	517.9	67	59	40
20 (138)	1300 (704)	865.2	75	63	25
18 (124)	1300 (704)	1390.8	67	58	19
16 (110)	1300 (704)	2343.0	62	56	9.55
15 (103)	1300 (704)	3532.6	64	57	8.55
		Heat E, 0.15 percent nitrogen			
40 (276)	1200 (649)	49.5	20	22	...
35 (241)	1200 (649)	148.8	16	17	42
32.5 (224)	1200 (649)	532.8	18	17	10.6
30 (207)	1200 (649)	1091.3	17	18	6.14
28 (193)	1200 (649)	3210.9	39	40	3.40
		Heat F, 16 percent ferrite			
35 (241)	1200 (649)	106.1	65	54	...
30 (207)	1200 (649)	370.7	65	68	84
27 (186)	1200 (649)	1004.8	80	67	33
25 (172)	1200 (649)	1485.0	68	70	21
23 (159)	1200 (649)	3081.2	92	70	10.2
21 (145)	1200 (649)	5738.0	94	73	5.43

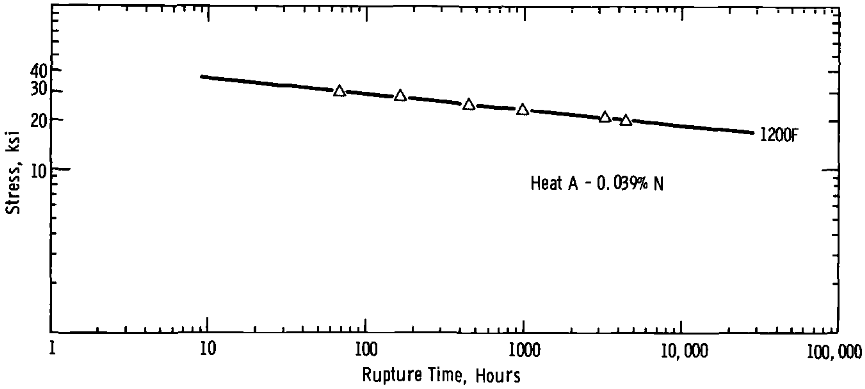

FIG. 2—*Stress-rupture time behavior of 0.039 percent nitrogen material.*

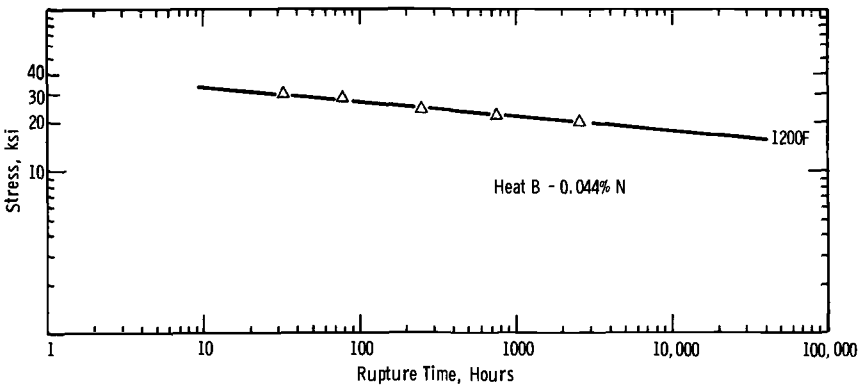

FIG. 3—*Stress-rupture time properties of 0.044 percent nitrogen alloy.*

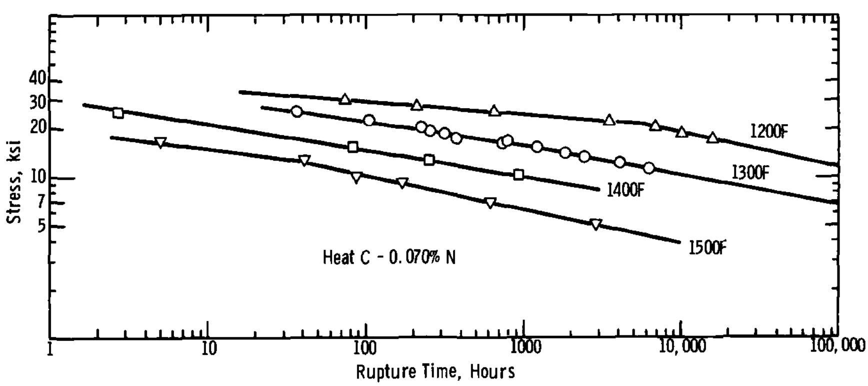

FIG. 4—*Stress-rupture time properties of 0.07 percent nitrogen alloy.*

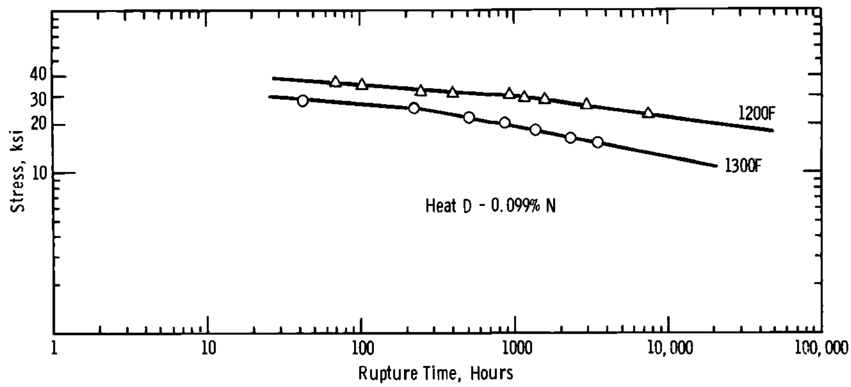

FIG. 5—*Stress-rupture time properties of 0.099 percent nitrogen material.*

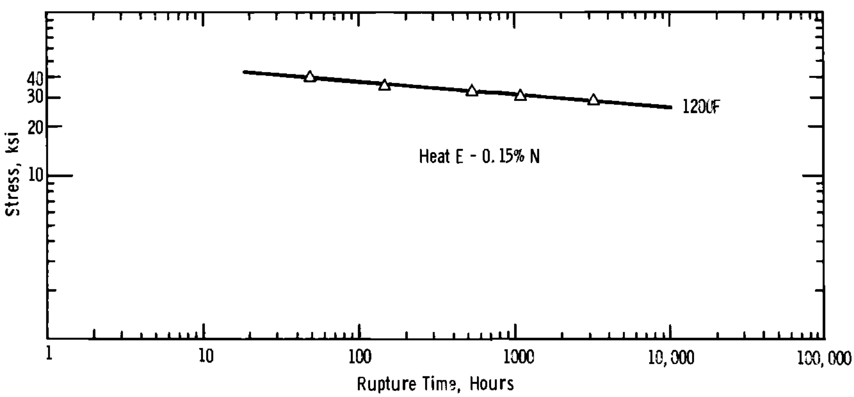

FIG. 6—*Stress-rupture time properties of 0.15 percent nitrogen alloy.*

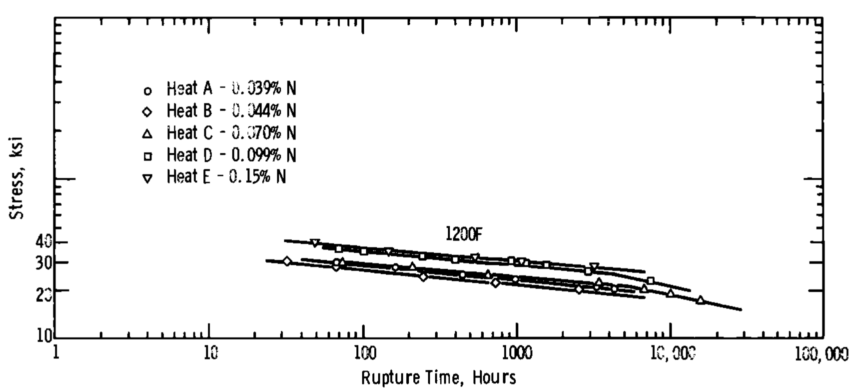

FIG. 7—*Comparison of 1200 F (649 C) rupture properties of varying nitrogen alloys.*

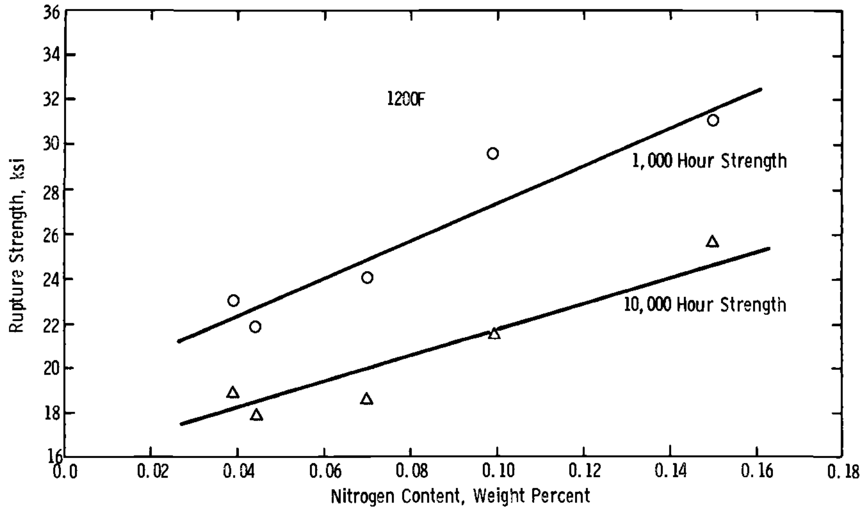

FIG. 8—*Variation of 1000 and 10 000 h rupture strength at 1200 F (649 C) with nitrogen content.*

1400, and 1500 F (732, 760, and 816 C) and Heat D at 1300 F (704 C). Test durations in excess of 15 000 h were recorded in this phase of the experimental program.

The rupture curves obtained from individual alloys are shown in Figs. 2 through 6. Straight lines seem to fit the data quite well with the exception of Heats C and D which show distinct breaks in their rupture curves at 1200 and 1300 F (649 and 704 C). Breaks of this type are generally manifestations of structural instability and, in this case, it is thought that the downward breaks were associated with a precipitation reaction occurring in the material.

The 1200 F (649 C) rupture results for the five alloys with varying nitrogen contents are given in Fig. 7. This comparison clearly shows the beneficial effect of nitrogen on the rupture properties of Type 316 stainless steel. The 1000 and 10 000 h rupture strengths of these materials are plotted as a function of nitrogen content in Fig. 8. Again, the strong dependence of rupture strength on nitrogen content is clearly evident.

Due to the presence of sharp downward breaks in the rupture curves of the 0.070 and 0.099 percent nitrogen alloys, no attempt has been made to relate 100 000 h rupture strength to nitrogen level. This is because similar breaks may also be characteristic of the rupture curves of the other alloys and may occur, at times, beyond the duration of the longest test. If such breaks did exist, then straight line extrapolations of the short time data could lead to large errors in the assessment of long time strength.

The minimum-creep rates determined for each of the tests at 1200 F (649 C) are plotted in Fig. 9. These data again show the beneficial influence

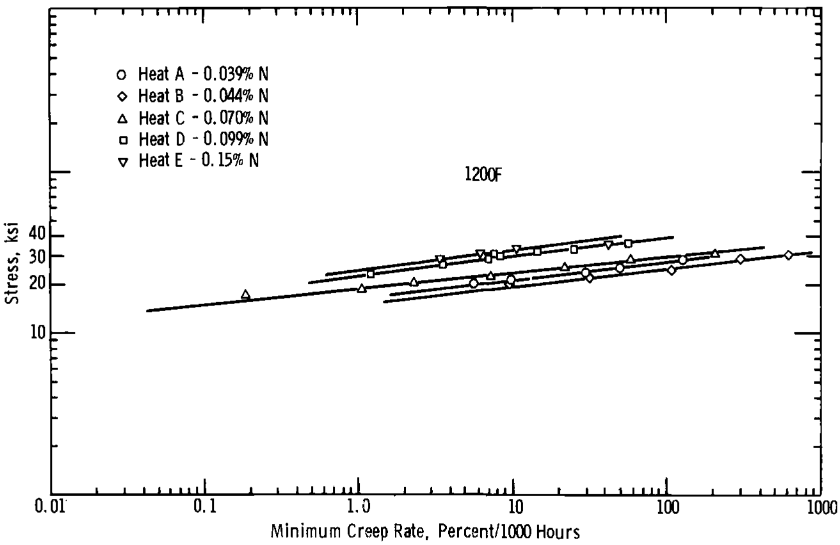

FIG. 9—*Comparison of minimum-creep behavior at 1200 F (649 C) of varying nitrogen alloys.*

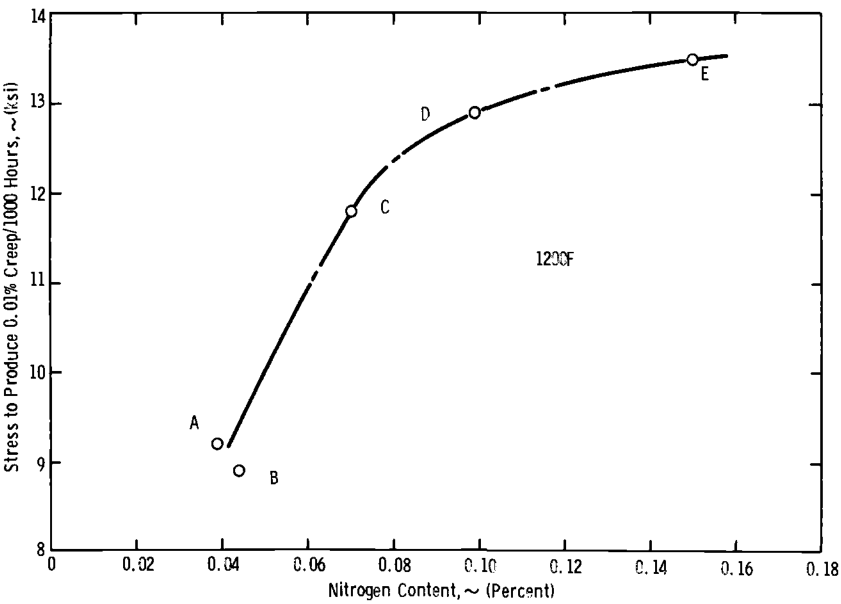

FIG. 10—*Variation of stress to produce a minimum-creep rate of 0.01 percent per 1000 h with nitrogen content.*

of nitrogen on creep strength. At any given stress, the higher the nitrogen level the lower the minimum-creep rate. These results are in good agreement with the rupture test results shown in Fig. 7.

