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Product Form Characterization of Reference Heat of Type 316 Stainless Steel

V. K. Sikka

~~APPLIED TECHNOLOGY~~

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TYPE 316 STAINLESS STEEL

V. K. Sikka

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PRODUCT FORM CHARACTERIZATION OF REFERENCE HEAT OF
TYPE 316 STAINLESS STEEL*

V. K. Sikka

ABSTRACT

The product form characterization of the reference heat (8092297) of type 316 stainless steel was completed. Ten product forms were studied: three plates, four pipes, and three bars. Melting, fabrication processes, composition variations, optical microstructure and grain size, room-temperature Rockwell and microhardness data, and tensile properties in both mill-annealed and reannealed conditions are described. Residual cold work in various product forms was estimated from the tensile properties. Tensile data was modeled and compared with "minimum" value curves. Stress-strain curves (up to 4%) were predicted and compared with the experimental data. Room-temperature tensile properties on various product forms were compared with the vendor certified data.

Tensile properties and microstructure of specimens cold-worked from 0 to 30% and annealed for 0.5 hr at 1065 or 1150°C were studied to explain differences observed in tensile properties of various product forms.

INTRODUCTION

Austenitic stainless steels of types 304 and 316 are important structural materials for nuclear reactors and other energy systems. Mechanical properties testing programs on these materials are under way at Oak Ridge National Laboratory (ORNL). The programs include studies on:

1. product form characterization¹⁻⁵ of a single heat (reference heat) of types 304 and 316 stainless steel,
2. heat-to-heat variations⁶⁻⁸ in tensile and creep properties of 20 heats of type 304 and nine heats of type 316 stainless steel,

* Work performed under ERDA/RDD 189a OH050, Mechanical Properties for Structural Materials.

3. influence^{9,10} of residual stresses in mill-annealed material on tensile and creep properties of types 304 and 316 stainless steel,
4. influence of long-term thermal aging^{11,12} with and without stress on tensile and creep properties of types 304 and 316 stainless steel.

Work is continuing in the areas listed above, and the objective of this report is to present the product form characterization of the reference heat (8092297) of type 316 stainless steel. Specifically, this report will present the following:

1. melting details,
2. fabrication processes for different products,
3. composition variations among various product forms,
4. optical microstructure and grain size of various products,
5. room-temperature Rockwell and microhardness data,
6. tensile properties of various products in the mill-annealed and reannealed conditions,
7. estimate of residual cold work in various product forms from tensile properties in as-received and reannealed conditions,
8. modeling of tensile data for various product forms,
9. effect of cold work on reannealed properties,
10. comparison of expected and minimum properties,
11. stress-strain behavior,
12. relation between room-temperature yield strength and hardness,
13. comparison of 0.2% yield strength data with data on other heats, and
14. comparison of 0.2% yield and ultimate tensile strengths with vendor-certified mechanical property data.

MATERIALS AND EXPERIMENTAL DETAILS

Melting Details

The reference heat of type 316 stainless steel was air melted in a 200-ton electric furnace at Republic Steel's No. 4 melt shop of the Steel Division, Canton, Ohio. The heat was made in February 1974 and was intended to meet the ORNL-MC-316 specification.¹³ The ladle analysis in Table 1 shows that the chemical analysis of the reference heat was in

Table 1. Comparison of Ladle Chemical Analysis for the
Reference Heat (8092297) of Type 316 Stainless Steel
with ORNL, RDT, and *Nuclear Systems Materials*
Handbook Specifications

Chemical Element	Content, wt %			
	RDT Standards	NSMH	ORNL-MC-316	Ladle Analyses
C	0.04–0.10	0.08 max	0.050–0.080	0.057
Mn	2 max	2.00 max	1.50–2.00	1.86
P	0.030 max	0.045 max ^a	0.02–0.03	0.024
S	0.030 max	0.030 max	0.010–0.025	0.019
Si	0.75 max	1.00 max ^b	0.030–0.60	0.58
Ni	11.00–14.00	10.00–14.00 ^c	13.25–13.75	13.48
Cr	16.00–18.00	16.00–18.00	16.5–17.5	17.25
Mo	2.0–3.0	2.00–3.00	2.20–2.50	2.34
Co	None	None	0.10 max	0.02
Cu	None	None	0.20 max	0.10
N	None	None	0.05 max	0.03
Nb + Ta	d	None	0.020 max	e
B	None	None	0.003 max	0.0005
Ti	None	None	0.020 max	0.02
Pb				0.003
Sn				0.004
Al			Not required	

^a0.030 max for seamless pipe (SA 376).

^b0.75 max for seamless pipe (SA 376).

^c11.00–14.00 for seamless pipe (SA 376).

^dThe Nb + Ta content shall be not less than ten times the carbon content and not more than 1.00%.

^eNot detectable at level of 0.01 wt %.

close agreement with ORNL-MC-316, RDT, and *Nuclear Systems Materials Handbook*¹⁴ (NSMH) specifications. Various product forms were made from this heat, herein we describe the work being carried out at ORNL on mechanical property characterization of these products.

Fabrication Processes

The product forms being studied include plate, pipe, and bar of various sizes, listed in Table 2. They were fabricated as follows:

Plate Product — The 16-mm-thick plates were produced from 635- by 685-mm ingots. These ingots were bloomed to 457 by 102 mm. Each bloom was cut into three sections and each section was hot rolled to plate approximately 100- by 200-mm long. The 25- and 51-mm-thick plates were processed similarly, except that the ingot size was 508 by 1041 mm and it was bloomed to 863- by 127-mm slabs. All plates were solution annealed at $1065 \pm 30^{\circ}\text{C}$ ($1950 \pm 50^{\circ}\text{F}$) before shipping.

Pipe Products — All pipes except 406- and 711-mm-diam pipe were produced at the Ellwood City works of U.S. Steel. Seamless pipe was produced by the Mannesman process, in which the round, after being heated to temperature, is squeezed between rotating rolls while being rotated at high speed and drawn through the mill over a piercing point located between the rolls. After piercing, the pipe is reduced by either plug rolling and reeling or bar rolling and sizing. The 406- and 711-mm-diam by 10-mm-wall pipes were produced at Rollmet by roll extrusion, a reduction process at room temperature that involves intermediate annealing. The 406-mm pipe was produced by external roll extrusion in which the die ring works from the outside, increasing the length and decreasing the thickness while maintaining constant inside diameter. The 711-mm-diam by 10-mm-wall pipe was produced by internal roll extrusion, in which solid rollers inserted within the forged ring apply pressure on the internal surfaces, while a tight-fitting external die ring maintains the outside diameter within very close tolerances. All pipe was solution annealed at $1065 \pm 30^{\circ}\text{C}$ ($1950 \pm 50^{\circ}\text{F}$).

Table 2. Product Form, Size, and Grain Sizes of Various Products of Reference Heat (8092297) of Type 316 Stainless Steel

Product Form	Size mm(in.)	Grain Size, ASTM (μm)							
		As-Received Condition				Reannealed Condition			
		Longitudinal		Transverse		Longitudinal		Transverse	
		With Twins	Without Twins	With Twins	Without Twins	With Twins	Without Twins	With Twins	Without Twins
Plate	16 (5/8)	6.2 (37)	5.3 (50)	6.4 (34)	5.4 (48)	5.5 (46)	3.6 (90)	5.8 (41)	5.0 (56)
Plate	25 (1)	6.2 (36)	4.2 (74)	6.1 (38)	4.2 (74)	6.3 (35)	4.2 (74)	5.5 (47)	4.2 (74)
Plate	51 (2)	5.3 (50)	4.2 (74)	4.8 (59)	4.0 (79)	5.3 (50)	4.2 (74)	4.8 (59)	3.8 (85)
Pipe ^a	114 OD $\times$ 13 wall (4 1/2 $\times$ 1/2)			{ not measurable 6.3 (35) 5.0 (56) not measurable				{ not measurable 6.1 (38) 4.2 (74) 5.1 (53) 2.5 (130)	
Pipe ^a	219 OD $\times$ 13 wall (8 5/8 $\times$ 1/2)			{ 6.0 (39) 4.0 (78) 6.6 (32) 4.8 (59) 6.6 (32) 4.4 (68)				{ 6.3 (35) 4.8 (59) 6.0 (40) 4.8 (59) 6.2 (37) 4.2 (73)	
Pipe ^a	406 OD $\times$ 10 wall (16 $\times$ 0.4)			{ 6.1 (38) 4.8 (59) 6.1 (38) 3.8 (85) 6.1 (38) 4.2 (73)				{ 6.1 (38) 4.0 (78) 5.3 (50) 3.5 (93) 6.2 (37) 4.4 (68)	
Pipe ^a	711 OD $\times$ 10 wall (28 $\times$ 0.4)			{ 6.5 (36) 4.0 (78) 5.1 (53) 3.5 (93) 5.3 (51) 3.5 (93)				{ 5.4 (48) 3.7 (85) 5.5 (45) 3.5 (93) 5.0 (56) 2.9 (115)	
Bar	25 (1)	6.2 (37)	4.2 (73)	6.0 (40)	4.2 (73)	6.3 (35)	3.7 (86)	6.2 (37)	4.4 (68)
Bar ^a	51 (2)	{ 5.5 (46) 5.7 (44)	3.1 (108)	6.1 (38)	4.4 (68)	5.4 (48)	3.5 (92)	5.9 (41)	4.0 (79)
				5.7 (44)	3.5 (93)			4.8 (58)	3.2 (102)
Bar ^a	64 (2.5)	{ 5.7 (44) 6.0 (40)	4.0 (78)	5.7 (44)	4.0 (78)	5.9 (41)	3.5 (92)	5.6 (45)	4.0 (78)
				6.0 (40)	3.5 (93)			5.9 (41)	3.7 (85)

^aThe three lines of entries for each pipe size are, in order, for the inner edge, the midwall, and the outer edge. The second transverse values for the larger bars are for the outer edge.

Bar Products — All bars were produced from 635- by 689-mm ingots, bloomed to 229 by 197 mm, cut into multiples, and hot-rolled through a series of intermediate breakdowns to slightly above final product diameter. All bars were solution annealed at $1065 \pm 30^{\circ}\text{C}$ ($1950 \pm 50^{\circ}\text{F}$) and subsequently straightened, turned, and ground to final size. The bars being investigated are 25, 51, and 64 mm (1, 2, and 2.5 in.) in diameter.

Chemical Analysis

The vendor analyses along with the ORNL check analyses on several products are summarized in Table 3. For comparison the ORNL-MC-316 specification and ladle analysis are also included. The chemical analysis of all ten products is essentially the same.

Microstructure

Optical microstructure of specimens etched electrolytically with 10% $\text{HNO}_3/\text{H}_2\text{O}$ solution is shown in Figs. 1 through 10 for various product forms of the reference heat in both as-received and reannealed conditions. Grain sizes were measured¹⁵ from these micrographs and are summarized in Table 2. Grain sizes for pipe product were measured at the inner surface, midwall, and outer surface. The grain size at the outer surface was generally larger than at the other two locations for both as-received and reannealed conditions. The outer surface of the 51- and 64-mm bars also showed coarser grain size in both mill- and laboratory-annealed conditions. In general, none of the products showed unusual or excessive grain growth on reannealing for 0.5 hr at 1065°C (1950°F). The backup work to select the reannealing treatment is presented in Appendix A.

Microhardness Studies

Previous studies^{1,3,9} on product form characterization of type 304 stainless steel indicated that the bars varied more in hardness across the section than did other products. Therefore, bar products of the reference heat of type 316 stainless steel were also subjected to careful hardness traverses. These are shown in Fig. 11. The as-received 51- and

Table 3. Summary of Chemical Analysis for Variance Product Forms of Reference Heat (8092297) of Type 316 Stainless Steel

Chemical Element	ORNL-MC-316 Specification	Ladle Analysis	Concentration, wt %												
			Vendor Analysis for Various Product Forms and Size in mm										ORNL Check Analysis		
			Plates			Pipe				Bar			Plate	Pipe	
			16	25 ^a	51 ^b	13 × 114 ^c	13 × 219 ^d	10 × 406 ^d	10 × 711 ^e	25	51	64	16	10 × 406	10 × 71
C	0.050–0.080	0.057	0.060	0.059–0.060	0.062–0.065	0.061–0.065	0.061–0.68	0.01–0.065	0.065–0.07	0.060	0.051	0.054	0.0645	0.064	0.066
Mn	1.50–2.00	1.86	1.88	1.84–1.86	1.82–1.85	1.86	1.85–1.87	1.75–1.81	1.77–1.84	1.85	1.87	1.86		1.75	1.6
P	0.02–0.03	0.024	0.023	0.024	0.022–0.024	0.023–0.024	0.026–0.027	0.04–0.20	0.015–0.02	0.024	0.030	0.024	0.022	0.020	0.022
S	0.01–0.025	0.019	0.020	0.018	0.018–0.020	0.018	0.018	0.010–0.013	0.012–0.014	0.019	0.018	0.019	0.0188	0.018	0.019
Si	0.30–0.60	0.58	0.62	0.57–0.58	0.57–0.58	0.57–0.59	0.56–0.58	0.58–0.60	0.55–0.58	0.58	0.53	0.60	0.51	0.65	0.62
Cu	0.20 max.	0.10	0.08	0.10	0.08	0.10	0.10–0.11	0.05–0.14	0.05–0.13	0.09	0.09	0.08	0.12	0.04	0.03
Ni	13.25–13.75	13.48	13.40	13.40–13.45	13.30–13.40	13.50–13.60	13.48–13.50	12.80–12.95	12.65–12.80	13.70	13.45	13.50	13.86	13.50	13.3
Cr	16.5–17.5	17.25	17.30	17.15	16.90–17.15	17.10–17.20	17.07–17.20	17–50	17.18–17.40	17.10	17.28	17.19	16.46	17.50	16.8
Mo	2.20–2.50	2.34	2.34	2.34	2.29–2.34	2.34	2.32–2.35	2.34–2.41	2.18–2.37	2.35	2.32	2.34	2.44	2.38	2.38
Ti	0.020 max.	0.02	<0.01	<0.01	<0.01	0.020	0.01–0.02	<0.01–0.01	<0.01–0.01	0.01	0.02	0.02	<0.01	<0.01	<0.01
Co	0.10 max.	0.02	0.02	0.02	0.01	<0.01	<0.01			0.02	0.02	0.02	0.01		
N	0.05 max.	0.03	0.034	0.031–0.033	0.031–0.033	0.031–0.032	0.031–0.032			0.032	0.030	0.03	0.0305	0.05	0.03
B	0.003 max.	0.0005	0.0005	0.0005–0.0006	0.0005–0.0006	0.0005	0.0004–0.0005		<0.01–<0.001	0.0005	0.0005	0.0005	0.0005	0.0003	0.0015
Nb + Ta	0.020 max.	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05–<0.01	<0.05–<0.01	<0.01	<0.01	<0.01	0.10 ^f	<0.05	<0.05
Al	Not Required					0.015–0.017	0.014–0.017	<0.01–<0.001		0.023			<0.02		
Pb		0.003											<0.02		
Sn		0.004											<0.02		
O													0.0043		
H													0.0007		
W													0.0020		

^aRange for three lots of plates (individual analyses available in ORNL/TM-5196).

