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Characterization of Four Prestressed Concrete Reactor Vessel Liner Steels

R. K. Nanstad

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CHARACTERIZATION OF FOUR PRESTRESSED CONCRETE REACTOR VESSEL LINER STEELS

R. K. Nanstad

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CONTENTS

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ABSTRACT

The High-Temperature Gas-Cooled Reactor (HTGR) designed by General Atomic Company is housed within a prestressed concrete reactor vessel (PCRV). The multicavity design has various thick-section plates and forgings, which serve as structural members at various penetrations in the vessel.

A program of fracture toughness testing and analysis is being performed with the PCRV steels to determine the applicability of the reference fracture toughness (K_{IR}) guidelines of Appendix G, Section III of the *ASME Boiler and Pressure Vessel Code* and to establish whether a separate K_{IR} curve and indexing procedure should be developed for PCRV pressure boundary steels. This report focuses on background information for the base materials and results of characterization testing, such as tensile and impact properties, chemical composition, and microstructural examination.

The steels tested were an SA-508 class 1 forging, two plates of SA-537 class 1, and one plate of SA-537 class 2, with thicknesses of 140, 89, 51, and 64 mm (5.5, 3.5, 2, and 2.5 in.), respectively. Chemical analyses, hardness tests, and metallographic examination verified that all four steels meet the appropriate specifications and exhibit expected microstructures. Drop-weight tests were performed to determine the nil-ductility temperature (NDT) for each steel, and Charpy V-notch impact tests were used to determine each reference temperature NDT (RT_{NDT}) as described in Appendix G of the ASME code. Tensile tests and Charpy V-notch impact tests were conducted over a wide temperature range to characterize the strength, deformation, and toughness behavior of the materials.

Tensile requirements in effect at the time of procurement are met by all four steels. However, by current ASME procedures, the SA-537 class 2 plate would not meet the minimum requirement for yield strength. Drop-weight and Charpy impact tests verified that the RT_{NDT} is equal to the NDT for each steel. Charpy impact energies at the NDT range from 40 J (30 ft-lb) for one heat of SA-537 class 1 to 100 J (74 ft-lb) for the SA-537 class 2 plate; upper-shelf energies range from 170 to 310 J (125 to 228 ft-lb) for the same two steels, respectively. The onset of upper-shelf energy occurred at temperatures ranging from 0 to 50°C (32 to 122°F).

1. INTRODUCTION

The High-Temperature Gas-Cooled Reactor (HTGR) designed by General Atomic Company (GA) is housed within a prestressed concrete reactor vessel (PCRV). In the multicavity design (Fig. 1) the steel liner acts as a leak-tight barrier to the helium coolant and does not serve as a primary structural member; however, various thick-section plates and forgings serve as closures at various penetrations in the vessel. These closures are structural and Sect. III, Div. 2 of the *ASME Boiler and Pressure Vessel Code*[1] requires that components of the closures meet the toughness requirements[2] of Sect. III, Div. 1. Appendix G (Protection Against Nonductile Failure) of Div. 1 provides guidelines for reference fracture toughness K_{IR}. These guidelines are presented in the form of a K_{IR} curve that requires indexing procedures using Charpy V-notch impact and drop-weight nil-ductility temperature (NDT) tests.

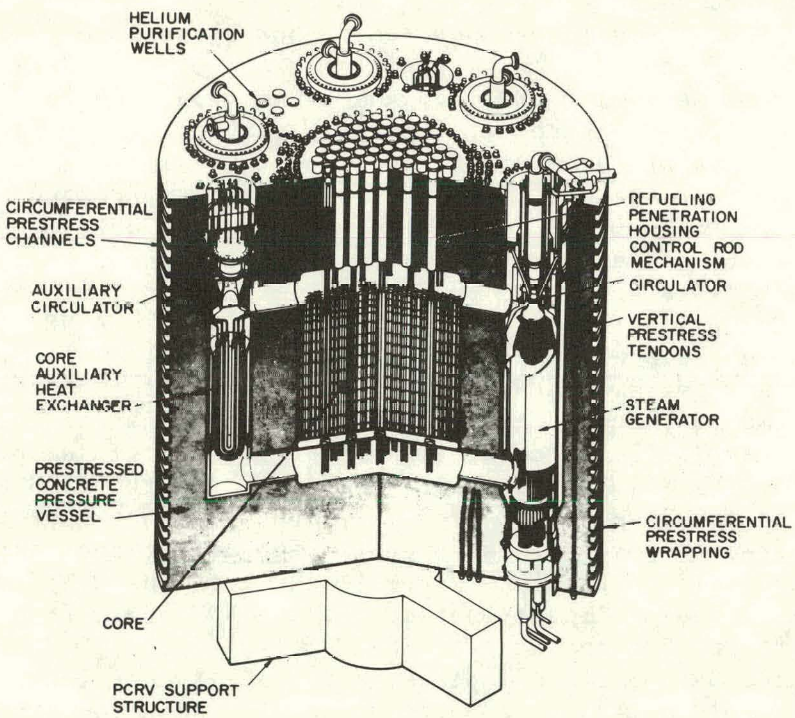

Fig. 1. Cutaway View of the Prestressed Concrete Reactor Vessel for the High-Temperature Gas Reactor. Print courtesy of General Atomic Company.

The guidelines were developed[3] with low-alloy steels, SA-533, grade B, class 1 plates and SA-508 class 2 forgings. The structural steels used in the PCRV are SA-508 class 1, SA-537 classes 1 and 2, SA-182 grade F11, and weldments of those steels. Because the PCRV steels are substantially different from the light-water reactor (LWR) steels, the applicability of the current Appendix G guidelines to those steels is being reassessed. A program of fracture toughness testing and analysis is being performed with the PCRV steels to determine the applicability of the Appendix G guidelines and to establish whether a separate K_{IR} curve and/or indexing procedure should be developed for PCRV pressure boundary steels.

The fracture roughness study is preceded by a program of material characterization testing, which involves determination of tensile and impact properties, chemical composition, and microstructure. This report focuses on the background information for the base materials and the results of the characterization testing.

2. TESTING PROCEDURES

2.1 Specimen Removal

Tensile specimens were obtained from the materials with two orientations: transverse and longitudinal to the major working direction. For the Charpy impact specimens from plate materials, the orientation convention of ASTM E399 was used.[4] For example, a TL orientation indicates a specimen with its major axis transverse to the rolling direction and the notch oriented in the longitudinal direction. For ring forging F1, the major working direction was circumferential. The transverse direction is designated as the axial direction. Thus, an AC specimen would be oriented axially in the cylinder with the notch oriented in the circumferential direction. Drop-weight NDT specimens were removed with the TL orientation in the plates and the AC orientation in the forging.

Regarding locations within the plate steels, specimens were taken at a depth equal to at least one-fourth the thickness from a rolled surface (designated 1/4 t, where t is nominal thickness). In forging F1, a 178-mm-wide (7-in.) ring was removed from one end of the cylinder following heat treatment. Paragraphs NB-2223.2 (Forging with Thicknesses Exceeding Two Inches) and NB-2223.3 (Very Thick and Complex Forgings) of Sect. III, Div. 1 of the ASME code contain different requirements for obtaining test specimens from quenched and tempered forging materials. Paragraph NB-2223.2 requires that specimens be at least 1/4 *t* from any surface and at least 1 *t* from any second surface (i.e., 1/4 *t* × *t*), while paragraph NB-2223.2 requires removal at least 19 mm (3/4 in.) from one surface and 38 mm (1.5 in.) from a second (i.e., 19 × 38 mm). The 178-mm ring removed from the forged cylinder represents material up to 1 1/4 *t* from a quenched end. Because the testing program has a goal of establishing reference fracture toughness behavior and indexing procedures for PCRV liner steels, forging F1 was examined to determine any significant differences between the two locations mentioned above. For the bulk of the characterization testing, forging specimens were removed as close to the 1/4 *t* × *t* locations as possible. Chemical, metallographic, and hardness tests were conducted with specimens from the 1/4 *t* × *t* locations.

2.2 Nil-Ductility Temperature Tests

The drop-weight NDT was determined for the four PCRV steels according to the procedures[5] of ASTM Standard E 208. Specimen P3, shown in Fig. 2, was used for all tests. Specimens were cooled by immersion in a bath of isopentane and dry ice. The NDT is the highest temperature (tests conducted in increments of 10°F) at which a break occurs as defined by E-208. Following impact, some unbroken specimens were infused with dye and broken at liquid nitrogen temperature (−196°C) to examine the fracture surface formed during the NDT test.

The reference temperature NDT (RT_{NDT}) was determined according to Sect. III, Div. 1, Appendix G of the ASME code.[2] That is, if the material exhibits at least 68 J energy absorption and 0.89 mm lateral expansion (50 ft-lb and 0.035 in. are stated units in Appendix G) in a Charpy V-notch test at a temperature 33°C (60°F) higher than the NDT, the RT_{NDT} is equal to the NDT. If the Charpy requirements are not met at the temperature, tests are conducted at increasing temperature increments of 5.5°C (10°F) until the energy and lateral expansion minimums are met. The

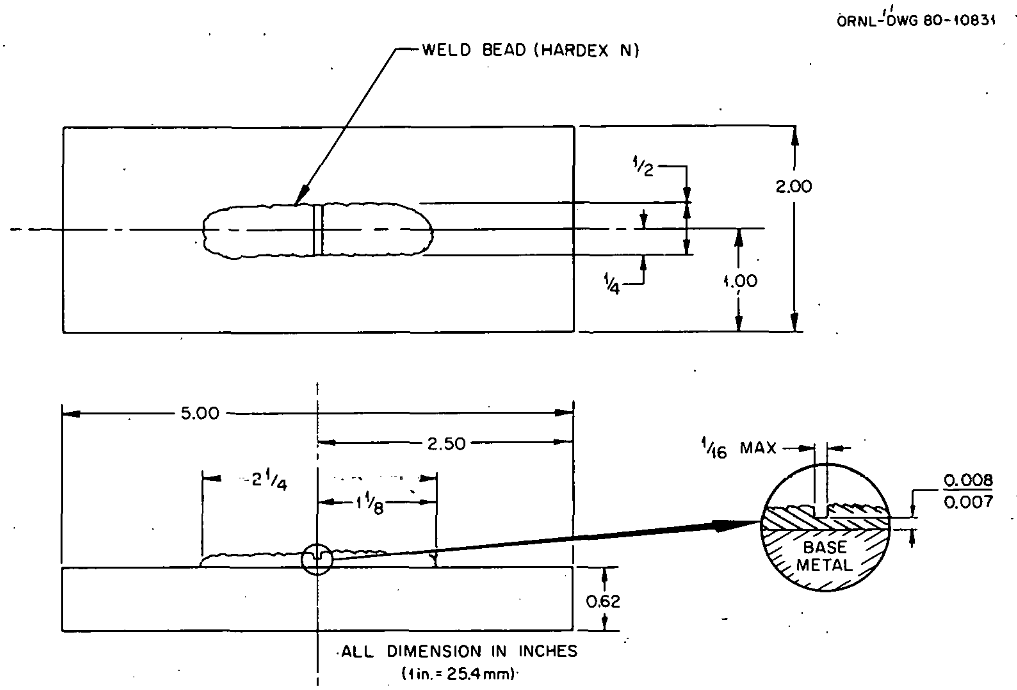

Fig. 2. Drop-Weight Nil-Ductility Temperature Specimen (P3) Configuration.

RT_{NDT} is then determined by subtracting 33°C (60°F) from the test temperature at which the impact requirements are satisfied. Although the RT_{NDT} was determined using the existing procedures, it should be noted that one of the goals of the overall liner testing program is to examine the possibility of a revised RT_{NDT} indexing procedure for PCRV liner steels. However, specific examination and analysis of the indexing procedure will not be performed until all phases of the testing program are completed.

2.3 Tensile Testing

Tensile testing was performed over a wide temperature range in accordance with ASTM Procedure E8 to characterize the material tensile properties and to provide strength data for use in performing fracture toughness evaluations.[6] Properties measured include yield strength (0.2% offset or upper and lower when appropriate), ultimate strength, fracture strength, luders, uniform and total elongations, and reduction in area. The tensile specimen is shown in Fig. 3. The length-to-diameter (L/D) ratio is 7, and total elongation results are corrected to compare with an L/D ratio of 4. Tests were conducted at a crosshead speed of 0.51 mm/min (0.02 in./min), and records of load vs time were obtained. Test temperatures above ambient were obtained by immersing the specimen in heated oil. Temperatures below ambient were obtained by cooling specimens in isopentane with dry ice or liquid nitrigoen or by liquid nitrogen alone for tests at −196°C.

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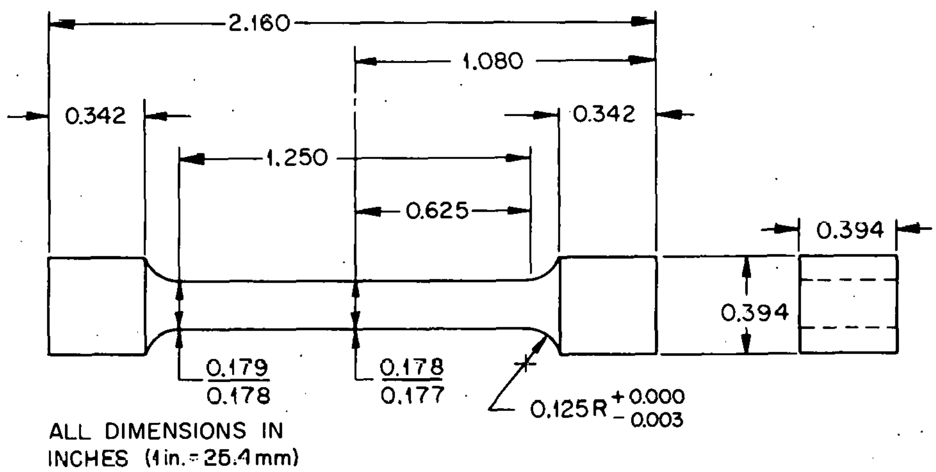

Fig. 3. Tensile Specimen (L/D = 7) Configuration.

2.4 Charpy V-Notch Impact Testing

Charpy V-notch impact tests were conducted over a wide temperature range[7] and in accordance with ASTM Procedure E 23. The Charpy specimen design is shown in Fig. 4. A Dynatup instrumented tup and associated electronics were used to obtain force-time records of the test on a high-speed Nicolet digital oscilloscope. A pendulum-type impact machine was used, and all tests were conducted with an impact energy of 325 J (240-ft-lb) and an impact velocity of 5.2 m/s (17 fps). All force-time traces were kept as permanent records and used to assist in fracture analyses when necessary. Dial energy was recorded for each test and is the value reported as specimen absorbed energy.

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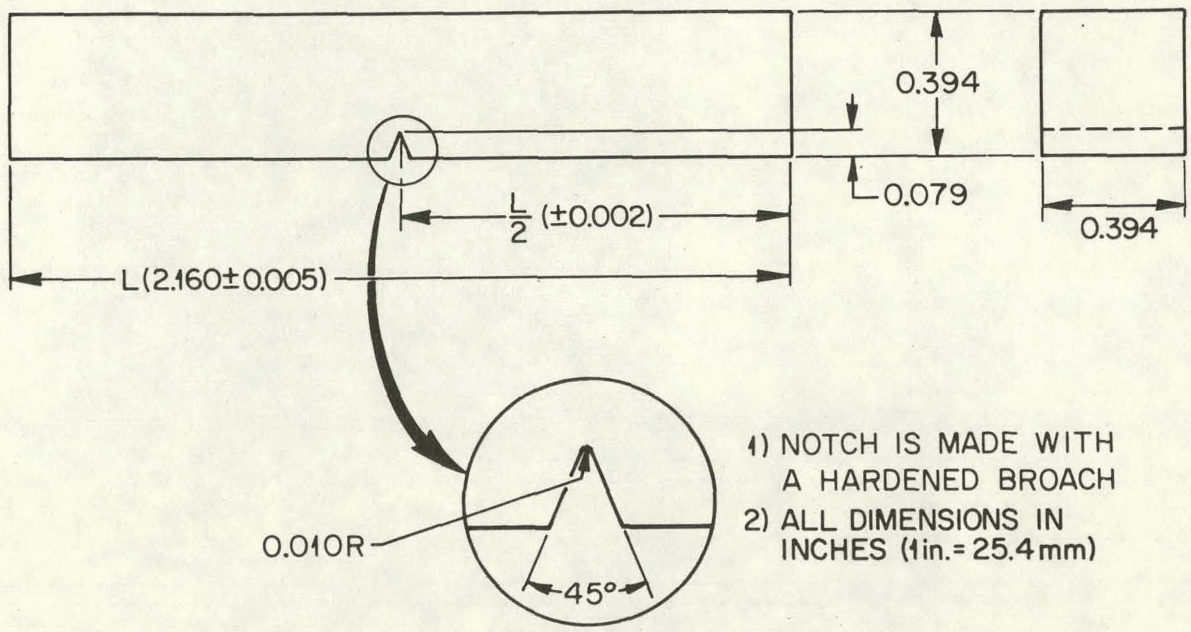


Fig. 4. Charpy V-Notch Impact Specimen Configuration.

The instrumented impact system is shown in Fig. 5. The semiautomatic specimen transfer device includes a temperature control chamber where specimens are heated by electrical resistance and cooled with nitrogen gas. Tests with thermocouples welded to the surface and buried in the interior of a Charpy specimen have demonstrated that the interior of the specimen comes to equilibrium with the surface in a matter of seconds. This is true for both heating and cooling situations. The advantages of the transfer device over the more common manual method of a bath, furnace, and centering tongs are (1) testing is performed very consistently with respect to handling and time (impact in 2 to 2.5 s following extraction from the temperature chamber) and (2) the specimen is not covered with liquid, allowing for good contact of the specimen and anvil.

In addition to absorbed energy, the lateral expansion was measured with a dial gage device, and the fracture appearance (percent shear) was estimated using the visual procedure described in ASTM E 23. A drop-in-load (ΔP) measurement is obtained from the force-time trace on the oscilloscope. A rapid, unstable fracture event is recorded by the

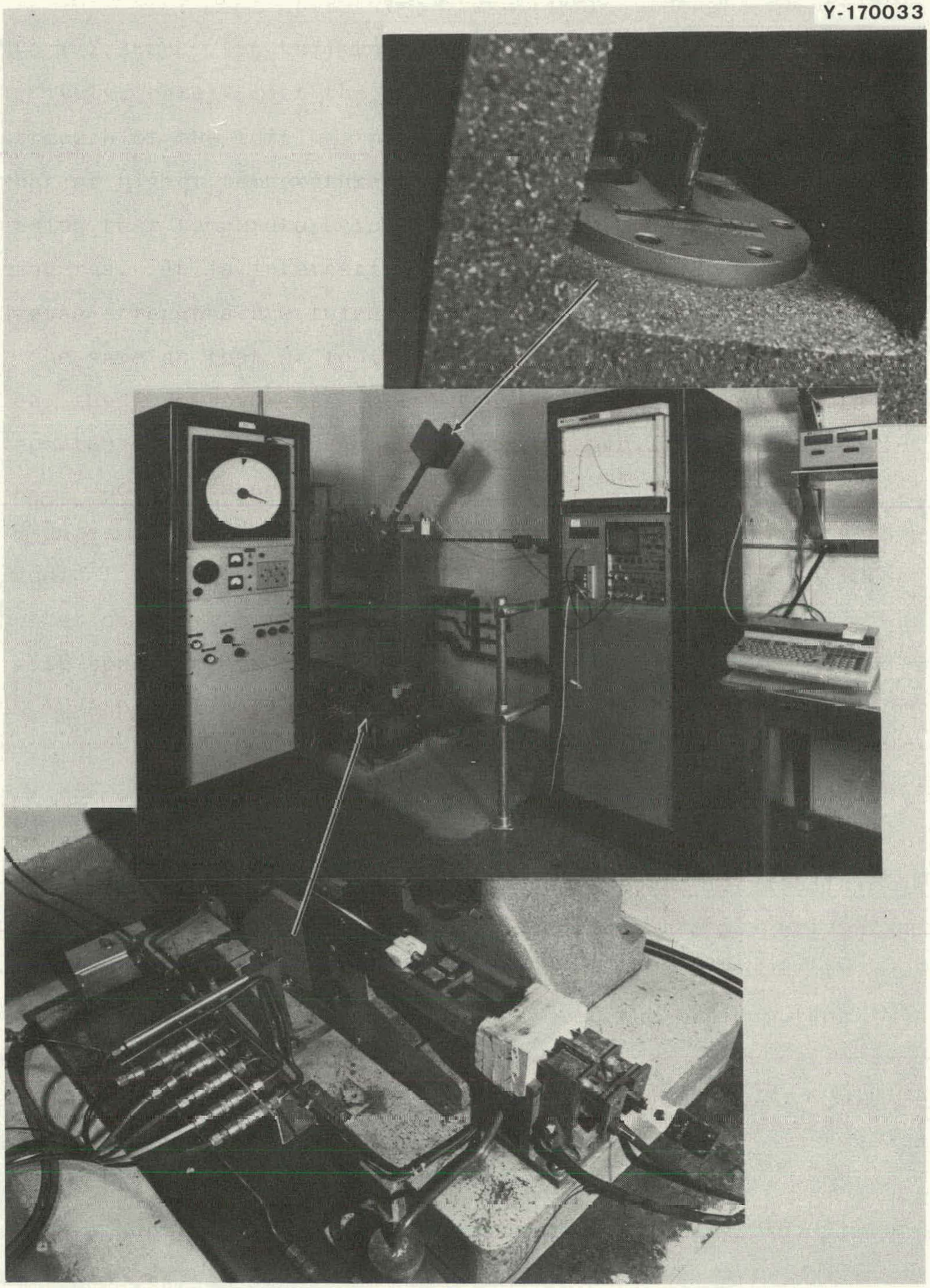


Fig. 5. Instrumented Impact Tester. Center photograph shows the entire system: impact tester, temperature-measuring equipment, electronic equipment including computer, for measuring and recording load-time behavior. Upper right photograph is closeup view of strain-gaged tup. Lower left corner is view of automated Charpy specimen cooling (and heating) and loading apparatus.

instrumentation and is represented on the oscilloscope trace as a rapid decrease in load. The drop in load was measured as a percentage of maximum load. Reference 8 discusses the procedure in detail and provides evidence of a correspondence between zero ΔP and 100% shear (ref. 8 used actual load to measure ΔP, whereas the percent drop-in-load method was used in this program).