The variation of stress required to produce a minimum-creep rate of 0.01 percent per 1000 h as a function of nitrogen content is shown in Fig. 10. The values shown are extrapolations of actual data and are intended only to show the trend of the data. The stress required to produce a minimum-creep rate of 0.01 percent per 1000 h is a material property considered in the setting of ASME Boiler Code allowable stresses and, as such, is a property commonly used to compare high temperature behavior.

Microstructural Studies

Figure 11 depicts the microstructures of several rupture specimens from Heat C. These photomicrographs show an increasing amount of matrix precipitate as testing time increases. This precipitate is thought to be a carbide phase, probably $M_{23}C_6$. Particles of sigma phase were also noted

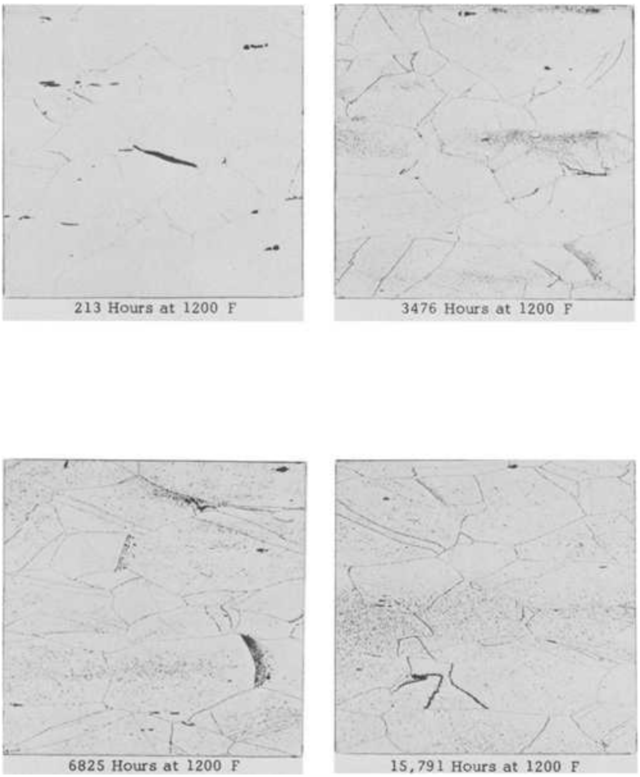

FIG. 11—*Microstructures of ruptured specimens from Heat C (0.07 percent nitrogen). Etched in 10 percent oxalic acid (×500).*

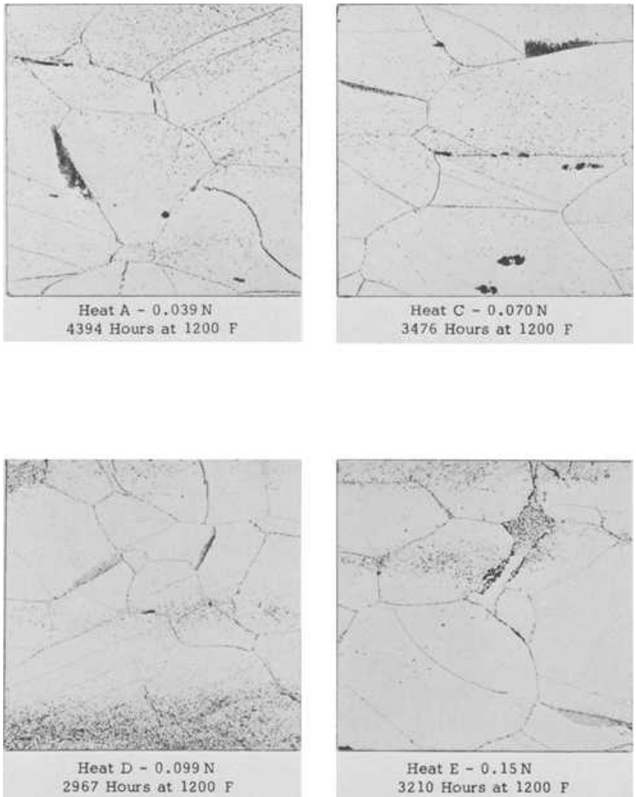

FIG. 12—*Microstructures of specimens with different nitrogen contents having approximately equivalent rupture times at 1200 F (649 C). Etched in 10 percent oxalic acid (×1000).*

in the microstructure of this material. These particles, however, were neither very large nor very numerous even in the specimen which ruptured in 15 791 h.

The microstructures of four specimens from different heats which exhibited approximately equivalent rupture times are shown in Fig. 12. The amount of matrix precipitate was about the same for each heat. The small variance in quantity of precipitate which did exist is believed to be more related to the slightly higher carbon content of Heat D than to any other variable.

Duplex Material—Heat F

The influence of ferrite on high temperature behavior is not well understood. Consequently, Heat F (containing 16 percent ferrite) was subjected to the same type of evaluation as the other alloys in order to measure its effect on high temperature strength and ductility.

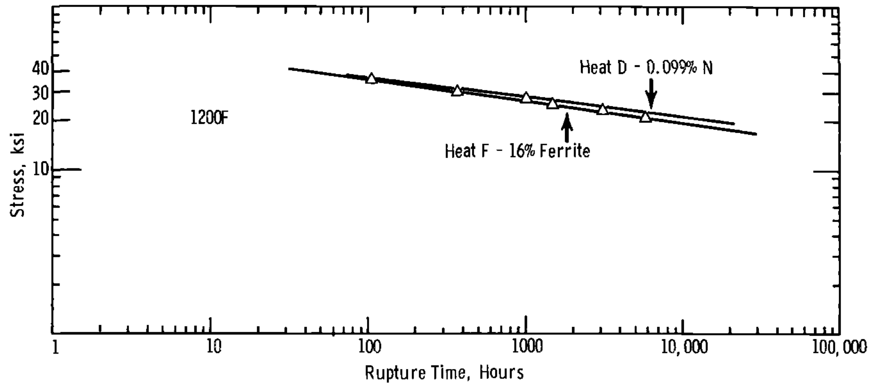

FIG. 13—*Stress-rupture time properties of ferrite containing material compared to those of 0.099 percent nitrogen alloy.*

The rupture results obtained from this material at 1200 F (649 C) are plotted in Fig. 13. For comparison purposes, a line representing the rupture data obtained from Heat D is also plotted in this graph. Heats D and F have similar carbon and nitrogen levels but vary greatly in chromium and nickel. These latter two elements were intentionally modified in order to stabilize ferrite in the microstructure. As can be seen, the rupture properties of Heat F are only slightly lower than those recorded from Heat D.

The creep properties of these two heats are plotted in Fig. 14. In this case, the creep resistance of Heat F is considerably less than that of Heat D. Evidently, the presence of the ferrite drastically reduced the creep resistance of the material.

Examination of the rupture ductilities recorded in Table 3 shows the pronounced influence of ferrite on ductility. The elongations recorded from the fractured specimens of Heat F were approximately four times those of

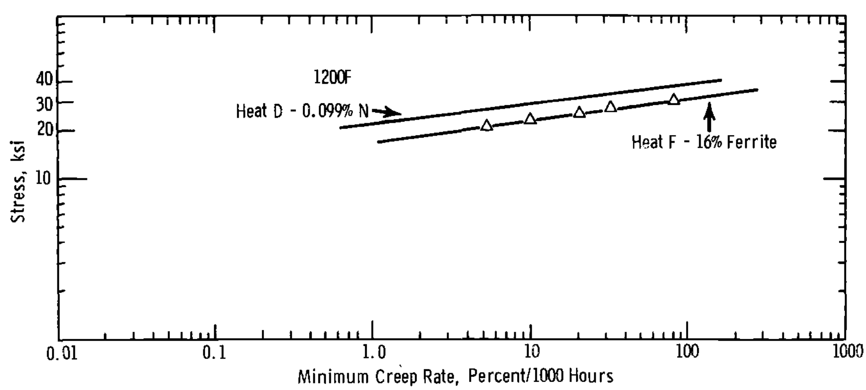

FIG. 14—*Minimum-creep rate behavior of ferrite containing material compared to that of 0.99 percent nitrogen alloy.*

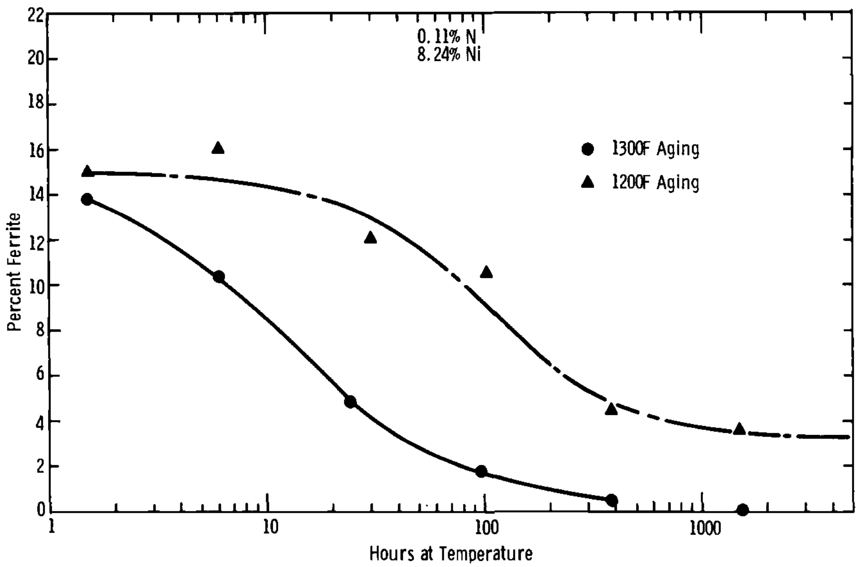

FIG. 15—*Ferrite content of Heat F as a function of aging time.*

Heat D for the corresponding shorter test times at 1200 F (649 C). This is probably due to the transformation of ferrite to sigma phase during the course of the test.

Figure 15 illustrates how percent of ferrite varies with aging time at 1200 and 1300 F (649 and 704 C), while the microstructure of these specimens are shown in Fig. 16. The ferrite level of the alloy was measured with a Magne-Gage. Since sigma phase is noted for its beneficial effects on elevated temperature rupture ductility, it is thought that most of the ferrite transformed to sigma phase during the high temperature exposures.

The transformation of the ferrite during exposure was associated with a reduction in creep resistance (see Fig. 14). The improved rupture ductility of the material, however, almost negated the accompanying lowering of rupture strength. In other words, equivalent rupture times were obtained in alloys of significantly different creep resistance due to higher ductility of the lower creep strength alloy. The increased rupture ductility prolonged the tertiary creep and thereby extended life. For this reason, the ferrite did not have any significant effect on rupture strength of this material at 1200 F (649 C).

Parameter Extrapolation

One of the most interesting phases of this study was the effort to predict the position (time) of the break in the 1200 F (649 C) rupture curve of Heat C. The variation in slope between the rupture curves drawn through the short time test results at 1200 and 1300 F (649 and 704 C) made it

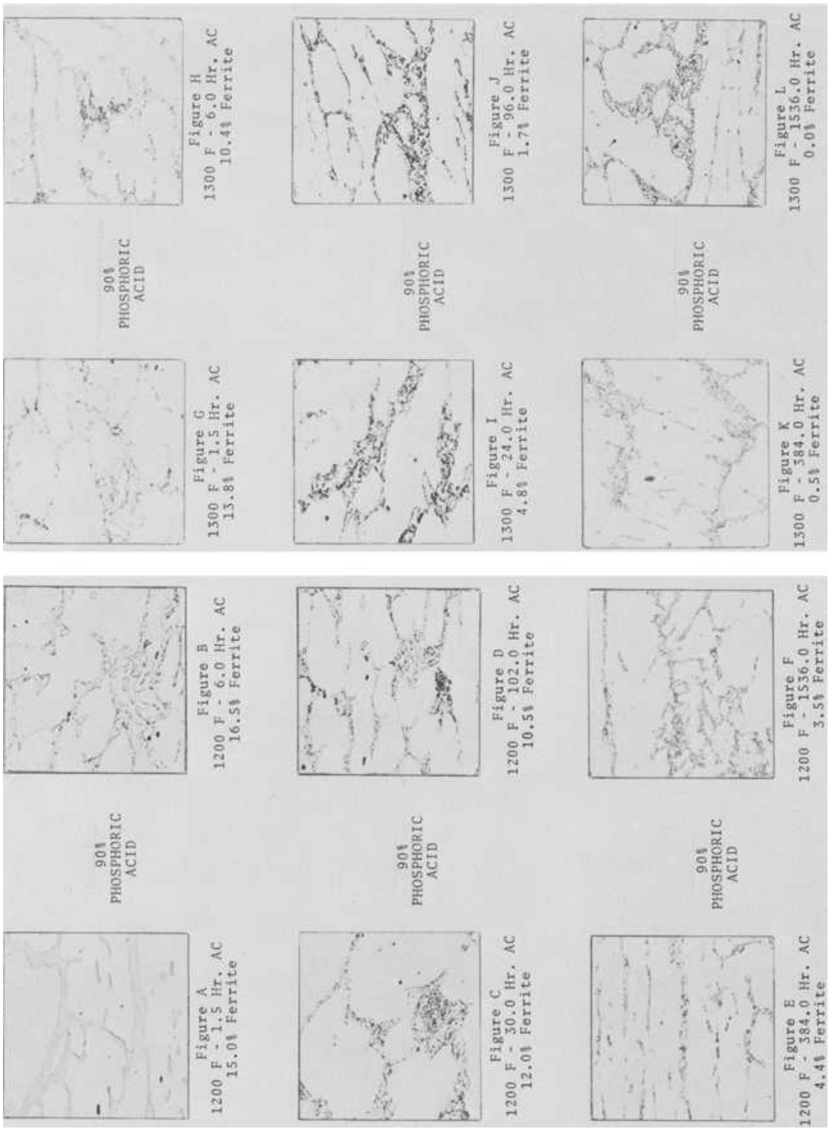

FIG. 16—*Microstructure of Heat F as a function of aging time at 1200 F (649 C) and 1300 F (704 C) (×1000).*