^bRange for four lots of plates (individual analyses available in ORNL/TM-5196).

^cRange for six analyses on three different lots (individual analyses available in ORNL/TM-5196).

^dRange for four analyses on two different lots (individual analyses available in ORNL/TM-5196).

^eRange for three analyses on three different lots (individual analyses available in ORNL/TM-5196).

^fFor Ta; 0.0004% Nb.

Fig. 1. Optical Microstructure of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scales are 0.0079 in. Plate is 5/8 in.

Fig. 2. Optical Microstructure of 25-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scales are 0.0079 in. Plate is 1 in.

Fig. 3. Optical Microstructure of 51-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scales are 0.0079 in. Plate is 2 in.

Fig. 4. Optical Microstructure of 13- by 114-mm Pipe of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Inner surface, (b) midwall, and (c) outer surface, as received. (d) Inner surface, (e) midwall, and (f) outer surface, reannealed. Scale is 0.0079 in. Pipe is 1/2 by 4 1/2 in.

Fig. 5. Optical Microstructure of 13- by 219-mm Pipe of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Inner surface, (b) midwall, and (c) outer surface, as received. (d) Inner surface, (e) midwall, and (f) outer surface, reannealed. Scale is 0.0079 in. Pipe is 1/2 by 8 5/8 in.

Fig. 6. Optical Microstructure of 10- by 406-mm Pipe of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Inner surface, (b) midwall, and (c) outer surface, as received. (d) Inner surface, (e) midwall, and (f) outer surface, reannealed. Scale is 0.0079 in. Pipe is 0.4 by 16 in.

Fig. 7. Optical Microstructure of 10- by 711-mm Pipe of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Inner surface, (b) midwall, and (c) outer surface, as received. (d) Inner surface, (e) midwall, and (f) outer surface, reannealed. Scale is 0.0079 in. Pipe is 0.4 by 28 in.

Fig. 8. Optical Microstructure of 25-mm Bar of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scale is 0.0079 in. Bar is 1 in.

Fig. 9. Optical Microstructure of 51-mm Bar of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scale is 0.0079 in. Bar is 2 in.

Fig. 10. Optical Microstructure of 64-mm Bar of the Reference Heat (8092297) of Type 316 Stainless Steel. (a), (b) Longitudinal and transverse sections, as received. (c), (d) Longitudinal and transverse sections, reannealed. Scale is 0.0079 in. Bar is 2.5 in.

Fig. 11. Hardness Profiles for Bars of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Rockwell hardness number. (b) Microhardness. To convert: 1 mm = 0.03937 in.

64-mm-diam bars showed consistent hardness gradients. The 25-mm-diam bar did not, but it showed a large variation in hardness, indicating a highly inhomogenous product. Reannealing for 0.5 hr at 1065°C removed the hardness gradients and variations and lowered the average values.

Tensile Test Specimen

The test specimen used in this study is shown in Fig. 12. The specimens were lathe-machined. Cut-up diagrams for tensile specimens from various product forms are shown in Fig. 13.

A set of 24 specimens was machined from each product form of the reference heat except 16-mm (5/8-in.) plate, from which 150 specimens were machined. To determine the uniformity of each product form, Rockwell hardness was measured on both ends of each specimen. The hardness data so obtained were plotted as hardness distribution histograms for each product and are shown in Figs. 14 through 16. The average hardness values for each product are summarized in Table 4. This table also includes average values from data plotted in Fig. 11 and some additional data obtained on reannealed specimens of various product forms. The following are some comments from Figs. 14 through 16 with the data summarized in Table 4.

Fig. 12. Tensile Test Specimen. To convert dimensions to millimeters, multiply by 25.4.

Fig. 13. Tensile Test Specimen Cut-Up Diagrams for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel.

Fig. 14. Hardness Distribution of Specimens Machined from Plate of the Reference Heat of Type 316 Stainless Steel. Left: three different sections of 16-mm (5/8-in.) plate. Below: top, 25-mm (1-in.), and bottom 51-mm (2-in.) plate.

Fig. 15. Hardness Distribution of Specimens Machined from (a) 25-mm- (1-in.-), (b) 51-mm- (2-in.-), and (c) 64-mm- (2.5-in.-) Diam Bars of the Reference Heat of Type 316 Stainless Steel.

Fig. 16. Hardness Distribution of Specimens Machined from Pipe of the Reference Heat of Type 316 Stainless Steel. (a) 0.114 m diam (4 1/2 in.). (b) 0.219 m diam (8 5/8 in.). (c) 0.406 m diam (16 in.). (d) 0.711 m diam (28 in.).

Table 4. Summary of Room-Temperature Hardness Values of Various Products of the Reference Heat of Type 316 Stainless Steel

Product Form	Dimensions		As-Received Material				Material Reannealed 0.5 hr at 1065°C			
			Hardness, R _B			Micro-hardness ^b (DPH)	Hardness, R _B			Micro-hardness ^b (DPH)
	(mm)	(in.)	Round ^a	Flat ^a	Flat ^b		Round ^c	Flat ^c	Flat ^b	
Plate	16	5/8	68.7	71.8	76.6 ^d				70.5 ^e	
Plate	25	1	67.4	70.5			63.2	66.2		
Plate	51	2	69.3	72.3			61.9	64.9		
Bar	25	1	76.9	79.8	85.5	210	68.4	71.5	72.6	149
Bar	51	2	75.9	78.8	79.4	176	66.2	69.3	68.0	147
Bar	64	2 1/2	77.5	80.3	79.9	173	68.0	71.1	72.6	150
Pipe	13 × 114 OD	0.5 × 4 1/2	72.5	75.6			67.6	70.7		
Pipe	13 × 219 OD	0.5 × 8 5/8	72.1	75.2			67.4	70.5		
Pipe	10 × 406 OD	0.4 × 16	68.6	71.7			63.8	66.8		
Pipe	10 × 711 OD	0.4 × 28	68.1	71.2			62.7	65.7		

^aAverage of two measurements each on the longitudinal cylindrical surfaces of 24 specimens of each product form (150 specimens of 16-mm plate). Round values are as measured. Flat values have a correction for curvature taken from hardness conversion tables.

^bMeasured on flat surface. Values are averages taken over the diameter of 25-mm bar and radius of 51- and 64-mm bar.

^cValues obtained similarly to the corresponding as-received values,^a except that each is the average of four measurements each on five different specimens.

^dAverage of three measurements each on the surface of 18 different blocks cut from the plate.

^eAverage of three measurements each on the surface of 12 different blocks cut from the plate.

1. The most uniform set of specimens, Fig. 15(a), was obtained only from the 25-mm (1-in.) bar product. All other products showed variation in hardness among specimens. These variations were most widely spread for plate. The specimens made from the edges of the plates were hardest.

2. For as-received material, all bars showed the higher hardness values than the plate and pipe.

3. The plate and the two large-diameter pipes (406 and 711 mm diam) showed the lowest values among all as-received product forms. The two small-diameter pipes made by the Mannesman process were harder than the large-diameter pipes made by Rollmet.

4. All product forms decreased in hardness on reannealing for 0.5 hr at 1065°C. However, the bars, which had highest hardness in the as-received condition, showed the largest drop in both Rockwell and microhardness.

5. The plots in Fig. 11 show that reannealing makes the hardness of the bars more uniform.

6. All product forms appear to reach approximately the same hardness values on reannealing.

Tensile Test Procedure

Tensile tests were run on a 44-kN capacity (10,000-lb) Instron universal testing machine at constant crosshead speeds. Strains measured by extensometers and loads from cells in the load train were obtained for the first 0.05 strain, while crosshead displacement versus load was graphed simultaneously and monitored continuously to rupture. The yield strength values were obtained from the extensometer chart (by the 0.2% offset method), and ultimate tensile strength was obtained from the load-deflection chart. The nominal strain rate of 0.004/min was obtained by controlling the crosshead movement. However, ASTM testing procedure¹⁶ requires that the strain rate of the specimens be controlled with a strain pacer. Limited work with a strain pacer, reported in Appendix B, showed that the results obtained by crosshead movement and strain pacer control were not significantly different. During this investigation, the specified strain rate of 0.004/min was maintained constant throughout the test.

Tensile Test Matrix

The tensile test matrix for product form characterization was as follows:

1. For each product form and condition, one specimen was tested at a strain rate of 0.004/min at each test temperature.
2. As-received material was tested at room temperature and 93, 204, 316, 427, 538, and 649°C.
3. Material reannealed 0.5 hr at 1065°C was tested at room temperature and 204, 427, 593, and 649°C.

RESULTS AND DISCUSSION

Tensile Properties of As-Received Product Forms

Tensile data on various product forms in the as-received condition are summarized in Tables 5 and 6. Plots of 0.2% yield stress, ultimate tensile strength, uniform and total elongation, and reduction of area as functions of test temperature are presented in Figs. 17 through 21. For the sake of clarity, properties for plate and pipe are compared in (a) and for 16-mm plate and bar in (b) of those figures. *Nuclear Systems Materials Handbook*¹⁴ minimum value curves for various properties are also included in these plots.

0.2% Yield Strength — All product forms except 10 × 711-mm pipe met the room-temperature minimum specified value of 207 MPa (30 ksi). Bars of all sizes showed higher yield strength values than plate and pipe. This observation is consistent with previously published results.⁹ As compared with plate and pipe, bar showed more variation in the data, which is expected from hardness gradients observed for bar in Fig. 11. Figure 17(a) also shows that meeting the room-temperature minimum value does not assure that the elevated-temperature data will lie above the Handbook minimum curve. Such an observation points out that the ratio method of defining minimum value curves may not be adequate for elevated-temperature applications.

Table 5. Tensile Properties of 16-mm (5/8-in.) Plate of Reference Heat 8092297 of Type 316 Stainless Steel, Tested in Mill-Annealed (As-Received) Condition at a Strain Rate of 0.004/min

Test	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)	Work to Plastic Instability	
			Proportional Limit	Yield		Tensile	Uniform	Total			$\left(\frac{\text{MJ}}{\text{m}^3}\right)$	$\left(\frac{\text{ft-lb}}{\text{in.}^3}\right)$
	(°C)	(°F)		0.02%	0.2%			1 in.	2 in.			
15539	25	77	115 (16.7)	194 (28.1)	227 (33.0)	583 (84.5)	60.1		73.9 ^a	79.6	313	3787
15540	93	200	76 (11.0)	150 (21.8)	191 (27.7)	513 (74.4)	39.5		51.6 ^a	77.2	177	2123
15541	204	400	70 (10.2)	125 (18.2)	155 (22.5)	493 (71.5)	38.8		44.7 ^b	73.5	162	1953
15542	316	600	70 (10.2)	117 (17.0)	143 (20.8)	505 (73.3)	39.0		44.9 ^a	70.0	162	1952
15543	371	700	68 (9.9)	111 (16.1)	142 (20.6)	513 (74.4)	37.7		46.0 ^a	67.0	157	1900
15544	427	800	62 (9.0)	102 (14.7)	137 (19.9)	504 (73.1)	39.9		46.4 ^a	68.0	166	2003
15545	482	900	62 (9.0)	101 (14.6)	127 (18.4)	505 (73.2)	44.3		48.3 ^b	66.4	181	2188
15546	538	1000	73 (10.6)	104 (15.1)	125 (18.1)	478 (69.3)	38.6	54.9	47.1 ^a	67.4	150	1810
15547	593	1100	67 (9.8)	101 (14.7)	120 (17.4)	425 (61.6)	40.2	61.0	51.6 ^a	67.5	140	1695
15548	649	1200	63 (9.2)	95 (13.8)	117 (16.9)	316 (45.8)	27.0	51.7	54.4 ^b	48.7	78	938
15549	704	1300	70 (10.2)	90 (13.1)	111 (16.1)	234 (34.0)	17.9	75.9	59.5 ^a	63.9	36	439
15550	760	1400	70 (10.2)	90 (13.0)	105 (15.3)	174 (25.3)	9.9	55.4	55.9 ^b	70.6	17	204

^aSpecimen broke at center and thus contained the neck.

^bSpecimen broke off-center and therefore did not contain the neck.