The motivation for developing the procedure described in ref. 8 was the desire to provide a method that could be used to determine the onset of the upper shelf when a limited number of specimens are available (as is often the case in irradiation effects and surveillance programs). It will be seen in this study that some materials exhibit a significant capacity for energy absorption at temperatures higher than that at which 100% shear (zero ΔP) occurs. Nevertheless, further studies with the ΔP parameter may show it to be a useful benchmark for ductile fracture behavior (analogous to the NDT for brittle behavior and the 50% shear transition temperature). The parameter may be especially useful for tests with weld metal specimens because of the occasional difficulties in interpreting the fracture surface with regard to percent shear fracture.

3. MATERIAL DESCRIPTION

3.1 General

The base materials studied are shown in Table 1. Forging F1 was given a simulated postweld heat treatment (SPWHT) at ORNL, while the three plate materials were received in the SPWHT condition. Manufacturing and heat treatment details are presented in Appendix A. The plates were formed to strains corresponding to those that would be used in production of actual PCRV components (Table 1).

3.2 Chemical Composition

The Chemical compositions and specifications for each material are shown in Table 2. The materials are generally similar in composition and

Table 1. Description of Materials

PDM[a]	Producer	Producer's Heat	Specification	Thickness (mm)	Thickness (in.)	Heat Treatment	Form
	Japan Steel Works	49C 510-1-1-3	SA-508 class 1 (F1) Case 1332-6	140	5.5	WQ + T + SPWHT	Ring forging
8407	Armco Steel	472 39	SA-537 class 1 (P1)	89	3.5	N + SPWHT	Plate, formed to 3.95% strain
6885	Lukens Steel	RO 273	SA-537 class 1 (P2) Case 1557-1	51	2	N + SPWHT	Plate, formed to 1.95% strain
9098	Lukens Steel	RO 907	SA-537 class 2 (P4) Case 1557-1	64	2.5	WQ + T + SPWHT	Plate, formed to 1.56% strain

[a]Pittsburgh Des Moines.

[b]WQ — water quenched, T — tempered, N — normalized, SPWHT — simulated postweld heat treatment.

Table 2. Chemical Composition[a]

Heat	Specification	Source	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	Co	V
			Composition, wt %											
F1	SA-508 class 1 Case 1332-6	Specification	0.30	0.36–1.39	0.025	0.025	0.13–0.37	0.43	0.30	0.15				0.07
		Mill	0.16	1.27	0.008	0.009	0.27	0.37						<0.01
		ORNL	0.17	1.27	0.006	0.006	0.30	0.40	0.05	0.12	0.05	0.025	0.005	0.001
P1	SA-537 class 1	Specification	0.24	0.95–1.65	0.035	0.040	0.13–0.55	0.25	0.25	0.08	0.35			
		Mill	0.20	1.35	0.010	0.008	0.39	0.15	0.22	0.07	0.12			
		ORNL	0.208	1.45	0.009	0.006	0.23	0.16	0.21	0.08	0.06	0.017	0.012	<0.001
P2	SA-537 class 1 Case 1557-1	Specification	0.24	0.95–1.65	0.035	0.040	0.13–0.55	0.25	0.25	0.08	0.35			
		Mill	0.20	1.45	0.007	0.008	0.22	0.24	0.07	0.08	0.23			
		ORNL	0.216	1.56	0.007	0.006	0.16	0.25	0.06	0.08	0.10	0.018	0.017	<0.001
P4	SA-537 class 2 Case 1557-1	Specification	0.24	0.95–1.65	0.035	0.040	0.13–0.55	0.25	0.25	0.08	0.35			
		Mill	0.24	1.50	0.009	0.001	0.26	0.25	0.12	0.05	0.15			
		ORNL	0.217	1.58	0.009	0.001	0.27	0.25	0.10	0.05	0.07	0.015	0.017	<0.001

[a]Composition specifications shown are for check analyses. Single values for specifications are maximums.

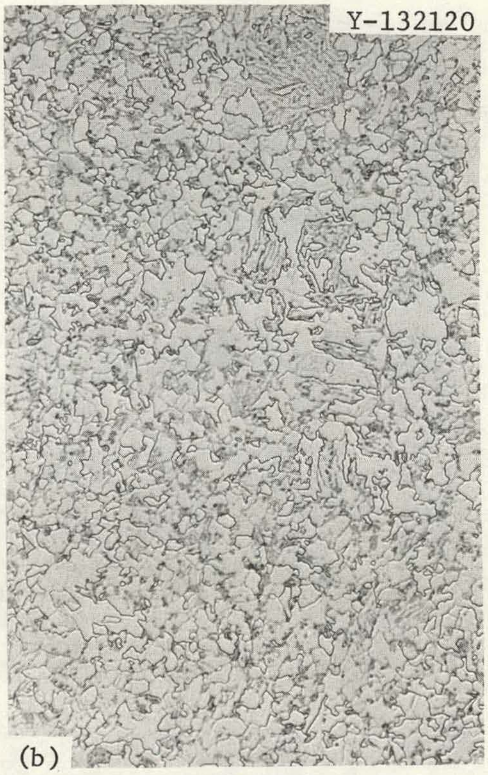
in conformance with appropriate specifications. The forging is somewhat lower in carbon and manganese but higher in nickel than the three plate materials. However, all heats are within the general classification of carbon steels, and substantial property differences will be the result of variations in thickness, processing, and heat treatment. Additionally, all four materials are quite low in both sulfur and phosphorus, which will significantly aid in improving toughness.

3.3 Metallography and Hardness

Metallographic samples were prepared from broken test specimens and are representative of the microstructures at the 1/4 t locations of all four materials. Figure 6 shows the quenched and tempered SA-508 class 1 (F1) forging microstructure. The fine grains (ASTM No. 7 to 8) are interspersed with larger patches of ferrite and pearlite. Figure 7 shows the banded ferrite-pearlite microstructure of the normalized SA-537 class 1 plate (P1). The grain size of this material is ASTM No. 6. The second heat (P2) of SA-537 class 1 (electroslag remelt process) is shown in Fig. 8. This material also exhibits a banded structure but the grain size (ASTM No. 7) is slightly smaller than that of the other normalized steel, P1. Plate P4, a quenched and tempered steel (SA-537 class 2), is shown in Fig. 9. There is only slight evidence of banding in this microstructure, and the grain size (ASTM No. 7 to 8) is somewhat smaller than that of the normalized plates.

Forging F1 was examined through the cross section to determine the hardness gradients as a function of distance from the quenched surfaces. Rockwell B hardness readings were taken at intervals of 12.7 mm (0.5 in.) on a section of the forging before the SPWHT and on another section after the SPWHT. Figure 10 shows a plot of isohardness lines before the SPWHT, while Fig. 11 is a similar plot following the heat treatment. The SPWHT apparently resulted in a hardness decrease throughout the cross section of two to four Rockwell B units. The specimen removal locations referred to in Sect. 2.1 are represented in Fig. 11 and show little difference in hardness between the 19 × 38 mm locations and the 1/4 $t \times t$ locations. It

200 µm



100 µm

50 µm

Fig. 6. SA-508 Class 1 (F1) Microstructure, Circumferential Orientation.

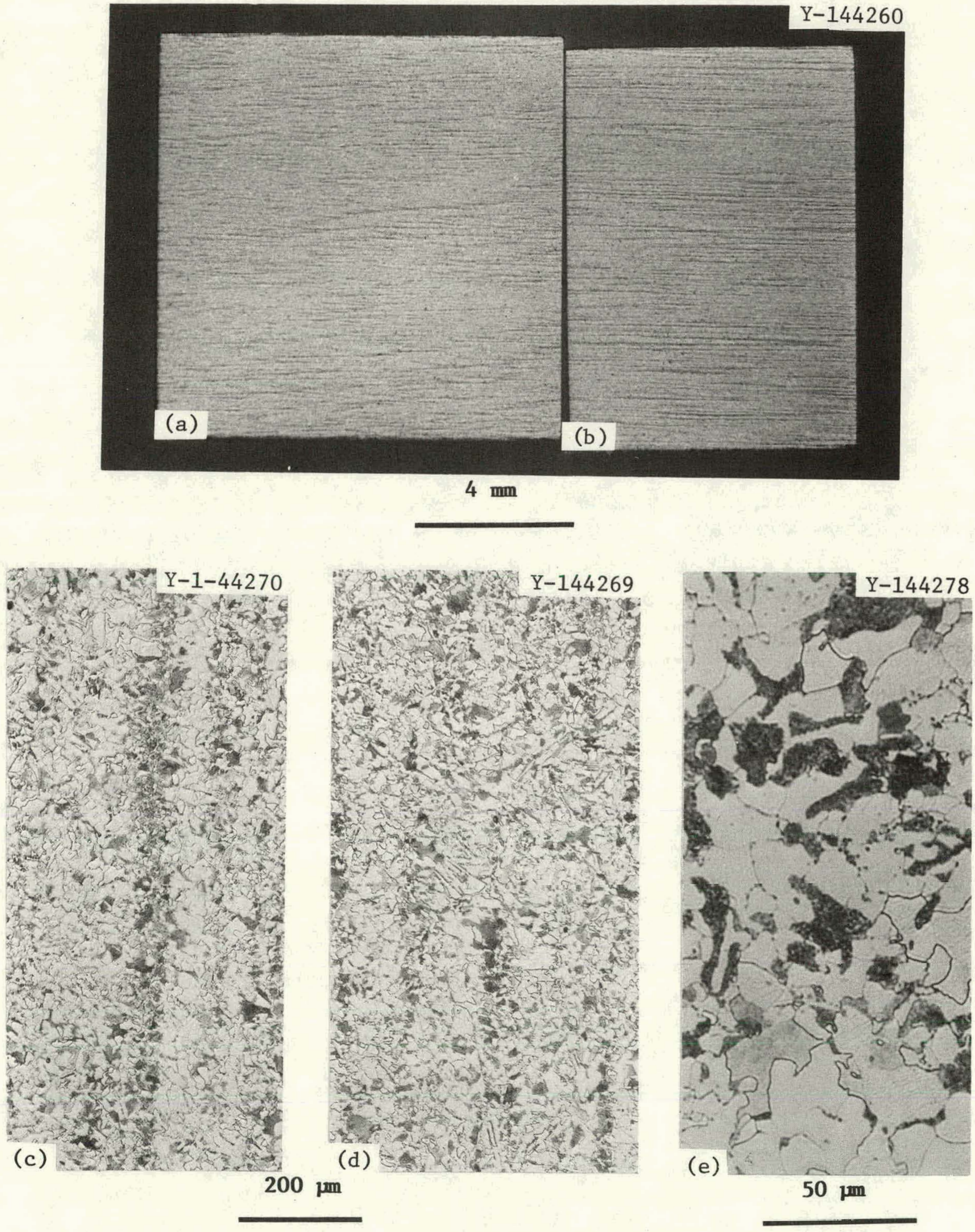


Fig. 7. SA-537 class 1 (P1) Microstructures. (a) Longitudinal macrostructure; (b) transverse macrostructure; (c) longitudinal; (d) transverse; (e) longitudinal.

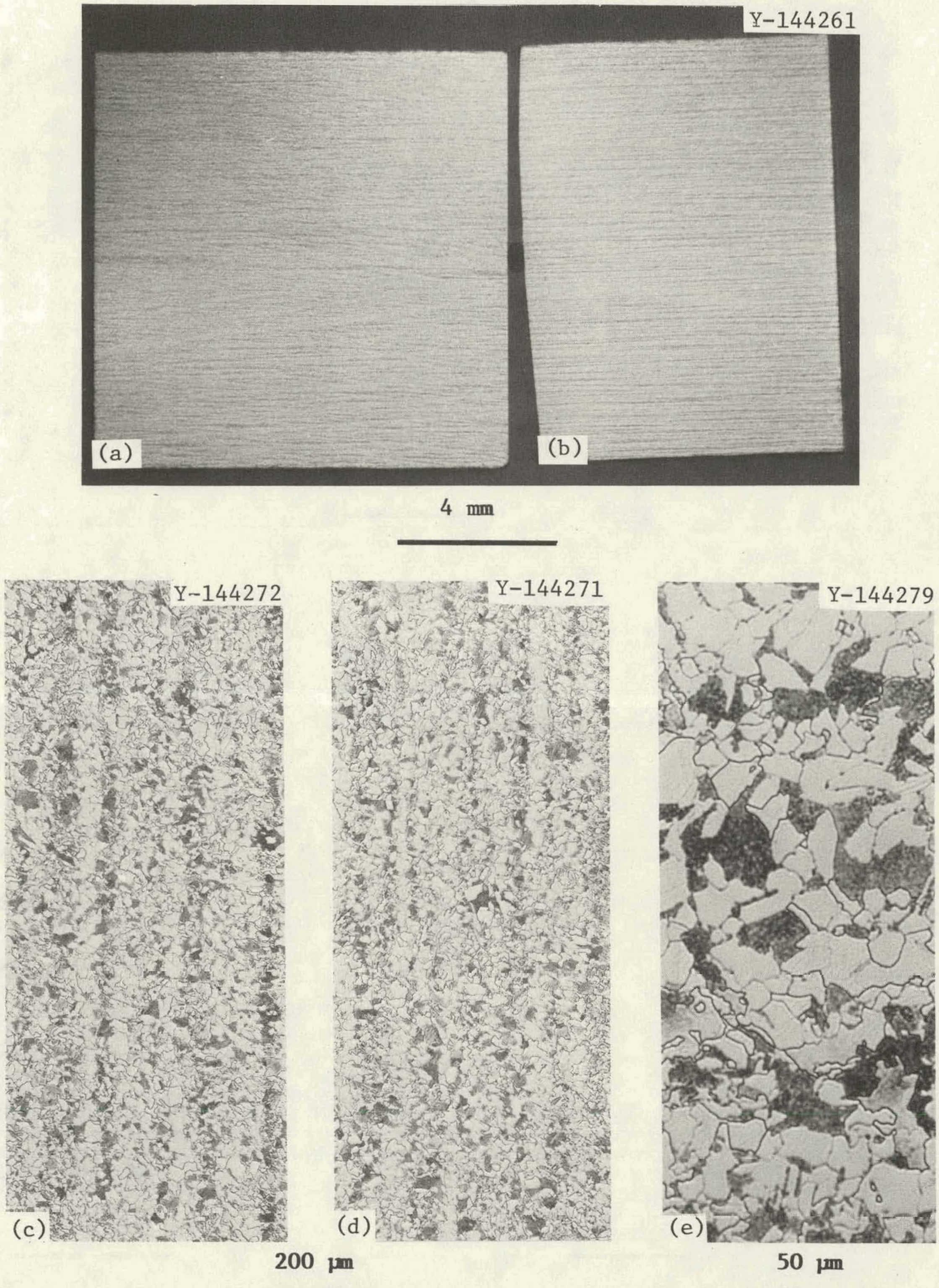


Fig. 8. SA-537 Class 1 (P2) Microstructures. (a) Longitudinal macrostructure; (b) transverse macrostructure; (c) longitudinal; (d) transverse; (e) longitudinal.

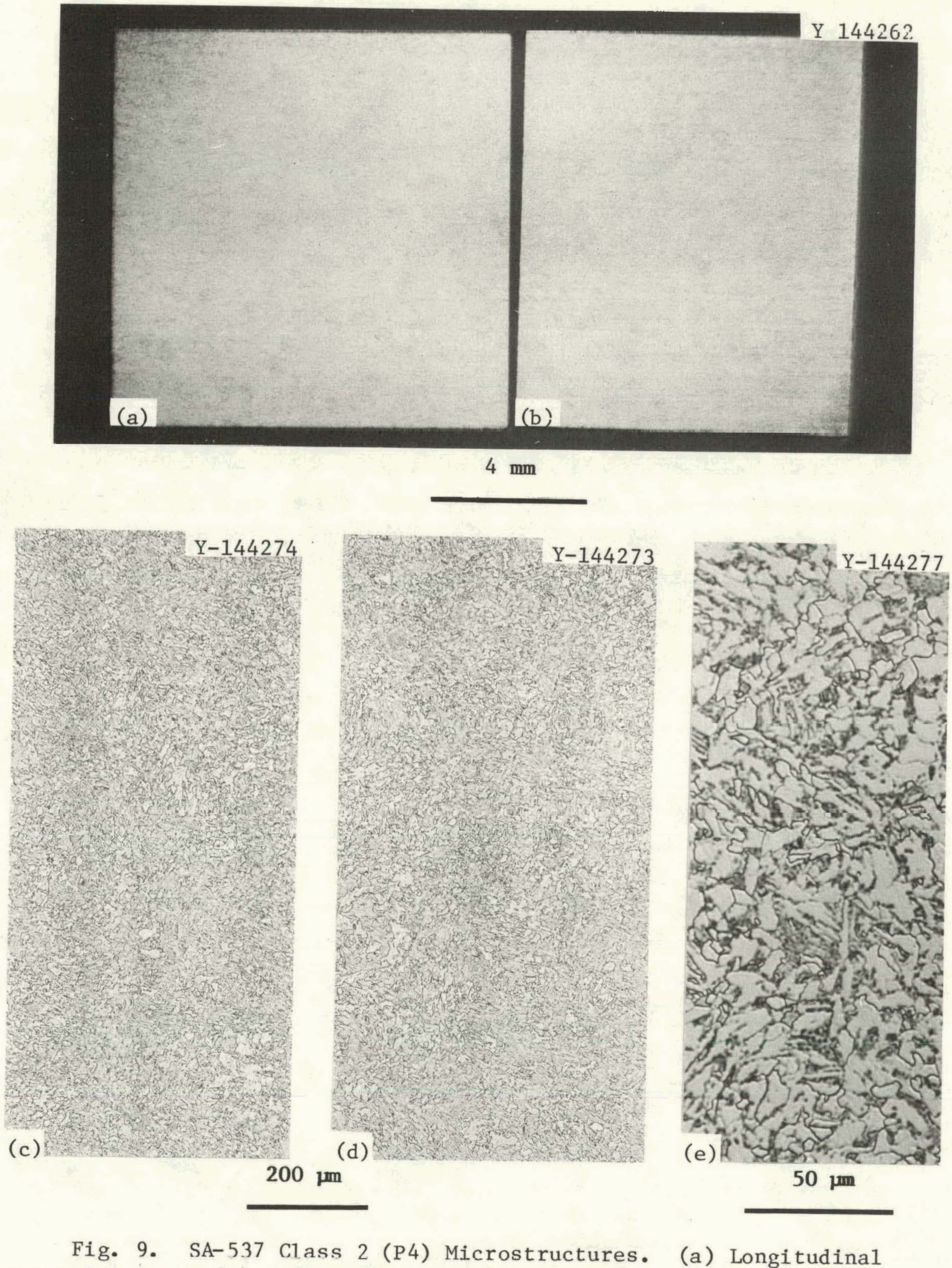


Fig. 9. SA-537 Class 2 (P4) Microstructures. (a) Longitudinal macrostructure; (b) transverse macrostructure; (c) longitudinal; (d) transverse; (e) longitudinal.

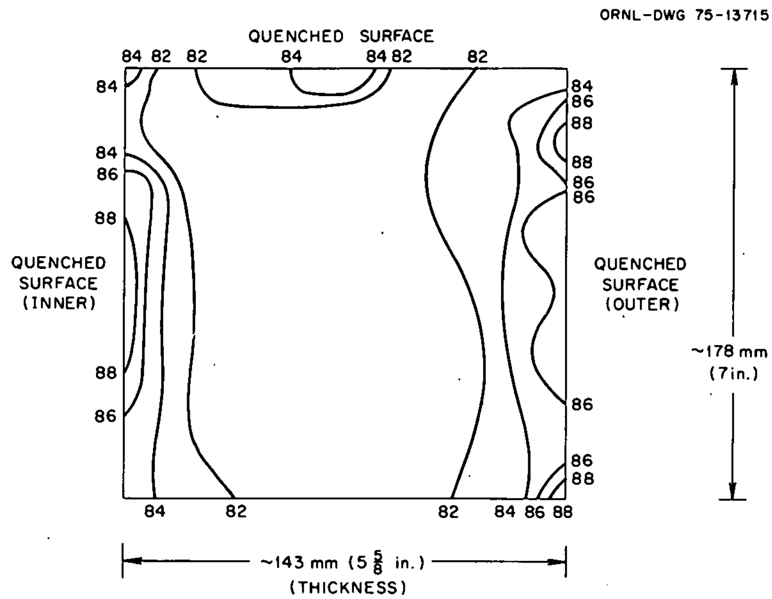


Fig. 10. Rockwell B Isohardness Plot for SA-508 Class 1 (F1) Forging before Simulated Postweld Heat Treatment.