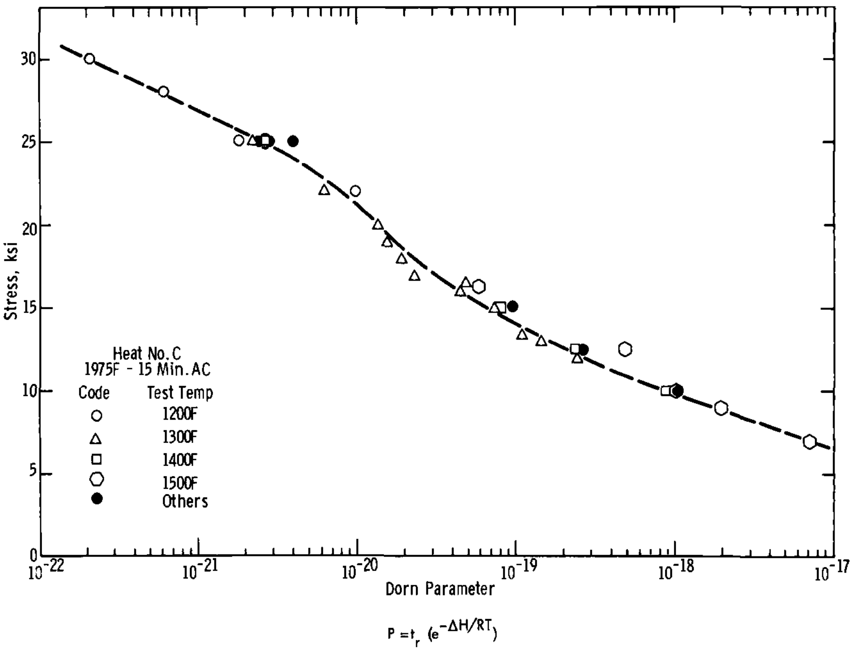

FIG. 17—*Correlation of rupture data from 0.07 percent nitrogen alloy using Dorn parameter.*

apparent that the 1200 F (649 C) rupture curve had to break sharply downward at some time beyond 3400 h. In order to predict the position of this break, the rupture data from this alloy were analyzed using the Larson-Miller [*1*],[2] the Dorn-Sherby [*2*], and the Manson-Haferd [*3*] time-temperature parameters. In addition, the portion of the linear rupture curve through the short time data was extrapolated as a straight line to define an outer limit to the estimate of rupture life. Next, three stresses were selected at which to conduct long time 1200 F (649 C) rupture tests. It was expected that one or more of these tests would fall beyond the break, and thus enable its position to be pinpointed. The stresses selected for these tests were 20, 18.5, and 17 ksi (138, 128, and 117 MPa).

Dorn Parameter—This parameter is based on the Arrhenius rate equation and has the following form:

$$P = t_r(e^{-\Delta H/RT})$$

where

P = parameter value,
t_r = rupture time, h,
ΔH = activation energy for creep,

[2] The italic numbers in brackets refer to the list of references appended to this paper.

R = gas constant, and
T = temperature, deg K.

The value of the activation energy is determined from the slope of the curve of rupture time versus reciprocal absolute temperature for tests conducted at constant stress. The slope of this curve equals $\Delta H/R$. The results of the tests conducted at 25 ksi (172 MPa) on Heat C fell on a curve with a slope equal to 5×10^4. From this value, an activation energy (ΔH) of 99 000 cal/g mole was determined. Figure 17 is a graph of the rupture data from Heat C utilizing the Dorn parameter for correlation.

Larson-Miller Parameter—This parameter is perhaps more widely used than any other because of its simplicity. The Larson-Miller parameter has the following form:

$$P = T(\log t_r + C)$$

where

P = parameter value,
T = temperature, deg R,

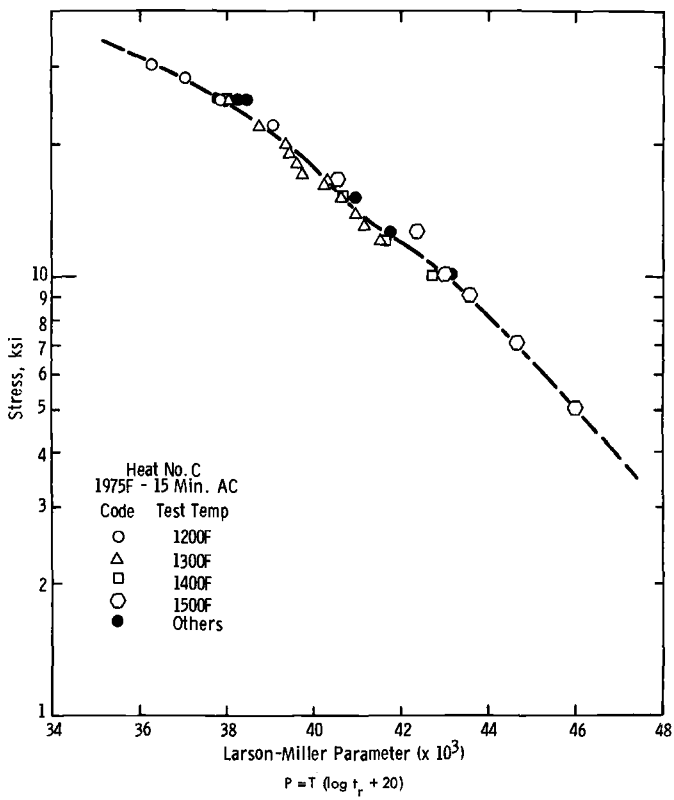

FIG. 18—*Correlation of rupture data from 0.07 percent nitrogen alloy using Larson-Miller parameter.*

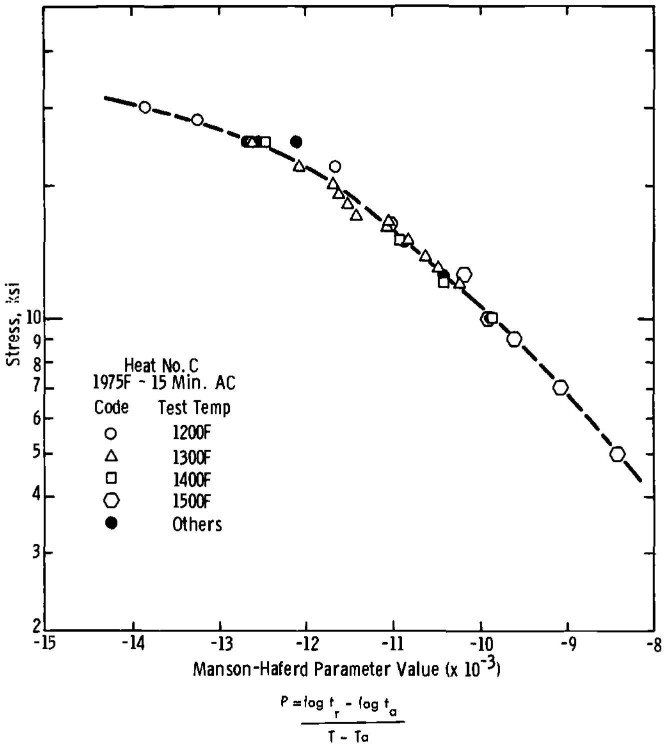

FIG. 19—*Correlation of rupture data from 0.07 percent nitrogen alloy using Manson-Haferd parameter.*

t_r = rupture time, h, and
C = constant, usually assumed to be equal to 20.

The value of the constant can be determined by plotting log rupture time at constant stress versus $1/T$ and extrapolating the resultant curve to $1/T = 0$. The data obtained were programmed into a computer for determination of the value of the parameter constant. A value of $C = 20.4$ was obtained, which agreed remarkably well with the normally assumed value of $C = 20$.

Figure 18 depicts a Larson-Miller correlation of the rupture data from Heat C. In this correlation a value of $C = 20$ was used.

Manson-Haferd Parameter—This parameter assumes the following form:

$$P = \frac{\log t_r - \log t_a}{T - Ta}$$

where

P = parameter value,
t_r = rupture time, h,

TABLE 4—*Summary of parameter testing, 1200 F (649 C).*

Extrapolation Method	Time to Rupture, h		
	20 ksi (138 MPa)	18.5 ksi (128 MPa)	17 ksi (117 MPa)
Larson-Miller	4500	6200	11000
Dorn-Sherby	7200	10000	16000
Manson-Haferd	2800	5800	7800
Straight line	8800	21500	58000
Actual test result	6825.3	10076.5	15790.8

t_a = material constant, equals 12.4,
T = absolute temperature, deg R, and
Ta = material constant, equals 900.

The values of the two constants can be determined by plotting two or more sets of constant stress data on a graph of log rupture time versus absolute temperature. The coordinates of the point of intersection of the lines are log t_a and Ta. (See Fig. 19 for the Manson-Haferd correlation of the data.)

Evaluation of Parameter Fit—The three parameters, along with a linear extrapolation of the 1200 F (649 C) log stress-log rupture time curve, were used to estimate time to rupture at 1200 F (649 C) under stresses of 20, 18.5, and 17 ksi (138, 128, and 117 MPa) (see Table 4). Evaluation of these results makes it quite obvious that the Dorn-Sherby parameter came closest by far in predicting actual rupture test results.

Conclusions

1. Nitrogen significantly improves rupture strength in Type 316 steel at 1200 F (649 C) for time periods up to 10 000 h.

2. Whether or not nitrogen is beneficial to the 100 000 h rupture strength of the alloy at 1200 F (649 C) is not known due to the presence of breaks in the rupture curves of some of the alloys. The other alloys may or may not exhibit similar behavior in longer time tests.

3. Ferrite lowers the creep resistance of Type 316 steel at 1200 F (649 C), possibly through a mechanism involving its transformation to the sigma phase.

4. Any decrease in rupture strength due to the presence of ferrite is masked by its beneficial influence on rupture ductility.

References

[1] Miller, J. and Larson, F. R., *Transactions*, The American Society of Mechanical Engineers, Vol. 74, 1952.
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[3] Manson, S. S. and Haferd, A. M., "A Linear Time-Temperature Relation for Extrapolation of Creep and Stress Rupture Data," NASA-TN-2890, National Aeronautics and Space Administration, March 1953.

I. A. Rohrig[1]

A Nitrogen Grade of Types 304 and 316 Austenitic Stainless Steels; Specification and Code Considerations

REFERENCE: Rohrig, I. A., "**A Nitrogen Grade of Types 304 and 316 Austenitic Stainless Steels; Specification and Code Considerations,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522,* American Society for Testing and Materials, 1973, pp. 79–85.

ABSTRACT: In the past twenty years it has been observed by test that there has been an increase in the high temperature strength of the austenitic stainless steel Types 304, 316, 321, and 347 with the result that the ASME Boiler and Pressure Vessel Committee has permitted two increases in allowable stress values since 1952 based on additional data. Creep and stress rupture studies of these materials led to the conclusion that nitrogen in controlled additions had a strengthening effect. Nitrogen grades of Types 304 and 316 referred to as 304N and 316N are permitted for use through ASME Boiler and Pressure Vessel Committee Code Case 1423 originally issued in September 1969 (now Case 1423-2), and efforts are underway to include 304N and 316N in ASTM specifications. Three public utilities have installed 304N for high temperature steam piping, and additional installations are expected.

KEY WORDS: nitrogen, mechanical properties, austenitic stainless steels, piping, pressure vessels, boilers, tubing

Approximately 15 years ago, there was considerable activity in the studies being made of Types 321 and 347 austenitic stainless steels, due to the premature failures that had occurred in 321 superheater tubing and in heavy wall 347 high temperature steam piping adjacent to welded joints. The studies of these two alloys were carried out under the auspices of the Joint Committee on the Effect of Temperature on the Properties of Metals (Joint Committee of American Society for Testing and Materials (ASTM), American Society of Mechanical Engineers (ASME), and Metal Properties

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Council (MPC)), and were designated as SP-5 (concerned with Type 347) and SP-6 (dealt with Type 321).

The effect of nitrogen in improving the high temperature strength of Type 304 was observed and mentioned by White and Freeman [*1*][2] during the course of the SP-6 study. In 1962 the Edison Electric Institute contracted with the University of Michigan for further study of mechanisms for high temperature strengthening of Type 304. The underlying reason for this was to prevent the occurrence of low-strength heats of material getting into service in superheaters.

The correlation of the effects of carbon, manganese, nitrogen, and high temperature heat treatment in improving the high temperature strength of Type 304 was verified by Goodell, Cullen, and Freeman [*2*]. The investigators concluded that the 304 made today is consistently stronger at high temperature than 304 manufactured two decades ago, and that such improvement appears to be due to the controlled addition of nitrogen.