Table 6. Tensile Properties of Various Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel Tested at a Strain Rate of 0.004/min

Test	Test Temperature		Proportional Limit	Stress, MPa (ksi)			Elongation, %			Reduction of Area (%)	Work to Plastic Instability	
	(°C)	(°F)		Yield		Ultimate Tensile	Uniform	Total, in			(MJ/m ²)	(ft-lb/in. ²)
				0.02%	0.2%			1 in.	2 in.			
25-mm (1-in.) Plate												
16819	25	77	105(15.2)	169(24.5)	216(31.3)	572(82.9)	57.0	80.4	65.9	78.8	290	3496
16820	93	200	79(11.4)	130(18.8)	174(25.3)	513(74.4)	40.4	62.0	55.0	79.9	180	2169
16821	204	400	67(9.76)	97(14.1)	135(19.5)	483(70.1)	36.3	51.4	42.7	73.6	144	1734
16822	316	600	68(9.8)	91(13.2)	119(17.2)	496(71.9)	44.2	43.7	48.2	67.9	182	2197
16823	427	800	42(6.1)	86(12.4)	115(16.6)	496(72.0)	45.9	58.0	51.6	69.5	156	1883
16824	538	1000	52(7.5)	78(11.3)	103(15.0)	458(66.4)	36.5	56.7	48.6	66.3	132	1590
16825	649	1200	59(8.6)	77(11.2)	102(14.8)	316(45.8)	27.1	51.0	43.4	41.9	75	910
51-mm (2-in.) Plate												
16826	25	77	99(14.3)	182(26.4)	242(35.1)	556(80.7)	63.1	82.8	80.2	78.8	314	3791
16827	93	200	99(14.3)	151(21.9)	207(30.0)	494(71.7)	38.8	60.2	47.8	79.8	168	2026
16828	204	400	73(10.6)	126(18.3)	171(24.8)	464(67.3)	36.0	51.4	42.0	69.0	141	1703
16829	316	600	90(13.1)	121(17.6)	159(23.1)	463(67.1)	38.6	38.7	44.4	64.8	147	1781
16830	427	800	59(8.56)	113(16.4)	153(22.2)	478(69.3)	38.5	36.6	42.1	70.0	150	1815
16831	538	1000	65(9.41)	101(14.6)	141(20.5)	458(66.5)	38.7	54.3	48.5	65.8	144	1744
16832	649	1200	74(10.8)	101(14.7)	137(19.9)	305(44.3)	23.5	32.2	28.1	41.6	66	795
13 × 114-mm (1/2 × 4 1/2-in.) Pipe												
16854	25	77	127(18.4)	183(26.5)	235(34.1)	573(83.1)	56.0	78.8	65.8	79.6	286	3459
16855	93	200	79(11.4)	143(20.7)	195(28.3)	515(74.8)	39.3	60.5	47.5	78.2	178	2155
16856	204	400	85(12.3)	123(17.9)	169(24.5)	488(70.7)	34.4	51.8	41.6	72.5	144	1737
16857	316	600	68(9.8)	110(15.9)	155(22.5)	509(73.9)	41.3	50.5	44.8	65.9	176	2132
16858	427	800	56(8.1)	101(14.6)	141(20.5)	500(72.5)	39.3	49.2	40.0	64.0	164	1986
16859	538	1000	50(7.3)	90(13.1)	128(18.6)	478(69.3)	38.5	51.0	45.3	64.1	152	1842
16860	649	1200	68(9.8)	91(13.2)	125(18.2)	307(44.6)	21.8	35.8	33.9	28.1	61	743
13 × 219-mm (1/2 × 8 5/8-in.) Pipe												
16861	25	77	134(19.4)	186(27.0)	241(35.0)	568(82.5)	58.7	80.4	68.2	79.5	297	3588
16862	93	200	80(11.6)	152(22.1)	201(29.1)	504(73.2)	40.2	58.6	48.0	79.0	175	2115
16863	316	600	54(7.8)	112(16.2)	152(22.1)	490(71.1)	39.1	52.8	46.2	67.3	160	1928
16865	427	800	65(9.4)	107(15.5)	145(21.1)	497(72.1)	39.1	54.2	46.1	67.7	159	1922
16866	538	1000	62(9.0)	91(13.2)	128(18.6)	458(66.4)	40.5	53.4	48.0	64.7	154	1859
16867	649	1200	57(8.2)	88(12.7)	123(17.8)	304(44.1)	23.2	38.0	32.7	34.9	64	774
10 × 406-mm (0.4 × 16 in.) Pipe												
17354	25	77	117(17.0)	185(26.8)	212(30.8)	564(81.8)	64.4	75.3	77.5	79.4	323	3900
17355	93	200	99(14.3)	162(23.5)	179(26.0)	499(72.4)	41.6	63.7	50.6	79.5	178	2146
17356	204	400	87(12.6)	126(18.2)	141(20.5)	474(68.8)	37.0	54.6	43.7	74.6	144	1740
17357	316	600	74(10.7)	113(16.4)	128(18.5)	488(70.8)	42.2	53.6	45.9	67.8	168	2026
17358	427	800	72(10.5)	103(14.9)	115(16.7)	488(70.7)	43.2	44.1	46.2	66.9	169	2047
17359	538	1000	68(9.9)	93(13.5)	106(15.3)	454(65.9)	40.6	53.6	45.4	68.7	149	1798
17360	649	1200	76(11.0)	91(13.2)	101(14.6)	301(43.7)	26.1	46.8	38.3	37.6	71	853
10 × 711-mm (0.4 × 28-in.) Pipe												
17361	25	77	126(18.3)	183(26.5)	205(29.7)	556(80.7)	58.0	66.2	69.1	79.2	288	3479
17362	93	200	83(12.1)	146(21.1)	176(25.5)	502(72.8)	41.6	62.6	50.5	78.8	180	2176
17363	204	400	84(12.2)	121(17.5)	140(20.3)	476(69.0)	37.7	52.2	43.8	74.3	147	1777
17364	316	600	65(9.4)	104(15.1)	123(17.8)	484(70.2)	43.4	41.7	47.4	69.1	170	2051
17365	315	598	77(11.1)	114(16.5)	125(18.1)	482(69.9)	44.5	47.3	49.2	66.2	176	2123
17366	538	1000	64(9.3)	90(13.0)	104(15.1)	451(65.4)	41.2	53.4	49.2	62.7	150	1808
17367	649	1200	58(8.4)	80(11.6)	98(14.2)	300(43.5)	24.2	42.0	35.3	38.7	64	776
25-mm (1-in.) Bar												
16833	25	77	110(15.9)	196(28.5)	270(39.2)	574(83.3)	56.0	83.1	68.9	79.0	292	3532
16834	93	200	87(12.6)	183(26.5)	245(35.5)	513(74.4)	37.1	58.7	46.4	78.5	171	2064
16835	204	400	101(14.6)	162(23.5)	204(29.6)	486(70.5)	34.7	50.6	42.8	74.7	156	1887
16836	316	600	90(13.0)	135(19.6)	179(25.9)	483(70.1)	37.5	52.0	44.3	69.9	154	1864
16837	427	800	101(14.7)	146(21.2)	176(25.6)	497(72.1)	40.4	54.8	46.5	69.7	170	2053
16839	649	1200	85(12.3)	122(17.7)	150(21.8)	312(45.3)	23.6	49.8	42.1	43.2	68	826
51-mm (2-in.) Bar												
16840	25	77	73(10.6)	163(23.6)	274(39.7)	571(82.8)	58.3	81.8	68.4	79.1	300	3625
16841	93	200	73(10.6)	233(33.2)	233(33.8)	511(74.2)	37.9	60.1	48.4	78.9	172	2080
16842	204	400	112(16.3)	154(22.3)	194(28.2)	482(70.0)	34.0	49.0	40.6	75.8	140	1695
16843	316	600	93(13.5)	131(19.0)	174(25.2)	479(69.5)	37.0	50.9	44.1	69.8	151	1810
16844	427	800	87(12.6)	134(19.5)	174(25.2)	494(71.7)	36.7	52.5	46.4	68.7	150	1813
16845	538	1000	93(13.5)	120(17.4)	155(22.5)	464(67.4)	37.5	52.0	45.7	67.1	143	1731
16846	649	1200	83(12.1)	108(15.7)	148(21.4)	307(44.5)	24.1	48.8	41.4	41.5	68	826
64-mm (2.5-in.) Bar												
16847	25	77	59(8.6)	225(32.7)	324(47.0)	580(84.2)	55.9	77.9	65.4	80.1	299	3617
16848	93	200	76(11.0)	141(20.5)	196(28.5)	499(72.4)	39.0	61.7	49.1	80.9	163	1965
16849	204	400	85(12.3)	123(17.9)	160(23.2)	470(68.1)	35.0	53.8	44.4	76.5	171	2068
16850	316	600	126(18.3)	181(26.3)	225(32.6)	498(72.3)	39.3	39.8	45.1	72.2	171	2068
16851	427	800	141(20.5)	190(27.5)	229(33.2)	506(73.4)	36.6	49.2	43.2	68.3	162	1959
16852	538	1000	90(13.0)	140(20.3)	176(25.6)	467(67.7)	38.4	50.4	43.5	68.2	151	1826
16853	649	1200	99(14.4)	141(20.4)	181(26.3)	309(44.9)	21.1	45.3	38.4	36.4	62	753

Fig. 17. The 0.2% Yield Strength as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm plate and bar.

Fig. 18. The Ultimate Tensile Strength as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm plate and bar.

Fig. 19. The Uniform Elongation as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm plate and bar.

Fig. 20. The Total Elongation as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm plate and bar.

Ultimate Tensile Strength — Room-temperature ultimate tensile strength values for all product forms were above the minimum specified value of 517 MPa (75 ksi). Unlike yield strength data, there was no significant difference between the ultimate tensile strength data on various product forms for the whole temperature range. Ultimate tensile strength for all product forms was above the Handbook minimum curve for all test temperatures except 649°C (1200°F). Strain-rate sensitivity of ultimate tensile strength at 649°C is the possible reason for the observed values to fall below the minimum curve. Ultimate tensile strength values for all products showed a slight increase in the temperature range from 300 to 500°C (570–930°F), and this is associated with possible dynamic strain-aging effects.

Uniform Elongation — Uniform elongation data for all product forms were above the Handbook minimum for the whole temperature range of this investigation. Dynamic strain aging over the range 300 to 500°C resulted in increased values of uniform elongation for all product forms. The Handbook includes one minimum value curve for pipe and tube and another for plate and bar. The present data on various products show no real differences in values for the different products, but if a separation is desired the plate should be combined with pipe and tube rather than with bar. Furthermore, the minimum value curve should be higher for plate, pipe, and tube than for bar, which is contrary to the values reported in the Handbook.

Total Elongation — Total elongation values for all product forms were above the Handbook minimum curves. The comments made for uniform elongation on separate minimum curves for plate, pipe, tube, and bar also hold true for total elongation.

One feature missing from the Handbook minimum value curves is the experimentally observed sharp drop in total elongation at 649°C (1200°F). Such a drop is associated with tensile ductility minimum conditions, which are discussed elsewhere.¹⁷

Reduction of Area — Reduction of area values for various product forms are plotted in Fig. 21. The Handbook does not contain any minimum value curve for this property. However, it is interesting to note that

reductions of area for all product forms were essentially the same, and all showed a sharp drop at 649°C. Such a drop is again associated with the ductility minimum conditions, which are discussed elsewhere.¹⁷

Work to Plastic Instability — The area under the stress-strain curve up to the ultimate tensile strength point is a measure of toughness of the material. Values of this quantity were computed for various product forms of the reference heat and are displayed as a function of test temperature in Fig. 22. These plots show that the toughness of all products decreases sharply at a test temperature of 649°C. This is the same temperature at which creep effects become important and fracture becomes intergranular.¹⁷ The dynamic strain-aging effects were also reflected in toughness values.

Fig. 22. Work to Plastic Instability as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm plate and bar.

Tensile Properties of Reannealed Product Forms

Tensile data on various products in the reannealed condition are summarized in Tables 7 and 8. Test temperature variation of 0.2% yield strength, ultimate tensile strength, uniform and total elongation, and reduction of area are plotted in Figs. 23 through 27. For the sake of clarity, properties for plate and pipe are compared in (a) and for 16-mm plate and bar in (b) of those figures. *Nuclear Systems Materials Handbook*¹⁴ minimum value curves for various properties are also included in the plots.

Yield Strength — Reannealing lowered the 0.2% yield strength of all products. Some plate and pipe products met the room-temperature minimum specified value of 207 MPa (30.0 ksi). However, all plate and pipe products showed yield strength values below the Handbook minimum at elevated temperatures. Bars of all sizes met the room-temperature minimum specified value of 207 MPa (30.0 ksi). Bars of 16- and 64-mm (5/8- and 2.5-in.) diameter had elevated-temperature yield strength values above the Handbook minimum curve. Elevated-temperature yield strength values for 51-mm-diam (2-in.) bar were below the Handbook minimum curve. Figure 23 shows that reannealing lowers the yield strength of all products. This observation is consistent with the previously published results^{9,10} on types 304 and 316 stainless steel. This figure also shows that meeting the room-temperature minimum value does not assure that elevated-temperature data will lie above the Handbook minimum curve. Such an observation points out that the ratio method of defining minimum value curves may not be adequate for elevated-temperature applications. Results presented above and earlier^{9,10} also suggest that the room-temperature minimum specified value of types 304 and 316 stainless steel should be less than 207 MPa (30 ksi) for the reannealed condition.

Ultimate Tensile Strength — Room-temperature ultimate tensile strength values for all product forms in the reannealed condition were above the minimum specified value of 517 MPa (75.0 ksi). Unlike yield strength data, the ultimate tensile strength data on various products did not differ significantly for the whole temperature range. Ultimate

Table 7. Tensile Properties of 16-mm (5/8-in.) Plate^a of the Reference Heat of Type 316 Stainless Steel, Tested at a Strain Rate of 0.004/min

Test	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)	Work to Plastic Instability	
	(°C)	(°F)	Proportional Limit	Yield		Tensile	Uniform	Total			$\left(\frac{\text{MJ}}{\text{m}^3}\right)$	$\left(\frac{\text{ft-lb}}{\text{in.}^3}\right)$
				0.02%	0.2%			1 in.	2 in.			
15452	25	77	168 (24.4)	198 (28.7)	211 (30.6)	571 (82.8)	62.0	83.9 ^b	69.8	78.8	314	3798
15453	93	200	119 (17.2)	161 (23.4)	179 (25.9)	514 (74.6)	40.3	61.8 ^b	49.4	76.9	177	2134
15454	204	400	107 (15.5)	133 (19.3)	144 (20.9)	490 (71.1)	36.7	51.4 ^b	43.5	76.4	147	1771
15455	316	600	101 (14.7)	119 (17.2)	126 (18.5)	500 (72.5)	44.0	42.5 ^c	45.9	71.8	179	2168
15456	371	700	96 (13.9)	106 (15.4)	117 (17.0)	499 (72.4)	40.8	39.9 ^c	44.9	71.8	163	1965
15457	427	800	77 (11.1)	105 (15.2)	117 (16.9)	502 (72.8)	40.7	39.6 ^c	44.7	69.8	161	1948
15458	482	900	77 (11.2)	99 (14.3)	106 (15.4)	488 (70.8)	45.3	57.0 ^b	50.0	70.8	179	2164
15459	538	1000	79 (11.4)	92 (13.4)	105 (15.2)	464 (67.3)	39.2	57.0 ^b	47.7	65.4	147	1782
16089	565	1050	65 (9.4)	96 (13.9)	99 (14.4)	432 (62.7)	43.5	d	49.1	69.7	153	1850
15595	593	1100	88 (12.8)	99 (14.3)	110 (16.0)	413 (59.9)	41.7	50.4 ^c	52.7	64.9	143	1724
15596	649	1200	90 (13.0)	97 (14.0)	110 (15.9)	304 (44.1)	25.0	42.3 ^c	40.6	46.3	68	822
16086	704	1300	63 (9.2)	85 (12.4)	95 (13.7)	228 (33.0)	20.2	d	51.1	47.9	42	506
16087	732	1350	60 (8.8)	82 (11.9)	92 (13.4)	198 (28.7)	14.2	d	61.9	50.5	27	332
16088	760	1400	57 (8.3)	79 (11.5)	90 (13.0)	170 (24.7)	10.1	d	70.3	60.6	17	200

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

^bContains the necked region.