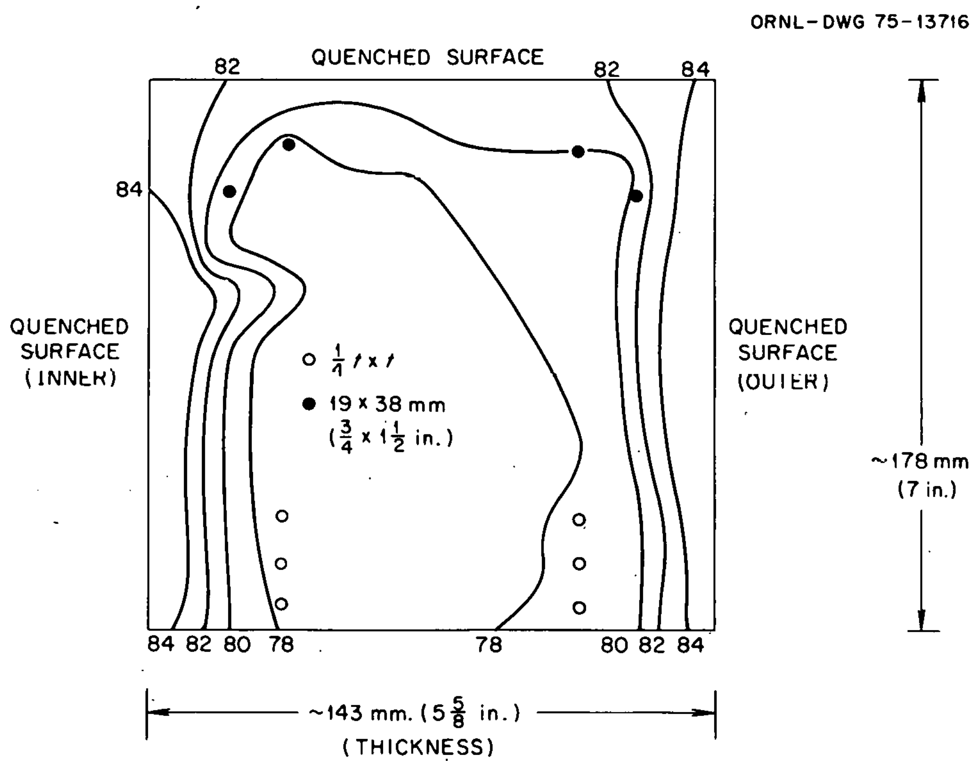


Fig. 11. Rockwell B Isohardness Plot for SA-508 Class 1 (F1) Forging after Simulated Postweld Heat Treatment.

should be pointed out that material removed from the 19 × 38 mm locations reside in areas of steeper hardness gradients. It is more likely that differences might be experienced throughout the forging at that location than at the 1/4 *t* × *t* location. However, the bulk of the cross section between the 1/4 *t* locations shows very little change in hardness readings.

Hardness readings for the plate materials were obtained at the 1/4 *t* location in each plate. They range from R_B 83 for P1, R_B 84 for P2, and R_B 86.5 for P4, all within the expected range for these materials.

4. RESULTS AND DISCUSSION

4.1 Nil-Ductility Temperature Tests

Drop-weight test results for all four PCRV steels are presented in Table 3. The NDT is given as the highest break temperature and the mill test results are provided for comparison. It is interesting that the SA-508 class 1 forging has the lowest NDT (−57°C) since it is the thickest of the four steels tested. Both F1 and P4 are quenched and tempered, but F1 has lower carbon and higher nickel contents than P4, both of which would tend to lower the NDT. It is not surprising that the two quenched and tempered steels (F1 and P4) have lower NDTs than the two normalized steels (P1 and P2). Of the two normalized SA-537 class 1 steels (P1 and P2), the electroslag remelted P2 [51 mm (2 in.) thick] has a slightly lower NDT than P1 [89 mm thick (3 1/2 in.)] (−46°C vs −40°C, respectively). There is exact agreement between the mill and ORNL results for forging F1.

Except for the SA-508 class 1 (F1), mill tests were conducted only to verify that the NDT of the specific material satisfied the appropriate purchase specifications. For example, for SA-537 class 1 (P1), the NDT requirement is specified as −29°C (−20°F) (for 3.5-in.-thick material or lower). Thus, two tests were conducted at −23°C (−10°F) with "no break" results, indicating an NDT of −29°C (−20°F) or below. The tests performed in this study provide the actual values of the NDT for all plate steels.

Table 3. Drop-Weight Nil-Ductility Temperature Test Results

Material	Results at each Test Temperature in °C (°F)							NDT, °C (°F)	
	−72 (−80)	−57 (−70)	−51 (−60)	−46 (−50)	−40 (−40)	−34 (−30)	−29 (−20)	ORNL	Mill[a]
SA-508 class 1 (F1)	Break	Break	No break	No break					
			No break						
								−57 (−70)	−57 (−70)
SA-537 class 1 (P1)				Break	No break	No break			−29 (−20) or Below
					Break	No break			
					Break			−40 (−40)	
SA-537 class 1 (P2)				Break	No break				−34 (−30) or Below
					No break			−46 (−50)	
SA-537 class 2 (P4)			Break	No break	No break				−34 (−30) or Below
				No break				−51 (−60)	

[a]See Appendix A.

Table 3 reflects the requirement that the lowest no-break temperature be repeated for each heat. In the case of P1, the first test at −40°C (−40°F) resulted in no break and required a test at −46°C (−50°F). The subsequent verification of no break at −40°C (−40°F) resulted in a break and thus a third test was conducted at that temperature followed by two no break verification tests at −34°C (−30°F).

Section 4.3 presents Charpy impact test results and shows that the RT_{NDT} is equal to the NDT for all four steels.

4.2 Tensile Test Results

The minimum tensile properties required by the ASME Code, Sect. II, Part A for each material are given in Table 4. For SA-537 class 1, the minimum requirements depend on thickness, as evidenced by the differences in the tensile requirements for P1 and P2 in the table. Results of all tensile tests are given in Appendix B, where the tables describe orientation, orientation, location, and test temperature for each test specimen. Test results shown are upper and lower yield strengths, ultimate tensile strength, uniform elongation, total elongation, and reduction in area. The lower yield strengths are plotted in the figures in every instance. The lower yield strength generally corresponds to the 0.2% offset strength.

4.2.1 SA-508 Class 1 (F1)

Plots of tensile properties for SA-508 class 1 (F1) are shown in Figs. 12 to 19. As stated in Sect. 2.1, testing was performed with specimens from the 1/4 $t \times t$ location with a few tests of material from the 19 × 38 mm location for comparison. Detailed test results are given in Tables B-1 and B-2 of Appendix B.

The required tensile properties for this alloy at room temperature are shown in Table 4. Figures 12 to 15 show the strength and ductility behavior of F1 with temperature for 1/4 $t \times t$ specimens with transverse and longitudinal orientations. The figures (also see tables in Appendix B) show that, although the forging satisfies the tensile

Table 4. Minimum Tensile Requirements

Specification	Thickness (mm)	Thickness (in.)	Stress, MPa (ksi) Minimum Yield	Stress, MPa (ksi) Tensile	Minimum Elongation (%)	Minimum Reduction in Area (%)
SA-508 class 1 (F1) Case 1332-6	140	5.5	241 (35)	482–655 (70–95)	20	38
SA-537 class 1 (P1)	89	5.5	317 (46)	448–586 (65–85)	22	
SA-537 class 1 (P2) Case 1557-1	51	2	344 (50)	482–620 (70–90)	22	
SA-537 class 2 (P4) Case 1557-1	64	2.5	413 (60)	551–689 (80–100)	22	

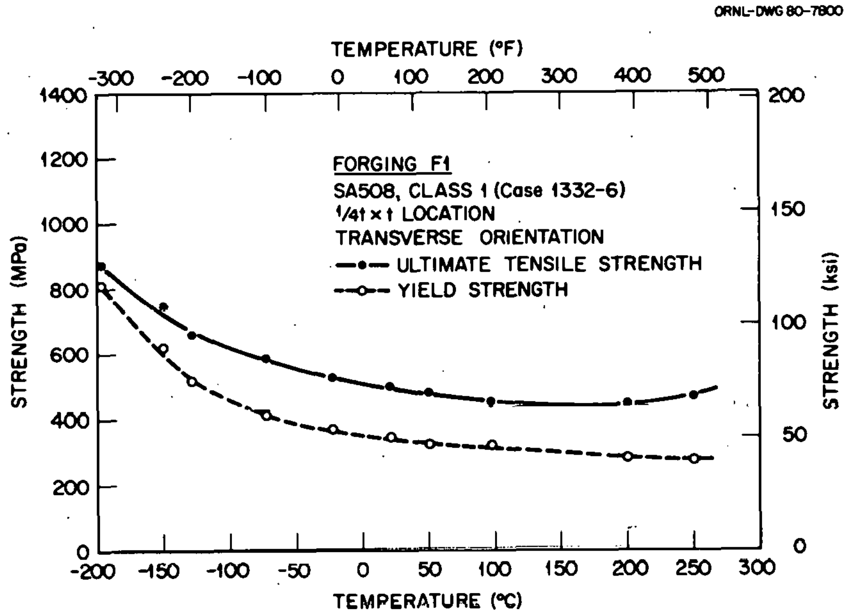


Fig. 12. Strength vs Temperature for SA-508 Class 1 (F1) Forging, Transverse Orientation, Quarter Thickness Location.

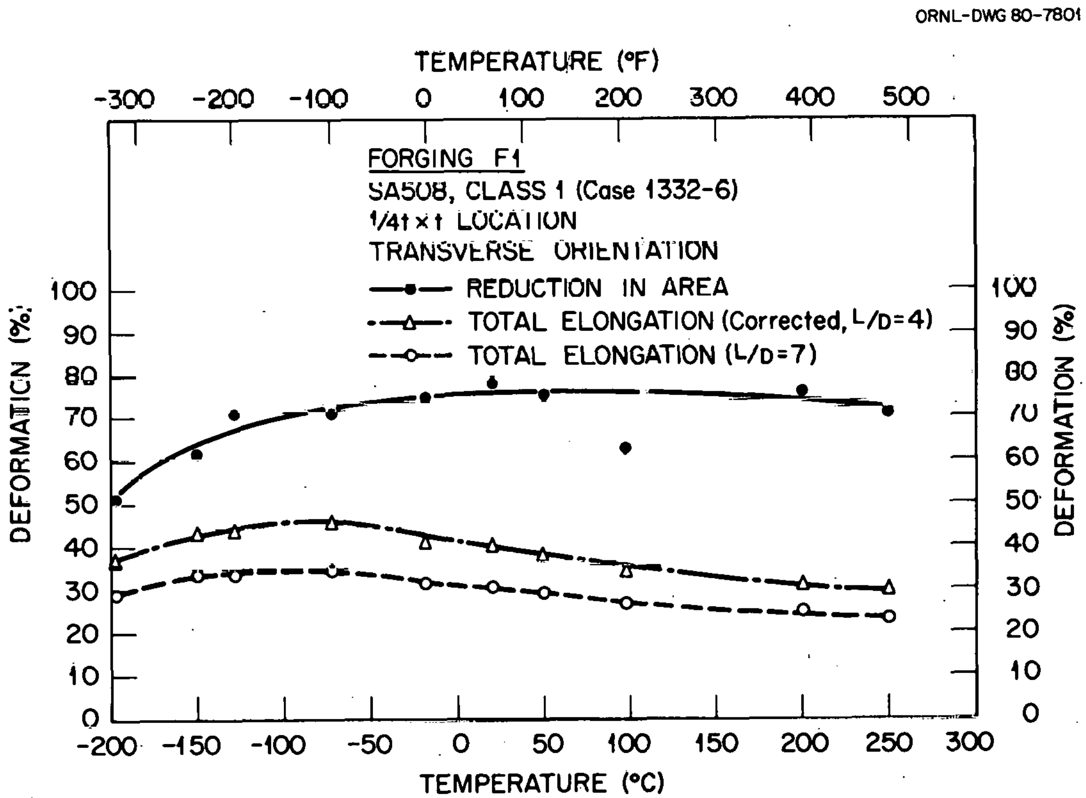


Fig. 13. Tensile Deformation vs Temperature for SA-508 Class 1 (F1) Forging, Transverse Orientation, Quarter Thickness Location.

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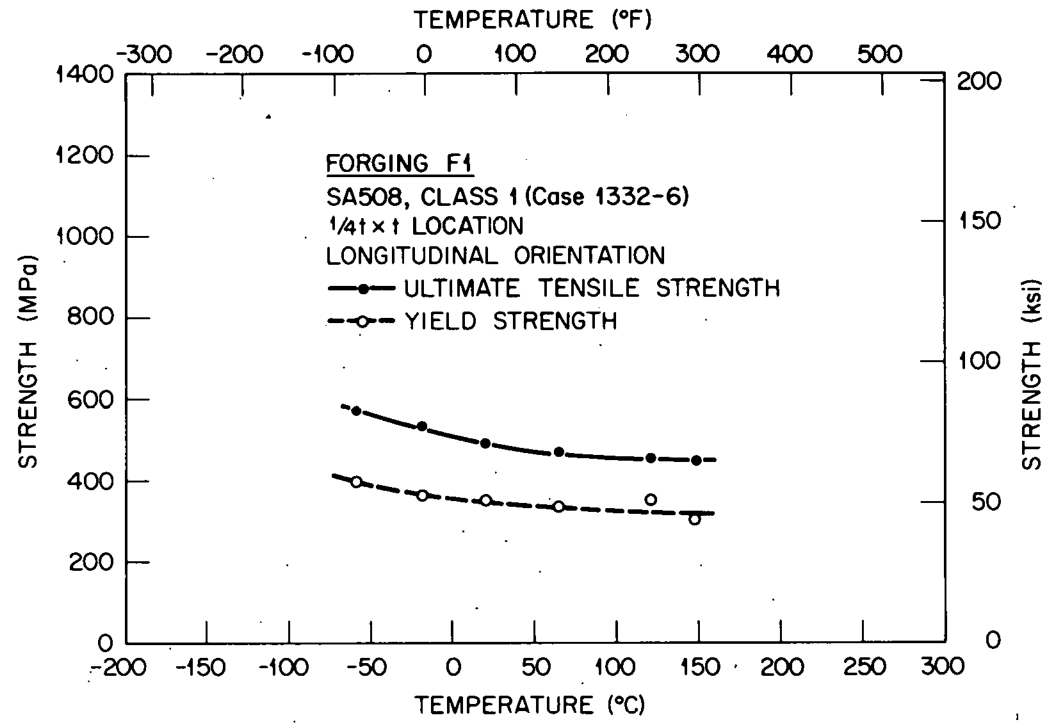

Fig. 14. Strength vs Temperature for SA-508 Class 1 (F1) Forging, Longitudinal Orientation, Quarter Thickness Location.

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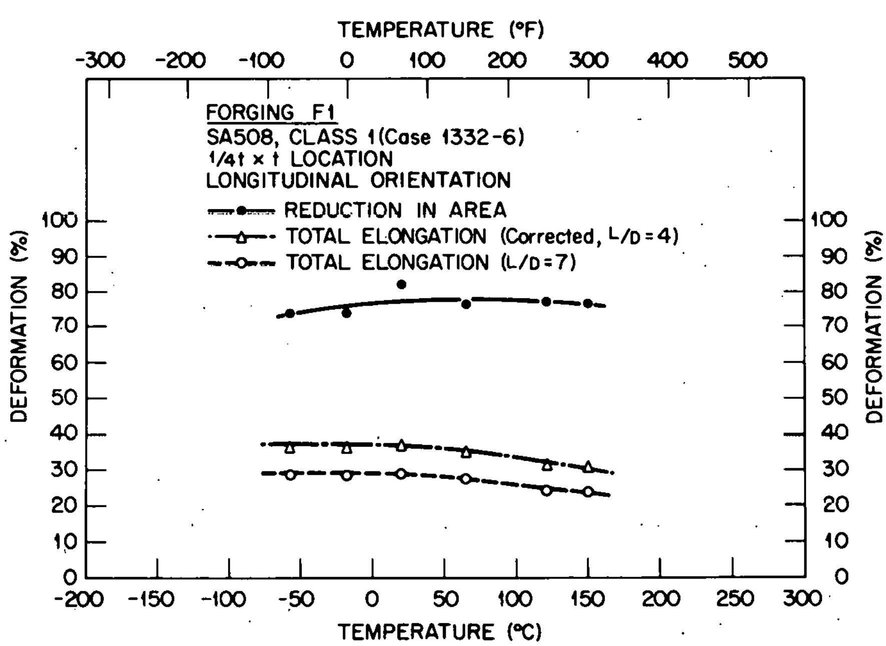

Fig. 15. Tensile Deformation vs Temperature for SA-508 Class 1 (F1) Forging, Longitudinal Orientation, Quarter Thickness Location.

requirements at room temperature, its ultimate strength values of 499 and 492 MPa (72.3 and 71.4 ksi) for the transverse and longitudinal specimens, respectively, barely meet the 482-MPa minimum requirement. As expected, the strength of the forging increased at lower temperatures and decreased somewhat at higher temperatures. Similarly, the elongation increased with decreasing test temperature to –75°C and then decreased at lower temperatures. It is interesting to note that at –196°C (–320°F), the transverse strengths are twice those at room temperature and elongation is about the same as that at room temperature. As will be shown in a later section, these improvements in the tensile properties of smooth bar are not repeated by notched toughness behavior, amplifying the need for testing of notched specimens.

Figures 16 to 19 show the same properties for both transverse and longitudinal specimens from the 38 × 19 mm (1 1/2 × 3/4 in.) location. The number of available specimens were limited, but a comparison can be made with specimens from the 1/4 $t \times t$ location. The curves (and the tables in Appendix B) show the strengths of 38 × 19 mm specimens to be about 20 MPa (~3 ksi) higher and elongation about 4% lower than those for 1/4 $t \times t$ specimens at corresponding test temperatures. These observations apply to both transverse and longitudinal orientations. In general, for the 1/4 $t \times t$ location, transverse and longitudinal strengths are about the same, while transverse elongations are slightly higher than those for the longitudinal orientation.

As stated earlier, the F1 heat does meet the minimum tensile requirements for SA-508 class 1 steel.

4.2.2 SA-537 Class 1 (P1 and P2)

Figures 20 to 23 show the tensile properties of SA-537 class 1 (P1) in the transverse and longitudinal orientations, and Figs. 24 to 27 show similar plots for the other heat of SA-537 class 1 (P2). Detailed test results are given in Tables B-3 through B-6 of Appendix B. The yield strengths of P1 are somewhat lower (around 25 MPa) than those for P2 over the range of test temperatures for both transverse and longitudinal

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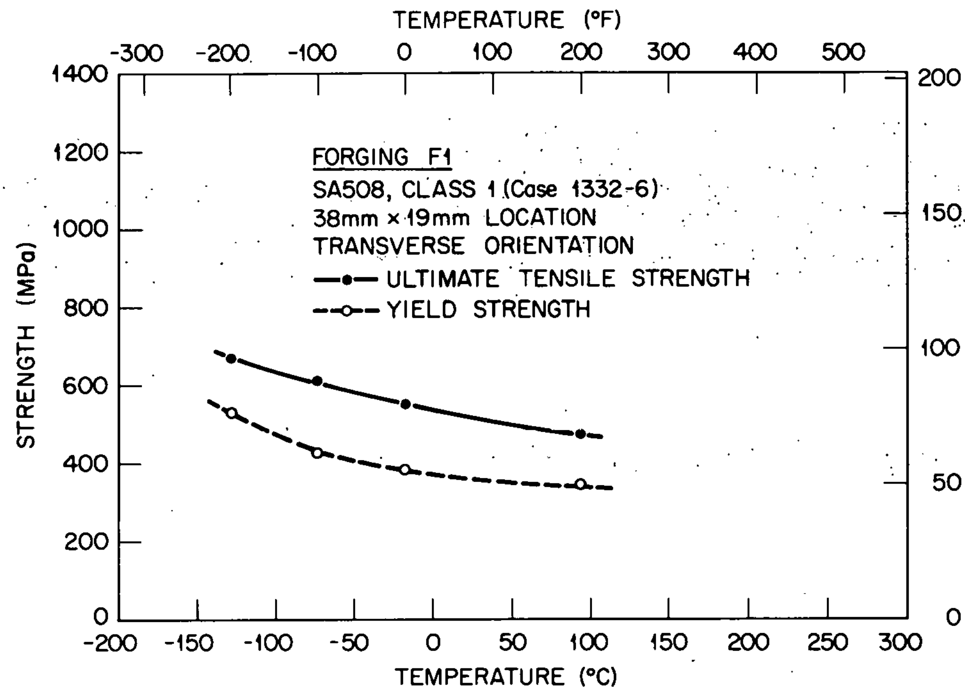

Fig. 16. Strength vs Temperature for SA-508 Class 1 (F1) Forging, Transverse Orientation, 38 × 19 mm Location.

ORNL-DWG 80-7805

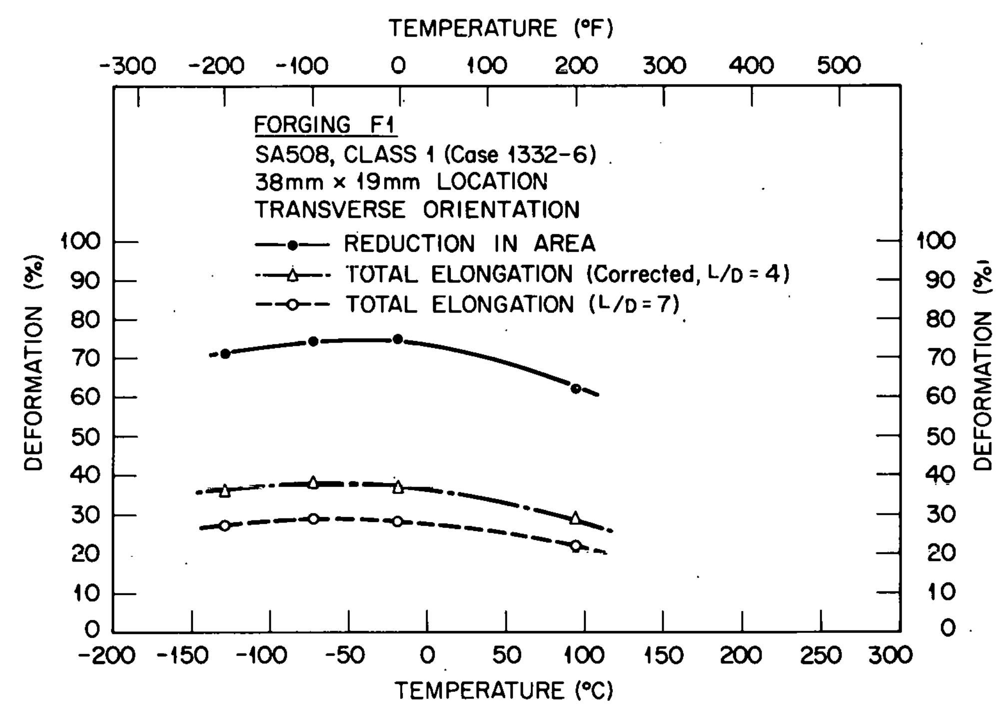

Fig. 17. Tensile Deformation vs Temperature for SA-508 Class 1 (F1) Forging, Transverse Orientation, 38 × 19 mm Location.