A further objective of this study was to obtain sufficient information for the writing of a specification, or a specified composition, which would assure a high level of strength in Type 304 austenitic stainless steel. The final result of the study appeared in April 1967 [*2*].

Prior to the presentation of the final report, the Metallurgy and Piping Task Force of the Prime Movers Committee of the Edison Electric Institute proposed the inclusion of a nitrogen grade of Type 304 into ASTM specifications for tubular products; namely, A213, A249, A312, A376, and A430. This was done at the 1967 Annual Meeting of ASTM, in Boston, and was presented before Subcommittee X of A-1 at its meeting of 27 June 1967. It was proposed that the new grade, to be called 304N, would have the following requirements:

Carbon	0.04 to 0.10
Nitrogen	0.07 to 0.20
Manganese	1.0 min

Heat treatment at 1800 F (982 C) min, solution treatment

No change was proposed for the room temperature physical properties which would remain at 75 000 psi (517 MPa) tensile strength, 30 000 psi (207 MPa) yield strength, and no change in the allowable stresses was requested. The allowable stress for Type 304H had been increased from 3600 psi (24.8 MPa) to 4500 psi (31.0 MPa) at 1200 F (649 C) in 1952 and to 5500 psi (37.9 MPa) in 1965, a total increase of 35 percent with no change in specified composition. It was believed that the nitrogen grade would ensure the user that he could rely on the material having the 5500 psi (37.9 MPa) later increased to 6050 psi (42.8 MPa) allowable strength or creep resistance at 1200 F (649 C). The increase in S-values made in 1965

[2] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 1—*Maximum allowable stress, psi.*[a]

Material	Year	Metal Temperatures 1000 F (538 C)	1050 F (566 C)	1100 F (593 C)	1150 F (621 C)	1200 F (649 C)
304	1949	10 000	8 000	6 000	4 600	3 600
304	1952[b]	12 500	10 000	7 500	5 750	4 500
304H	1965[c]	12 500	11 100	8 700	6 900	5 500
304	1969[d]	13 750	12 150	9 750	7 700	6 050
304H	1969[d]	13 750	12 150	9 750	7 700	6 050
304N	1969[e]	15 000	12 400	9 750	7 700	6 050
316	1949	11 200	9 000	7 000	5 300	4 000
316	1952[b]	14 000	12 200	10 400	8 500	6 800
316H	1965[c]	14 000	13 300	12 000	9 500	6 950
316	1969[d]	15 300	14 500	12 400	9 800	7 400
316H	1969[d]	15 300	14 500	12 400	9 800	7 400
316N	1969[e]	17 400	15 800	12 400	9 800	7 400
321	1949	10 000	8 000	6 000	4 600	3 600
321	1952[b]	13 500	13 100	10 300	7 600	5 000
321H	1965[c]	14 500	13 700	10 500	7 700	5 500
321	1969[d]	13 800	9 600	6 900	5 000	3 600
321H	1969[d]	14 000	11 700	9 050	6 900	5 350
347	1949	10 000	8 000	6 000	4 600	3 600
347	1952[b]	13 500	13 100	10 300	7 600	5 000
347H	1965[c]	14 500	13 900	12 000	8 500	6 000
347	1969[d]	14 000	12 100	9 100	6 100	4 400
347H	1969[d]	14 400	14 100	13 000	10 500	7 900

[a] To convert psi to megapascals, multiply by .006894757.
[b] Increase due to change in the ASME Boiler Code Stress Criteria.
[c] Revised stresses approved by Main Committee following review of data, published June 1965. (ASME Boiler and Pressure Vessel Committee.) The 1965 values are the upper stresses only, of the H grades. Table PG-23.1, Section 1 Power Boilers, ASME Code 1965.
[d] ASME Boiler and Pressure Vessel Code, Winter 1969 Addenda. Table PG-23.1; the values are the upper stresses only for both the standard and the H grades.
[e] ASME Boiler and Pressure Vessel Code Case 1423-1, October 1969. The values shown are the upper stresses only for the nitrogen-bearing grades, 304N and 316N.

and a further increase in 1969 are shown in Table 1 which also shows, for comparison, the allowable stress values for Types 304, 316, 321, and 347. The upper stress values only are shown for the dual stresses permitted for these materials. For detailed tabulations regarding published allowable stresses, the reader is referred to the appropriate tables in Section I, Section III, and Section VIII of the ASME Boiler and Pressure Vessel Code [*3*].

The proposal for Type 304N grade was accepted at the June 1967 Meeting of Subcommittee X of ASTM Committee A-1, but when sent out for letter ballot received negative votes. The negative voters questioned the need for 304N, considering that 304H existed. They also questioned the need for nitrogen in the range of 0.07 to 0.20, because the opposition stated that their product was equally strong at 1200 F (649 C) with nitrogen consistently below 0.07 percent.

In October 1968 the Westinghouse Corporation formally proposed a Case to the ASME Boiler and Pressure Vessel Committee for use of Types 304 and 316 modified with controlled nitrogen additions of 0.10 to 0.16 percent. The nitrogen grade of both 304 and 316 was proposed to have a tensile strength of 80 000 psi (552 MPa) in place of 75 000 psi (517 MPa) for the regular grade, and yield strength of 35 000 psi (241 MPa) in place of 30 000 psi (207 MPa). Allowable stresses were requested to 1000 F (538 C) for Section I and Section VIII, Division 1, and also for Section III and Section VIII, Division 2. Considerable data on commercial heats of 304N and 316N had been generated by Cameron Iron Works in support of the Case proposed by Westinghouse.

In November 1968 at the ASTM Committee A-1 Meeting at Williamsburg, Va., discussions were held regarding the negative votes that had been received in Subcommittee X, with no resolution of the differences. A meeting in Pittsburgh in December 1968 ended with the suggestion that the Grade 304H be replaced with 304N, and that the nitrogen content be reduced from a range of 0.10 to 0.20 to 0.10 to 0.16. This also failed to resolve the negative votes and brought out the further objection that use of nitrogen grades should be restricted to temperatures below 1350 F (732 C).

The request to the ASME Boiler Code Committee for a Case to permit use of the nitrogen grades of 304 and 316 had received negative votes based on the suggestion that the case should be broadened to include plate, sheet, and forgings rather than be limited to pipe products, as Case 1423 was written originally. Case 1423 was approved in May 1969. Although data on tubular products had been received from a number of sources, there had been no data received for the other wrought product forms until June 1969, when data for plates and forgings were submitted.

The Case was revised; Boiler and Pressure Vessel Committee Code Case 1423-1 was adopted in October 1969, and expanded the use of Grades 304N and 316N to include wrought product forms for welded construction for temperatures up to 1200 F (649 C) with an allowable stress at that temperature of 6050 psi (41.7 MPa), see Tables 1 and 2. (Note that in Table 2, dual values are shown under the heading "Maximum Allowable Stress"). As shown in Table 1, the improved strength of the nitrogen Grades 304N and 316N was carried up to 1050 F (566 C). At temperatures of 1100, 1150, and 1200 F (593, 621, and 649 C), the allowable stress is the same for both the nitrogen grades, the "H" Grades, and the regular grades of 304 and 316. The allowable stresses, or design stress intensity values, permitted by Case 1423-1 and 1423-2 are shown in Table 2. For detailed tabulations regarding published allowable stresses, the reader is referred to the appropriate tables

TABLE 2—*ASME Code Case 1423-2* design stress, ksi*[a].

	Maximum Allowable Stress Section I, Section III Class 2 and 3, and Section VIII, Division 1				Stress Intensity Section III, Class 1, and Section VIII, Division 2	
Temperature deg F (deg C)	Grade 304N		Grade 316N		Grade 304N	Grade 316N
75 (24)	20.0	20.0	20.0	20.0	23.33	23.33
100 (38)	20.0	20.0	20.0	20.0	23.33	23.33
200 (93)	17.9	20.0[b]	19.4	20.0[b]	23.33	23.33
300 (149)	15.7	19.0[b]	17.8	19.2[b]	22.6	23.33
400 (204)	14.1	18.3[b]	16.5	18.8[b]	20.4	22.33
500 (260)	13.0	17.8[b]	15.4	18.6[b]	18.7	22.2
600 (316)	12.4	17.4[b]	14.6	18.6[b]	17.8	21.1
650 (343)	12.2	17.3[b]	14.2	18.6[b]	17.55	20.5
700 (371)	11.9	17.15[b]	13.9	18.6[b]	17.2	20.1
750 (399)	11.75	16.9[b]	13.6	18.5[b]	16.9	19.6
800 (427)	11.55	16.6[b]	13.3	18.4[b]	16.65	19.2
850 (454)	11.3	16.3[b]	13.1	18.3[b]	...	...
900 (482)	11.05	15.9[b]	12.8	18.1[b]	...	...
950 (510)	10.8	15.6[b]	12.6	17.8[b]	...	...
1000 (538)	10.55	15.0[b]	12.4	17.4[b]	...	...
1050 (566)	10.3	12.4[b]	12.2	15.8[b]	...	...
1100 (593)	9.75	9.75	11.7	12.4[b]	...	...
1150 (621)	7.7	7.7	9.8	9.8	...	...
1200 (649)	6.05	6.05	7.4	7.4	...	...

[a] To convert ksi to MPa, multiply by 6.894757.

[b] Due to the relatively low yield strength of these materials, these higher stress values were established at temperatures where the short time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 62½ percent, but do not exceed 90 percent of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain.

* Approved by ASME Council March 9, 1972.

in Section I, Section III, and Section VIII of the ASME Boiler and Pressure Vessel Code [*3*].

With the adoption of Case 1423-1, the way was cleared for inclusion of Grades 304N and 316N in appropriate ASTM specifications, and such action was begun in Committees A-1 and A-10. (Both Committees were combined in a new A-1 Committee in June 1972). The chemical composition and mechanical properties adopted in Code Case 1423-1 and later amended to Case 1423-2 are given in Table 3. The Grades 304N and 316N being considered for inclusion in ASTM specifications are to have the composition and mechanical properties shown in Case 1423-2.

In summary, there is agreement that nitrogen is a strengthening agent within the elastic range, but there is an area of disagreement as regards whether or not nitrogen is beneficial in the plastic or creep range. Also,

TABLE 3—*Inquiry form of ASME Code Case 1423-2.*

INTERPRETATIONS OF ASME BOILER AND PRESSURE VESSEL CODE

Approved by Council March 9, 1972

Case 1423-2
(*Special Ruling*)
Wrought Type 304 & 316 with Nitrogen Added.
Sections I, III, VIII, Divisions 1 and 2

Inquiry: Is it permissible in welded construction to the requirements of Section I, III, and VIII to use the austenitic grades of 304 and 316, with controlled additions of nitrogen, as wrought pipes and tube and as other wrought product forms conforming to the requirements of the applicable SA material specification listed in Tables PG-23.1 of Section I, I-1.2 of Section III, UHA-23 of Section VIII Division 1, and AHA-1 of Section VIII Division 2, except that the material shall conform to the following chemical and tensile requirements?

1. The chemical requirements shall be as follows:

	Grade 304N	Grade 316N
Carbon, % max	0.08	0.08
Manganese, % max	2.00	2.00
Phosphorus, % max	0.03	0.03
Sulphur, % max	0.03	0.03
Silicon, % max	0.75	0.75
Nickel, %	8.0 to 11.0	11.0 to 14.0
Chromium, %	18.0 to 20.0	16.0 to 18.0
Molybdenum, %	...	2.0 to 3.0
Nitrogen, %	0.10 to 0.16	0.10 to 0.16

2. The room temperature minimum mechanical properties shall be as follows:

	Grade 304N	Grade 316N
Ultimate tensile strength, psi	80 000 (552 MPa)	80 000 (552 MPa)
0.2% offset yield strength, psi	35 000 (241 MPa)	35 000 (241 MPa)
% Elongation—2 in. (51 mm) gage length		
longitudinal	30	30
transverse	25	25
% reduction of area		
longitudinal	50	50
transverse	45	45

there is a minor difference of opinion regarding the nitrogen range; the range favored for elevated temperature use of 304N and 316N is 0.10 to 0.16, as adopted in the Case. Three public utilities have used 304N for high temperature steam piping, and use of the nitrogen grades is expected to grow.

References

[1] Freeman, J. W., and White, J. E., *Transactions*, American Society of Mechanical Engineers, Vol. 85, Series A, No. 2, April 1963, pp. 119–146.

[2] Goodell, P. D., Cullen, T. M., and Freeman, J. W., "The Influence of Nitrogen and Certain Other Elements on the Creep Rupture Properties of Wholly Austenitic Type 304 Steel", presented at the Metals Engineering Conference, The American Society of Mechanical Engineers, Houston, Tex., April 1967.
[3] "Boiler and Pressure Vessel Code, Section I, 1971, Table PG-23.1, pp. 146–153, Section III, ASME Boiler and Pressure Vessel Code Case 1423-2, Case Interpretations, 1972, pp. 603–605, and Section VIII, 1971, Table UHA-23, pp. 158–168", American Society of Mechanical Engineers.

W. F. Domis[1]

Creep and Creep-Rupture Properties of Types 304N and 316N Stainless Steels

REFERENCE: Domis, W. F., "**Creep and Creep-Rupture Properties of Types 304N and 316N Stainless Steels,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522*, American Society for Testing and Materials, 1973, pp. 86–99.

ABSTRACT: If Types 304 and 316 steels with improved elevated temperature strength existed, equipment manufacturers could design to higher stresses, thereby reducing the weight and consequently the cost of fabricated equipment. The addition of nitrogen appears to be one means of improving the strength of Types 304 and 316 steels with little additional cost. Although appreciable work has been done, most of it over a limited temperature range, the effect of nitrogen on the creep and creep-rupture properties of Types 304 and 316 steels has not been quantitatively established. This paper reviews studies to determine quantitatively the effect of nitrogen on the (*a*) creep and creep-rupture properties of Types 304 and 316 steels within AISI composition limits over a large temperature range and (*b*) toughness of Types 304 and 316 steels after long time exposures at elevated temperatures.