^cSpecimen broke off-center and therefore did not contain the neck.

^dPretest gage marks not made on specimen.

Table 8. Tensile Properties of Various Reannealed Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel Tested at a Strain Rate of 0.004/min

Test	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)	Work to Plastic Instability	
	(°C)	(°F)	Proportional Limit	Yield		Ultimate Tensile	Uniform	Total, in			(MJ/m³)	(ft-lb/in.³)
				0.02%	0.2%			1 in.	2 in.			
25-mm (1-in.) Plate												
17612	25	77	126(18.3)	188(27.3)	205(29.7)	568(82.3)	66.22	82.90	70.23	77.61	333	4023
17613	204	400	98(14.2)	123(17.8)	130(18.8)	468(67.9)	37.77	53.10	43.00	74.22	144	1741
17614	427	800	53(7.7)	88(12.8)	106(15.3)	492(71.4)	38.17	59.25	51.75	69.77	144	1744
17615 ^a	593	1100	61(8.8)	83(12.0)	92(13.3)	397(57.5)	44.06	48.20	58.03	60.52	147	1772
17616	649	1200	61(8.8)	84(12.2)	90(13.1)	303(44.0)	29.97	42.65	38.04	38.36	80	972
51-mm (2-in.) Plate												
17617	25	77	116(16.8)	170(24.7)	198(28.7)	543(78.7)	65.58	84.45	72.93	79.36	309	3735
17618	204	400	57(8.2)	104(15.1)	124(18.0)	443(64.3)	40.17	52.30	43.80	70.58	139	1674
17619	427	800	46(6.6)	86(12.5)	102(14.8)	460(66.7)	44.27	54.20	47.05	64.22	158	1907
17620	593	1100	46(6.7)	77(11.2)	88(12.7)	374(54.2)	43.73	57.92	49.25	57.94	133	1601
17621	649	1200	62(9.0)	79(11.4)	88(12.7)	297(43.1)	31.50	45.15	37.43	41.28	81	976
13 × 114-mm (1/2 × 4 1/2-in.) Pipe												
17637	25	77	144(20.9)	199(28.9)	214(31.1)	572(83.0)	59.35	81.00	67.66	78.89	299	3612
17638	204	400	99(14.3)	136(19.7)	149(21.6)	477(69.2)	37.30	52.25	43.54	74.42	147	1771
17639	427	800	87(12.6)	117(16.9)	125(18.1)	485(70.3)	42.35	54.40	47.53	69.18	166	2000
17640	593	1100	62(9.0)	93(13.5)	104(15.1)	399(57.9)	43.00	61.19	51.55	65.35	144	1745
17641	649	1200	66(9.6)	92(13.3)	101(14.6)	310(45.0)	28.87	43.90	41.35	43.57	80	966
13 × 219-mm (1/2 × 8 5/8-in.) Pipe												
17642	25	77	152(22.1)	197(28.6)	216(31.4)	571(82.8)	59.53	67.87	69.53	78.38	299	3609
17643	204	400	84(12.2)	123(17.9)	143(20.7)	479(69.5)	36.70	51.40	42.94	72.34	144	1734
17644	427	800	78(11.3)	109(15.8)	120(17.4)	489(70.9)	45.42	57.30	50.09	68.38	180	2177
17645	593	1100	62(9.0)	97(14.1)	102(14.8)	404(58.5)	44.40	59.85	50.10	63.61	151	1829
17646	649	1200	52(7.6)	86(12.5)	99(14.3)	310(44.9)	28.13	38.80	37.20	36.18	79	950
10 × 406-mm (0.4 × 16-in.) Pipe												
17647	25	77	147(21.3)	64(28.5)	208(30.2)	569(82.6)	64.19	84.55	71.45	76.77	319	3855
17648	204	400	72(10.5)	123(17.8)	132(19.1)	475(68.9)	38.52	52.25	43.05	72.84	148	1784
17649	427	800	80(11.6)	103(15.0)	109(15.8)	483(70.0)	42.60	56.40	45.35	69.27	163	1966
17650	593	1100	75(10.8)	92(13.4)	95(13.8)	395(57.3)	43.82	60.05	50.85	68.27	147	1772
17651	649	1200	79(11.5)	91(13.2)	94(13.6)	315(45.7)	27.75	42.00	43.98	43.83	77	936
10 × 711-mm (0.4 × 28-in.) Pipe												
17652	25	77	140(20.3)	191(27.7)	203(29.5)	563(81.6)	61.97	84.30	71.08	79.53	307	3710
17653	204	400	62(9.0)	117(16.9)	128(18.5)	470(68.2)	39.46	54.60	45.49	73.80	148	1794
17654	427	800	75(10.8)	97(14.1)	105(15.2)	477(69.1)	43.99	57.10	48.65	68.32	164	1981
17655	593	1100	50(7.3)	82(11.9)	90(13.0)	392(56.8)	48.36	52.25	53.55	56.56	160	1938
17656	649	1200	81(11.7)	84(12.2)	89(12.9)	309(44.8)	29.40	40.80	38.50	34.45	79	952
25-mm (1-in.) Bar												
17622	25	77	126(18.3)	206(29.9)	228(33.0)	573(83.1)	58.28	80.30	67.45	79.24	295	3564
17623	204	400	93(13.5)	143(20.8)	161(23.3)	477(69.2)	35.94	52.10	43.34	74.90	141	1707
17624	427	800	76(11.0)	122(17.7)	135(19.6)	485(70.3)	37.60	55.05	47.50	70.38	145	1756
17625	593	1100	72(10.4)	105(15.2)	117(16.9)	407(59.0)	38.66	59.12	49.94	61.19	132	1591
17626	649	1200	69(10.0)	103(14.9)	115(16.7)	317(45.9)	26.80	50.58	42.79	44.17	76	916
51-mm (2-in.) Bar												
17627	25	77	112(16.3)	190(27.6)	213(31.0)	563(81.7)	61.92	84.65	69.81	80.45	307	3714
17628	204	400	90(13.0)	123(17.9)	141(20.5)	470(68.1)	39.43	53.20	45.64	75.71	152	1834
17629	427	800	90(13.1)	114(16.5)	122(17.7)	482(69.9)	42.96	53.40	47.25	68.59	165	1999
17630	593	1100	55(7.9)	94(13.6)	104(15.1)	400(58.0)	44.52	59.15	52.10	62.43	150	1815
17631	649	1200	66(9.6)	90(13.0)	103(14.9)	308(44.7)	29.30	48.05	40.61	43.83	80	969
64-mm (2.5-in.) Bar												
17632	25	77	135(19.5)	193(28.0)	215(31.2)	567(82.2)	59.21	80.00	67.53	80.35	294	3547
17633	204	400	112(16.3)	150(21.8)	169(24.5)	475(68.9)	36.11	52.15	42.93	76.15	142	1721
17634	427	800	90(13.1)	129(18.7)	144(20.9)	494(71.6)	43.35	43.35	46.80	71.58	175	2120
17635	593	1100	74(10.7)	111(16.1)	124(18.0)	408(59.1)	42.35	55.51	47.03	65.00	148	1785
17636	649	1200	75(10.8)	104(15.1)	121(17.6)	309(44.8)	26.81	41.20	42.04	41.71	74	891

^a Specimen broke at gage marks.

Fig. 23. The 0.2% Yield Strength as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition (0.5 hr at 1065°C) at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

Fig. 24. The Ultimate Tensile Strength as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

Fig. 25. The Uniform Elongation as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

Fig. 26. The Total Elongation as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

Fig. 27. The Reduction of Area as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

tensile strengths for all product forms were above the Handbook minimum curve for all test temperatures except 649°C (1200°F). Strain-rate sensitivity of ultimate tensile strength at 649°C may explain why the observed values fall below the minimum curve. Ultimate tensile strength values for all products in the reannealed condition showed a slight increase in the temperature range from 300 to 500°C (570–930°F), and this is associated with possible dynamic strain aging effects.

Uniform Elongation — Uniform elongation data for all product forms in the reannealed condition were above the Handbook minimum for the whole temperature range of this investigation. Reannealing, which removes the residual processing and straightening work from these products, increased their uniform elongation by 1.5 to 6%. Dynamic strain aging over the range 300 to 500°C resulted in increased values of uniform elongation for all product forms.

Total Elongation — Total elongation values for all reannealed product forms were above the Handbook minimum curve. Reannealing increased the total elongation of all products by 1.5 to 6%. Dynamic strain-aging effects observed for ultimate tensile strength and uniform elongation were also observed for total elongation. The experimentally

observed sharp drop in total elongation at 649°C (1200°F) for as-received material, Fig. 20 was also observed in reannealed material. Such a drop is associated with tensile ductility minimum conditions, which are discussed elsewhere.¹⁷

Reduction of Area — Reduction of area values for various product forms in the reannealed condition are plotted in Fig. 27. The Handbook does not contain any minimum value for this property. However, it is interesting to note that reductions of area for all product forms were essentially the same, and all showed a sharp drop at 649°C. Such a drop is again associated with the ductility minimum, which is discussed elsewhere.¹⁷

Work to Plastic Instability — The area under the stress-strain curve up to the ultimate tensile strength point is a measure of toughness of the material. Values of this quantity were computed for various product forms in the reannealed condition and are displayed as a function of test temperature in Fig. 28. The toughness of reannealed product forms showed trends similar to those observed for the as-received material in Fig. 22.

Fig. 28. Work to Plastic Instability as a Function of Test Temperature for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at a Strain Rate of 0.004/min. (a) Plate and pipe. (b) 16-mm (5/8-in.) plate and bar.

Estimate of Residual Cold Work in Various Product Forms from Tensile Properties in As-Received and Reannealed Material

To determine the amount of residual cold work in various products, we have plotted the 0.2% yield strength of the reannealed material as a function of its value in the as-received condition. These values are plotted in Fig. 29 for the temperature range from room temperature to

Fig. 29. Reannealed Yield Strength as a Function of As-Received Yield Strength for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel at a Strain Rate of 0.004/min. (a) Plate. (b) Pipe. (c) Bar.

649°C (1200°F). For 16-mm (5/8-in.) plate these values extend to a test temperature of 760°C (1400°F). This figure indicates that the reannealed yield strength can be linearly related to as-received yield strength by the following expression:

$$S_y^{RA} = A + BS_y^{AR}, \quad (1)$$

where

S_y^{RA} = 0.2% yield strength in the reannealed condition,

S_y^{AR} = 0.2% yield strength in the as-received condition,

A, B = constants.

Previous work⁹ has shown that A and B can be expressed as:

$$A = S_0^{\text{RA}} - S_0^{\text{AR}} \sqrt{d_{\text{AR}}/d_{\text{RA}}} , \quad (2)$$

$$B = \sqrt{d_{\text{AR}}/d_{\text{RA}}} , \quad (3)$$

where

d_{AR} = as-received grain size,

d_{RA} = reannealed grain size,

S_0^{AR} = as-received frictional stress,

S_0^{RA} = reannealed frictional stress.

Figure 30 shows reannealed grain size as a function of as-received grain size from Table 2. Data in this figure can be represented by:

$$d_{\text{RA}} = d_{\text{AR}} , \quad (4)$$

Equation (4) indicates that the reannealing treatment does not produce grain growth in any of the ten product forms. Substituting Eq. (4) in Eqs. (2) and (3) gives the following:

$$A = S_0^{\text{RA}} - S_0^{\text{AR}} , \quad (5)$$

and

$$B = 1 . \quad (6)$$

When grain size does not change on reannealing, Eq. (5) represents a measure of the residual cold work.

To get a measure of residual cold work, we have drawn lines with $B = 1$ in Fig. 29. Results from this figure are summarized in Table 9. The residual cold work values listed are in terms of stress. To measure residual cold work in terms of strain, we have plotted reannealed uniform

Fig. 30. Reannealed Grain Size as a Function of As-Received Grain Size for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel.

Table 9. Summary of Residual Cold Work in Various Mill-Annealed Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel

Product Form	Size (mm)	Residual Cold Work			Fabrication Process
		(MPa) ^a	(ksi) ^a	(%) ^b	
Plate	16	16	2.3	2	Hot Rolled
Plate	25	16	2.3	2	Hot Rolled
Plate	51	50	7.2	6.5	Hot Rolled
Pipe	114 × 13	24	3.5	4.5	Mannesman
Pipe	219 × 13	24	3.5	4.5	Mannesman
Pipe	406 × 10	8	1.2	1.5	Roll Extrusion
Pipe	711 × 10	8	1.2	1.5	Roll Extrusion
Bar	25	38	5.5	3.0	Hot Rolled
Bar	51	52	7.5	5.5	Hot Rolled
Bar ^c	64				Hot Rolled

^aFrom 0.2% yield strength.

^bFrom uniform elongation.

^cCould not be determined because of nonuniform cold work.

elongation as a function of as-received uniform elongation in Fig. 31. Using the procedure of Fig. 29, we have determined the percentage residual strains and summarized them in Table 9. Table 9 shows that estimated residual cold work is different for different product forms. In general, hot-rolled mill-annealed plates show less cold work than bar products. The unusually high residual cold work in 51-mm (2-in.) plate is possibly a result of taking specimens from the top level of three possible levels (top, middle, and bottom). This also suggests that residual cold work may be nonuniform through the cross section of a given product. Residual cold work in various pipes shows that it is a function of fabrication process. The roll extrusion process appears to introduce the minimum amount of residual cold work.

Fig. 31. Reannealed Uniform Elongation as a Function of As-Received Uniform Elongation for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel at a Strain Rate of 0.004/min. (a) Plate. (b) Pipe. (c) Bar.