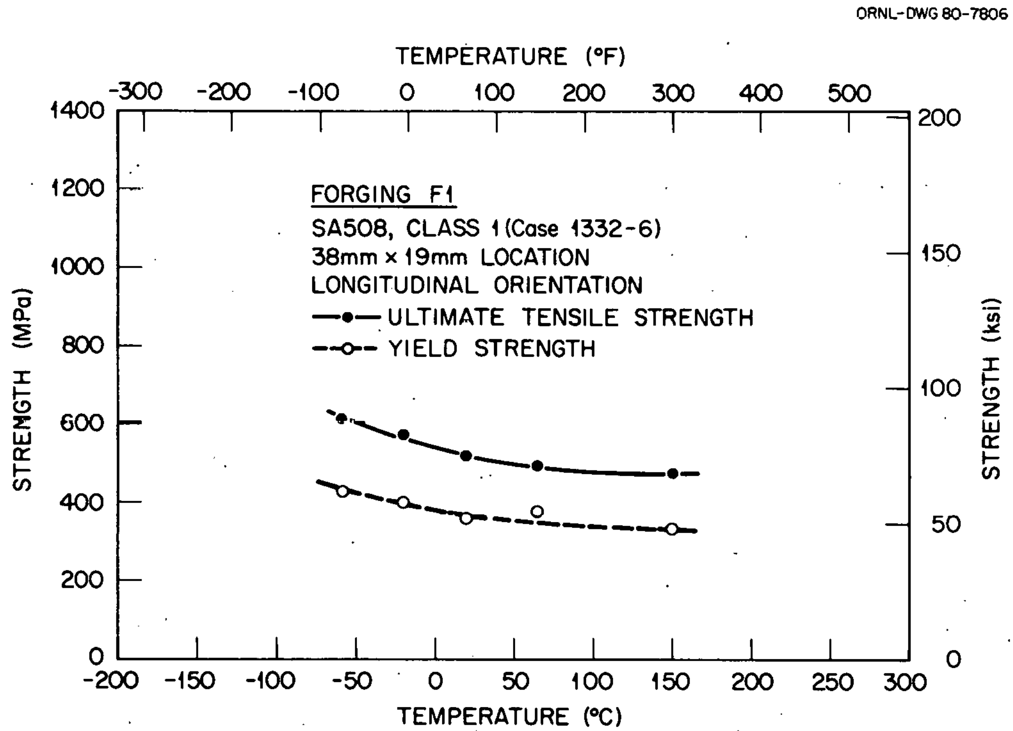

Fig. 18. Strength vs Temperature for SA-508 Class 1 (F1) Forging, Longitudinal Orientation, 38 × 19 mm Location.

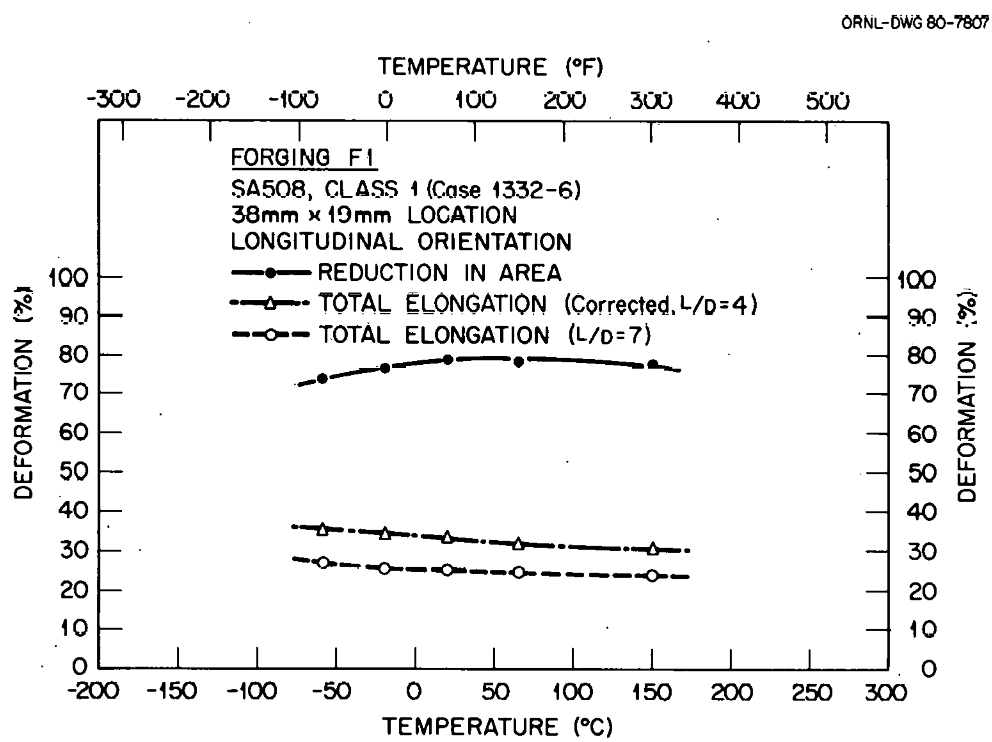

Fig. 19. Tensile Deformation vs Temperature for SA-508 Class 1 (F1) Forging, Longitudinal Orientation, 38 × 19 mm Location.

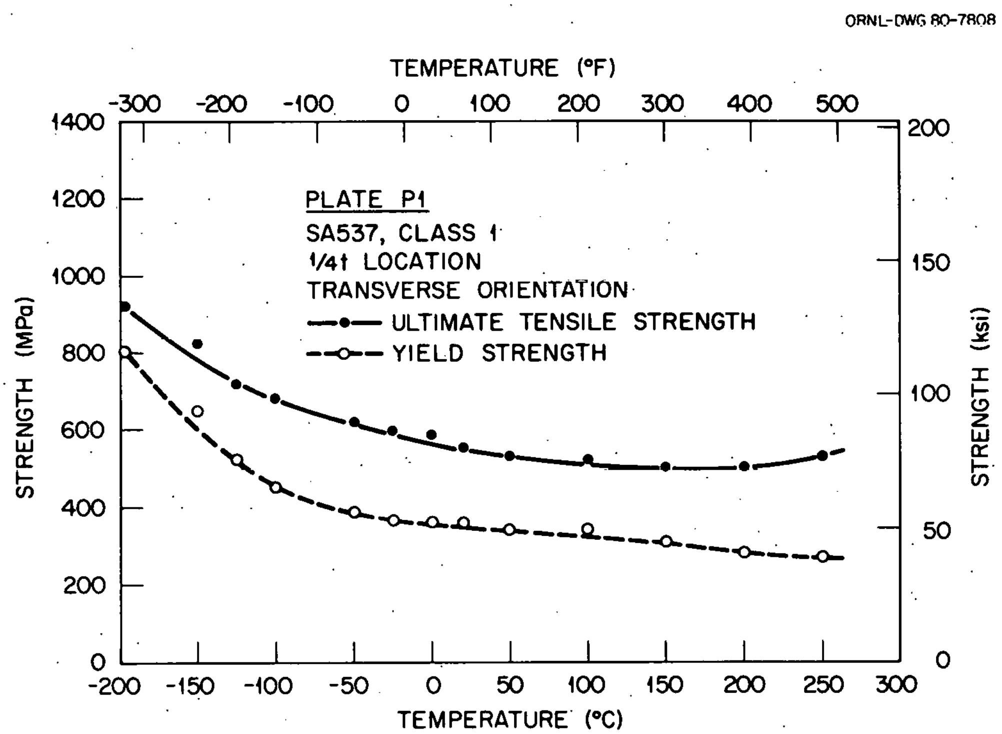

Fig. 20. Strength vs Temperature for SA-537 Class 1 (P1) Plate, Transverse Orientation.

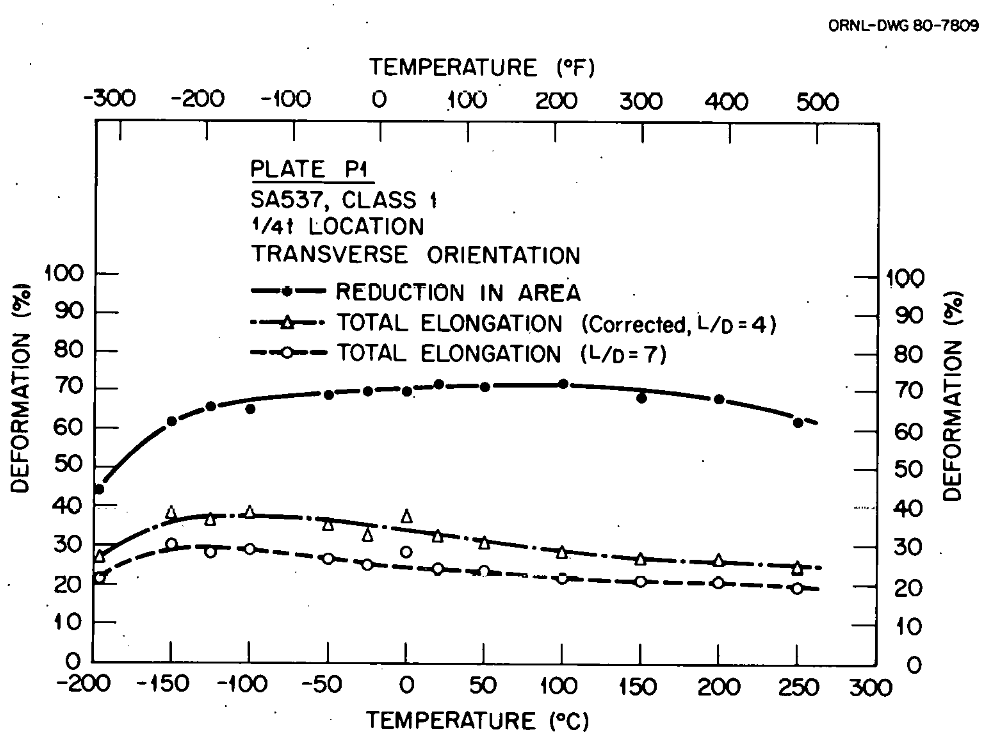

Fig. 21. Tensile Deformation vs Temperatures for SA-537 Class 1 (P1) Plate, Transverse Orientation.

ORNL-DWG 80-7810

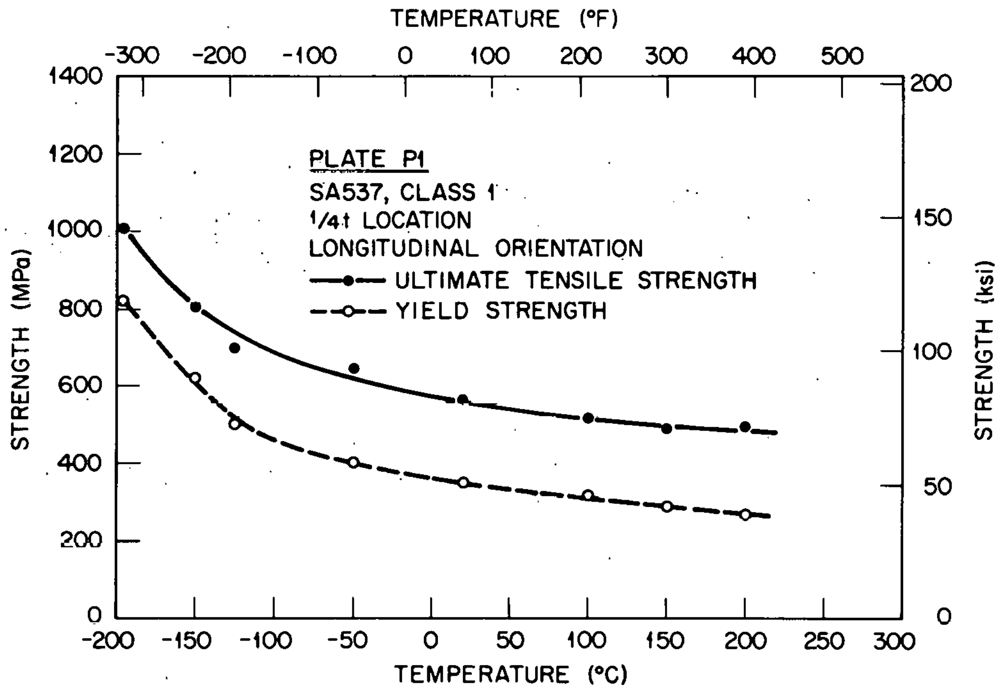

Fig. 22. Strength vs Temperature for SA-537 Class 1 (P1) Plate, Longitudinal Orientation.

ORNL-DWG 80-7811

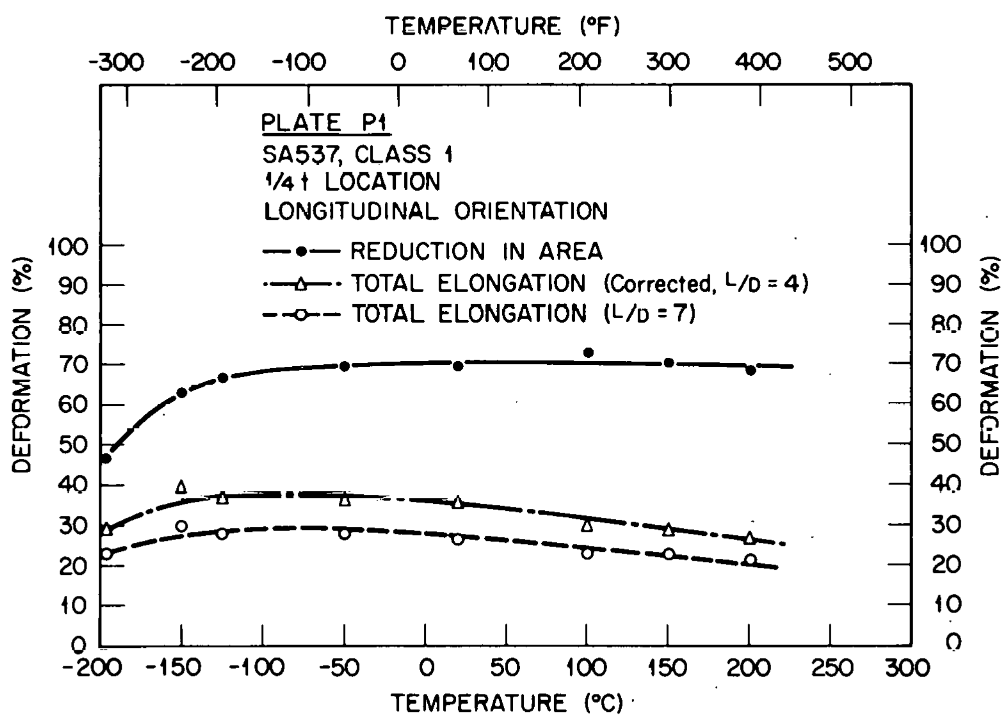

Fig. 23. Tensile Deformation vs Temperature for SA-537 Class 1 (P1) Plate, Longitudinal Orientation.

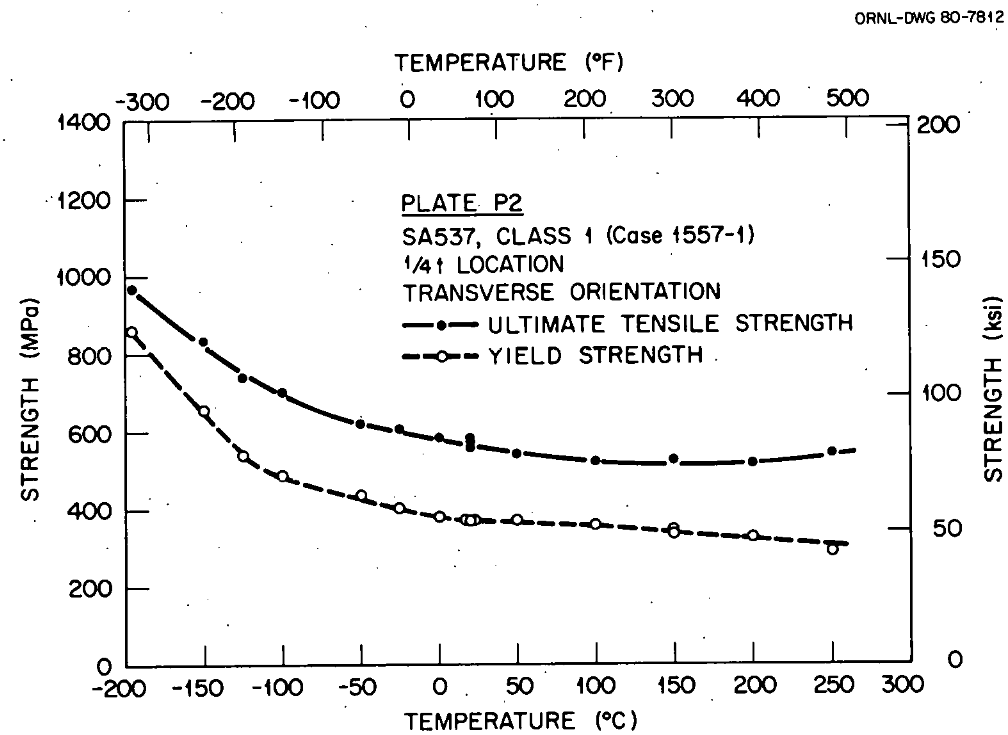

Fig. 24. Stength vs Temperature for SA-537 Class 1 (P2) Plate, Transverse Orientation.

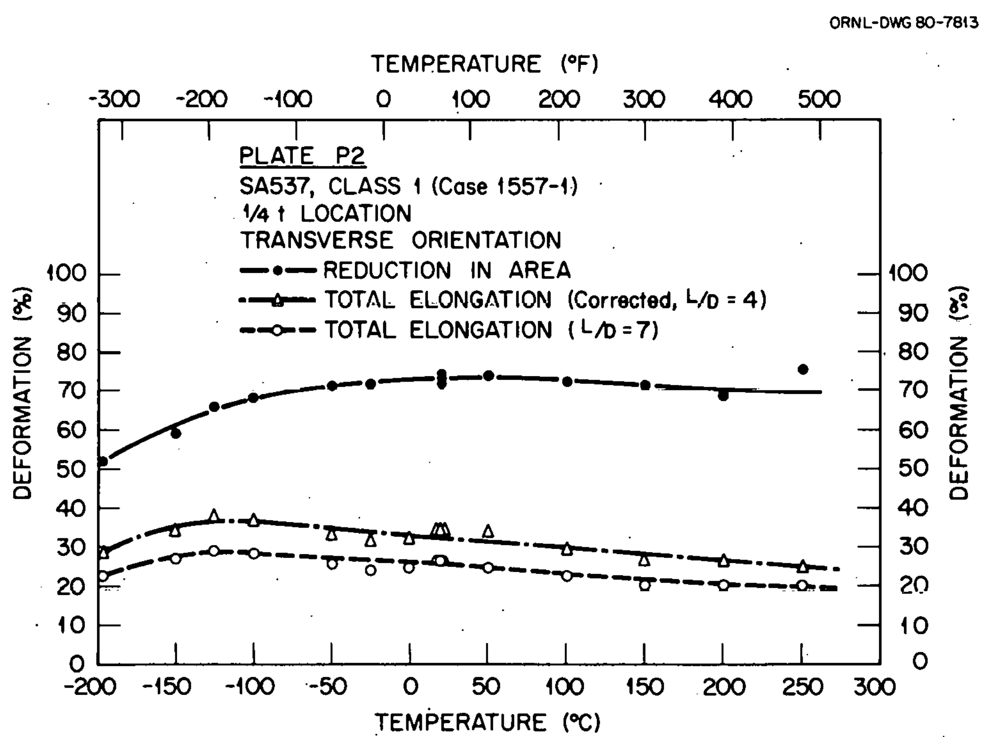

Fig. 25. Tensile Deformation vs Temperature for SA-537 Class 1 (P2) Plate, Transverse Orientation.

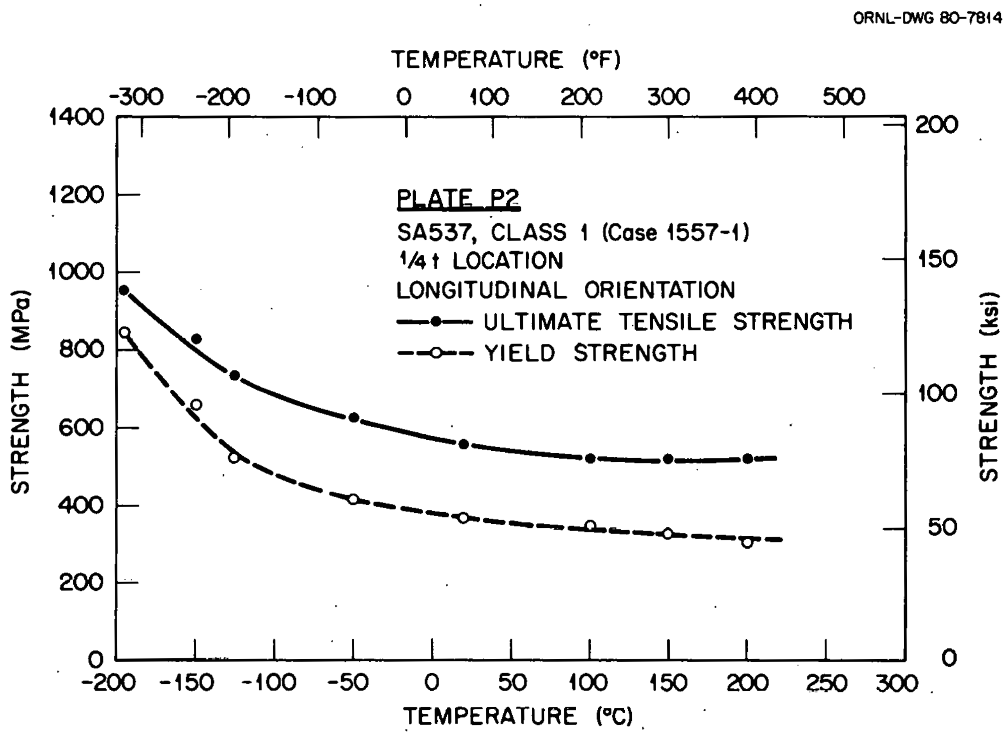

Fig. 26. Strength vs Temperature for SA-537 Class 1 (P2) Plate, Longitudinal Orientation.