KEY WORDS: nitrogen, creep rate, creep rupture strength, creep strength, energy absorption, stainless steels, toughness

Austenitic chromium-nickel stainless steels are widely used for architectural, consumer, and industrial applications because of their excellent toughness, formability, and weldability. In addition, because of their excellent corrosion resistance, they are used for handling highly corrosive materials or for resisting severe oxidation. For elevated temperature applications such as tubing and piping in the chemical, oil, and electrical power industries, AISI 304 (18 percent chromium, 9 percent nickel) and 316 (17 percent chromium, 12 percent nickel, 2.5 percent molybdenum)

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

stainless steels are frequently used at temperatures up to 1500 F because of their relatively high creep and creep-rupture strengths.

Accordingly, for many elevated temperature applications, it would be desirable to increase the elevated temperature strengths of Types 304 and 316 steels. If these steels with improved elevated temperature strength were available, equipment manufacturers could design to higher stresses, thereby reduce the weight and, consequently, the cost of fabricated equipment.

The addition of nitrogen appears to be one means of improving the strength of Types 304 and 316 steels with little additional cost [*1–6*].[2] Recently, for applications at temperatures up to 1000 F, the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Committee assigned design stresses to high nitrogen (0.10 to 0.16 percent) Types 304 and 316 steels [*7*] that are higher than those assigned to normal nitrogen (0.04 percent) Types 304 and 316 steels. Although appreciable work has been done, the effect of nitrogen on the creep and creep-rupture properties of Types 304 and 316 steels has not been quantitatively established. Some investigators have worked with steels of high carbon content [*5*] and others with steels having boron additions [*6*]. Also, most of the investigations have been conducted over a limited temperature range. Therefore, it was decided to determine quantitatively the effect of nitrogen on the creep and creep-rupture properties of Types 304 and 316 steels within AISI composition limits over a large temperature range. Because nitrogen may have an adverse effect on toughness, the effect of nitrogen on the toughness of Types 304 and 316 steels after long time exposures at elevated temperatures was determined. The results of these studies are presented herein.

Materials and Experimental Work

For this study, Type 304N steel, in the form of an 8-in. square bloom, was obtained from a commercial heat intended for a regular production order. The bloom was laboratory hot-rolled at 2200 F to a 4½-in. square bar and then forged at 2150 F to a 3-in. square bar. Specimens for all

TABLE 1—*Chemical compositions of steels investigated, percent.*

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	N
A	0.04	1.45	0.025	0.017	0.62	9.4	18.5	ND[a]	0.14
B	0.063	1.54	0.016	0.014	0.52	10.1	19.2	ND	0.065
C	0.065	1.55	0.017	0.016	0.55	9.8	18.8	ND	0.18
D	0.050	1.47	0.016	0.014	0.49	11.5	17.0	2.32	0.065
E	0.058	1.51	0.014	0.014	0.53	11.9	16.6	2.38	0.13
F	0.059	1.51	0.017	0.014	0.44	11.8	17.3	2.52	0.20

[a] ND = not determined.

subsequent tests were machined from this 3-in. square bar. The chemical composition of this steel, designated as Steel A, is shown in Table 1.

Because of the limited amount of material available from the aforementioned commercial heat and because of the desire to establish the effect of nitrogen, two 100-lb laboratory heats of Type 304 stainless steel were melted with normal and high nitrogen contents, respectively, and were cast into 4 by 4 by 18-in. ingots. One heat was melted under argon to a nitrogen content of 0.065 percent, and the second heat was melted in air to a nitrogen content of 0.18 percent (Type 304N). The chemical compositions of these two steels, designated as Steels B and C, are also shown in Table 1.

In addition, three 300-lb induction furnace heats of Type 316 stainless steel with controlled variations in nitrogen content were melted, and each heat was cast into molds to obtain three 4-in. square by 18-in. long 100-lb ingots. One heat was melted under argon to a nitrogen content typical of Type 316 steel (0.06 percent), and was designated as Steel D. Two other heats were melted in air to nitrogen contents of 0.13 and 0.20 percent, and were designated as Steels E and F, respectively. The chemical compositions of the three steels are also shown in Table 1.

The ingots of the laboratory produced steels, Steels B, C, D, E, and F were machined, heated to 2150 F, and forged without reheating to 1.25-in. square bars. These bars and the material from the aforementioned commercial heat, Steel A, were annealed at 1975 F for 1 h and water quenched. Subsequently, standard 0.250-in. diameter creep and creep-rupture specimens and Charpy V-notch impact specimens were machined from these annealed bars.

Creep and creep-rupture tests were conducted on all six steels at 1200 and 1350 F. In addition, creep and creep-rupture tests were conducted on Steels A, D, E, and F at 1050 and 1500 F. Charpy V-notch impact specimens machined from bars of Steels C and F, that were exposed at 750, 900, 1050, and 1200 F for times extending to 10 000 hours, were tested at room temperature.

Results and Discussion

Steel A, commercially produced Type 304N steel

The results of creep and creep-rupture tests on Steel A at 1050, 1200, 1350, and 1500 F are summarized in Table 2 with the actual test results shown in Table 3. For comparison, the average creep and creep-rupture strengths for commercially produced Type 304 steel are also included in Table 2. As shown in this table, Steel A exhibited appreciably higher creep-rupture strength than Type 304 steel. For example, the stresses for rupture in 10 000 and 100 000 h at 1200 F for Steel A were 18.0 and 12.5 ksi, respectively, compared with 13.8 and 9.8 ksi for Type 304 steel. At 1500 F,

TABLE 2—*Creep and creep-rupture properties of Steel A (commercially produced Type 304N steel).*

Test Temperature, deg F	Stress, ksi, for Rupture in		Stress, ksi, for a Minimum-Creep Rate of	
	10,000 h	100 000 h	0.0001 %/h	0.00001 %/h
1050	34.0	27.0	31.0	25.0
1200	18.0	12.5	15.0	10.2
1350	8.8	6.0	7.5	5.5
1500	4.8	3.3	4.0	[a]
Average Creep and Creep-Rupture Properties for Type 304 Steel[b]				
1050	28.0	20.0	20.5	14.0
1200	13.8	9.8	10.8	7.2
1350	6.7	4.7	5.7	3.6
1500	3.25	2.3	2.95	1.8

[a] Insufficient data.
[b] Data obtained from *ASTM DS5S2*, Supplement to *DS5*, Feb. 1969.

NOTE—Above values were obtained from interpolation and extrapolation of data on logarithmic plots.

these stresses were 4.8 and 3.3 ksi for Steel A, and 3.25 and 2.3 ksi for Type 304 steel. Overall, the stresses for rupture in 10 000 and 100 000 h at the four temperatures investigated were 21 to 47 percent higher for Steel A than the average stresses for Type 304 steel.

The creep data for Steel A are also summarized in Table 2. The results show that the creep strength of Steel A was appreciably higher than that of Type 304 steel. For instance, the stresses for minimum-creep rates of 0.0001 and 0.00001 percent per hour at 1200 F for Steel A were 15.0 and 10.2 ksi, respectively, compared with 10.8 and 7.2 ksi for Type 304 steel. At 1500 F, the stress for a minimum-creep rate of 0.0001 percent was 4.0 ksi for Steel A, and 2.95 ksi for Type 304 steel. Overall, the stresses for minimum-creep rates of 0.0001 and 0.00001 percent per h at the four temperatures investigated were about 31 to 78 percent higher for Steel A than the average stresses for Type 304 steel.

In Table 3, note that all the Steel A specimens tested at 1050 and 1200 F fractured at the gage marks, which may be indicative of notch weakening. Notched-bar tests would have to be conducted to confirm that the steel is notch sensitive. The minimum elongation (specimen fractured at the gage marks) and reduction of area values exhibited by Type 304N steel were 8 and 16 percent, respectively.

Steels B and C, laboratory produced Type 304 and 304N steels

The results of creep and creep-rupture tests on Steels B and C at 1200 and 1350 F are summarized in Table 4, and the actual test results are

TABLE 3—*Creep and creep-rupture properties of Steel A (commercially produced Type 304N steel).*

Test Temperature, deg F	Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
1050	50.0	208.5	18[a]	38.5	0.0129
	45.0	579.8	15[a]	34.7	0.00437
	40.0	1303.9	10[a]	33.4	0.00156
	37.5	2733.3	9[a]	28.8	0.00049
	35.0	7692.2	8[a]	19.1	0.00022
	32.5	3000.0[b]	ND[d]	ND[d]	0.000135
1200	35.0	99.0	13[a]	28.8	ND[d]
	30.0	443.1	13[a]	26.0	0.0069
	27.5	902.5	10[a]	20.0	0.0035
	25.0	1411.9	9[a]	18.4	0.00152
	22.5	3197.5	10[a]	16.0	0.00113
	20.0	5197.0	10[a]	21.1	0.00069
	17.0	9000.0[c]	ND	ND	0.000216
1350	20.0	88.6	40	30.8	0.120
	17.5	217.7	35	32.1	0.0424
	15.0	675.9	39	43.4	0.0144
	12.5	1910.9	47	44.6	0.00562
	10.0	4720.9	34	34.4	0.00081
	8.0	8000.0[c]	ND	ND	0.000146
1500	12.5	34.5	52	48.0	0.469
	10.0	128.7	50	46.2	0.111
	8.0	542.2	38	38.4	0.00713
	6.0	2443.6	30	34.8	0.00206

[a] Fractured at gage marks.
[b] Test discontinued prior to failure.
[c] Elapsed time, test still in progress.
[d] ND = not determinable.

TABLE 4—*Creep and creep-rupture properties of Steels B and C.*

Test Temperature, deg F	Stress, ksi, for Rupture in		Stress, ksi, for a Minimum-Creep Rate of	
	1000 h	10 000 h	0.001%/h	0.0001%/h
	Steel B—Laboratory Produced Type 304 Steel.			
1200	18.5	13.5	12.0	8.7
1350	10.5	6.4	5.8	4.2
	Steel C—Laboratory Produced Type 304N Steel.			
1200	23.0	17.5	17.5	12.0
1350	13.0	7.9	9.0	6.3

NOTE—Above values were obtained from interpolation and extrapolation of data on logarithmic plots.

TABLE 5—*Creep and creep-rupture properties of Steels B and C.*

Test Temperature, deg F	Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
	Steel B—Laboratory Produced Type 304 Steel.				
1200	30.0	22.9	38	43.3	1.13
	25.0	122.2	41	41.2	0.192
	20.0	605.2	43	40.6	0.0353
	17.0	1861.1	47	42.7	0.0126
1350	20.0	10.2	55	51.0	2.63
	15.0	75.5	53	52.8	0.405
	12.5	253.7	57	50.6	0.136
	10.0	1391.9	57	48.9	0.0227
	8.0	3878.6	47	48.9	0.00664
	Steel C—Laboratory Produced Type 304N Steel.				
1200	35.0	11.1	6[a]	30.8	ND[c]
	32.5	60.3	10	22.6	0.0848
	30.0	118.8	6[a]	21.4	0.0384
	27.5	237.1	7[a]	17.6	0.0193
	25.0	511.3	10	17.6	0.0095
	22.5	1357.8	11	15.8	0.0040
	20.0	2808.8	13	12.9	0.00208
	17.0	14435.8	21	24.1	0.000225
	15.0	11000.0[b]	ND[c]	ND[c]	0.00035
1350	20.0	47.7	17	20.0	0.172
	17.5	178.8	26	24.3	0.0682
	15.0	412.2	31	31.1	0.0272
	12.5	1147.0	32	26.7	0.0105
	10.0	3864.0	31	29.4	0.00236
	8.0	9539.1	27	21.8	0.00045

[a] Fractured at gage marks.
[b] Test discontinued prior to failure.
[c] ND = not determinable.

shown in Table 5. As mentioned previously, the chemical compositions of these two steels are similar with the exception of nitrogen. As disclosed in Table 4, Steel C (0.18 percent nitrogen) exhibited appreciably higher creep-rupture strength than Steel B (0.065 percent nitrogen). For example, the stresses for rupture in 1000 and 10 000 h at 1200 F for Steel C were 23.0 and 17.5 ksi, respectively, as compared with 18.5 and 13.5 ksi for Steel B. Overall, the stresses for rupture in 1000 and 10 000 h at the two temperatures investigated were 23 to 29 percent higher for Steel C than the corresponding stresses for Steel B.

As also shown in Table 4, similar to the stress-rupture time results, the creep strength of Steel C was appreciably higher than that of Steel B. For instance, the stresses for minimum-creep rates of 0.001 and 0.0001 percent

TABLE 6—*Charpy V-notch energy absorption of Steel C (laboratory produced Type 304N steel) after elevated temperature exposure.*

Exposure Temperature, deg F	Energy Absorbed at Room Temperature, ft·lb, After Exposure for Indicated Times		
	1000 h	5000 h	10 000 h
750	240	240	240
900	240	240	240
1050	192	135	112
1200	106	63	55

NOTE—Charpy V-notch energy absorption of annealed Type 304N steel is 240 ft·lb.

per hour at 1200 F for Steel C were 17.5 and 12.0 ksi, respectively, as compared with 12.0 and 8.7 ksi for Steel B. Overall, the stresses for minimum-creep rates of 0.001 and 0.0001 percent per hour at the two temperatures investigated were 37 to 55 percent higher for Steel C than for Steel B.