The grain size can influence the yield strength, and the two are commonly related by the following equation:

$$S_y = S_0 + k_y d^{-1/2} \quad (7)$$

where

S_y = 0.2% yield strength,

S_0 = frictional stress,

k_y = constant.

Figure 32 shows 0.2% yield strength plotted against $d^{-1/2}$ for all ten reannealed product forms. For S_y in MPa and d in μm , constants S_0 and k_y for ten product forms were 167.5 and 375, respectively. This figure shows that the differences in 0.2% yield strength of various product forms in the reannealed condition can be accounted, for the most part, by slight grain size variation between the various product forms. Factors causing variation in grain size will be discussed in a later section.

Fig. 32. The 0.2% Yield Strength as a Function of Grain Size for Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel. These data are at room temperature and a strain rate of 0.004/min.

Modeling of Tensile Data for Various Product Forms

The 0.2% yield and ultimate tensile strength data from Tables 5 through 8 are plotted as a function of test temperature in Fig. 33 for as-received (mill-annealed) material and Fig. 34 for reannealed (laboratory annealed) material for all ten product forms. Similar plots for ductility quantities (uniform and total elongation and reduction of area) are shown in Figs. 35 and 36.

A third-degree polynomial was fit to the data:

$$P = a_0 + a_1T + a_2T^2 + a_3T^3, \quad (8)$$

where

P = tensile property (strength in MPa or ductility in %),

T = test temperature, °C,

a_i = constants.

The goodness of fit was determined by R^2 , the coefficient of determination. ($R^2 = 1.0$ means that the model describes the data perfectly.) The constants in Eq. (8) were estimated by the method of least squares and are summarized in Table 10. The expected values based on Eq. (8) have been plotted in Figs. 33 through 36. The variability about the expected values is measured by the standard error of estimate (SEE).

According to the SEE values in Table 10, all tensile properties showed significant product form variations in the as-received condition but not in the reannealed condition. Among other properties, 0.2% yield strength showed the maximum variation, which is consistent with similar observations made previously^{10,18} on type 304 stainless steel.

Equation (8) and constants in Table 10 have been used to compute expected and expected minus 2SEE values. The expected minus 2SEE values are computed to define the lower bound values, which have previously^{18,19}

Fig. 33. The 0.2% Yield and Ultimate Tensile Strength as Functions of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Yield strength. (b) Ultimate tensile strength.

Fig. 34. The 0.2% Yield and Ultimate Tensile Strength as Functions of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition (0.5 hr at 1065°C) at a Strain Rate of 0.004/min. (a) Yield strength. (b) Ultimate tensile strength.

Fig. 35. Various Ductility Quantities as Functions of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel in the As-Received Condition at a Strain Rate of 0.004/min. (a) Uniform elongation, (b) total elongation, (c) reduction of area.

Fig. 36. Various Ductility Quantities as Functions of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition (0.5 hr at 1065°C) at a Strain Rate of 0.004/min. (a) Uniform elongation, (b) total elongation, (c) reduction of area.

Table 10. Summary of Constants for Tensile Data Analysis on Plate, Bar, and Pipe
of Reference Heat 8092297 of Type 316 Stainless Steel

Condition	Number of Data Points	Regression Coefficients				SEE	R^2 (%)
		a_0	a_1	a_2	a_3		
0.2% Yield Strength, MPa							
Mill Annealed	73	256.4	-0.7390	1.662 E-03	-1.287 E-06	28.90	63.44
Reannealed	55	225.6	-0.6125	1.196 E-03	-8.540 E-07	11.63	92.71
Ultimate Tensile Strength, MPa							
Mill Annealed	73	604.7	-1.5267	5.267 E-03	-6.119 E-06	10.13	98.31
Reannealed	55	599.7	-1.4501	5.203 E-03	-5.631 E-06	10.69	98.52
Uniform Elongation, %							
Mill Annealed	73	65.00	-0.3289	1.107 E-03	-1.075 E-06	3.65	87.27
Reannealed	55	69.74	-0.3462	1.116 E-03	-1.042 E-06	3.34	90.89
Total Elongation, %							
Mill Annealed	73	76.86	-0.3351	9.989 E-04	-8.818 E-07	4.49	81.70
Reannealed	55	77.86	-0.3504	1.066 E-03	-9.414 E-07	2.80	92.82
Reduction of Area, %							
Mill Annealed	73	84.92	-0.1403	4.995 E-04	-5.398 E-07	4.30	89.50
Reannealed	55	82.43	-0.1266	5.038 E-04	-6.128 E-07	4.36	89.39

been shown to be more representative of experimental data than results from the ratio or the central tolerance method. The expected and lower bound values of each property are summarized in Table 11.

The room-temperature expected value of yield strength for ten reannealed product forms was 211 MPa. The SEE for these product forms was 11.63 MPa. Recently, we performed 24 room-temperature tensile tests on reannealed 16-mm plate. The average yield strength from 24 tests was 214 MPa, with an SEE of 1 MPa. An SEE of 1 MPa for 24 tests indicates that the reannealed material is microstructurally uniform and that the testing variation is minimal. The total variation in yield strength (SEE = 11.6 MPa) of all product forms in reannealed condition is

Table 11. Summary of Expected and Minimum Values of Tensile Properties of Ten Product Forms of Reference Heat (8092297) of Type 316 Stainless Steel

Test Temperature (°C)	0.2% Yield, MPa		Ultimate Tensile Strength, MPa		Uniform Elongation (%)		Total Elongation (%)		Reduction of Area (%)	
	Expected	Minimum ^a	Expected	Minimum	Expected	Minimum	Expected	Minimum	Expected	Minimum
<u>As-Received Condition</u>										
25	239	181	570	550	55	48	69	60	82	73
50	223	165	542	522	51	44	62	53	79	70
100	198	140	502	482	42	35	53	44	75	66
150	179	121	482	462	37	30	46	37	73	64
200	165	107	476	456	35	28	43	34	72	63
250	155	97	479	459	35	28	42	33	72	63
300	150	92	488	468	37	30	42	33	72	63
350	146	88	497	477	39	32	44	35	72	63
400	144	86	503	483	42	35	46	36	71	62
450	143	85	500	480	43	36	48	38	69	60
500	142	84	483	463	43	36	49	39	65	56
550	139	81	449	429	40	33	48	38	60	51
600	133	75	393	373	34	27	45	36	52	43
650	125	67	309	289	24	17	39	30	42	33
<u>Reannealed Condition</u>										
25	211	187	567	546	62	55	70	64	80	71
50	198	174	539	518	55	48	63	57	78	69
100	175	151	501	480	45	38	53	47	75	66
150	158	134	480	459	39	32	46	40	73	64
200	144	120	473	452	37	30	43	37	73	64
250	134	110	464	453	37	30	42	36	73	64
300	126	102	481	460	38	31	43	37	74	65
350	121	97	488	467	41	34	45	39	74	65
400	117	93	492	471	43	36	48	42	74	65
450	114	90	488	467	45	38	50	44	72	63
500	112	88	472	451	45	38	52	46	69	60
550	108	84	439	418	44	37	51	45	64	55
600	104	80	386	365	39	32	48	42	56	47
650	98	74	309	288	30	23	42	36	45	36

^aMinimum values = expected - 2SEE.

significantly greater than the variations observed with a single product form and testing variations (1 MPa). To help explain these differences, the experimental work described in the next section was performed on the effects of cold work on properties of post-cold-work-annealed 16-mm-plate.

Effect of the Amount of Cold Work on the Room-Temperature Tensile Properties after Subsequent Annealing

In this section we will show how room-temperature tensile properties of cold-worked-and-annealed specimens depend on the amount of cold work. We reannealed 24 as-received specimens from 16-mm plate of the reference heat for 0.5 hr at 1065°C. Specimens in two sets were subjected to 12 different amounts of cold work (plastic strain) up to 30% in an Instron machine at a nominal strain rate of 0.004/min. Tensile properties (proportional limit, 0.02% offset yield, 0.2% offset yield, stress at the end of plastic straining, and reduction of area) were obtained from extensometer traces, Instron load-time charts, and measurements on the specimens after straining. These data are summarized in Table 12.

Of the specimens listed in Table 12, one set of 12 cold-worked specimens was annealed for 0.5 hr at 1065°C and the other at 1150°C. Then, the specimens were tensile tested at a nominal strain rate of 0.004/min. The tensile data are summarized in Table 13. Various tensile properties of cold-worked-and-annealed specimens are plotted as a function of cold work in Figs. 37 and 38. These figures show the following:

1. Specimens cold worked and then annealed at 1065°C show an increase in the strength properties up to 4% cold work. Beyond 4% cold work the strength properties show a sharp drop. The 0.2% yield strength falls below the room-temperature minimum specified value of 207 MPa at a cold work level of 5 to 6%. The yield strength attains a minimum value of 197 MPa at a cold-work level of 10%. Beyond 10% cold work strength properties again show an increase, which levels off at cold-work levels of 15 to 30%. In this region strengths become independent of cold work and even the annealing temperature after cold-working.

Table 12. Tensile Data Taken During Cold Working Reannealed 16-mm Plate of Reference Heat (8092297) of Type 316 Stainless Steel.

All specimens were annealed 0.5 hr
at 1065°C before cold working.

Test		Intended Cold Work (%)	Young's Modulus (GPa)	Stress, MPa			Strain at Max Load (%)	Reduction of Area (%)	
Before Cold Work	After Cold Work			Proportional Limit	0.02% Offset Yield	0.2% Offset Yield			Maximum Load
Specimens to be Annealed 0.5 hr at 1065°C									
18174	18210	0.5	198	126	197	213	219	0.499	0.559
18175	18211	1.0	190	146	198	214	237	1.016	1.206
18130	18162	2.0	189	127	198	215	260	1.962	1.84
18131	18163	4.0	188	149	199	213	302	3.98	3.72
18173	18209	5.0	174	166	197	212	314	4.90	4.674
18132	18164	6.0	185	129	199	215	333	5.97	6.28
18133	18165	8.0	201	113	193	214	373	8.015	7.15
18134	18166	10.0	202	133	202	214	392	10.00	8.16
18135	18167	15.0	175	157	196	213	426	14.66	13.35
18136	18168	20.0	134	177	208	215	478	19.32	15.89
18137	18169	25.0	253	156	212	215	502	24.04	18.14
18138	18170	30.0	187	163	197	215	527	28.12	21.71
Average					200	214			
Standard Error of Estimate					±5.3	±0.94			
Specimens to be Annealed 0.5 hr at 1150°C									
18172	18190	1.0	188	163	199	212	235	1.015	1.197
18176	18191	2.0	206	134	195	214	259	1.924	1.67
18177	18192	2.5	193	120	192	213	271	2.484	2.54
18178	18202	4.0	186	140	197	213	299	3.989	3.48
18179	18203	5.0	197	157	197	214	318	5.039	4.79
18180	18204	6.0	216	112	183	214	330	6.047	5.06
18181	18214	8.0	197	129	192	214	360	7.917	7.05
18182	18215	10.0	189	127	195	214	389	10.094	8.41
18183	18216	15.0	200	112	190	213	441	14.31	11.92
18184	18217	20.0	201	140	192	214	485	19.11	15.58
18185	18218	25.0	210	113	197	213	508	24.34	19.35
18186	18219	30.0	199	127	198	214	525	28.63	22.12
Average					194	214			
Standard Error of Estimate					±4.4	±0.73			

2. Specimens cold worked and then annealed at 1150°C showed a drop in strength properties for a cold-work less than 1%. The yield strength again drops below the room-temperature minimum specified value and attains a value of approximately 190 MPa for cold-work levels of 2 to 6%. At higher cold-work levels the yield strength increases and approaches the values obtained for the 1065°C anneal at cold-work levels of 20% and greater.

3. Annealing at 1150°C after cold working did not show the initial hardening observed in yield strength for annealing at 1065°C.

Table 13. Tensile Data on Cold-Worked-and-Annealed 16-mm Plate of Reference Heat (8092297) of Type 316 Stainless Steel.

All specimens were annealed 0.5 hr at 1065°C before cold working.

Test		Nominal Cold Work (%)	Young's Modulus (GPa)	Stress, MPa				Elongation, %		Reduction of Area (%)
Before Cold Work	After Cold Work			Proportional Limit	0.02% Offset Yield	0.2% Offset Yield	Ultimate Tensile Strength	Uniform	Total	
Specimens Annealed 0.5 hr at 1065°C										
18174	18210	0.5	176	163	197	214	572	58.50	67.38	76.48
18175	18211	1.0	183	159	209	225	583	59.55	70.30	79.26
18130	18162	2.0	197	130	214	234	575	57.13	66.20	74.78
18131	18163	4.0	198	131	226	251	578	57.12	68.25	78.00
18173	18209	5.0	197	139	194	213	562	53.96	63.85	79.31
18132	18164	6.0	204	107	187	202	561	61.32	71.86	78.88
18133	18165	8.0	199	109	182	200	553	60.89	73.58	79.13
18134	18166	10.0	192	135	190	197	537	62.24	71.05	78.06
18135	18167	15.0	202	149	203	213	590	58.69	73.00	78.46
18136	18168	20.0	203	104	197	207	560	57.38	67.58	77.78
18137	18169	25.0	200	140	198	206	557	61.19	72.50	79.11
18138	18170	30.0	194	144	203	211	565	55.11	67.90	78.40
Specimens Annealed 0.5 hr at 1150°C										
18358	18358	0.0	186	186	182	205	558	63.10	74.90	80.06
18172	18190	1.0	196	140	187	203	550	58.54	68.75	78.18
18176	18191	2.0	186	119	171	190	542	67.18	77.34	80.48
18177	18192	2.5	203	103	171	191	546	65.14	76.58	79.14
18178	18202	4.0	187	110	178	193	544	66.26	78.00	79.63
18179	18203	5.0	197	105	171	195	549	66.24	75.75	80.03
18180	18204	6.0	176	90	169	191	545	63.15	71.95	79.97
18181	18214	8.0	183	126	181	198	557	63.92	73.70	79.37
18182	18215	10.0	199	124	184	198	548	61.40	75.48	79.40
18183	18216	15.0	184	137	189	201	553	60.08	71.10	78.58
18184	18217	20.0	185	136	191	205	558	58.01	68.10	78.91
18185	18218	25.0	195	126	197	204	561	57.07	69.65	79.17
18186	18219	30.0	196	127	194	207	571	59.11	71.35	78.50

4. Ductility quantities (uniform and total elongation and reduction of area) decreased where strength properties showed an increase and increased where strength properties showed a decrease.