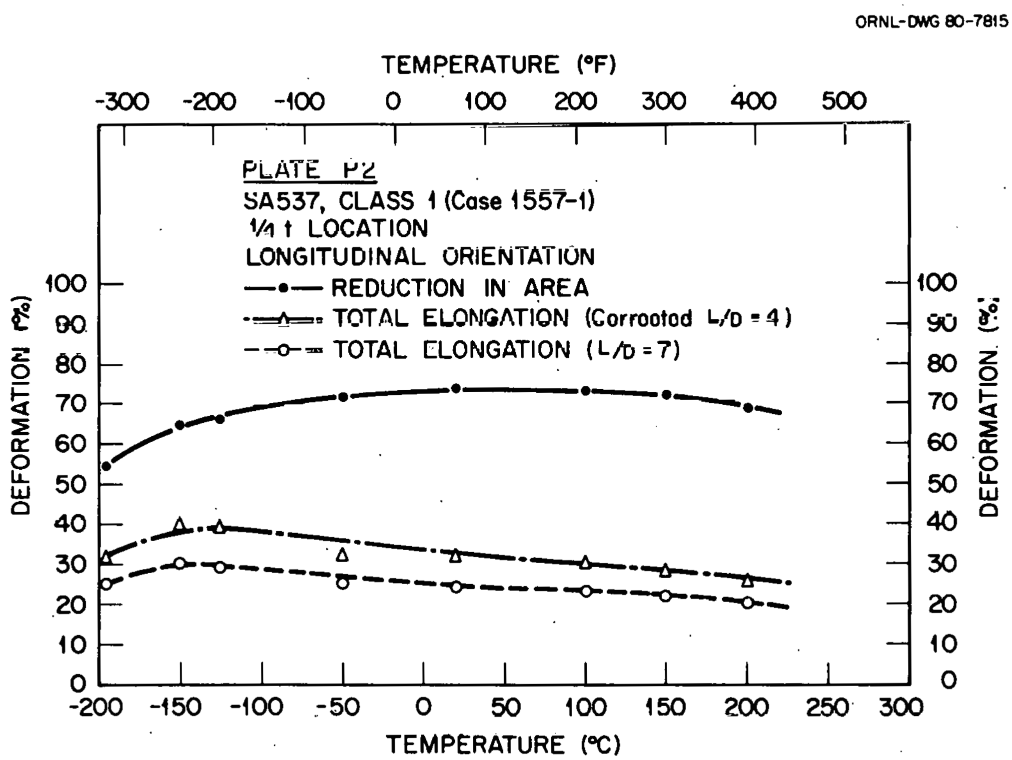

Fig. 27. Tensile Deformation vs Temperature for SA-537 Class 1 (P2) Plate, Longitudinal Orientation.

orientations. Ultimate strength values are approximately the same for transverse specimens except at fairly low temperatures with P2 ultimate strengths being somewhat greater. Ultimate strengths of both steels in the longitudinal direction are substantially the same for the entire temperature range. In general, the yield strengths for the longitudinal orientation are slightly lower than those for the transverse orientation for both P1 and P2. Ultimate strength values, however, do not exhibit an obvious trend in that regard.

Total elongation and reduction in area values for P1 and P2 are very similar for both orientations. Furthermore, values of those measures of ductility for the longitudinal specimens are about the same as those for the transverse specimens for both P1 and P2.

A comparison of P1 and P2 tensile results at room temperature with Table 4 shows that both steels satisfy the minimum requirements of SA-537 class 1.

4.2.3 SA-537 Class 2 (P4)

Tensile test results for the one heat of SA-537 class 2 steel (P4) are shown in Figs. 28 to 31, and detailed data are provided in Tables B-7 and B-8 of Appendix B. Yield and ultimate strengths are substantially the same for transverse and longitudinal orientations over the entire range of test temperatures. The same behavior is reflected by the elongation and reduction-in-area results. The primary observations regarding the results involve the yield strengths at room temperature. The requirements for SA-537 class 2 are 413 MPa (60 ksi) yield strength minimum, 551 to 689 MPa (80 to 100 ksi) ultimate tensile strengths and 22% minimum elongation (see Table 4). The yield strengths of P4 at room temperature are 396 MPa (57.5 ksi) for the longitudinal specimen and 404 MPa (58.6 ksi) for the transverse specimen. These values are below the specification requirement and conflict with the results quoted in the mill test report, summarized in Appendix A. The mill test report gives yield strength values of 505 and 449 MPa (73.3 and 65.2 ksi) for test coupons (12.7 mm diam) given an SPWHT. These values are well above those of this study and also above the

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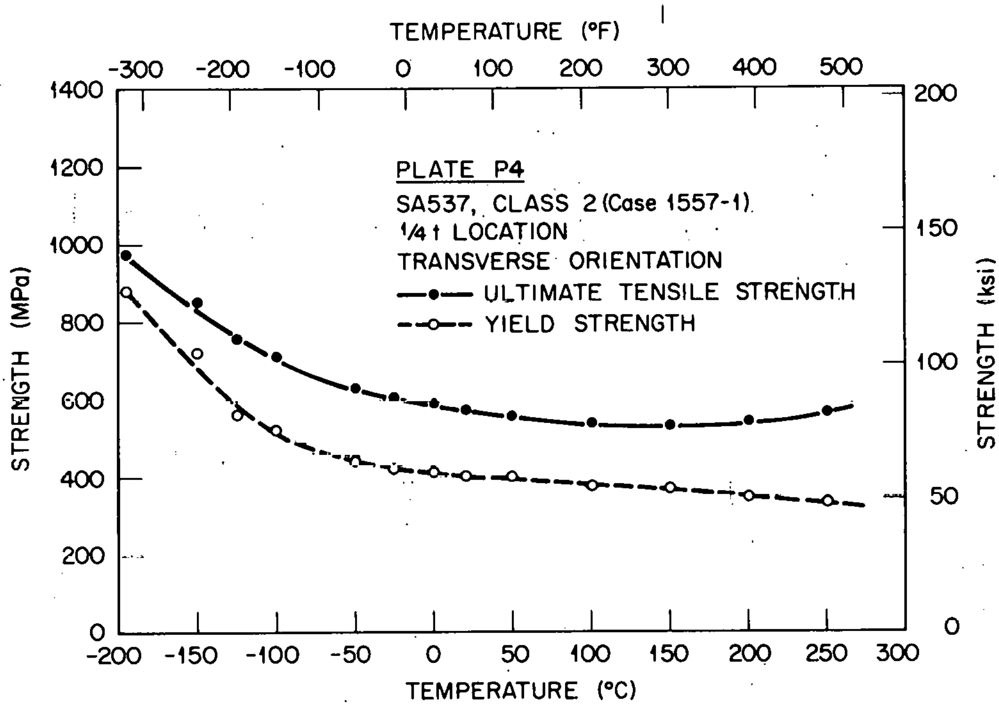

Fig. 28. Strength vs Temperature for SA-537 Class 2 (P4) Plate, Transverse Orientation.

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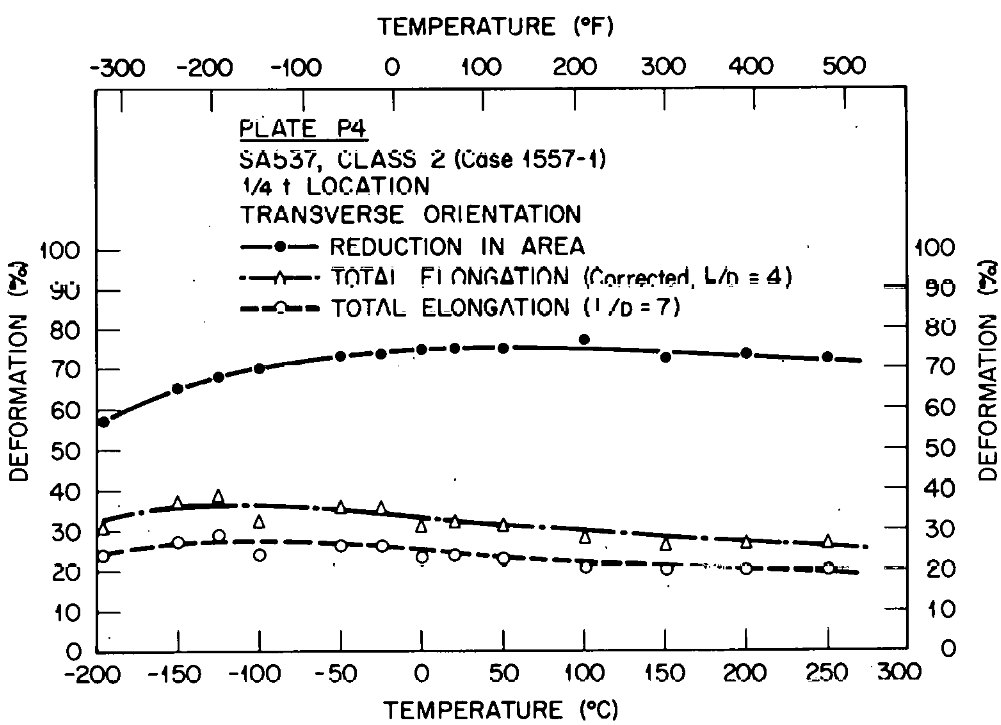

Fig. 29. Tensile Deformation vs Temperature for SA-537 Class 2 (P4) Plate, Transverse Orientation.

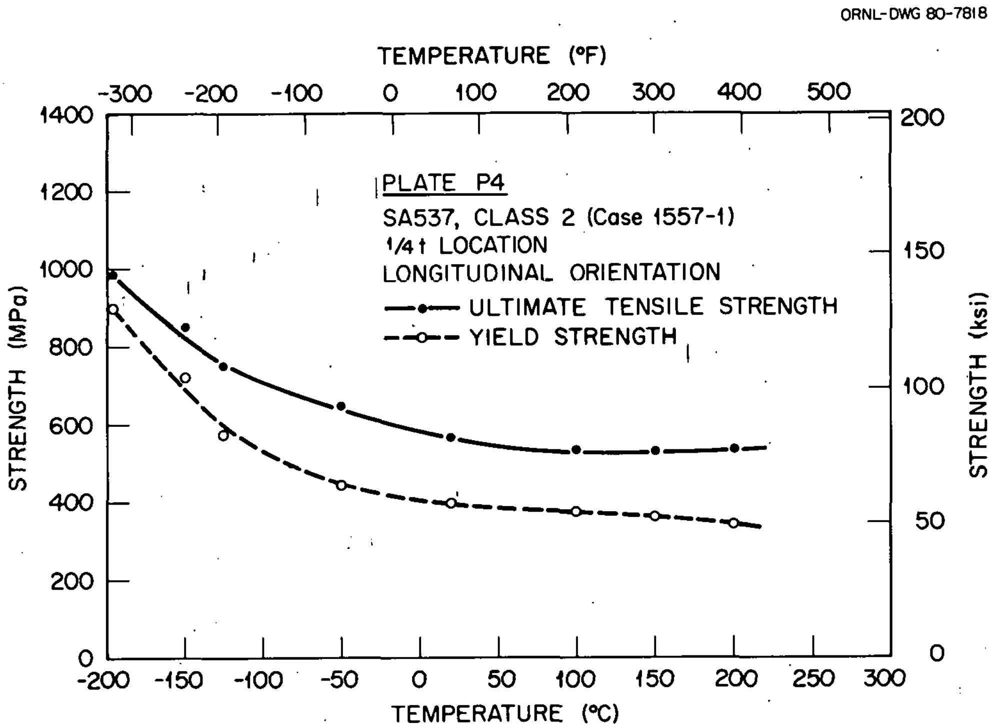

Fig. 30. Strength vs Temperature for SA-537 Class 2 (P4) Plate, Longitudinal Orientation.

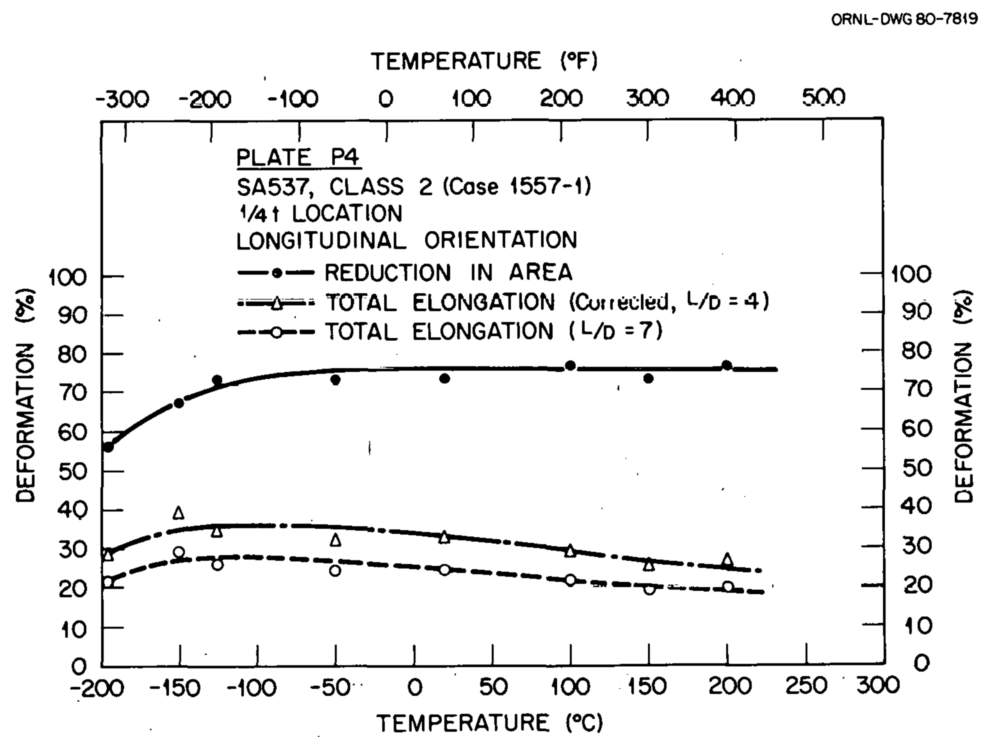

Fig. 31. Tensile Deformation vs Temperature for SA-537 Class 2 (P4) Plate, Longitudinal Orientation.

minimum requirement. As stated in ASME specification SA-370, the mill test results from test coupons representing the final product heat treatment will be used as the acceptance criteria for mechanical properties.[9] The ultimate strength values from the mill tests are also much higher than those of this study and meet the minimum requirements. The higher strength values of the mill reports are accompanied by elongation values that are lower than those obtained from specimens tested at ORNL. A study by the Electric Power Research Institute (EPRI)[10] reported tensile results very similar to those of this study for a different heat of SA-537 class 2 with similar composition, fabrication, and heat treatment (as well as the same thickness) to P4. Those tests [with 12.7-mm-diam (0.500-in.) specimens] resulted in a yield strength of 395 MPa (57.4 ksi) at room temperature and thus show similar disagreement with mill test reports for the particular heat tested.

It should be noted that mechanical test procedures must conform to the specifications of SA-370. The 1971 ASME code up to and including the Summer 1973 Addenda for SA-370 (code in effect at time of procurement) provided various methods of determining the yield strength. The most common method used is the 0.2% strain offset procedure, and SA-370 describes that procedure. A note in the paragraph on 0.2% offset states that the load at the 0.2% offset position may be preceded by a higher load (e.g., an upper and lower yield behavior) and that the higher load attained may be used to calculate the yield strength. The implication, then, is that the "upper yield" may be used to determine material yield strength. For the results obtained in this study, the use of upper yield data would give yield strengths of 457 and 451 MPa (66.4 and 65.4 ksi) for transverse and longitudinal specimens, respectively. In contrast, the current version of SA-370 does not allow for the above interpretation when determining yield strength by the 0.2% offset method. If the procedures allowed in the code in effect at the time of procurement are used, the upper yield strength agrees faily well with the mill test reports and satisfies the requirements of Table 2.

4.3 Charpy V-Notch Impact Test Results

The tables in Appendix C give Charpy V-notch impact test results along with orientation, location, and test temperature for each specimen. Test results shown are absorbed energy (dial energy from impact machine), lateral expansion, fracture appearance (% shear), and drop in load (P). Figure 32 shows three force-time traces representing test results at three different test temperatures with F1 specimens. As the test temperature increases, the P decreases and the percent shear increases. Specimens with no rapid drop in load always exhibit a 100% shear fracture.

4.3.1 SA-508 Class 1 (F1)

The orientations of forging F1 specimens are given as AC (axial orientation with a circumferential notch) or CA (circumferential orientation with an axial notch). Since F1 is a ring rolled forging, the circumferential direction is analogous to the rolling (longitudinal) direction in a plate. Thus, orientations AC and CA would correspond to orientations TL and LT, respectively, for plate samples. Detailed test results for F1 are given in Tables C-1 and C-2 of Appendix C.

Figures 33 and 34 are plots of energy absorption vs temperature for AC and CA oriented specimens, respectively, from the 1/4 $t \times t$ location; Fig. 35 is a combined plot of those results for direct comparison. The CA oriented specimen shows a more rapid increase in energy absorption with temperature, but both curves are similar at the lower temperatures and tests at −7°C (20°F) actually stopped the impact hammer from its full input energy of 325 J (240 ft-lb). The upper-shelf level of the AC orientation is about 300 J (220 ft-lb), which is also representative of a very high energy absorbing capacity. At 10°C (50°F), the material absorbed about 200 J and exhibited 100% shear ($P = 0$). At higher test temperatures, the material absorbs over 300 J.

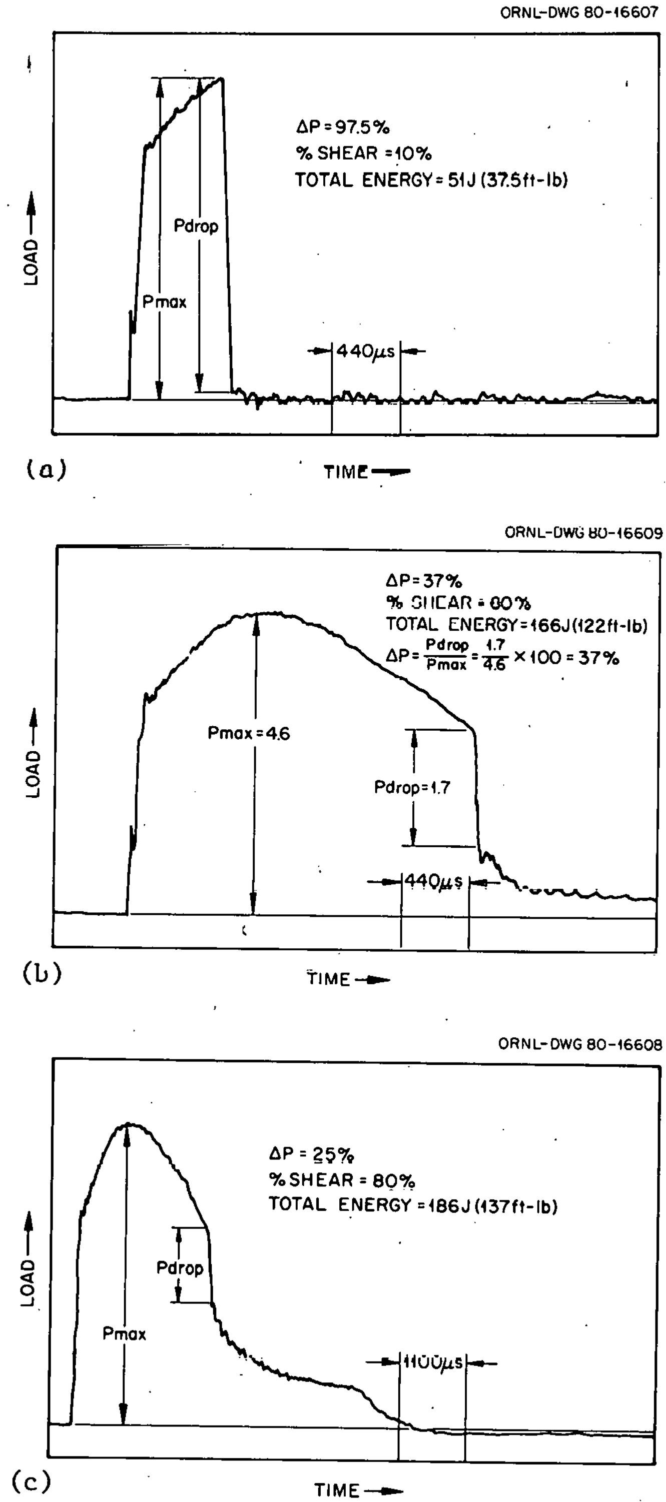

Fig. 32. Load-Time Trace Showing Drop in Load. (a) Prior to maximum load; (b) after maximum load; (c) after maximum load, showing drop in load similar to that in (b) but an earlier onset of arrest as reflected by the percent shear.