At the two temperatures investigated, Steel C exhibited markedly lower elongation and reduction of area values than Steel B (see Table 5). For a rupture time of 1000 h at 1200 F, for example, Steel C would be expected to exhibit elongation and reduction of area values of approximately 11 and 16 percent, respectively, whereas Steel B would exhibit values of about 44 and 42 percent. For a rupture time of 1000 h at 1350 F, Steel C would be expected to exhibit elongation and reduction of area values of approximately 32 and 27 percent, respectively, whereas Steel B would exhibit values of about 56 and 48 percent. The minimum elongation and reduction of area values exhibited by Steel C in the tests at 1200 F were 10.0 and 12.9 percent, respectively. However, similar to some specimens of the commercially produced Steel A, several of the specimens tested at 1200 F fractured at the gage marks, which again may be indicative of notch weakening.

The results of room temperature Charpy V-notch impact tests on Steel C after exposure at 750, 900, 1050, and 1200 F for times up to 10 000 h are given in Table 6. As shown, the Charpy V-notch energy absorption of Steel C in the annealed condition was 240 ft·lb. Exposures extending to 10 000 h at 750 and 900 F had no effect on the energy absorption characteristics. After an exposure of 10 000 h at 1050 F, the Charpy V-notch energy absorption of Steel C decreased to 112 ft·lb and after 10 000 h at 1200 F to 55 ft·lb. Charpy V-notch energy absorptions of 95 ft·lb have been measured for Type 304 stainless steel after exposure for 10 000 h at 1200 F [*8*]. Although it appears that the addition of nitrogen decreased the energy absorption of Type 304 steel after exposure at elevated temperatures, the energy absorption of Type 304N steel was still very high.

In summation, nitrogen appears to increase markedly the creep and creep-rupture strengths of Type 304 steel within the temperature range investigated. However, as would be expected, this increase in strength is accompanied by a decrease in ductility (as measured by elongation and reduction of area) and a slight drop in room temperature energy absorption after elevated temperature exposure. Additional testing would be required to determine whether this decrease in ductility is detrimental to the life of an elevated temperature component.

Steels D, E, and F, laboratory produced Types 316 and 316N steels

The results of creep and creep-rupture tests at 1050, 1200, 1350, and 1500 F on Steels D, E, and F are summarized in Table 7 with the actual test data shown in Tables 8 through 10. Table 7 shows that nitrogen increased the strength of Type 316 steel at the temperatures investigated, with the exception that at 1500 F, the 0.13 percent nitrogen of Steel E did not result in increased strength. At 1200 F, for example, the stresses to produce rupture in 10 000 h for Steels D, E, and F were 15.0, 19.0, and 21.5 ksi, respectively. At 1050 F, the stresses to produce rupture in 10 000 h for Steels D, E, and F were 4.2, 4.0, and 5.2 ksi.

TABLE 7—*Results of creep and creep-rupture tests on Steels D, E, and F (Type 316 steels).*

Test Temperature, deg F	Stress, ksi, for Rupture in		Stress, ksi, for a Minimum-Creep Rate of	
	1000 h	10 000 h	0.001%/h	0.0001%/h
Steel D (0.065 percent nitrogen)				
1050	39.0	31.5	35.0	27.5
1200	23.2	15.0	15.0	10.9
1350	12.0	8.2	6.7	4.5
1500	6.5	4.2	4.2	2.8
Steel E (0.13 percent nitrogen)				
1050	41.5	33.0	37.0	29.0
1200	26.0	19.0	17.0	12.5
1350	14.0	9.3	8.7	6.1
1500	6.5	4.0	4.0	2.6
Steel F (0.20 percent nitrogen)				
1050	42.5	34.5	41.0	33.0
1200	30.2	21.5	26.0	20.0
1350	17.0	10.5	11.5	7.5
1500	8.5	5.2	5.2	3.4

NOTE—Above values were obtained from interpolation and extrapolation of data on logarithmic plots.

TABLE 8—*Creep and creep-rupture properties of Steels D, E, and F at 1050 F (Type 316 steels).*

Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
		Steel D (0.065 percent nitrogen)		
50.0	74.3	37	28.7	0.039
45.0	209.5	19	24.4	0.0193
40.0	749.9	15	20.8	0.00362
35.0	4651.1	17	23.2	0.00102
32.5	7131.4	ND[b]	ND[b]	0.00031
30.0	5000.0[a]	ND	ND	0.000242
		Steel E (0.13 percent nitrogen)		
55.0	73.5	27	32.6	0.0758
50.0	137.6	21	24.9	0.0215
45.0	357.5	15	23.3	0.00916
40.0	1171.3	13	20.0	0.00246
35.0	2838.6	13	19.3	0.000937
		Steel F (0.20 percent nitrogen)		
55.0	161.2	18	27.6	0.0090
50.0	272.5	13	17.1	ND[b]
45.0	506.0	12	25.3	0.0028
42.5	960.5	12	19.5	0.00159
40.0	1237.0	10	13.9	0.00086
35.0	8543.0	5	8.1	0.000128
30.0	6200.0[a]	ND	ND	0.000040

[a] Discontinued prior to failure.
[b] ND = not determinable.

The creep strength of Type 316 steel also increased with increasing nitrogen content at 1050, 1200, 1350, and 1500 F (see Table 7), except that Steels D and E again exhibited similar creep strengths at 1500 F. At 1200 F, for instance, the stresses to produce a minimum-creep rate of 0.0001 percent per hour for Steels D, E, and F were 10.9, 12.5, and 20.0 ksi, respectively. At 1500 F, the stresses to produce a minimum-creep rate of 0.0001 percent per hour for Steels D, E, and F were 2.8, 2.6, and 3.4 ksi. However, longer time tests would be desirable to verify that the 0.13 percent nitrogen of Steel E did not result in increased strength at 1500 F.

At 1050 F (Table 8) increasing nitrogen content appeared to decrease the ductility somewhat (as measured by elongation and reduction of area values) of Type 316 steel. For example, the estimated elongations at rupture for a rupture time of 1000 h were 15.0, 13.0, and 11.5 percent for Steels D, E, and F, respectively. In longer time tests, 0.20 percent nitrogen further decreased the elevated temperature ductility of Type 316 steel at 1050 F, with Steel F exhibiting an elongation of five percent in the 8543.0-h test. This may be too low to be acceptable in the design of most components for applications at this temperature. Tests on Steel E for longer times are in progress to determine the effect of 0.13 percent nitrogen on its ductility.

At the higher temperatures of 1200, 1350, and 1500 F, however, the trend of elongation and reduction of area values with respect to rupture time varied for Steels D, E, and F. At 1200 F, as shown in Table 9, the elongation at rupture of Steel D generally decreased with increasing rupture time, whereas the elongation at rupture of Steel F generally increased with increasing rupture time. In the 14.3-h test at 1200 F, Steel D exhibited a 48 percent elongation at rupture, but this decreased to 24 percent in the 5963.2-h test. However, in the 6.7-h test, Steel F exhibited 16 percent elongation at rupture, and this increased to 52 percent in the 6316.2-h test. At 1350 F (Table 10) similar trends in the elongation at rupture of the three steels are again evident. The elongation of Steel D remained essentially constant with time, and the elongations of Steels E and F generally

TABLE 9—*Creep and creep-rupture properties of Steels D, E, and F at 1200 F (Type 316 steels).*

Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
		Steel D (0.065 percent nitrogen)		
35.0	14.3	48	56.6	ND[b]
30.0	113.8	54	57.1	0.164
25.0	548.1	66	62.0	0.0363
22.5	1251.3	50	51.0	0.0147
20.0	2180.1	39	41.9	0.00806
17.0	5963.2	24	28.1	0.00213
		Steel E (0.13 percent nitrogen)		
40.0	20.3	39	41.3	ND
35.0	88.5	39	37.1	0.175
30.0	261.2	23	30.1	0.4077
25.0	1556.3	44	48.4	0.0109
20.0	3392.5	65	59.3	0.00428
17.0	8000.0[a]	ND[b]	ND[b]	0.00128
		Steel F (0.20 percent nitrogen)		
45.0	6.7	16	27.3	ND
40.0	136.3	13	16.8	0.030
35.0	285.7	12	21.3	0.0105
30.0	1067.5	25	36.6	0.00356
27.5	2344.8	42	42.7	0.00253
25.0	3648.3	26	33.6	0.00082
22.5	6316.2	52	54.0	0.00029

[a] Discontinued prior to failure.
[b] ND = not determinable.

TABLE 10—*Creep and creep-rupture properties of Steels D, E, and F at 1350 F (Type 316 steels).*

Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
		Steel D (0.065 percent nitrogen)		
20.0	35.8	59	63.0	0.671
17.5	106.2	82	69.2	0.129
15.0	265.6	77	76.8	0.0848
12.5	847.1	75	71.3	0.0345
10.0	3208.9	78	67.0	0.00986
8.0	8000.0[a]	ND[b]	ND[b]	0.00238
7.0	2000.0[a]	ND	ND	0.00089
		Steel E (0.13 percent nitrogen)		
25.0	27.4	52	50.6	0.698
20.0	116.9	72	62.7	0.241
15.0	585.6	74	60.2	0.0367
12.5	1787.7	103	65.7	0.0146
10.0	5969.4	64	56.3	0.00352
		Steel F (0.20 percent nitrogen)		
30.0	36.7	22	25.9	0.278
25.0	163.2	35	37.7	0.072
22.5	290.0	52	48.4	0.0398
20.0	587.3	61	56.8	0.0209
17.5	927.0	65	66.6	0.00962
15.0	1654.2	86	70.3	0.00515
12.5	2940.1	55	51.0	0.00196
8.0	8710.0[a]	ND	ND	0.000136

[a] Discontinued prior to failure.
[b] ND = not determinable.

increased with time. However, at 1500 F the elongations of all three steels decreased with increasing rupture time (Table 11). In general, the addition of nitrogen did not appear to lower the long time elongation and reduction of area values below acceptable levels at temperatures in the 1200 to 1500 F range.

The results of room temperature Charpy V-notch impact tests conducted on Steel F after exposure at 750, 900, 1050, and 1200 F for times up to 10 000 h are given in Table 12. The Charpy V-notch energy absorption of Steel F in the annealed condition was 240 ft·lb. Exposures extending to 10 000 h at 750 and 900 F had no effect on the energy absorption characteristics. However, after exposure for 10 000 h at 1050 F, the energy absorption decreased to 46 ft·lb, and after exposure for 10 000 h at 1200 F, to 10 ft·lb. Charpy V-notch energy absorptions of 70 ft·lb have been measured for Type 316 stainless steel that had been exposed for 10 000 h

TABLE 11—*Creep and creep-rupture properties of Steels D, E, and F at 1500 F (Type 316 steels).*

Stress, ksi	Time to Rupture, h	Elongation in 1 in., %	Reduction of Area, %	Minimum-Creep Rate, %/h
		Steel D (0.065 percent nitrogen)		
12.5	28.4	78	70.6	0.833
10.0	98.8	88	65.2	0.275
8.0	392.4	55	56.4	0.0570
6.0	1179.5	50	41.9	0.0165
5.0	4293.6	23	29.5	0.00144
4.0	2000.0[a]	ND[b]	ND[b]	0.00075
		Steel E (0.13 percent nitrogen)		
12.5	45.7	80	60.1	ND[b]
10.0	149.2	62	53.7	0.18
8.0	424.0	54	48.7	0.0563
6.0	1461.3	44	41.5	0.0134
5.0	3551.1	45	34.7	0.00503
		Steel F (0.20 percent nitrogen)		
17.5	35.8	65	60.6	0.518
15.0	80.8	62	59.6	0.212
12.5	165.5	77	65.4	0.0825
10.0	477.9	ND	54.7	0.0185
6.0	4864.5	38	42.5	0.00365
5.0	2300.0[a]	ND	ND	0.00045

[a] Discontinued prior to failure.
[b] ND = not determinable.

TABLE 12—*Charpy V-notch energy absorption of Steel F after elevated temperature exposure.*

Exposure Temperature, deg F	Energy Absorbed at Room Temperature, ft·lb, After Exposure for Indicated Times		
	1000 h	5000 h	10 000 h
750	240	240	240
900	240	240	240
1050	166	70	46
1200	44	20	10

NOTE—Charpy V-notch energy absorption of Steel F in the annealed condition was 240 ft·lb.

at 1200 F [8]. It is believed that the deterioration in energy absorption with exposure at elevated temperatures would also occur in the lower nitrogen (0.13 percent) steel, although probably at a slower rate. The energy absorption of Steel E after 10 000 h exposure at 1200 F would presumably be between 10 and 70 ft·lb. However, further testing would be required to verify this.

As was true for the Type 304 steel, the addition of nitrogen to the Type 316 steel increased the creep and creep-rupture strengths within the temperature range investigated with the exception of the 0.13 percent nitrogen addition at 1500 F. These additions of nitrogen, in turn, decreased the long time creep-rupture ductility at 1050 F. Nevertheless, nitrogen did not appear to affect the long time ductility at the other three temperatures investigated, namely, 1200, 1350, and 1500 F. The 0.20 percent nitrogen addition did, however, sharply decrease energy absorption of Type 316 steel after elevated temperature exposure.

Summary

The results of the current investigation on the effect of nitrogen on the creep and creep-rupture properties of Types 304 and 316 steels may be summarized as follows:

1. Type 304N steel exhibited appreciably higher creep and creep-rupture strengths at 1050, 1200, 1350, and 1500 F than did Type 304 steel.
2. Type 304N steels exhibited lower elongation and reduction of area values than Type 304 steel and a high incidence of fracture at the gage marks of the specimens, which may be indicative of notch weakening.
3. The Charpy V-notch energy absorption of Type 304N steel after 10 000 h exposure at 1050 and 1200 F was moderately lower than that of Type 304 steel.
4. The creep and creep-rupture strengths of Type 316 steel at 1050, 1200, 1350, and 1500 F generally increased with increasing nitrogen contents from 0.06 up to 0.20 percent.
5. The addition of nitrogen to Type 316 steel did not adversely affect the long time creep-rupture elongation and reduction of area values at 1200, 1350, and 1500 F, but did decrease the creep-rupture ductility after long time exposure at 1050 F.
6. The addition of 0.20 percent nitrogen to Type 316 steel resulted in a sharp decrease in Charpy V-notch energy absorption after 10 000 h exposure at 1050 and 1200 F.