To describe the cold work effects, we have defined recovery of yield strength in the following manner:

$$\text{Recovery (\%)} = \frac{S_{\max} - S_y}{S_{\max} - S_{y0}} \times 100, \quad (9)$$

where

$S_{\max}$ = flow stress at a given cold work (total strain) level,

S_{y0} = 0.2% yield strength for annealed specimens,

S_y = 0.2% yield strength for cold-worked-and-annealed specimens.

Fig. 37. Various Tensile Strength Properties as Functions of Cold Work for Cold-Worked-and-Annealed 16-mm Plate of Reference Heat (8092297) of Type 316 Stainless Steel. All specimens were annealed for 0.5 hr at 1065°C before cold working. One set of cold-worked specimens was annealed at 1065°C and the other at 1150°C. (a) 0.02% yield strength. (b) 0.2% yield strength. (c) Ultimate tensile strength.

Fig. 38. Various Ductility Quantities as Functions of Cold Work for Cold-Worked-and-Annealed 16-mm Plate of Reference Heat (8092297) of Type 316 Stainless Steel. All specimens were annealed for 0.5 hr at 1065°C before cold working. One set of cold-worked specimens was annealed at 1065°C and the other at 1150°C. (a) Uniform elongation. (b) Total elongation. (c) Reduction of area.

The S_{y0} values for specimens cold worked and then annealed at 1150°C were obtained by reannealing an as-received specimen at 1065°C for 0.5 hr and then again at 1150°C for 0.5 hr and tensile testing at room temperature. This specimen served as a reference material for other specimens that were cold worked and then annealed at 1150°C.

Recovery percent defined by Eq. (9) is plotted as a function of cold work in Fig. 39. The recovery curves for both annealing temperatures start at 100% recovery for zero cold work. These curves for both annealing temperatures have been divided into regions. Regions for the 1065°C

Fig. 39. Recovery as a Function of Cold Work for Cold-Worked-and-Annealed Specimens of the Reference Heat (8092297) of Type 316 Stainless Steel. Regions 1, 2, and 3 are marked for annealing at 1065°C after cold-working, and the numbers with primes show the regions for annealing at 1150°C. Region 1 is the recovery region. Regions 2 and 2' show recrystallization with large grain size as end product. Regions 3 and 3' show recrystallization with fine grain size as end product.

anneal are marked by 1, 2, and 3, whereas regions for 1150°C anneal are marked by numbers with primes. The following optical microstructural observations were performed in an effort to explain various regions observed in Fig. 39.

1. Tensile tested specimens after various amounts of cold work and annealed at 1065 and 1150°C are shown in Figs. 40 and 41. Note that tensile specimens annealed at 1065°C showed an orange peel effect at cold work levels of 5, 6, 8, and 10%, whereas specimens annealed at 1150°C showed orange peel effect at cold work levels of 2, 2.5, 4, 5, and 6%. This effect reflects coarse grain structure.

2. Figures 42 through 48 show the optical microstructures in the unstressed and stressed regions of tensile tested specimens annealed at 1065 and 1150°C after cold work levels of 1, 2, 6, 10, 15, 20, and 30%. The stressed microstructure shows elongated grains and also martensite formed during tensile testing. Grain size varied not only with cold work levels and annealing temperature, but also from specimen to specimen in the unstressed regions. Grain sizes (Table 14) were measured¹⁵ for both unstressed and stressed regions. Since grain size in the unstressed region varied from specimen to specimen, a grain intercept ratio (GIR) was determined as a function of cold work. The GIR is given by:

$$\text{GIR} = \frac{(\text{cold-worked plus reannealed}) \text{ size}}{(\text{no cold work plus reannealed}) \text{ size}}, \quad (10)$$

The no cold-work-plus-reannealed size represents microstructure in the buttonhead region of the tensile tested specimen. The grain size measurements in Table 14 did not include annealing-twin boundaries.

The GIR data from Table 14 are plotted against cold work in Fig. 49. We have marked a band of 1 ± 0.2 GIR as an error region due to grain size variations within the same specimen and to errors in measurement of grain size. This figure also shows two peaks in GIR for both annealing temperatures.

Fig. 40. Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel Cold-Worked the Indicated Percentages, Annealed 0.5 hr at 1065°C, and Tensile Tested.

Fig. 41. Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel Cold-Worked the Indicated Percentages, Annealed 0.5 hr at 1150°C, and Tensile Tested.

100 μm

Fig. 42. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 1% and annealed for 0.5 hr at 1065 (top) or 1150°C (bottom).

Fig. 43. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 2% and annealed for 0.5 hr at 1065 (top) or 1150°C (bottom).

Fig. 44. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 6% and annealed for 0.5 hr at 1065 (top) and 1150°C (bottom).

Fig. 44. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 6% and annealed for 0.5 hr at 1065 (top) and 1150°C (bottom).

Fig. 45. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 10% and annealed for 0.5 hr at 1065 (top) or 1150°C (bottom).

100 μm

Fig. 46. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 15% and annealed for 0.5 hr at 1065 (top) or 1150°C (bottom).

Fig. 47. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 20% and annealed for 0.5 hr at 1065 (top) or 1150°C (bottom).

Fig. 48. Optical Microstructure of Unstressed (Left) and Stressed (Right) Regions of Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel. Tensile specimens were cold-worked 30% and annealed for 0.5 hr at 1065 (top) and 1150°C (bottom).

Table 14. Summary of Grain Sizes for Specimens Annealed after Various Amounts of Cold Work

Cold Work (%)	Grain Size, μm (ASTM)				GIR, Grain Intercept Ratio	
	Reannealed at 1065°C		Reannealed at 1150°C		1065°C	1150°C
	Unstressed	Stressed	Unstressed	Stressed		
1	51 (5.2)	57 (4.9)	76 (4.1)	56 (4.9)	1.11	0.74
2	56 (4.9)	57 (4.9)	70 (4.3)	110 (3.0)	1.02	1.57
6	64 (4.6)	103 (3.2)	76 (4.1)	110 (3.0)	1.61	1.45
10	57 (4.9)	90 (3.6)	64 (4.6)	78 (4.0)	1.58	1.22
15	73 (4.2)	108 (3.1)	70 (4.3)	76 (4.1)	1.48	1.09
20	66 (4.5)	76 (4.1)	48 (5.4)	58 (4.8)	1.15	1.21
30	46 (5.5)	56 (4.9)	70 (4.3)	62 (4.7)	1.22	0.89

Fig. 49. Grain Intercept Ratio as a Function of Cold Work for Cold-Worked-and-Annealed Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel.

The various regions in Fig. 39 can now be explained as follows:

Region 1 shows recovery. This region has recovery values of less than 100%. The yield strength values in this region are higher than values after the first reanneal — before the cold work. This region is observed only for annealing at 1065°C after cold working and does not exist for the higher annealing temperature. The suggested recovery process in region 1 is supported by the essential lack of change in grain size in this region (Fig. 49).

Regions 2 and 2' show recrystallization, with large grain size as the end product. This region is characterized by recovery values exceeding 100%. The yield strength in this region is below the yield strength of reannealed material. The higher annealing temperature (1150°C) has shifted the initiation of region 2' to lower cold work values and has spread it over a wide range of cold work values as compared with region 2 observed for an annealing temperature of 1065°C. The suggested recrystallization with large grain size as the end product is supported by the grain size peaks observed in Fig. 49.

Regions 3 and 3' start at the same cold work level of 14% for both annealing temperatures. Recovery in these regions again shows values close to 100%. These regions also represent recrystallization, but it produces a fine grain size as the end product. The cold-worked-and-annealed yield strength in these regions is independent of both the amount of cold work and the annealing temperature. Furthermore, yield strength in these regions approaches the ASTM minimum specified value of 207 MPa.

The suggested recrystallization with fine grain size as end product in regions 3 and 3' is again supported by the grain size observations presented in Fig. 49.

The yield strength data for the recrystallized regions are plotted as a function of $d^{-1/2}$ in Fig. 50. Included is the line fitted to yield strength data for various reannealed product forms in Fig. 32. We have also included in this figure the line determined from the following relationship observed for seven different reannealed heats:

Fig. 50. The 0.2% Yield Strength as a Function of Grain Size for Cold-Worked-and-Annealed Tensile Specimens of 16-mm Plate of the Reference Heat (8092297) of Type 316 Stainless Steel.

$$S_y = S_0 + B(C + N)d^{-1/2}, \quad (11)$$

where S_0 and B are constants with room-temperature values of 162 and 4286, respectively, for S_y in MPa, carbon (C) and nitrogen (N) in wt (%), and grain size (d) in μm . For comparison, we have drawn an estimated line of slope shown in Fig. 32 through the data on cold-worked-and-annealed specimens. The following points are to be noted from Fig. 50.

1. Lines determined from data on ten different product forms of a single heat (8092297) agree reasonably well with the line determined from data on seven different heats.
2. Data on cold-worked-and-annealed specimens show a slope similar to that shown by ten different product forms or seven different heats. However, the data fall 8.5 and 4.5 MPa (1.23 and 0.65 ksi), respectively, below the two lines.

3. The changes observed in yield strength for regions 2, 2' and 3, 3' of Fig. 39 are indeed a consequence of corresponding changes in

grain size in these regions by recrystallization and grain growth. However, a difference of 8.5 MPa (1.23 ksi) between the results obtained from various product forms and the data from cold-worked-and-annealed specimens need explanation. In our opinion, the shift in the estimated line to the right of that observed for ten different product forms (which gives lower values) is caused by the following two reasons:

- a. The grain size measured from elongated grains of stressed region is most likely to give smaller values (from geometric considerations) as compared with equiaxed grains. The correction factors to correct for elongated grains will depend on grain size and thus require an extensive test program for their determination. However, it is to be noted that the correction factor yielding higher grain size values will shift the estimated line towards the line for ten different product forms.
- b. The martensite present in the deformed elongated grains introduced additional problems in measuring the grain size. Since martensite feathers could be confused with grain boundaries, the measured grain size is possibly again smaller than the actual size. Correction for errors due to martensite will also shift the estimated line in the correct direction.

From what has been said above, one can state that the changes in yield strength in regions marked as recrystallized in Fig. 39, are indeed a result of grain size changes, although the exact position of the estimated line is shifted because of errors described above in measuring grain sizes.

Use of the Properties of Cold-Worked-and-Annealed Specimens to Explain Variations in Tensile Properties of Various Product Forms

Results presented in Table 9 showed that the residual cold work in various product forms can vary from 2 to 6.5%. Furthermore, the residual cold work for 51- and 64-mm bars (Fig. 11) varied from the center to the outside. The reannealing of various product forms involves the same steps

as are involved in cold-working and annealing. That is, the final step in manufacturing various products is solution annealing. The solution annealed products are subjected to straightening and sizing, which introduce varying amounts of cold work into these products. These products were reannealed 0.5 hr at 1065°C at ORNL. Thus, the reannealed material should be quite similar to the cold-worked-and-annealed material. The data for cold-worked-and-annealed material in Fig. 37(b) show that a variation in cold work of 0 to 14% can change the yield strength by approximately 40 MPa. The SEE of 11 MPa observed for all products minus 1 MPa observed for 24 tests on 16-mm plate gives a net variation of 10 MPa. Previous work^{18,19} and results plotted in Figs. 33 through 36 show that the total variations in experimental data are described by $\pm 2\text{SEE}$ about the expected value. Thus, an SEE of 10 MPa corresponds to approximately 40 MPa of variation in yield strength of these product forms, which is in excellent agreement with the cold-worked-and-annealed properties in Fig. 37(b).

The ultimate tensile strength for reannealed product form showed an SEE of 10.69 MPa (Table 10), which gives a total variation close to 43 MPa. Such a variation again agrees excellently with the data in Fig. 37(c) and Table 13 on cold-worked-and-annealed material. The uniform elongation for all reannealed products showed an SEE of 3.34% or a total variation of ($\pm 2\text{SEE}$) 13%. Such a variation also agrees reasonably well with the results of Fig. 38(a) and Table 13 on cold-worked-and-annealed material. Total variations in total elongation and reduction of area of all product forms can also be explained by the data for cold-worked-and-annealed material.

Thus, we can conclude that the product form variations observed in the reannealed data for this single heat are related to the effect of varying amount of cold work on recovery and recrystallization processes.

Comparison of Expected and Minimum Properties

The expected and minimum (expected minus 2SEE) values of yield and ultimate tensile strength from Table 11 are plotted in Fig. 51 for both as-received and reannealed material. Similar values for uniform and

Fig. 51. Expected and Minimum Values (Expected Minus 2SEE) of Yield and Ultimate Tensile Strength as a Function of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel. *Nuclear Systems Materials Handbook* minimum values are also included in these plots. (a) Yield strength. (b) Ultimate tensile strength.

total elongation and reduction of area are plotted in Fig. 52. These figures also include the *Nuclear Systems Materials Handbook* (NSMH) minimum values. The following comments can be made from these figures.

Yield Strength — The expected value curve for reannealed product forms falls approximately 29 MPa below the as-received expected values. Because of significantly higher variation in as-received data, the reannealed minimum values are slightly above the as-received minimum values. The NSMH minimum value curve is significantly higher than the as-received minimum defined as expected minus 2SEE. Furthermore, the NSMH minimum curve lies for most of the temperature range above the reannealed average. This is consistent with previously reported^{18,19} work on type 304 stainless steel.

Ultimate Tensile Strength — The expected and minimum value curves for ultimate tensile strength were quite close for both as-received and reannealed product forms. The NSMH minimum value curve agreed with the ORNL minimum curve for test temperatures below 600°C. At higher temperatures the NSMH minimum value curve crosses over the expected value curve.

Ductility Quantities — The expected and minimum value curves for all three ductility quantities (uniform elongation, total elongation, and reduction of area) in the reannealed condition were slightly above the as-received curves. The NSMH minimum value curves were well below the ORNL minimum curves for both the uniform and total elongation. There is no minimum value curve for reduction of area in the NSMH.