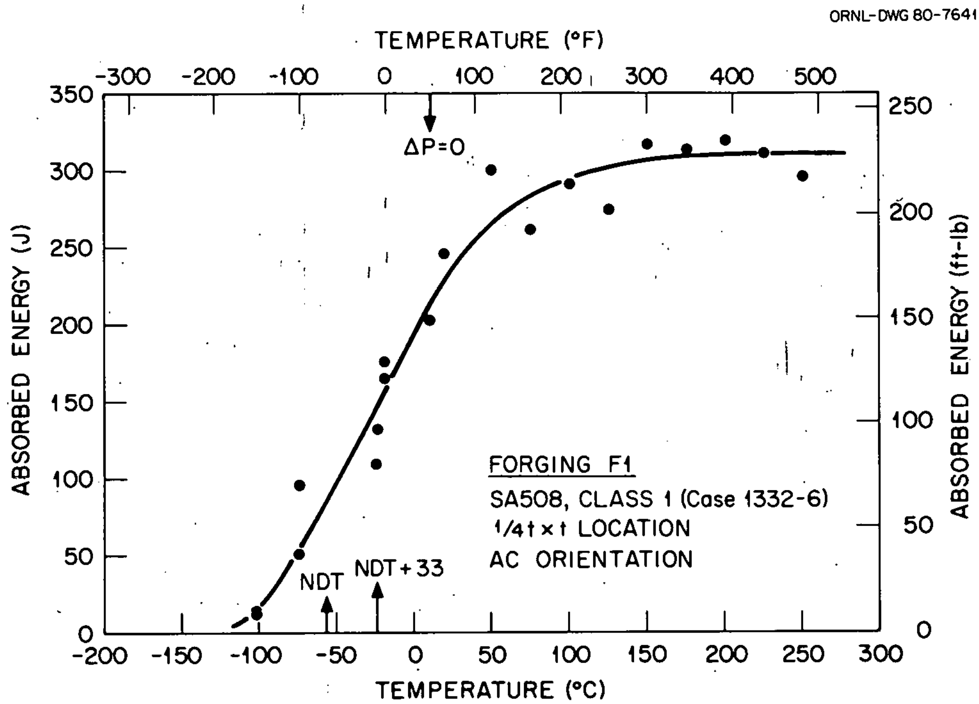

Fig. 33. Charpy Impact Energy vs Temperature for SA-508 Class 1 (F1) Forging, Axial Orientation, Quarter Thickness Location.

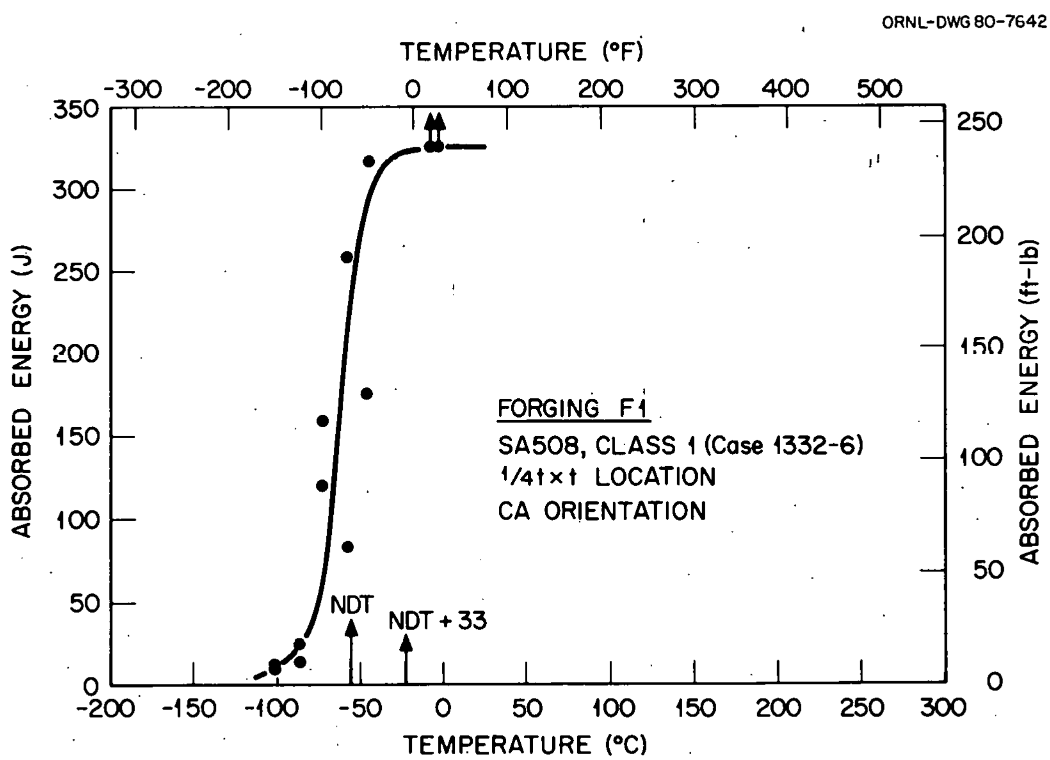

Fig. 34. Charpy Impact Energy vs Temperature for SA-508 Class 1 (F1) Forging, Circumferential Orientation, Quarter Thickness Location.

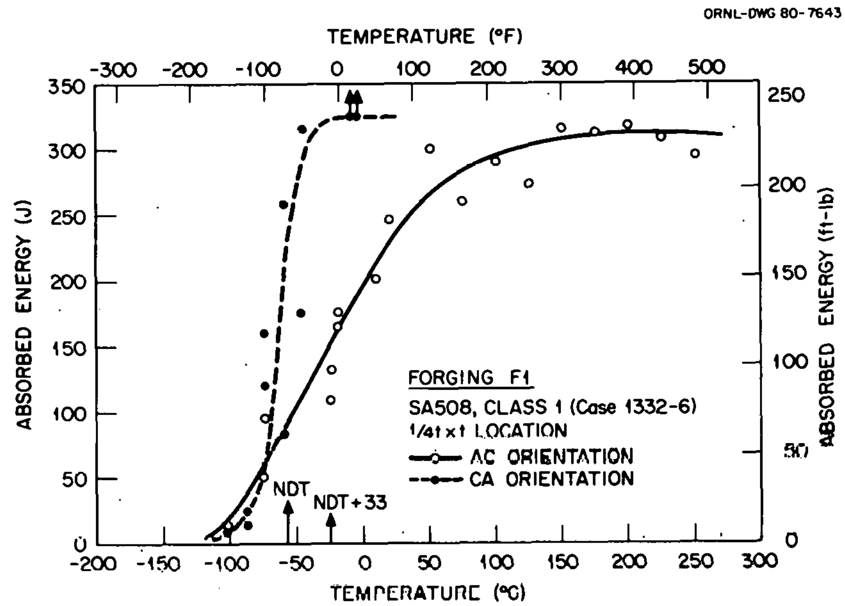

Fig. 35. Charpy Impact Energy vs Temperature for SA-508 Class 1 (F1) Forging, Comparison of Axial and Circumferential Orientations at the Quarter-Thickness Location.

One of the more interesting observations from these results is the impact energy relative to the NDT. The RT_{NDT} is equal to the NDT if, at NDT + 33°C (60°F), three Charpy impact specimens exhibit at least 68 J (50 ft-lb) energy and 0.89 mm (0.35 in.) lateral expansion. The data indicate that for F1 the requirements are met much nearer the NDT. In fact, one AC specimen exceeded those requirements at —73°C (—100°F), which is 17°C (30°F) below the NDT. At NDT + 33°C, the impact energy is about 122 J (90 ft-lb).

As discussed in Sect. 2.1, tests were conducted to determine any significant differences between forging material at the 1/4 $t \times t$ and the 38 × 19 mm locations. Figure 36 provides a comparison of those tests for AC oriented specimens. Within the temperature range of testing common to both cases (—100 to 38°C), the results are very similar considering the scatter of the data. If any substantial differences had been obtained, they would be manifested by the 38 × 19 mm location curve having a transition region at lower temperatures than that for the 1/4 $t \times t$ material because of the effects of more rapid cooling from two quenched surfaces. The data shown in Fig. 36 do not indicate, however, any substantial difference in Charpy impact behavior.

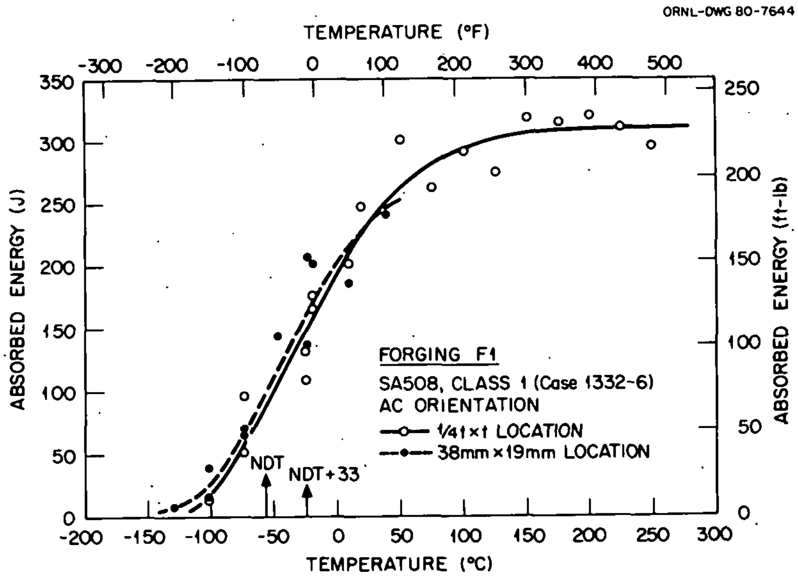

Fig. 36. Charpy Impact Energy vs Temperature for SA-508 Class 1 (F1) Forging, Comparison of the Quarter-Thickness and 38 × 19 mm Locations with an Axial Orientation.

4.3.2 SA-537 Class 1 (P1 and P2)

The results of Charpy impact tests with SA-537 class 1 (heats P1 and P2) are given in Tables C-3 through C-6 of Appendix C. Specimens were tested in both the TL and LT orientations. Figures 37 and 38 show plots of absorbed energy vs temperature for P1, while Fig. 39 compares the data for the TL and LT orientations. The transition region for the TL specimens lies at slightly higher temperatures, and the upper-shelf energies are substantially less than those for LT specimens. A greater number of TL specimens were tested at high temperatures to get a better fix on the upper shelf, which, for TL specimens, is quite flat at an energy level of about 170 J (125 ft-lb). The LT curve, however, appears to increase after the onset of upper-shelf behavior at about 50°C (the shear fracture is 100% and ΔP is zero at 50°C and above). Two TL specimens, one at 150°C and one at 225°C, absorbed much more energy than the other specimens in the upper-shelf region. No explanation for this behavior is offered other than to designate them as outliers relative to the large number of data points at lower energies. Other than those two tests, the TL oriented

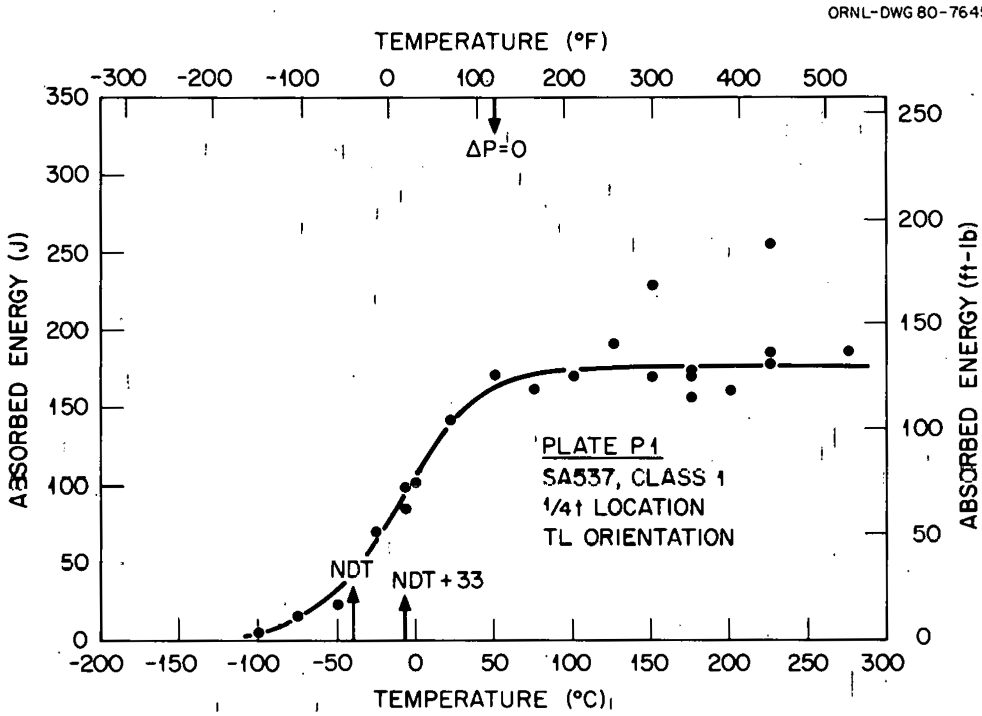

Fig. 37. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P1) Plate, Transverse Orientation.

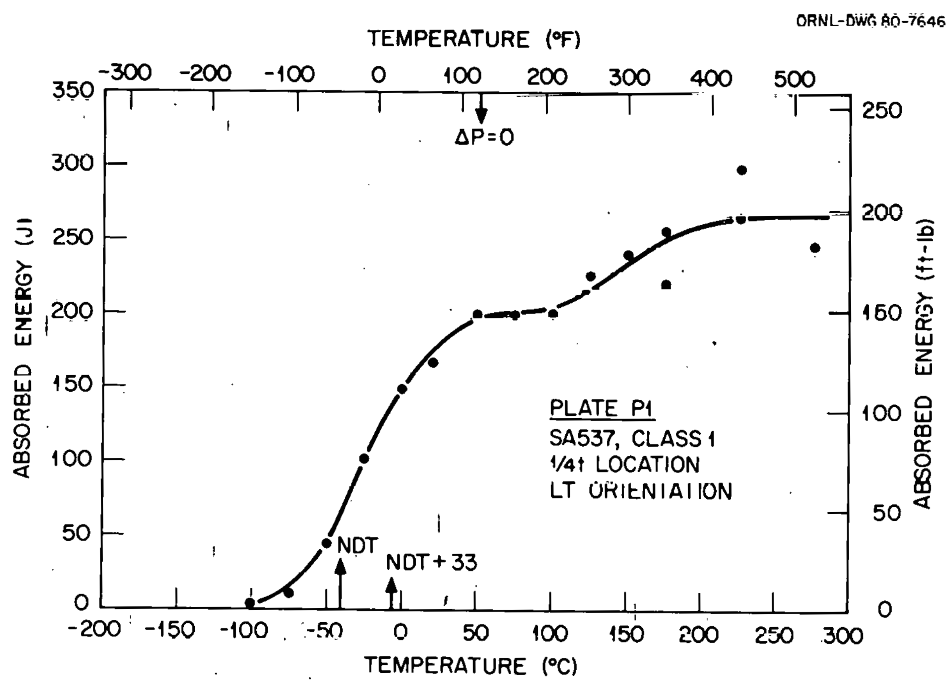

Fig. 38. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P1) Plate, Longitudinal Orientation.

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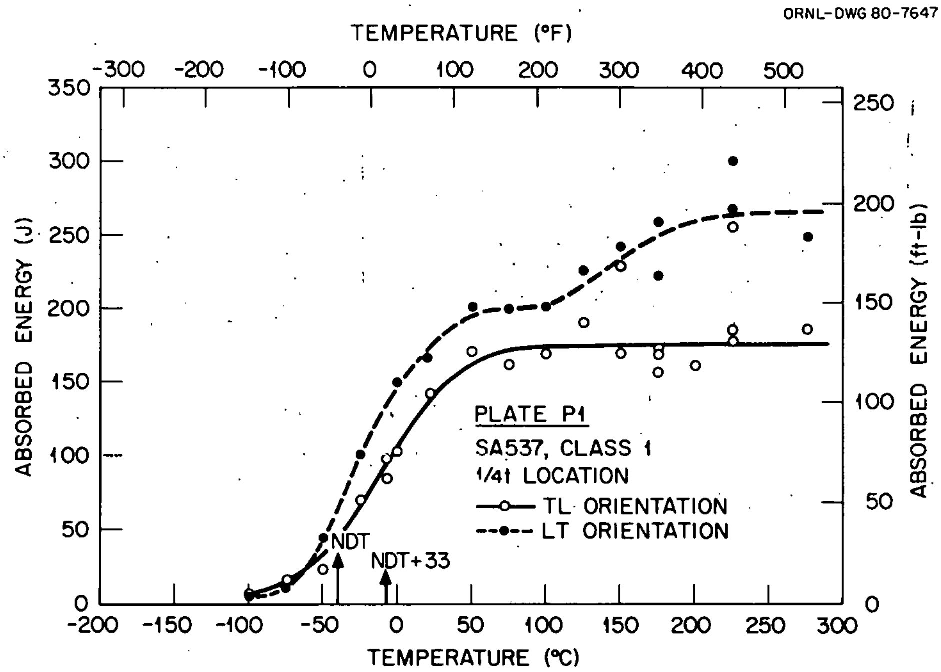

Fig. 39. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P1) Plate, Comparison of Transverse and Longitudinal Orientations.

specimens do not exhibit substantial energy absorption above that absorbed at the temperature at which 100% shear occurs. The LT data suggest the possible observation of an intermediate-shelf (from 50 to 100°C), but additional data would be needed to establish a statistically meaningful observation in that regard. Figure 38 shows that 100% shear ($P = 0$) occurred at 50°C and an energy of 200 J. At higher test temperatures, the material absorbed around 250 J.

Similar data plots for heat P2 are shown in Figs. 40 to 42. The results for the transition range are quite similar for the TL and LT orientations, but the onset of upper shelf occurs at about 20°C for the TL specimens and at about 0°C for LT specimens. For both orientations, it is easy to visualize an intermediate shelf that occurs just after the onset of 100% shear fracture. In the case of the TL specimens this intermediate-shelf energy is about 200 J (147 ft-lb) and extends from 20 to about 175°C. The P2 material exhibits a high upper-shelf energy of about 270 J (200 ft-lb) in the higher temperature range.

A comparison of Figs. 39 and 42 shows that P2 exhibits greater energy aborbing capacity at the NDT than does P1. In fact, the energy and

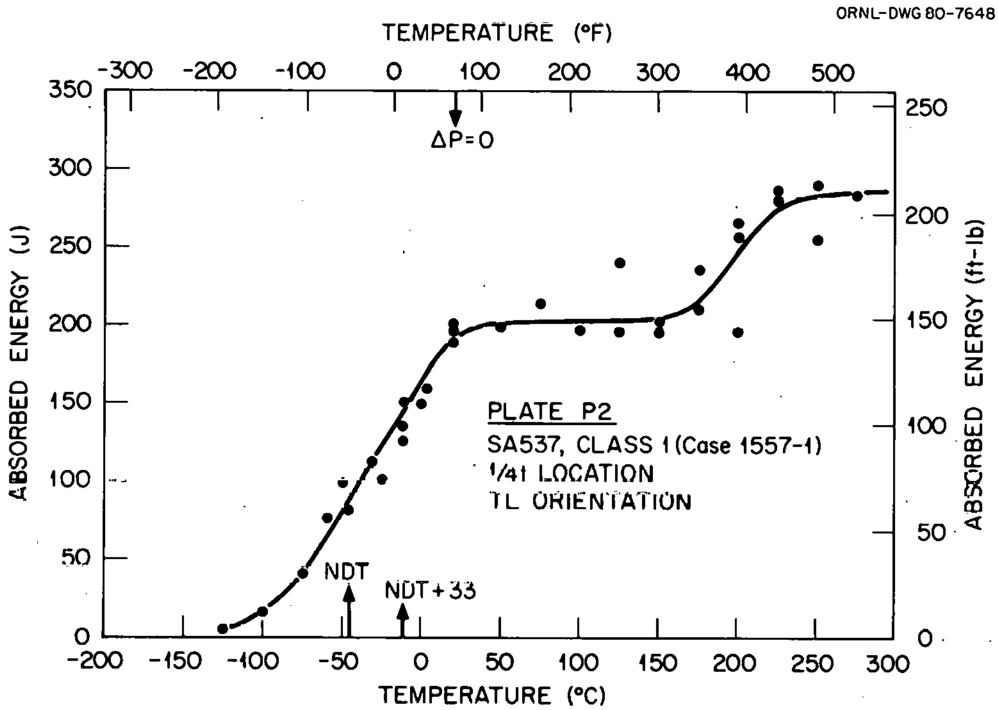

Fig. 40. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P2) Plate, Transverse Orientation.

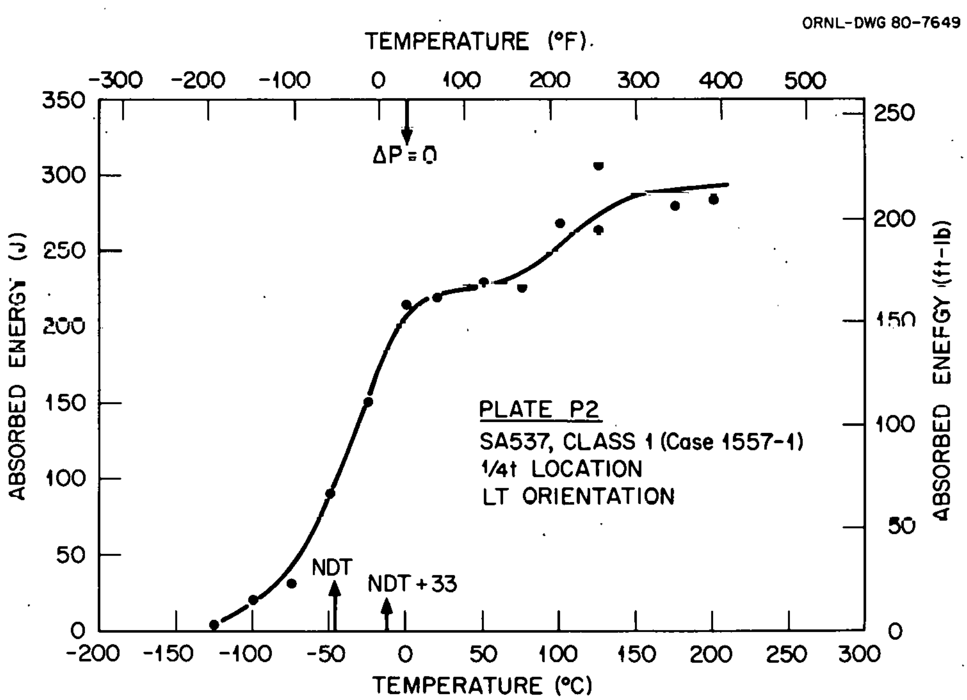

Fig. 41. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P2) Plate, Longitudinal Orientation.