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Service Experience with H Grades of Austenitic Steel

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ABSTRACT: Premature creep-rupture swelling of AISI 321 austenitic stainless steel superheater tubes resulted in failures in the middle 1950s and promoted an extensive investigation. These failures in large utility boilers operating at pressures above 1500 psi and temperatures above 1000 F seriously challenged the economics and reliability of high pressure and high temperature. Failures were initially attributed to an extremely fine grain size occasioned by a low temperature solution heat treatment. Reheat treatment at higher temperatures to produce a coarser grain structure reduced the incidence of failure.

Subsequent results of a research project provided evidence that the final solution heat treatment and not the grain size was the most significant factor. Control of the carbon content was also found to be an important factor. A new grade called the "H" grade was introduced which incorporated specific heat treatments and control of carbon. This was applied to the 300 series steel in all product forms. Service experience has been successful with the H grades.

Recent investigations of Type 304 austenitic stainless steel indicate that a controlled nitrogen addition significantly enhanced the rupture life of this material, thereby increasing reliability. While the quest for higher temperature steam fossil units has been blunted with the advent of nuclear power, the fact still exists that higher pressures and temperatures result in significant increases in efficiency, and eventually will be pursued.

KEY WORDS: nitrogen, creep rupture, failures, austenitic stainless steel, solution heat treatment, grain size, high pressure, high temperature

Failures in service of AISI 321 austenitic stainless steel superheater tubing occurred in the middle 1950s. Premature creep-rupture swelling was found as the cause. The tubing material exhibited extremely fine grain

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structure. The "H" grades were introduced to establish a more positive control of the short time creep-rupture properties and to assure continuation of long term service life. Experience with the H grades has been successful with service time up to three times the service life of the pre H grades which exhibited difficulty.

History

AISI 321 austenitic stainless steel was used in quantity immediately after World War II when the utility industry placed orders for new electric generating facilities to keep pace with increased power demands and to replace units which had been used past their normal retirement period during the war. Many of the new units were designed for 1500 psi (10.3 MPa) and 1000 to 1050 F (538 to 566 C) operating conditions. These were built to the 1946 or 1949 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. At that time the code allowable stresses were considerably lower than those published in the 1952 through 1962 codes.

The increased allowable stresses between 1949 and 1952 were primarily due to changes in criteria. These enabled a greater production with less use of materials, particularly the scarce ones which were needed by the military in the Korean conflict. No specific changes were made in the material specifications. The utilities, like many other industries who use pressure vessels, look to the ASME Boiler and Pressure Vessel Code to provide minimum standards for safety and reliability of operation.

The ASME Code is recognized by most of the state regulation boards as a basic minimum safety code, and as such, they have adopted this code with little, if any, modification as their legal codes. Because the power industry needs huge outlays of money and equipment to meet the demands of electricity in the United States, it has developed into a noncompetitive industry with a captive clientele. The government has several agencies such as the Public Utilities Commission and the Federal Power Commission to assure that all such utilities are operated in a safe, reliable, and efficient manner. Therefore, the earning power and costs are carefully monitored to assure that no undue irregularities exist. Consequently, the utilities have diligently searched for new and better ways of producing power more economically while maintaining the safety and reliability expected of them in serving the public. Increasing pressure, temperature, and size have enabled the utilities to produce electricity more economically. Therefore, when the allowable stresses were increased between 1949 and 1952, greater savings were available for the same types of unit produced or installed previously, and newer, larger, and higher temperature units were made more attractive economically. As a comparison, the same size Type 321 tube used for a 1750 psi (12.1 MPa), 1050 F (566 C) unit could now be used for a 2400 psi (16.5 MPa), 1100 F (593 C) unit.

Problems

The initial failures of superheater tubes with thinner walls and higher operating stresses occurred after approximately three years of service at elevated temperatures and was most serious in units operating at 1050 or 1100 F (566 or 593 C) terminal steam temperatures. It was found that two tubes welded together would show excessive swelling in the tube which had extremely small grain size while the tube on the other side of the weld, which exhibited a grain size of seven or coarser, did not indicate any excessive swelling. Investigations showed that the tubes had received a 1750 to 1900 F (954 to 1038 C) solution heat treatment, but it was difficult to establish the exact temperature level. Laboratory heat treatment of the fine grain tubes showed a response of grain coarsening when reheated to more than 2000 F (1093 C). Subsequently, it was decided to reheat all of the tubing which did not show an excess of two percent creep, and to replace the tubes that did with a tube material which was heat treated to produce a grain size of seven or coarser.

The degree of creep damage which occurred before reheat treatment was determined by a physical measurement of the outside diameter of the tube. After heat treatment a new primary creep growth occurred again. Therefore, some of the early reports of continued creep after heat treatment were probably because of measurements taken too soon after the reheat treatment.

Investigation

A research project sponsored by the ASTM-ASME Joint Committee on the Effect of Temperature on the Properties of Metals under the Steam Power Panel was conducted by Dr. Freeman of the University of Michigan [*1*].[2] The research showed that heat treatment and not grain size was the most significant factor. It was also found that a carbon level of 0.04 percent minimum was needed to assure higher creep rupture strength at least for the short time portion of the rupture life. It should be noted that all of the problems and corrections were related to Type 321 materials, primarily in superheater tube product forms. The institution of the H grades, however, has been applied to most of the 300 series austenitic steels and to all product forms.

Results

A recent survey of the service history of H grades of materials installed in superheaters and reheaters of high pressure, high temperature boilers indicates that there have been recurrences or continuations of problems because of swelling and rupture failures. All of the cases reported were in materials which were reheat treated after some time in service or had been

[2] The italic numbers in brackets refer to the list of references appended to this paper.

purchased originally as regular grades and subsequently reheat treated to conform to the H grade requirements before service. In many instances the mode of failure was somewhat clouded by the influence of lug weld attachments. Wall thinning, because of wastage and local overheating due to firing conditions or circulation distribution, has also been a factor. In addition, several failures have been attributed to improper welding or weld contours.

Replacement of superheaters has been dictated, in many instances, by excessive wall thinning caused by wastage rather than by excessive creep. Twenty-one utilities, with nearly 100 boilers built between 1950 and 1963, and with original materials of either pre H, modified H, or H grades of Type 321 material, have all had some difficulty with the pre H grades. Some of the modified H grades were entirely successful while others had difficulty ranging from slight to serious. Many of the more serious situations were those that had been modified after a significant period of service. It appears that the longer the prior service, the more difficulty after reheat treatment.

At least seven of the utilities have elected to replace superheaters with Type 347H. Two utilities have also used 316H or have replaced with 316H. Most of the 347H replacements were also associated with excessive tube wastage of the superheaters. All of the units which were put into service with H grades of materials or were replaced with H grade material had been satisfactory, insofar as creep rupture is concerned. However, since the service life to date of the H grades is approximately half of the pre H grade, an absolute statement of satisfactory service cannot be made. It is significant that the H grade now have up to three times the service life without any indications of similar problems of premature creep failures as the pre H grades had when they first exhibited difficulty.

Additional Developments

Recent investigations [*2*] have indicated that the rupture life of Type 304 austenitic stainless materials is enhanced by controlled additions of nitrogen. Many of the more recent heats of Type 304 have exhibited higher short time rupture strengths when compared with those produced more than a decade ago. The newer heats were significantly higher in nitrogen content than the older ones. It was also noted that the manganese content was considerably higher in the newer heats. It was difficult to get sufficient data on many older heats because nitrogen had not been an element which had been generally reported. In both cases however, the heats were within the limits of the ASTM specification for manganese, which was reported consistently. Nitrogen has never been a controlled element in the specifications, but it seems reasonable to expect that some elemental difference between the modified H grades and the actual H grades, other than heat treatment and a minimum carbon content, could account for the wide difference in service experience. It has been recently stated that with the advent of nuclear power and the decline in the use of high temperature installations of steam fossil units, the requirements for the H or nitrogen-bearing grades of materials will be of less concern, and, therefore, a continued effort on the H grade type of material is questionable. It seems reasonable, however, that for the same reasons that the industry has gone to the high temperature, high pressure units in the fossil industry, it will likewise, in the near future, be reaching for the high temperature, high pressure category in the nuclear field as well. The present fossil units will be required to operate for many more years, and when replacements are necessary for one reason or another, they should be made with the best material we know how to produce to maintain reliability.

References

[1] Freeman, J. W., *Journal of Engineering for Power*, Vol. 85, Series A, No. 2, April 1963, p. 119.

[2] "Improved Properties of Type 304 Austenitic Steels," EEI Publication No. 64-67, Edison Electric Institute, Dec. 1964.

J. A. Chivinsky[1]

Effect of Elevated Temperatures on the Properties of Nitrogen-Bearing Type 216 Steel

REFERENCE: Chivinsky, J. A., "**Effect of Elevated Temperatures on the Properties of Nitrogen-Bearing Type 216 Steel,**" *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, ASTM STP 522,* American Society for Testing and Materials, 1973, pp. 105–115.

ABSTRACT: Preliminary data indicate that Type 216, a high-nitrogen and molybdenum-bearing austenitic stainless steel offers improved strength over conventional Type 316 to temperatures approaching 1350 F (732 C). However, impact and intergranular corrosion tests conducted on the material suggest that Type 216 may be restricted to service temperatures near 1200 F (649 C). The superior strength of Type 216, coupled with its excellent corrosion properties, makes it attractive for application in the process industries (chemical, petrochemical, pulp, paper, etc.) as well as marine and space markets.

KEY WORDS: nitrogen, austenitic stainless steels, mechanical properties, elevated temperatures

The purpose of this presentation is to demonstrate with preliminary data the potential advantages and limitations of a high-nitrogen and molybdenum-bearing austenitic stainless steel. This material, T-216, has superior high temperature strengths (namely, tensile, stress to rupture, and creep) compared to Type 316. Type 216 like Type 316 does show reduced impact strengths and is susceptible to intergranular cracking in acidified copper sulfate after it has been exposed to elevated temperatures for long periods of time. However, the data suggest that Type 216 is suitable for applications in the chemical and petrochemical fields.

Type 216 is a chromium-manganese-nickel-molybdenum-nitrogen grade.

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TABLE 1—*Compositions (weight percent).*

Material	C	Mn	P	S	Si	Cr	Ni	Mo	N
Type 216:	0.08 max	7.50/9.00	0.045 max	0.030 max	0.50 max	17.50/22.00	5.00/7.00	2.00/3.00	0.25/0.50
Heat A	0.071	8.25	0.020	0.020	0.50	19.33	6.12	2.52	0.32
Heat B	0.067	8.08	0.015	0.023	0.69	19.57	5.67	2.13	0.34
Heat C	0.045	8.40	0.017	0.007	0.19	19.70	7.06	2.83	0.35
Heat D	0.026	7.50	0.018	0.009	0.23	19.70	6.55	2.52	0.34
Type 316:	0.08 max	2.00 max	0.045 max	0.030 max	1.00 max	16.00/18.00	10.00/14.00	2.00/3.00	...
Heat E	0.059	1.68	0.021	0.015	0.53	17.32	13.72	2.47	...
Heat F	0.025	1.40	0.017	0.018	0.55	17.45	13.40	2.45	...

TABLE 2—*Room temperature mechanical properties.*

Product	Type	0.2% Yield Strength, ksi[b]	Ultimate Tensile Strength, ksi[b]	% Elongation, 2 in. or 50.8 mm	Reduction of Area, %	Hardness, R_B [c]	Bend
Annealed:[a]							
Sheet (0.040 in. or 1.02 mm)	216	66.8(47.0)	115.6(81.3)	46.5	...	92(192)	180 deg; 2T
Sheet (0.060 in. or 1.52 mm)	216L	68.2(47.8)	115.2(81.0)	45.0	...	92(192)	not tested
Plate (0.250 in. or 6.35 mm)	216L	66.7(46.8)	115.0(80.8)	46.3	64.7	97(223)	not tested
Plate (0.830 in. or 21.1 mm)	216L	62.1(43.7)	112.6(79.3)	51.0	68.8	93(197)	180 deg; 2T
Bar (1 in. by 3 in. or 25.4 mm by 76.2 mm)	216L	62.4(43.8)	108.8(76.5)	51.5	74.1	89(179)	not tested
Sheet and bar	316	38(27)	85(60)	60	77	...	...

[a] Annealed at 1950 F (1066 C).
[b] Values listed in parentheses are metric equivalents (kg/mm^2).
[c] Values listed in parentheses are Vickers hardness equivalents.

TABLE 3—*Resistance to pitting corrosion.*

Material	10% Ferric Chloride Room Temperature 300 h Exposure, pits per in.[2] (pits per cm[2])	90% Acetic Acid plus Sodium Chloride[a] (boiling) 300 h Exposure, pits per in.[2] (pits per cm[2])
Type 216	Nil (Nil)	81 (12.6)
Type 316	5 (0.78)	523 (81.3)

[a] Chloride ion added to a concentration of 200 ppm.

The specific heat analyses, shown in Table 1, are those of the material used in developing these data. It possesses corrosion resistance equivalent to Type 316, and in some instances, particularly pitting media, Type 216 is superior. In addition, the alloy offers high strength in various product forms. Because of this desired combination of properties, it would be appropriate to describe briefly the corrosion and room temperature strengths before discussing high temperature data.