Stress-Strain Behavior (Up to 4% Strain)

The monotonic stress-strain behavior (up to 4% strain) of austenitic stainless steel can be described by:

$$\sigma - \sigma_{PL} = \frac{CPe_p}{1 + Pe_p} + He_p, \quad (12)$$

Fig. 52. Expected and Minimum Values for Various Ductility Quantities as Functions of Test Temperature for Ten Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel. *Nuclear Systems Materials Handbook* minimum values are also included in these plots. (a) Uniform elongation. (b) Total elongation. (c) Reduction of area.

where

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

H = steady-state hardening rate ($d\sigma/d\varepsilon$),

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

σ_{PL} = proportional limit of stress below which there is no plastic strain,

e_p = true plastic strain.

The value σ_{PL} was estimated to be $0.5\sigma_y$, where $0.5\sigma_y$ is the 0.2% offset yield strength. The constant H is 2758 MPa, while P is given by $500C$. The value of C is determined by the criterion that $\sigma = \sigma_y$ for $e_p = 0.002$. Since a knowledge of stress and Young's modulus yields the magnitude of the elastic strain, Eq. (12) can be used to calculate the total strain corresponding to a given stress. The analysis of stress-strain behavior is fully described elsewhere.²⁰

Sikka and Booker²¹ and Hammond and Sikka⁷ have found excellent agreement between experimental stress-strain curves and those predicted by Eq. (12) for several heats of types 304 and 316 stainless steel. From this agreement, the model was considered to be reliable and accurate. Therefore, Eq. (12) was used to predict the maximum and minimum stress-strain curves (up to 4%) for both the mill-annealed and reannealed product forms. These curves are compared with the range for experimental curves in Fig. 53. The maximum and minimum stress-strain curves were based on the average yield strength (Table 11) $\pm 2\text{SEE}$ (Table 10).

Figure 53 shows the following:

1. The range of experimental curves for both mill-annealed and reannealed product forms is well described by tensile curves based on maximum and minimum yield strength values and the model given by Eq. (12).
2. The range of experimental curves for the reannealed product forms, Fig. 53(b), is significantly narrower than observed for the mill-annealed product forms.

Fig. 53. Comparison of Experimental Stress-Strain Behavior with Predicted Maximum and Minimum Stress-Strain Curves for Ten Different Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel. (a) Mill-annealed material. (b) Reannealed material.

Relation Between Room-Temperature Yield Strength and Hardness Values

In Table 4 we noted that the average room-temperature hardness of various product forms varied from 70.5 to 80.3 R_B for the mill-annealed product forms and from 64.9 to 71.5 R_B for the reannealed product forms. The 0.2% yield strength is known to increase with increasing hardness. To check if various product forms showed changes in yield strength corresponding to changes in hardness, data were plotted in Fig. 54. For 63.5-mm bar, hardness of the specimen tested at room-temperature in the as-received condition was 84.9 R_B , compared with an average of 80.3 R_B for the bar, and therefore the value for the individual specimen was used in Fig. 54. This figure also includes data for the reannealed product forms. The following observations can be made from Fig. 54.

Fig. 54. Room-Temperature Yield Strength as a Function of Rockwell Hardness for As-Received and Reannealed Product Forms of the Reference Heat (8092297) of Type 316 Stainless Steel.

1. The 0.2% yield strength increases with increase in room-temperature hardness.

2. The 0.2% yield strength and hardness being on the lower end for the reannealed product forms suggests that the additional hardness and the corresponding increased yield strength of the as-received material are associated with finishing operations performed after mill-annealing treatment. The reannealed data are more representative of the base line properties.

3. The hardness curve in Fig. 54 can be used to estimate the room-temperature 0.2% yield strength of a given product form in the range of the data.

Comparison of 0.2% Yield Strength Data with Data on Previously Studied Heats

The 0.2% yield strength data on pipe and bar products are compared with the range of data on previously studied heats in Fig. 55. The literature data²² were fitted to a third-degree polynomial in temperature. The dotted lines in these plots are for the expected $\pm 2\text{SEE}$. Superimposed in Fig. 55(a) are our data on as-received pipe of four different sizes. Data on all pipe made from the reference heat between the expected and lower bound curves. Figure 55(b) shows that yield strength values of

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Fig. 55. Comparison of 0.2% Yield Strength Data on the Reference Heat of Type 316 Stainless Steel with the Range of Older Literature Data. (a) Pipe of four sizes. (b) Bar of three sizes. The solid line is a polynomial fit to the literature data; the dashed lines represent twice the standard error of estimate of the polynomial.

bar products of the reference heat are close to or above the expected-value curves for the older heats. Considering the expected $\pm 2\text{SEE}$ method of defining the range of properties, the ORNL reference heat can be classified to fall within the range of the older heats. However, when compared with the Handbook minimum value curve, the 10 by 406- and 10 by 711-mm pipes of the reference heat will have to be considered different from or weaker than the older heats. Thus, it appears that the real answer to whether the ORNL reference heat, melted recently, is comparable with older heats depends on the method of defining the minimum values.

Comparison of 0.2% Yield and Ultimate Tensile Strengths with Vendor-Certified Mechanical Property Data

Certified room-temperature mechanical property data were supplied by the vendor on each product form of the reference heat. Figure 56 compares the certified data with ASTM minimum values and our values of 0.2% yield and ultimate tensile strength. The ORNL values were obtained at a strain rate of 0.004/min for material in both as-received and reannealed conditions.

Yield Strength — Figure 56(a) shows a significant difference between the certified data supplied by the vendor and the ORNL data. The plate and pipe product data supplied by the vendor were significantly higher than the data obtained at ORNL. However, the reverse was true for the bar product. The differences between the two data sources became even greater for reannealed plate and pipe products. Again the reverse was true for the bar products.

Ultimate Tensile Strength — Figure 56(b) shows that only minimal differences existed for this property between the data supplied by the vendor and that obtained at ORNL. Such a result is expected because ultimate tensile strength values are relatively insensitive to residual stresses introduced by straightening and finishing (Fig. 37).

Previous work^{18,19} showed that 0.2% yield strength controls the time-independent design stresses for test temperatures below 600°C. Therefore, the difference observed between the two data sets raises some questions about the significance of the certified mechanical property data supplied by the vendor. The differences observed between

Fig. 56. Comparison of 0.2% Yield and Ultimate Tensile Strength Data with Certified Room-Temperature Properties Supplied by Vendors on Various Products of the Reference Heat (8092297) of Type 316 Stainless Steel.

the two data sets have further implications, if the vendor-certified room-temperature values of a given product were used in conjunction with yield strength ratios²³ to generate a yield strength versus temperature plot.

The vendor of the reference heat, Republic Steel, was contacted²⁴ to establish possible reasons for differences observed between the ORNL data and certified data supplied by the vendor. The following possible explanations were offered for the differences for various products:

Bar Products — The vendor took specimens from bars after annealing. However, after taking specimens the bars were straightened and ground to size before shipping. Thus, the higher values observed by ORNL data are a result of residual cold work introduced in the bar by straightening

and grinding. If the vendor's explanation is correct, ORNL reannealed data should agree with the certified value. Figure 56 shows that indeed ORNL reannealed data showed excellent agreement with the vendor data for all three bar products.

Plate Products — The vendor data on all plate products were higher than the ORNL data. Odar²⁴ of Republic Steel suggested that for the plate products specimens were taken from the trimmed ends of plates, which contain more straightening work than plate away from the trimmed ends (a consequence of more buckling at ends during mill annealing). If such is the case the difference between the plate trims and the area away from the trimmed end is expected to decrease with increasing plate thickness. The ORNL tensile specimens were taken from the plate section away from the trimmed end. The decrease with increasing plate thickness is confirmed by results presented in Fig. 56.

Pipe Products — The vendor data on all pipe products were higher than the values obtained at ORNL and the vendor has no satisfactory explanation for such an observation. However, Rollmet²⁵ and Republic Steel have been working with us to check the differences in machining specimens and testing procedures. Data from this program are summarized in Table 15. All tests were on two pieces of 10 by 711-mm pipes. The ORNL specimens were made by Tasco, whereas Atlas made specimens for Rollmet. All but one specimen were tested with an Instron machine. One specimen was tested with a Baldwin machine. Data in Table 15 show the following:

1. ORNL data show that specimens machined by Tasco or Atlas give the same results.
2. Instron data are in close agreement with Baldwin machine data.
3. Axial and circumferential test data show that Rollmet process produces an isotropic pipe product.
4. Both ORNL and Republic Steel data are in excellent agreement, whereas Rollmet obtained slightly higher values.
5. Yield strengths obtained at ORNL, Republic Steel, and Rollmet are significantly lower than the vendor-certified results reported in Table 16.

Table 15. Summary of Room-Temperature Tensile Data (at a Strain Rate of 0.004/min) Obtained at Various Laboratories on 10 by 711-mm Pipe of the Reference Heat of Type 316 Stainless Steel

Specimen ^a	Specimen Manufacturer	Testing Laboratory	Strength, MPa (ksi)		Elongation (%)		Reduction of Area (%)
			Yield	Ultimate	Uniform	Total in 25.4 mm	
3G1A	ORNL (TASCO)	ORNL ^b	216 (31.3)				
3G2A	ORNL (TASCO)	ORNL	208 (30.1)	561 (81.3)	58.0	67.2	80.3
3G4C	ORNL (TASCO)	ORNL	210 (30.5)	556 (80.7)	60.6	66.2	69.6
5G2A	ORNL (TASCO)	ORNL	211 (30.6)	561 (81.3)	60.0	71.6	79.9
5G4C	ORNL (TASCO)	ORNL	208 (30.1)	553 (80.2)	60.3	67.1	68.3
5G5A	Rollmet (ATLAS)	ORNL	212 (30.8)	580 (84.1)	71.1	80.6	79.1
5G8C	Rollmet (ATLAS)	ORNL	207 (30.1)	549 (79.6)	71.3	77.7	70.5
5G6A	Rollmet (ATLAS)	Republic Steel	212 (30.8)	548 (79.5)	c	c	c
5G9C	Rollmet (ATLAS)	Republic Steel	214 (31.1)	532 (77.2)	c	c	c
5G7A	Rollmet (ATLAS)	Atlas	224 (32.5)	557 (80.8)	c	63.0	79.0
5G10C	Rollmet (ATLAS)	Atlas	223 (32.3)	549 (79.6)	c	61.0	69.0

^aSpecimen numbers ending with A represent axial specimen, whereas numbers ending with C represent circumferential specimens.

^bTested on Baldwin machine. All other ORNL tests used Instron machines.

^cData not provided.

Table 16. Summary of Certified Mechanical Properties^a of 10 by 711-mm Pipe made by Rollmet of Type 316 Stainless Steel Reference Heat (8092297)

Identity	Strength, MPa (ksi)		Elongation (%)	Reduction of Area (%)
	Yield	Ultimate		
CF-003	262 (38.05)	563 (81.70)	61.0	76.1
CF-003G	258 (37.45)	560 (81.25)	56.0	78.1
CF-004	279 (40.40)	560 (81.25)	56.3	63.9
CF-004G	265 (38.45)	557 (80.75)	56.3	65.9
CF-005	251 (36.40)	561 (81.40)	60.0	78.3
CF-005G	258 (37.40)	566 (82.10)	56.0	74.4

^aAll tests were performed in the circumferential direction.

6. The reasons for differences between the certified and laboratory data are still not clear. ORNL, Republic, and Rollmet are working together to find an explanation.

In summary it may be stated that while laboratory tests at three different locations produced the same results, the significantly higher values of the certified tests (used in meeting the ASTM material specifications) raise some questions about their value.

SUMMARY AND CONCLUSIONS

The product form characterization of reference heat (8092297) of type 316 stainless steel was completed. Ten product forms were studied: three plates, four pipes, and three bars. The characterization process involved description of melting, fabrication processes, composition variations, optical microstructure and grain size, room temperature Rockwell and microhardness data, and tensile properties in both mill-annealed and reannealed conditions. Residual cold work in various product forms was estimated from the tensile properties. Tensile data were modeled and compared with a "minimum" value curve. Stress-strain curves (up to 4%) were predicted and compared with the experimental data. Room-temperature tensile properties on various product forms were compared with the vendor certified data. Following are some important observations and conclusions:

1. All ten product forms showed essentially the same composition.
2. Some grain size differences were observed between the outer and inner surfaces of all pipes and the outer surface and the center of the 51- and 64-mm bars in the as-received condition. However, reannealing for 0.5 hr at 1065°C did not significantly change grain size.
3. The 51- and 64-mm bars showed substantial hardness gradients from the outer edge to the center of the bar. Such gradients were not observed in the 25-mm bar, but hardness data showed large variations. The plate products also showed hardness gradients from the edges to the center.
4. All bar products showed higher hardness values in the as-received condition than did the plate and pipe products. However, all product forms approached approximately the same hardness on annealing for 0.5 hr at 1065°C.

5. The 0.2% yield strength data showed maximum differences between the various products in the as-received condition. Plate and pipe were weaker than bar. The room-temperature yield strength value for 10 by 711-mm (0.4×28 in.) pipe was slightly below the ASTM minimum specified value of 207 MPa (30 ksi). Results also showed that meeting the room-temperature specified value did not assure the elevated-temperature values to fall above the *Nuclear Systems Materials Handbook* minimum curve.

6. Reannealing lowered the yield strength of all product forms. Some of the product forms met the room-temperature ASTM minimum specified value of 207 MPa (30.0 ksi). However, all product forms except two bars showed yield strength values below the Handbook minimum at elevated temperature.

7. Ultimate tensile strength, uniform and total elongation, and reduction of area were not significantly different between the various products in the as-received condition.

8. Ultimate tensile strength was not significantly altered by laboratory reannealing. However, uniform and total elongation and reduction of area increased on reannealing for all product forms.

9. The reannealed 0.2% yield strength and uniform elongation were plotted as functions of as-received values. The intercepts of lines of unit slope through the data gave measures of residual cold work in terms of stress and strain. The stress and strain ranges for various product forms were 8 to 52 MPa and 1.5 to 6.5%, respectively.

10. The residual cold work was different for different product forms. Large pipe made by roll extrusion showed the least residual cold work, while bar product forms showed the most.

11. Reannealing for 0.5 hr at 1065°C did not produce any change in grain size for any of the ten product forms.

12. Total variations for all ten product forms, measured as standard error of estimate (SEE), were significantly greater for all tensile properties in the as-received condition than in the reannealed condition. Among other properties, yield strength showed the greatest variation.

13. Twenty-four room-temperature tests on 16-mm plate in the reannealed condition showed an SEE of 1 MPa for yield strength. The SEE of 1 MPa indicated that variations within the same reannealed product form and variations due to testing procedure were negligible.