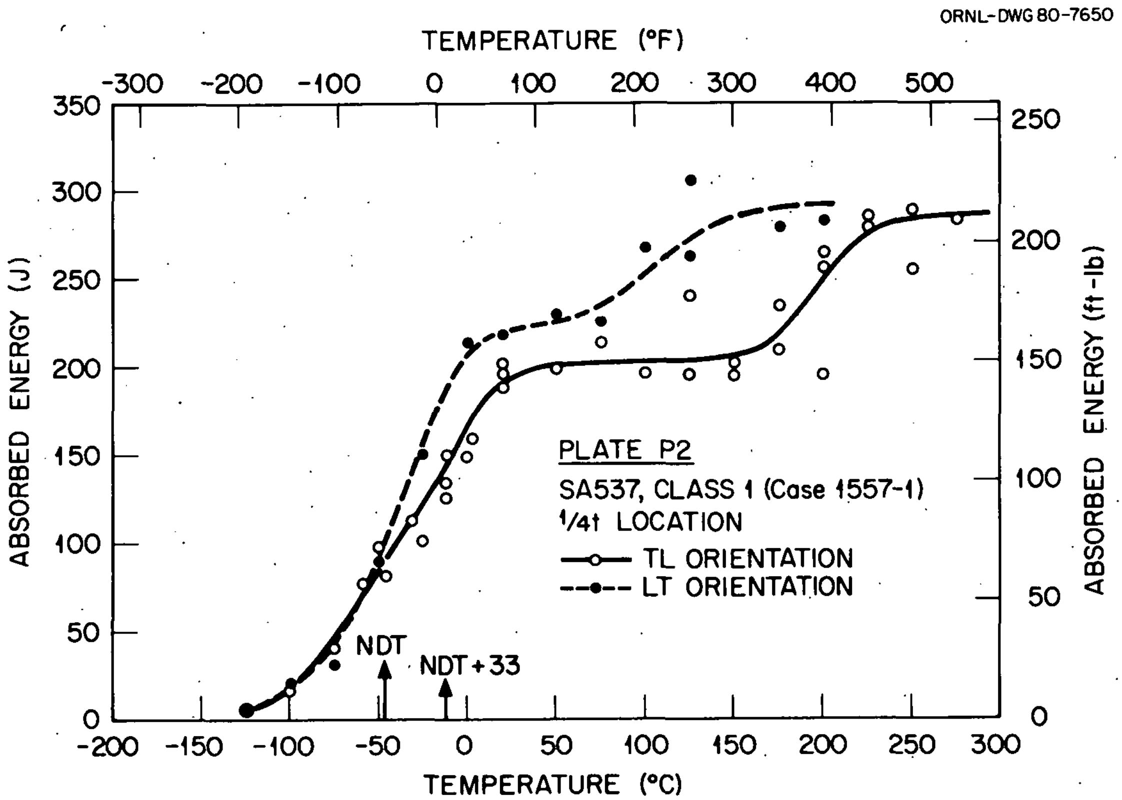

Fig. 42. Charpy Impact Energy vs Temperature for SA-537 Class 1 (P2) Plate, Comparison of Transverse and Longitudinal Orientations.

lateral expansion requirements at RT_{NDT} + 33°C are met at the NDT by P2. At NDT + 33°C, both P1 and P2 exceed the minimum requirements of 68 J energy and 0.89 mm lateral expansion. Heat P2 fared better at that reference temperature, with 142 J compared to 91 J for P1 (average of two tests in each case). It should be noted again that P1 is much thicker than P2 (89 and 51 mm respectively) and P2 was fabricated with an electroslag remelting procedure. Figure 43 provides a direct comparison of Charpy impact behavior of P1 and P2 for the TL orientation. The transition region of P2 occurs about 25°C lower than that for P1. Additionally, the onset of upper-shelf behavior (100% shear) occurs at about 20°C for P2 and about 50°C for P1, while the upper-shelf energy level of P2 is substantially higher than that for P1 (about 270 vs 170 J, respectively). These three observations support a conclusion that heat P2 has somewhat better impact properties than P1, irrespective of thickness considerations.

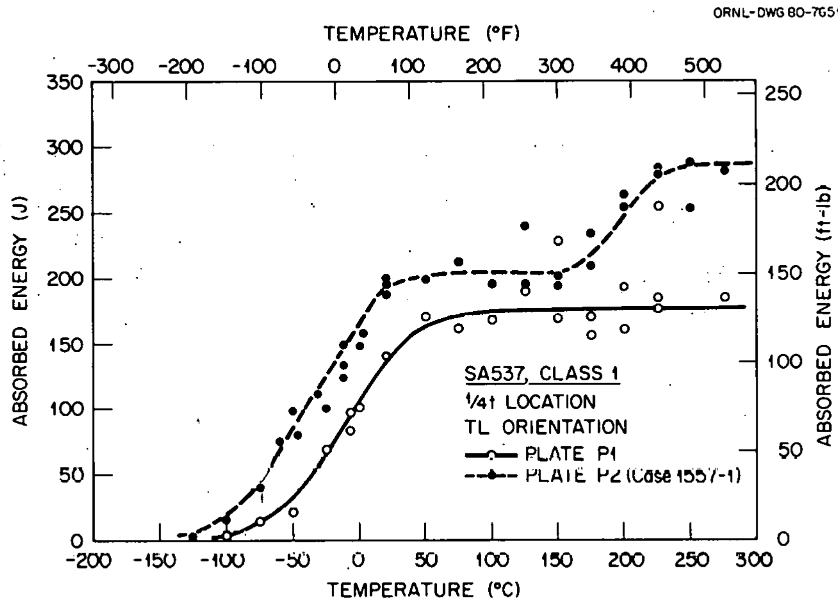

Fig. 43. Charpy Impact Energy vs Temperature for SA-537 Class 1 Plate, Comparison of Plates P1 and P2.

4.3.3 SA-537 Class 2 (P4)

Figures 44 and 45 show the results of Charpy impact testing of plate P4 in the TL and LT orientations, respectively. The detailed data are given in Tables C-7 and C-8 of Appendix C. The curves show the high degree of impact toughness sustained by this alloy. Both the TL and LT specimens exhibit an upper-shelf energy of over 310 J (over 230 ft-lb). All the specimens tested at temperatures of 150°C (302°F) and above did not break during impact. The absorbed energy for one specimen at the NDT is 140 J (105 ft-lb), a very high value for a steel to absorb at its measured NDT. In two tests (average) at NDT + 33°C, the material absorbed about 168 J (123 ft-lb). At only 25°C above the NDT (—25°C) the material experienced 100% shear fracture (ΔP = 0) and absorbed 237 J (175 ft-lb); thus the scatter in results can be substantial in the transition region. As with the normalized steel P2, this steel (P4) also appears to show an intermediate-shelf behavior in the TL orientation, although additional testing may result in enough scatter to smear that observation. The LT specimens also exhibit scatter in the transition region, and the intermediate-shelf behavior is not pronounced.

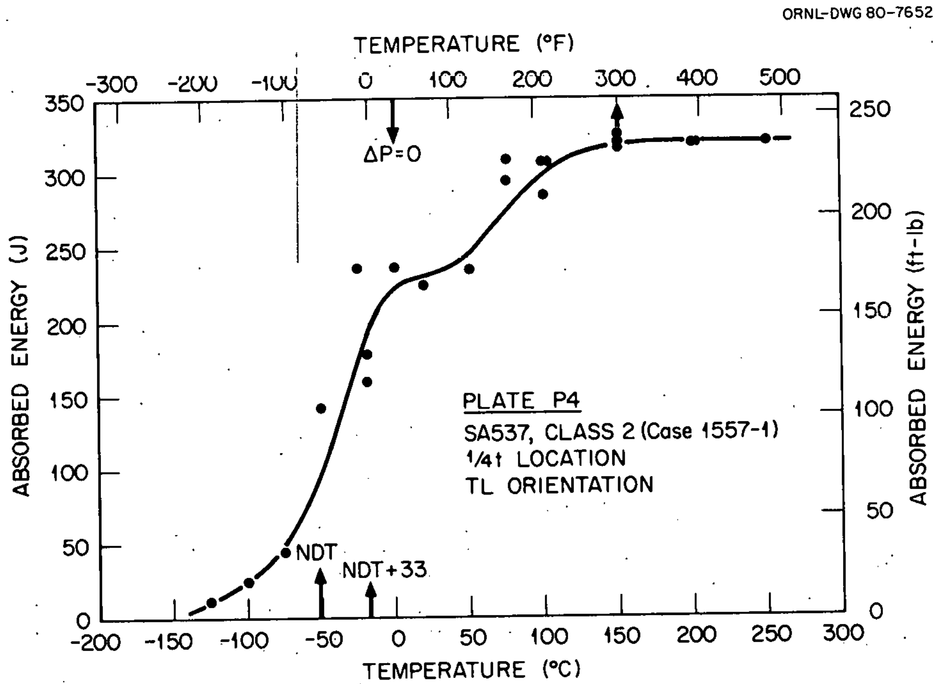

Fig. 44. Charpy Impact Energy vs Temperature for SA-537 Class 2 (P4) Plate, Transverse Orientation.

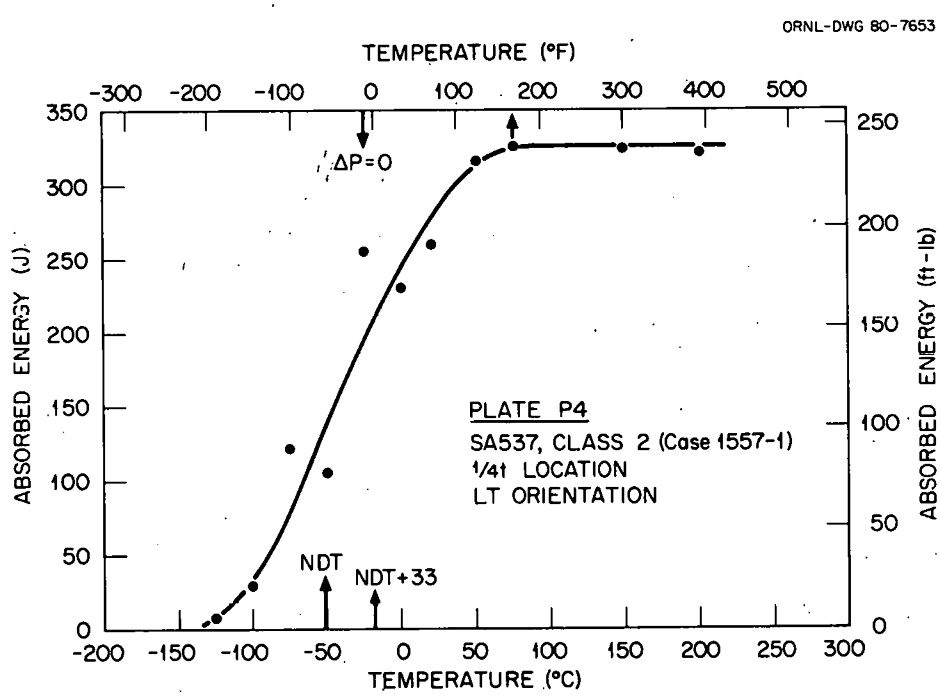

Fig. 45. Charpy Impact Energy vs Temperature for SA-537 Class 2 (P4) Plate, Longitudinal Orientation.

Figure 46, which provides a comparison of the TL and LT test results, shows no substantial difference in behavior relative to orientation. The high energy values at low temperatures obtained in this study are comparable to those given in the mill test reports (see Appendix A) for postweld heat treated material.

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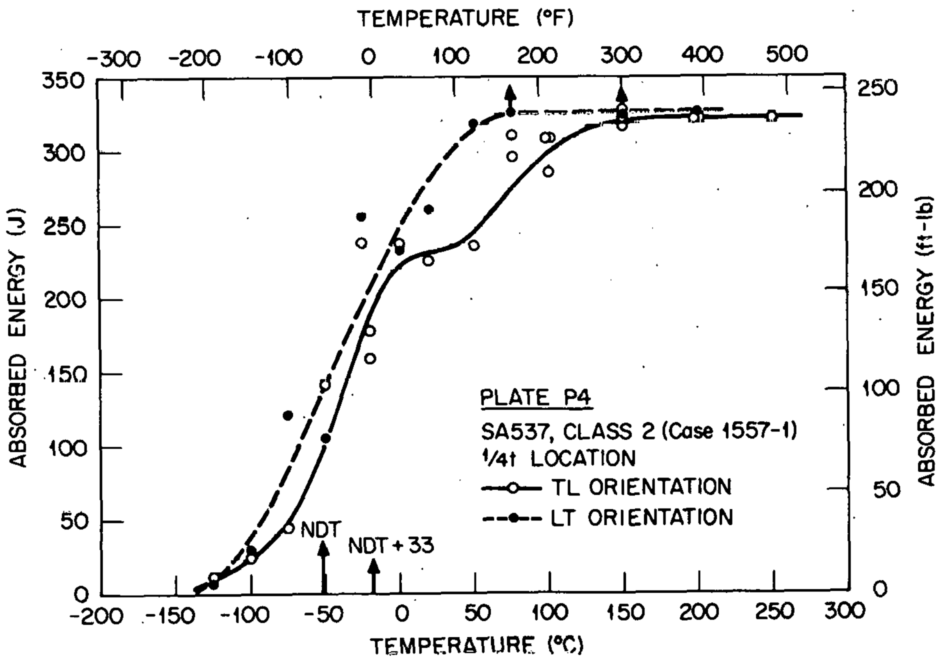

Fig. 46. Charpy Impact Energy vs Temperature for SA-537 Class 2 (P4) Plate, Comparison of Transverse and Longitudinal Orientations.

4.3.4 Summary of Charpy Impact Results

The results of Charpy impact tests with the steels used in this study have shown a fairly wide range of behavior with regard to impact toughness. Figure 47 provides a comparison of this behavior. Upper-shelf energies range from 170 J for P1 to 310 J for P4. The onsets of upper shelf range from 0°C for P4 to 50°C for P1. Of the three SA-537 plate materials, the quenched and tempered P4 exhibits superior Charpy impact toughness. The SA-508 class 1 forging (F1) shows high toughness also, especially considering its large section size [140 mm (5 1/2 in.) thick].

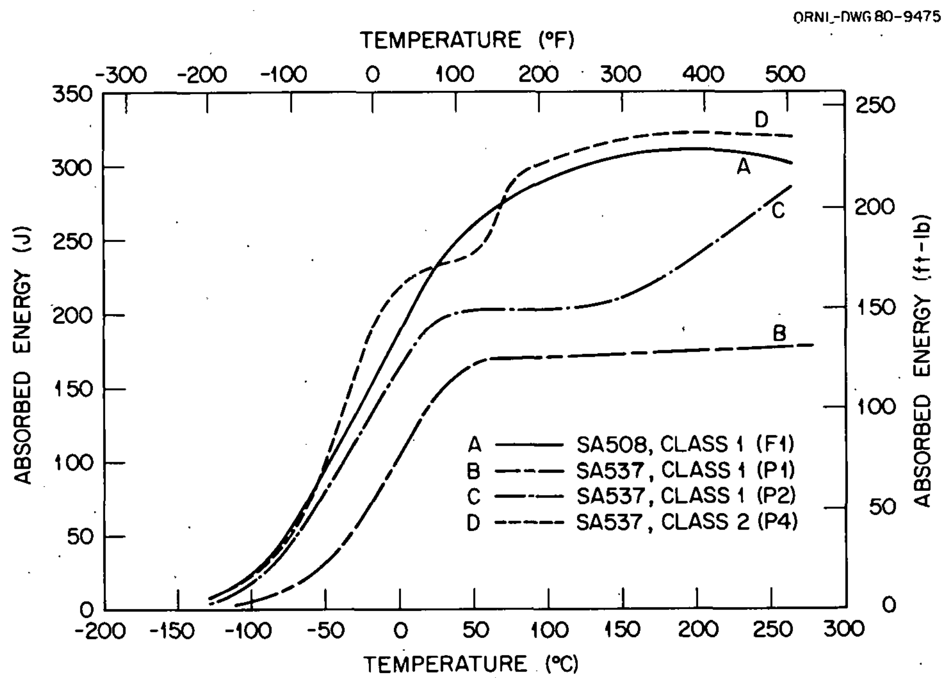

Fig. 47. Comparison of Charpy Impact Energy vs Temperature for Four PCRV Liner Steels, Transverse Orientation.

Regarding toughness relative to the NDT, Figure 48 shows a comparison of Charpy impact energy curves for all four steels plotted on a normalized temperature scale. The curves are plotted relative to the RT_{NDT} (= NDT in all cases) of each particular steel. This method provides a means of direct comparison of impact behavior relative to NDT when materials have different NDT values. The graph shows that impact energies at the NDT (where $T - RT_{NDT} = 0$) range from 40 J (30 ft-lb) for P1 to 100 J (74 ft-lb) for P4. All four steels exhibited greater than 68 J (50 ft-lb) energy and 0.89 mm (0.035 in.) lateral expansion at NDT + 33°C (60°F). Energies at NDT + 33°C range from 90 J (67 ft-lb) for P1 to 168 J (123 ft-lb) for P4. A curve is also shown for SA-533, grade B, class 1 (HSST Plate 02).[11,12] The plate referenced here is 305 mm (12 in.) thick and has been used as a reference heat for various material properties studies of LWR pressure vessel steels. This SA-533 steel shows about 40 J (30 ft-lb) absorbed energy at the NDT and 78 J (58 ft-lb) at NDT + 33°C. These values are similar to those observed for heat P1 of this study. Above NDT +33°C, however, the SA-533 steel shows an upper-shelf energy of about 143 J compared to about 172 J for heat P1. The reference fracture toughness (K_{IR})

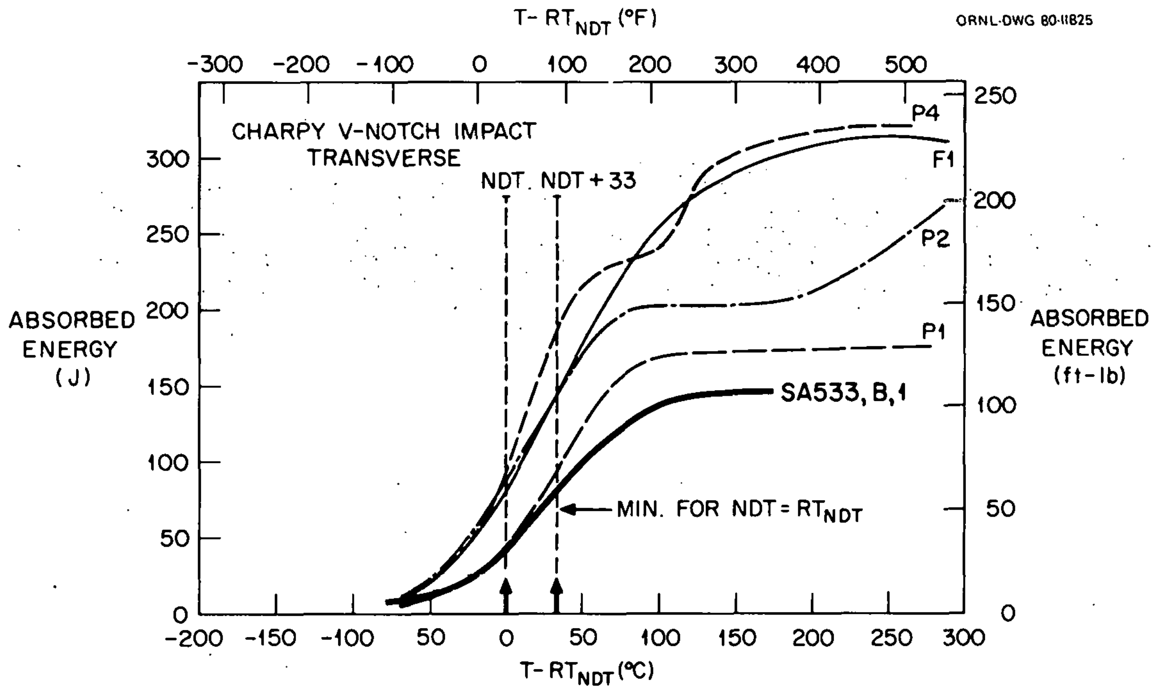

Fig. 48. Comparison of Charpy Impact Energy vs Temperature Normalized to RT_{NDT} for PCRV Liner Steels and SA-533, Grade B, Class 1 Steel (HSST Plate 02).

curve of the ASME code discussed in the introduction of this report was developed in part with thick-section SA-533, grade B, class 1 steel.[3] Thus, the four PCRV liner steels tested in this program exhibit impact toughness equal to or superior to that of a representative LWR pressure vessel (irrespective of thickness).

5. SUMMARY AND CONCLUSIONS

Pursuant to a program of fracture toughness testing, material characterization tests were performed with four carbon steels used for liner and penetration components in the PCRV of the GA-designed HTGR. The steels tested [SA-508 Class 1 forging (designated herein as F1), two plates of SA-537 class 1 (P1 and P2), and one plate of SA-537 class 2 (P4)] had thicknesses of 140, 89, 51, and 64 mm (5.5, 3.5, 2, and 2.5 in.), respectively. All materials were examined for chemical composition, hardness, and microstructure. Mechanical property testing was performed to determine tensile properties, drop-weight NDT, and Charpy V-notch impact behavior. This evaluation included the determination of the RT_{NDT}. For the RT_{NDT} to equal the NDT, the current requirement is that a minimum of 68 J (50 ft-lb) energy and 0.89 mm (0.035 in.) lateral expansion be attained in Charpy V-notch impact tests at NDT + 33°C (60°F). The Charpy V-notch testing will be used in conjunction with subsequent precracked specimen fracture toughness testing to evaluate the behavior of PCRV liner steels relative to the reference fracture toughness curve (K_{IR}) of the ASME code.