Room Temperature Properties

Strength in Various Product Forms

One can consider Type 216 as a 200 Series counterpart to Type 316 having significantly greater mechanical strength than the chromium-nickel type, due to the nitrogen addition. Type 216 is nonhardenable by heat treatment; annealed products, as shown in Table 2, have yield strengths of approximately 60 000 psi (42.2 kg/mm^2), tensile strengths in excess of 100 000 psi (70.3 kg/mm^2), and elongations in 2 in. (50.8 mm) of 45 percent. Such material can be cold worked to tensile strengths well over 200 000 psi (140.6 kg/mm^2) and remain nonmagnetic. It can be produced as plate, sheet, strip, bars, tubes, and wire using electric furnace (air) melting practices.

Corrosion Behavior

Type 216 possesses corrosion resistance equal to, and in some instances superior to, that of Type 316. For instance:

1. In solutions of 10 percent ferric chloride or chloride containing solu-

TABLE 4—*65 percent boiling nitric acid.*

Material	Average, Five 48-h Periods in./month (mm/month)
Type 216	0.0010 (0.0254)
Type 316	0.0016 (0.0406)
Type 304	0.0008 (0.0203)

tions of boiling acetic acid, Type 216 displays superior resistance to localized chemical attack compared to Type 316 (see Table 3).

2. In severe oxidizing conditions typified by 65 percent boiling nitric acid, corrosion rates of Type 216 are comparable to the chromium-nickel Types 304 and 316 (see Table 4).

3. Type 216 is slightly less resistant to attack by dilute sulfuric acid when compared to Type 316.

4. Stress corrosion tests in boiling magnesium chloride show Type 216 to be comparable with Type 316; both grades cracked within 4 h of exposure.

Effect of Elevated Temperatures on Properties

More recently, considerable attention has been given by industry to the effects of nitrogen in strengthening conventional grades of stainless steel, Types 304 and 316, at high temperatures. European and American interests are considering up to 0.20 percent nitrogen in conventional chromium-nickel grades for increased creep strengths and tensile strengths. Concern could be expressed over possible embrittling effects of nitrogen when such material has been exposed to elevated temperatures for long periods of time, particularly for materials with levels of nitrogen above 0.20 percent. Therefore, it is only proper that Types 216 and 316 be discussed comparatively with these aspects in mind.

Elevated Temperature Tensile Strengths

Table 5 illustrates the markedly superior short time strengths of Type 216 over that of Type 316 at temperatures up to 1400 F (760 C). The properties of Type 216 were developed on annealed bar material. Note that the elongation values of the high nitrogen material were above 30 percent in every instance.

Welded sheet specimens of Type 216 displayed as-weld strengths and elongations comparable to annealed material. All of these specimens were gas-tungsten-arc (GTAW) welded and failed outside of the weld area. These data are shown in Table 6.

Stress Rupture Strengths

The higher strengths of Type 216 were further substantiated by stress rupture tests as shown in Table 7. Note that the high nitrogen material has markedly superior stress rupture strength at 1200 F (649 C) when compared to Type 316. For longer times at higher temperatures, the rupture strengths of both grades become comparable. Table 7A lists the specific stress rupture data for the specimens tested.

Creep Strengths

Limited testing to date indicates that Type 216 has notably superior creep strength over Type 316 (Table 8). Additional testing at higher temperatures is underway.

TABLE 5—*Short time elevated tensile properties of annealed materials.*

Test Temperature, deg F (deg C)	0.2% Yield Strength, ksi		Ultimate Tensile Strength, ksi		% Elongation, 2 in. or 50.8 mm		Reduction of Area, %	
	T-216[a]	T-316[b]	T-216[a]	T-316[b]	T-216[a]	T-316[b]	T-216[a]	T-316[b]
68(20)	62.4(43.9)	42.4(29.9)	108.8(76.5)	82.4(58.0)	51.3	67.5	74.1	80.5
800(427)	40.1(27.2)	26.5(18.6)	82.8(58.3)	71.4(50.3)	45.0	47.0	70.1	71.0
1000(538)	36.3(25.5)	23.4(16.4)	75.4(53.0)	68.4(48.2)	43.3	55.0	68.7	70.0
1200(649)	35.7(25.1)	22.6(15.8)	66.7(46.8)	50.6(35.6)	42.3	24.0	69.6	32.0
1400(760)	33.0(23.2)	...	51.4(36.1)	30.7(21.6)	36.8	25.5	39.3	35.0

[a] Specimens removed from T-216L (annealed 1 in. by 3 in. bar or 25.4 mm by 76.2 mm). Values in parentheses are metric equivalents. (kg/mm^2).

[b] Allegheny Ludlum Steel Corporation, Blue Sheet. Values in parentheses are metric equivalents (kg/mm^2).

TABLE 6—*Effect of elevated temperatures on tensile properties of annealed Type 216 and as-welded 216.*

Test Temperature, deg F (deg C)	0.2% Yield Strength, ksi[a]		Ultimate Tensile Strength, ksi[a]		% Elongation 2 in. or 50.8 mm	
	Annealed	As-Welded[b]	Annealed	As-Welded[b]	Annealed	As-Welded[b]
68 (20)	77.2 (54.3)	79.7 (55.9)	120.8 (85.0)	125.9 (88.5)	44.0	38.3
800 (427)	41.5 (29.1)	42.5 (29.9)	91.5 (64.3)	92.0 (64.7)	43.3	36.0
1100 (593)	37.3 (26.2)	37.7 (26.5)	79.7 (55.3)	81.2 (57.0)	32.8	31.8
1300 (704)	33.9 (23.4)	36.3 (25.5)	62.6 (44.0)	64.4 (45.3)	37.8	40.0
1500 (816)	26.9 (18.9)	26.3 (17.8)	40.9 (27.7)	41.3 (29.0)	61.0	48.3

[a] Values in parentheses are metric equivalents (kg/mm^2).
[b] Annealed strips (0.060 in. or 1.52 mm), gas-tungsten-arc welded parallel to the rolling direction. All weld specimens broke in the base metal.

TABLE 7—*Stress-rupture strengths of annealed materials.*

Test Temperature, deg F (deg C)	100 h		1000 h	
	T-216[a] ksi	T-316[b] ksi	T-216[a] ksi	T-316[b] ksi
1200(649)	47.0(33.0)	32.0(20.4)	39.0(27.4)	25.0(15.5)
1350(732)	21.0(14.8)	18.0(12.7)	11.5(8.1)	12.0(8.4)
1500(816)	8.5(6.0)	9.0(6.3)	3.5(2.5)	5.5(4.2)

[a] Annealed strip (0.060 in. or 1.52 mm). Values in parentheses are metric equivalents (kg/mm^2).
[b] ASTM Special Publication No. DS5S2. Values in parentheses are metric equivalents (kg/mm^2).

Room Temperature Impact Strengths

If nitrogen has a beneficial effect on improving high temperature strengths of Type 216, could long times at elevated temperatures produce detrimental effects on the notch toughness or intergranular corrosion resistance of Type 216? This could be of particular concern in chemical or petrochemical equipment that is shutdown for repairs.

Oversize Charpy blanks removed from annealed products of Types 216 and 316 were exposed to temperatures between 700 F (371 C) and 1500 F (816 C) for times up to 1000 h. After exposure, longitudinal V-notch Charpies (0.394 in. or 10.0 mm) were machined with the length of the notch going through the thickness of the material. The impact tests were conducted at room temperature, and the average data developed for the heats are shown in Table 9. Note that as the time and temperatures of exposure increase, the impact values of the alloys decrease, both grades being essen-

TABLE 7A—*Stress-rupture properties of annealed Type 216*[a].

Test Temperature, deg F (deg C)	Stress, ksi (kg/mm^2)	Time, h	Elongation, %
1200(649)	50.0(35.1)	143.5	35.0
1200(649)	48.0(33.7)	166.3	21.1
1200(649)	46.0(32.3)	132.4	35.9
1200(649)	40.0(28.1)	624.0	43.0
1200(649)	35.0(24.6)	841.2	11.2
1200(649)	30.0(21.1)	2691.4	33.0
1350(732)	28.0(19.7)	32.0	49.5
1350(732)	20.0(14.1)	128.6	42.0
1350(732)	10.0(7.0)	3385.5	22.3
1350(732)	12.0(8.4)	942.4	52.0
1500(816)	22.0(15.5)	8.3	54.4
1500(816)	12.0(8.4)	26.3	56.2
1500(816)	6.0(4.2)	698.9	64.6

[a] Annealed strip (0.060 in. or 1.52 mm).

TABLE 8—*Creep strength of annealed materials.*

Test Temperature, deg F (deg C)	0.1% in 1000 h		0.01% in 1000 h	
	Type 216,[a] ksi	Type 316,[b] ksi	Type 216,[a] ksi	Type 316,[b] ksi
1100(593)	34.0(23.9)	22.5(15.8)	27.0(18.9)	12.4(8.7)
1200(649)	17.5(12.3)	14.2(10.0)	12.9(9.1)	7.9(5.6)

[a] Annealed plate (0.500 in. thick or 12.7 mm). Values in parentheses are metric equivalents (kg/mm²).
[b] *ASTM DS5S2*. Values in parentheses are metric equivalents (kg/mm²).

tially unaffected at temperatures up to 1000 F (538 C) for 1000 h. However, at 1200 F (649 C) the alloys show significant decrease in impact strength. At 1350 F (732 C) and 1500 F (816 C), Type 216 displayed very low values (3 ft·lb or 4.1 joules). The embrittlement of Type 216 appears to be due to chi-phase, whereas sigma caused embrittlement in Type 316.

Effect of Elevated Temperatures on Intergranular Corrosion

Intergranular corrosion tests are in progress to determine the comparative resistances of Types 216 and 316 to stress cracking after exposure to acidified copper sulfate solutions. This work follows the test procedures employed by Dr. Carl Samans [*1*].[2] According to Dr. Samans, the copper sulfate test can be used as an acceptance test for determining a material's resistance to stress cracking in polythionic acid, because the copper sulfate is a more severe test. Here, annealed specimens (0.060 by ¼ by 3 in. long, or 15.2 by 6.35 by 76.2 mm) were heat treated at temperatures between 700 F (371 C) and 1500 F (816 C) for times up to 1000 h. The specimens were then exposed to boiling copper sulfate (ASTM, A-393) and bent 180 deg around a diameter of ¼ in. (6.35 mm). The specimens were examined at ×20 for evidence of cracking. Initial data for 1000 h tests showed that the nitrogen-bearing grade can be crack-free at 1000 F (538 C) or lower. As the temperature increased, failure occured. The chromium-nickel types revealed cracking at 1200 F (648 C) and above. Data developed by Dr. Samans show that Types 316 and 316L are sensitized to copper sulfate test. This agrees with our initial findings.

Polythionic acid can form in sulfur-bearing refining streams and, thus, cause stress cracking of material during shutdown of equipment which had been exposed to service temperatures between 900 F (482 C) and 1500 F (816 C). The stress cracking data developed to date are minimal, therefore, it would be premature to form any conclusions.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 9—*Effect of Elevated Temperatures on Room Temperature Impact Strength.*[a]

Exposure Temperature, deg F (deg C)	1 h		100 h		1000 h	
	Type 216/216L, ft·lb[b]	Type 316/316L, ft·lb[b]	Type 216/216L, ft·lb[b]	Type 316/316L, ft·lb[b]	Type 216/216L, ft·lb[b]	Type 316/316L, ft·lb[b]
700 (371)	216 (293)	190 (258)	217 (294)	204 (277)	217 (294)	166 (225)
850 (454)	213 (289)	196 (266)	216 (293)	209 (284)	225 (305)	176 (239)
1000 (538)	212 (288)	202 (274)	209 (284)	202 (274)	206 (280)	188 (255)
1200 (649)	216 (293)	190 (258)	158 (214)	160 (217)	60 (83)	98 (133)
1350 (732)	193 (262)	202 (274)	46 (62)	97 (132)	4 (5.4)	58 (79)
1500 (816)	154 (209)	161 (219)	30 (41)	91 (124)	4 (4.1)	37 (50)

[a] Longitudinal CVN from annealed plate and bar stock (0.500 in. or 12.7 mm thick and 0.625 in. or 15.9 mm dia notched through thickness, tested in triplicate.

[b] Values in parentheses are metric equivalents (joules).

Summary

It is evident from the above data that Type 216 offers improved strengths over Type 316 to temperatures approaching 1350 F (732 C). Tension testing shows that this nitrogen-bearing grade has greater strength than Type 316 for temperatures of 1400 F (760 C) and higher. When the time at temperature is extended, as in the case of stress rupture testing, the strengths of both grades are comparable at 1350 F (732 C), while Type 216 maintains superior strength at 1200 F (649 C).

However, impact testing of materials exposed to elevated temperatures suggest that Type 216 may be restricted to service temperatures near 1200 F (649 C). For instance, Type 216 like Type 316 showed notable drops in impact strength (room temperature) after exposure to 1200 F (649 C) for 1000 h. Very low impact values of 4 ft·lb (5.4 joules) were evident for Type 216 after exposure to 1350 F (732 C) for 1000 h compared to 58 ft·lb (79 joules) for Type 316. This embrittling behavior is primarily attributed to chi formation and sigma formation in Types 216 and 316, respectively. Limited intergranular corrosion testing in acidified copper sulfate solution suggests that Type 216 can resist stressing (bending radius = twice thickness) so as to be crack-free after exposure to temperatures of 1000 F (538 C) or lower. The chromium-nickel types revealed cracking at 1200 F (649 C) and above.

The superior strength of Type 216 coupled with its excellent corrosion properties make Type 216 attractive for applications in the process industries (namely, chemical petrochemical, pulp, and paper) as well as marine and space markets.

Reference

[1] Samans, C. H., *Corrosion*, Vol. 20, 1960, pp. 256t–262t.