14. The SEE for yield strength of ten product forms in the reannealed condition was 11.6 MPa. The total variation about the expected value was measured by $\pm 2\text{SEE}$, and therefore an SEE of 11.6 MPa produces a variation of approximately ± 23 MPa in reannealed yield strength of various product forms.

15. Cold-worked-and-annealed specimens were studied to show that the observed variations in yield strength of various product forms were associated with varying amounts of cold work in these products through its influence on recovery and recrystallization behavior. This was supported by optical microstructural observations.

16. Variations in ultimate tensile strength and ductility were also explained from the study on cold-worked-and-annealed specimens.

17. The data on cold-worked-and-annealed specimens showed that for a certain cold work range (6 to 10%), reannealing at 1065°C can lower the yield strength of type 316 stainless steel below the room-temperature minimum specified value of 207 MPa.

18. The expected-value curve of reannealed yield strength was approximately 29 MPa below the as-received curve.

19. The NSMH minimum value curve was not only above the reannealed average curve, but also significantly higher than the as-received minimum curve. Similar observations were previously^{18,19} made for type 304 stainless steel.

20. Yield strength data on bar and pipe product forms showed that the ORNL reference heat is comparable to previously studied heats.

21. Certified 0.2% yield strength data supplied by the vendor differed significantly from the ORNL data.

22. A single rational polynomial tensile model could describe the stress-strain range in experimental data for all product forms.

ACKNOWLEDGMENTS

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APPENDIX A
HEAT TREATMENT BACKUP WORK

4

4

HEAT TREATMENT BACKUP WORK

The following backup work was performed to determine a suitable reannealing heat treatment. Four product forms — 16-mm (5/8-in.) plate, 25-mm (1-in.) plate, 69-mm (2.5-in.) pipe, and 219-mm (8 5/8-in.) pipe — of the reference heat were used in the program. These products were given the following reannealing treatments:

1. cold furnace + 0.5 hr at 1065°C (1950°F), followed by air cooling;
2. hot furnace at 1065°C (1950°F) + 0.5 hr at 1065°C (1950°F), followed by air cooling;
3. hot furnace at 800°C (1472°F) + 1 hr at 816°C (1500°F) + 0.5 hr at 1065°C (1950°F), followed by air cooling.

All reanneals were performed in an argon atmosphere. The air cooling rates were approximately 2000°C/hr (3600°F/hr) from 1065 to 420°C (1950 to 788°F).

As-received (mill-annealed) and reannealed (laboratory-annealed) aged blocks and specimens were subjected to the following tests:

1. room-temperature hardness, Rockwell B;
2. room-temperature tensile tests;
3. optical grain size determination on specimens etched electrolytically in 10% nitric acid solution.

Room-temperature hardness for various reanneal treatments are summarized in Table A1 and grain size measurements are summarized in Table A2. Changes in microstructure resulting from various heat treatments

Table A1. Effect of Annealing on Room-Temperature Hardness of the Reference Heat of Type 316 Stainless Steel

Product	Hardness, R_B			
	As Received	Cold Furnace + 0.5 hr at 1065°C	Hot Furnace + 0.5 hr at 1065°C	Hot Furnace + 1 hr at 816°C + 0.5 hr at 1065°C
16-mm (5/8-in.) plate	72.1	70.0	69.9	71.2
25-mm (1-in.) plate	76.6	70.7	71.7	
64-mm (2.5-in.) pipe				
wall	75.5		71.2	71.8
outer surface	81.8		59.2	64.9
inner surface	80.0		73.4	73.7
219-mm (8 5/8-in.) pipe	75.6	72.4	72.1	

Table A2. Summary of Grain Sizes for Reference Heat of Type 316 Stainless Steel

Product	Grain Size, ASTM (μm)							
	As Received		Cold Furnace Plus 0.5 hr at 1065°C		Hot Furnace Plus 0.5 hr at 1065°C		Hot Furnace Plus 1 hr at 816°C and 0.5 hr at 1065°C	
	Without Twins	With Twins	Without Twins	With Twins	Without Twins	With Twins	Without Twins	With Twins
16-mm Plate Longitudinal	5.3 (50)	6.2 (37)	3.7 (86)	5.6 (44)	3.6 (90)	5.5 (46)	4 (80)	5.3 (50)
16-mm Plate Transverse	5.4 (48)	6.4 (34)	4.6 (64)	6.1 (37)	5.0 (56)	5.8 (41)	5.5 (46)	6.2 (36)
64-mm Pipe Transverse								
Wall	6.7 (31)	7.5 (27)			5.4 (48)	6.2 (36)		
Outside	7.2 (24)	8.0 (19)			4.2 (74)	5.5 (46)	3.7 (85)	4.7 (60.5)
Inside	6.5 (33)	7.4 (24)			6.0 (38)	7.0 (27.5)	5.6 (44)	6.7 (31)
64-mm Pipe Longitudinal								
Outside							2.7 (122)	5.6 (45)
Inside							5.8 (42)	6.9 (28)
219-mm Pipe								
Outside	5.8 (42)	6.7 (31)	3.2 (100)	4.8 (60)	3 (110)	4.3 (70)		
Inside					5.4 (48)	6.7 (31)		

of the 16-mm (5/8-in.) plate and 64-mm (2.5-in.) pipe are shown in Figs. A1 through A5. Note that the reannealing treatments produced a fairly uniform microstructure for the 16-mm plate, whereas the reannealed microstructure of the 64-mm pipe varied across the pipe wall. The inside surface of the pipe was highly distorted in the as-received condition (Fig. A3), and it developed surface cracks on reannealing (Fig. A5). The outside surface of the pipe showed excessive grain growth on reannealing (Figs. A4 and A5). Consistent with microstructure, the hardness of the outside surface dropped from an average of 81.8 to 64.9 R_B (Table A1). All other products of the reference heat showed only small changes in hardness, and, furthermore, these changes were essentially the same for all heat treatments used. The initial temperature (cold or hot) of the reannealing furnace had apparently little or no influence on the final hardness and microstructure.

The ASTM Material Specifications¹⁻³ A 240 (plate), A 312 (pipe), and A 479 (bar) suggest that the heat treatment given these products should be such as to result in specified mechanical properties. One of these requirements is that the room temperature 0.2% yield strength shall not be less than 30 ksi (207 MPa). The *Metals Handbook*⁴ lists the following considerations in selecting a proper annealing temperature for austenitic stainless steels:

1. Carbides precipitate between 427 and 900°C (800–1650°F), and thus the annealing temperature should be above this range.
2. Because all carbides should be in solution before cooling begins, and because the chromium carbide dissolves slowly, the highest practical temperature consistent with limited grain growth should be selected. This temperature is in the vicinity of 1093°C (2000°F).
3. Cooling from the annealing temperature must be rapid, but not rapid enough to distort the specimen.

For type 316 stainless steel, the recommended⁴ annealing temperature range is 1038 to 1121°C (1900 to 2050°F). The time at the selected annealing temperature should be 3 to 5 min per 2.5 mm (0.10 in.) of thickness.

Fig. A1. Microstructure of As-Received and Reannealed 16-mm (5/8-in.) Plate of the Reference Heat of Type 316 Stainless Steel. Longitudinal sections. 100 $\times$. (a) A 240. (b) A 240 + Cold Furnace + 0.5 hr at 1065°C. (c) A 240 + Hot Furnace (1065°C) + 0.5 hr at 1065°C. (d) A 240 + Hot Furnace (800°C) + 1 hr at 816°C + 0.5 hr at 1065°C.

Fig. A2. Microstructure of As-Received and Reannealed 16-mm (5/8-in.) Plate of the Reference Heat of Type 316 Stainless Steel. Transverse sections. 100 $\times$. (a) A 240. (b) A 240 + Cold Furnace + 0.5 hr at 1065 $^{\circ}$ C. (c) A 240 + Hot Furnace (1065 $^{\circ}$ C) + 0.5 hr at 1065 $^{\circ}$ C. (d) A 240 + Hot Furnace (800 $^{\circ}$ C) + 1 hr at 816 $^{\circ}$ C + 0.5 hr at 1065 $^{\circ}$ C.

Fig. A3. Microstructure of Reannealed (Hot Furnace, 0.5 hr at 1065°C) 64-mm (2.5-in.) Pipe of the Reference Heat of Type 316 Stainless Steel. 100×. (a) Inside surface. (b) Midthickness. (c) Outside surface.

Fig. A4. Microstructure of As-Received 64-mm (2.5-in.) Pipe of the Reference Heat of Type 316 Stainless Steel. 100 $\times$. (a) Inside surface. (b) Midthickness. (c) Outside surface.

Fig. A5. Microstructure of Reannealed (Hot Furnace, 1 hr at 816°C + 0.5 hr at 1065°C) 64-mm (2.5-in.) Pipe of the Reference Heat of Type 316 Stainless Steel. 100×. (a) Inside surface. (b) Transition between midthickness and outside surface. (c) Outside surface.

Examination of these and other results, in light of ASTM Material Specifications¹⁻³ and considerations suggested in the *Metals Handbook*,⁴ indicates that *an annealing treatment of 0.5 hr at 1065°C (1950°F) followed by air cooling* should be used for the reference heat of type 316 stainless steel. Since using an initial hot or cold furnace did not produce any difference in resultant room-temperature hardness and grain size, a hot furnace is preferable to cut down on the long heat-up period.

Let us examine the results of the treatment in light of ASTM Specifications and recommendations made in the *Metals Handbook*.

1. The room-temperature yield strength of the plate reannealed 0.5 hr at 1065°C (1950°F) was 30.6 ksi (211 MPa), compared with a minimum specified value of 30.0 ksi (207 MPa).

2. This treatment produced a uniform grain size of approximately ASTM 4 without excessive grain growth. Note in Table 3.6 that the grain size in the transverse direction is smaller (approximately ASTM 5) than in the longitudinal direction, and thus might result in some tendency toward anisotropic properties, such as yield strength. The higher annealing temperature, 1100°C (2012°F), produces a coarse grain structure, approximately ASTM 2.6.

The yield strength, S_y , of several heats of type 316 stainless steel can be related to carbon (C) and nitrogen (N) contents and grain size intercept, $\bar{d}$, by a relationship of the form:

$$S_y = S_0 + B(C + N)\bar{d}^{-1/2} , \quad (1)$$

where S_0 and B are constants with room-temperature values of 162 and 4286, respectively, if S_y is in MPa, C and N in wt%, and $\bar{d}$ in μm . Equation (1) can be used to estimate the grain size necessary to meet the minimum yield strength of 207 MPa (30.0 ksi). Such a grain size for the reference heat was estimated to be ASTM 4.2 (75 μm) and is consistent with the grain size obtained by the recommended heat treatment. Any higher annealing temperature is likely to yield a coarse grain structure with yield values below the specified minimum.

The 219-mm (8 5/8-in.) pipe annealed for 0.5 hr at 1065°C was subjected to the ASTM A 262-70 sensitization test, which gave negative results, indicating that the air cooling rate was sufficient to prevent any precipitation at the grain boundaries.

We can make the following conclusions concerning heat treatment:

1. The recommended heat treatment for the reference heat of type 316 stainless steel 0.5 hr at 1065°C, followed by air cooling.
2. The temperature of the furnace before reaching the annealing temperature has no influence on the final grain size or room-temperature hardness.
3. The recommended reannealing treatment gives a microstructure that meets the minimum room-temperature yield strength requirement.
4. The transverse grain size is smaller than longitudinal grain size, and this might result in anisotropic properties.
5. The outer skin of the 64-mm (2.5-in.) pipe showed more grain growth than the rest of the material, so the outer skin should be avoided in fabricating the specimens.

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APPENDIX B
STRAIN RATE PACER RESULTS

STRAIN RATE PACER RESULTS

All tensile data presented in this report were obtained at controlled crosshead speeds. However, ASTM testing procedure¹ requires that the strain rate of the specimen be controlled with a strain pacer. Since the 0.2% yield strength of 16-mm (5/8-in.) plate showed² strain rate dependence at room temperature, we tried to use a strain pacer and compare the results with those obtained from a crosshead rate. Figure B1 shows specimen strain rate as a function of strain for a constant-crosshead-rate test. It also includes a plot of crosshead rate for a

Fig. B1. Relationship Between Strain Rate and Nominal Strain Rate Derived from Crosshead Speed from Experiments with 16-mm (5/8-in.) Plate of Type 316 Stainless Steel.

constant-strain-rate test controlled with a strain pacer. Both curves can be classified into three different regions:

Region I — This region is controlled by slack in the pull-rod system. For a constant-crosshead-controlled test, slack in the pull-rod system causes low strain in the specimen and therefore a low initial strain rate. For a strain-controlled test, slack in the pull-rod system demands a high crosshead rate to maintain a constant strain rate.

Region II — This region is controlled by plastic yielding of the specimen. For a constant-crosshead-control test, strain rate increases because of yielding in the specimen. In other words, a large strain is produced in the specimen for a small increase in the load. For the strain-controlled test, yielding produces a decrease in crosshead rate. This occurs because yielding produces so much strain in the specimen that the crosshead has to slow down to maintain a constant strain rate.

Region III — This region is controlled by strain hardening of the specimen. For a constant crosshead rate test, strain hardening lowers the rate of increase in the strain rate. For a constant-strain-rate test, strain hardening of the specimen requires an increase in the crosshead rate to maintain a constant strain rate.

The 0.2% yield strength values obtained from a constant-crosshead-controlled test and three constant-strain-rate tests are summarized in Table B1. The two types of tests produce essentially the same values of

Table B1. Effect of Strain Rate Control Method on Room-Temperature 0.2% Yield Strength Measurements on 16-mm (5/8-in.) Plate of As-Received Reference Heat of Type 316 Stainless Steel

Control Method	0.2% Yield Strength	
	(MPa)	(ksi)
Constant crosshead speed to give nominal 0.0044/min	228	33.0
Strain rate 0.0050/in.	224.7	32.59
controlled by pacer	225.1	32.65
(three experiments)	225.1	32.65

yield strength. Therefore, it appears that, at least for austenitic stainless steels, a strain pacer may not be necessary to perform a tensile test. Since the strain pacer produced an insignificant effect on yield strength at room temperature, where strain rate effects were maximum, its influence in elevated-temperature yield strength data is expected to be negligible because of negligible strain rate sensitivity at these temperatures.

REFERENCES FOR APPENDIX B

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