Chemical analyses verified that all four steels meet the requirements of the appropriate specification. Hardness values (~78–87 R_B) and grain sizes (ASTM No. 5–8) are within expected ranges. Both P1 and P2 show obvious evidence of banding, while P4 shows little.

Drop-weight tests were performed to determine the NDT for each of the four steels. The NDT values were –57°C (–70°F) for F1, –51°C (–60°F) for P4, –46°C (–50°F) for P2, and –40°C (–40°F) for P1. Forging F1 exhibits the lowest NDT of the four steels even though it has the thickest cross section. The quenched and tempered plate P4 has a lower NDT than the two normalized plates, P1 and P2. Plate P2 was fabricated by electroslag remelting and exhibits an NDT that is 6°C (10°F) lower than that of P1; however, that difference could be a reflection of the difference in plate thicknesses, 51 mm (2 in.) for P2 compared to 89 mm (3.5 in.) for P1.

Tensile tests were performed over a wide temperature range for strength and ductility determinations. Room temperature yield strengths (0.2% offset) were 342 MPa (49.5 ksi) for F1, 353 MPa (51.3 ksi) for P1, 378 MPa (54.9 ksi) for P2, and 404 MPa (58.6 ksi) for P4. All materials except P4 meet the minimum requirements for tensile properties in the current appropriate ASME specifications. The 0.2% offset yeild strength of P4 [404 MPa (58.6 ksi)] is below the required value of 413 MPa (60 ksi). The 1971 ASME code (1973 Summer Addenda), specification SA-370, allowed for an interpretation that the "upper yield strength" could be used to satisfy the yield strength requirement. Using that interpretation the yield strength of P4 is 457 MPa (66.4 ksi), which is well above the 413 MPa requirement. The latter value agrees well with the mill test report, but the method used to analyze for yield strength in that report is not known. Ultimate strength and elongation requirements were met by all steels.

Charpy V-notch impact testing was performed over a wide temperature range to examine impact behavior from brittle to ductile behavior. Upper-shelf energies ranged from 170 J for P1 to 310 J for P4. Impact energies at the NDT + 33°C (60°F) ranged from 90 J for P1 to 168 J for P4, and the lateral expansions exceeded 0.89 mm (0.35 in.) for all steels at that temperature. Thus, according to the current indexing procedure for determining the RT_{NDT}, all four steels have RT_{NDT} values equal to the NDT. The onset of upper-shelf energy (attainment of 100% shear fracture) occurred at temperatures ranging from 0°C for P4 to 50°C for P1.

The following conclusions can be drawn as a result of characterization testing with the four liner and penetration steels.

1. Chemical compositions are in conformance with applicable specifications.

2. Tensile requirements in effect at the time of procurement are met by all steels. By current analysis procedures, the SA-537 class 2 plate (P4) would not meet the minimum requirement for yield strength.

3. The RT_{NDT} is equal to the NDT for each material.

4. At the NDT, all steels except one heat of SA-537 class 1 (P1) exceed 68 J (50 ft-lb) of absorbed energy in a Charpy impact test.

5. For the SA-508 class 1 forging (F1), impact toughness behavior with specimens from the 19 × 38 mm (3/4 × 1.5 in.) location was not substantially different from that of specimens removed from the 1/4 t × t location in the ring forging.

7. ACKNOWLEDGMENTS

The author wishes to thank Wanda (Butcher) Cooke, Julia Bishop, and Darlene Keck for their patience in preparing and revising the draft manuscript. Harry Livesey is acknowledged and thanked for drafting the drawings. Thanks also go to Myrtleen Sheldon for editing this report and to Kathryn A. Witherspoon for preparation of the final manuscript. Rey Berggren and Grover Robinson reviewed the draft report and their helpful suggestions are appreciated. Ron Swain and Tollie N. Jones performed the testing for this program and are commended for their experimental expertise and attention to detail. Special thanks are expressed to Domenic Canonico for his guidance, helpful discussions, and suggestions during testing and report preparation.

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APPENDIX A

Material Source and Fabrication

PAGES 53 to 54

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A.1 General

The following summary information was gleaned from mill test reports provided by the fabricators listed for each heat of material. It is provided here to serve as additional background information on the materials investigated in this report and is not a complete reporting of the data in the mill tests reports.

A.2 SA-508 Class 1 (F1)

A.2.1 Specification and Source (See Figure A-1)

SA-508 class 1/Case 1332-6
Japan Steel Works Heat No. 49C510-1-1-3
Ring Rolled Forging 6 3/4 in. × 5 1/2 in. thick

A.2.2 Heat Treatment

Heated to 1560–1650°F; held for 8 h, 7 min; water quenched
Tempered at 1150–1190°F; held for 8 h, 20 min; air cooled
Mill test coupons given simulated post-weld heat treatment (PWHT) at 1100–1130°F, held for 18 h, furnace cooled

Note: Forging F1 given a similar simulated PWHT at ORNL

A.2.3 Mechanical Properties

Drop-weight NDT: –70°F, P3 specimen
RT_{NDT}: –70°F
Tensile properties (1/2 in. diam × 2 in. gage length, room temperature)

- Yield strength (0.2% offset): 49,800 psi
- Ultimate tensile strength: 73,600 psi
- Elongation: 37.7%
- Reduction in area: 76.9%

Charpy V-notch impact (at NDT + 60°F = –10°F):

Absorbed Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
91.3	64	60
186.1	93	100
119.9	89	70

A.3 SA 537 Class 1 (P1)

A.3.1 Specification and Source (See Figure A-2)

SA-537 Class 1

Armco Steel Corporation Heat No. 47239

Rolled plate, 3 1/2 in. thick

A.3.2 Heat Treatment

Heated to 1650°F, held for 70 min, air cooled

After forming, plate given SPWHT at 1050–1150°F, held for 15 h, furnace cooled

A.3.3 Mechanical Properties

Drop-weight NDT: –20°F or below (no break at –10°F), P3 specimen

RT_{NDT}: Not determined

Tensile properties:

Yield strength: 51,100 psi

Ultimate tensile strength: 82,900 psi

Elongation: 26.0%

Reduction in area: Not reported

Charpy V-notch impact (at 40°F):

Absorbed Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
80	80	70
80	81	75
80	97	80

A.4 SA-537 Class 1 (P2)

A.4.1 Specification and Source (See Figure A-3)

SA-537 Class 1/Case 1557-1 (electroslag remelt)

Lukens Steel Company Heat No. R0273

Rolled plate, 2 in. thick

A.4.2 Heat Treatment

Heated to 1625–1675°F, held for 4 h, air cooled

After forming, plate given SPWHT at 1050–1150°F, held for 15 h, furnace cooled

A.4.3 Mechanical Properties

Drop-weight NDT: –30°F or below (no break at –20°F), P2 specimen

RT_{NDT}: Not determined

Tensile properties

- Yield strength: 63,100 psi
- Ultimate tensile strength: 87,500 psi
- Elongation: 30%
- Reduction in area: Not reported

Charpy V-notch impact (at 30°F):

Absorbed Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
162	94	99
164	96	99
163	94	99

A.5 SA-537 Class 2 (P4)

A.5.1 Specification and Source (See Figure A-4)

SA-537 class 2/Case 1557-1 (electroslag remelt)

Lukens Steel Company Heat No. R0907

Rolled plate, 2 1/2 in. thick

A.5.2 Heat Treatment

Heated to 1625–1675°F, held for 5 h, water quenched

Tempered at 1160°F, held for 5 h, water quenched

Set 2 test coupons stress relieved at 1050–1100°F, held 15 h, furnace cooled

After forming, plate given SPWHT at 1050–1150°F, held for 15, furnace cooled

A.5.3 Mechanical Properties

Drop-weight NDT: –30°F or below (no break at –20°F), P2 specimen

RT_{NDT}: Not determined

Tensile properties (set 1):

Yield strength: 75,400 and 69,000 psi

Ultimate tensile strength: 95,000 and 90,500 psi

Elongation: 24 and 26%

Reduction in area: Not reported

Charpy V-notch impact (at 30°F):

Absorbed Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
199	94	99
210	92	99
211	96	99

Tensile properties (set 2):

Yield strength: 73,300 and 65,200 psi

Ultimate tensile strength: 92,500 and 87,900 psi

Elongation: 27 and 29%

Reduction in area: Not reported

Charpy V-notch impact (at 30°F):

Absorbed Energy (ft-lb)	Lateral Expansion (mils	Shear Fracture (%)
196	94	99
205	98	99
184	96	99

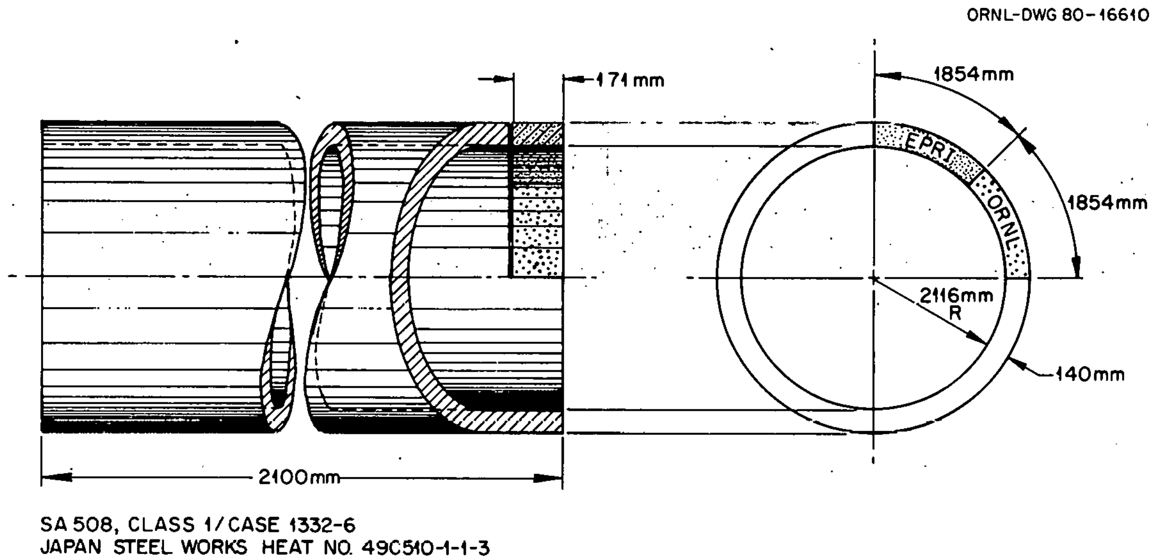

Fig. A-1. Location of Test Pieces Cut from Ring-Rolled Forging F1.

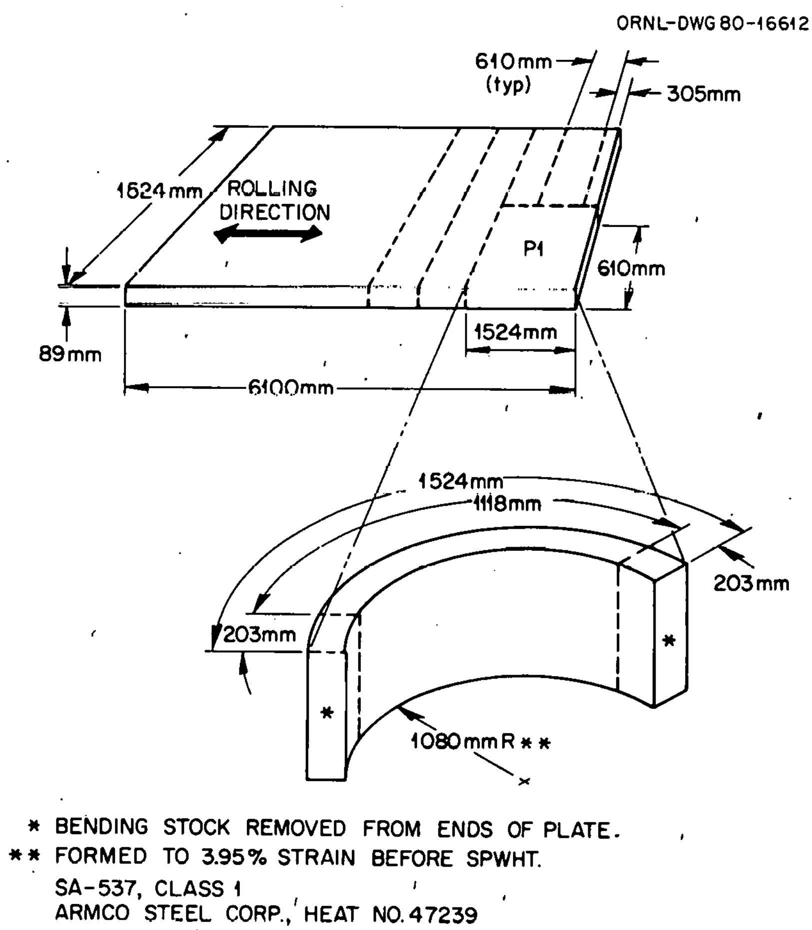

Fig. A-2. Location of Test Plate P1 Removed from Parent Plate.

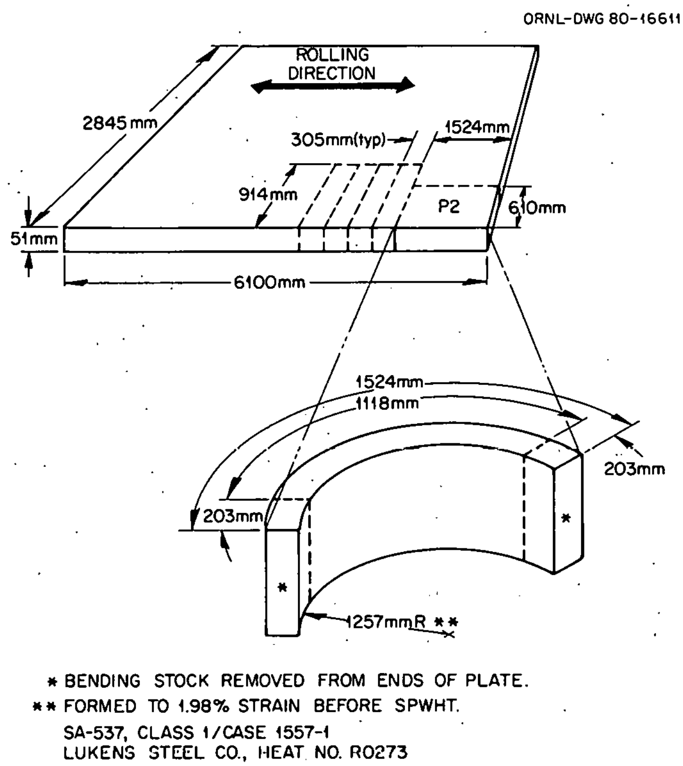

Fig. A-3. Location of Test Plate P2 Removed from Parent Plate.

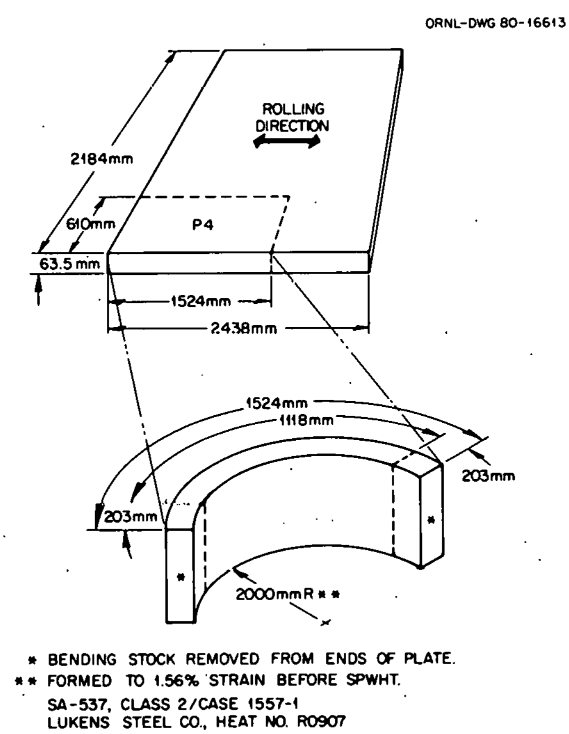

Fig. A-4. Location of Test Plate P4 Removed from Parent Plate.

APPENDIX B

Tables of Tensile Test Results

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Table B-1. Tensile Test Results, A-508 Class 1 (F1), Transverse Orientation

Specimen	Depth Location	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
		(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture	Uniform	Total		
									L/D = 7	L/D = 4	
04Q4F1	1/4 *t* × *t*	−196	−320	878 (127.8)	808 (117.3)	879 (127.6)	1482 (215.1)	17.7	28.7	37.0	51.0
02Q4F1	1/4 *t* × *t*	−150	−238	721 (104.6)	624 (90.5)	748 (108.6)	1422 (206.4)	20.6	33.7	43.5	62.2
02Q7F1	1/4 *t* × *t*	−129	−200	612 (88.8)	517 (75.0)	661 (95.9)	1429 (207.4)	19.9	33.7	44.1	71.3
04Q2F1	1/4 *t* × *t*	−73	−100	472 (68.5)	412 (59.8)	585 (84.9)	1261 (183.0)	20.0	34.8	45.9	71.1
02Q2F1	1/4 *t* × *t*	−18	0	395 (57.3)	366 (53.1)	529 (76.8)	1315 (190.9)	18.8	31.6	41.2	75.4
02Q6F1	1/4 *t* × *t*	21	70	350 (50.7)	342 (49.5)	499 (72.3)	1303 (189.0)	17.4	30.3	40.0	78.1
04Q7F1	1/4 *t* × *t*	93	200	356 (51.7)	319 (46.3)	456 (66.2)	694 (100.7)	16.8	26.9	34.5	77.3
02Q3F1	1/4 *t* × *t*	200	392	296 (42.9)	285 (41.3)	444 (64.4)	1105 (160.4)	15.4	24.6	31.5	75.9
04Q3F1	1/4 *t* × *t*	250	482	279 (40.5)	274 (39.7)	468 (67.9)	1050 (152.6)	15.2	23.5	29.7	71.1
04Q6F1	1/4 *t* × *t*	50	122	342 (49.5)	326 (47.3)	483 (70.1)	1196 (173.5)	17.7	29.3	38.0	75.4
03Q1F1	3/4 × 1 1/2 in.	−129	−200	614 (89.1)	528 (76.6)	667 (96.8)	1451 (210.6)	15.1	26.9	35.8	71.1
01Q8F1	3/4 × 1 1/2 in.	−73	−100	503 (73.0)	434 (63.0)	616 (89.4)	1450 (210.4)	16.3	28.8	38.2	74.1
01Q1F1	3/4 × 1 1/2 in.	−18	0	422 (61.2)	383 (55.6)	545 (79.1)	1297 (188.2)	17.2	28.5	37.0	74.9
03Q8F1	3/4 × 1 1/2 in.	93	200	378 (54.9)	346 (50.2)	478 (69.4)	716 (103.9)	12.5	22.0	29.1	62.0

Table B-2. Tensile Test Results, A-508 Class 1 (F1), Longitudinal Orientation

Specimen	Depth Location	Test Temperature (°C)	Test Temperature (°F)	Stress, MPa (ksi) Upper Yield	Stress, MPa (ksi) Lower Yield	Stress, MPa (ksi) Ultimate	Stress, MPa (ksi) True Fracture	Elongation, % Uniform	Elongation, % Total L/D = 7	Elongation, % Total L/D = 4	Reduction of Area (%)
12D2F1	1/4 $t \times t$	−59	−75	405 (58.8)	396 (57.5)	571 (82.9)	1309 (190.0)	17.7	28.6	36.8	74.0
11D2F1	1/4 $t \times t$	−18	0	423 (61.4)	361 (52.4)	532 (77.2)	1179 (171.1)	17.6	28.4	36.5	73.9
10D2F1	1/4 $t \times t$	20	68	352 (51.1)	345 (50.1)	492 (71.4)	1539 (223.4)	17.6	29.0	37.6	81.8
10D7F1	1/4 $t \times t$	66	150	367 (53.3)	330 (47.9)	470 (68.2)	1121 (162.7)	16.8	27.5	35.5	76.5
11D7F1	1/4 $t \times t$	121	250	347 (50.4)	318 (46.2)	451 (65.5)	1118 (162.3)	14.8	24.3	31.4	77.0
12D7F1	1/4 $t \times t$	149	300	336 (48.8)	303 (44.0)	445 (64.6)	1123 (163.0)	15.2	24.1	30.8	77.0
03D8F1	3/4 × 1 1/2 in.	−60	−76	486 (70.5)	430 (62.4)	611 (88.7)	1370 (198.6)	15.7	27.1	35.8	73.8
02D7F1	3/4 × 1 1/2 in.	−20	−4	440 (63.8)	403 (58.5)	570 (82.7)	1391 (201.8)	14.8	25.6	33.7	76.9
03B8F1	3/4 × 1 1/2 in.	21	70	336 (53.1)	361 (52.4)	512 (74.3)	1344 (195.1)	14.9	25.4	33.3	78.9
02D2F1	3/4 × 1 1/2 in.	65	149	374 (54.3)	374 (54.3)	494 (71.6)	1273 (184.7)	14.4	24.6	32.2	78.4
03D1F1	3/4 × 1 1/2 in.	150	302	347 (50.4)	329 (47.8)	475 (68.9)	1244 (180.4)	14.8	24.1	31.1	77.6

Table B-3. Tensile Test Results, A-537 Class 1 (P1), Transverse Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
	(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture	Uniform	Total *L/D* = 7	Total *L/D* = 4	
01B52P1	−196	−320	855 (124.1)	801 (116.2)	918 (133.2)	1467 (212.9)	15.6	21.8	26.5	44.1
04B51P1	−150	−238	716 (103.9)	651 (94.5)	811 (117.7)	1525 (221.4)	20.0	30.3	38.0	61.4
04B42P1	−125	−193	539 (78.2)	522 (75.7)	716 (103.9)	1370 (198.8)	18.1	28.3	36.0	65.5
03B42P1	−100	−148	532 (77.2)	457 (66.4)	681 (98.9)	1323 (192.0)	18.0	29.8	38.7	64.9
02B42P1	−50	−58	418 (60.6)	389 (56.5)	615 (89.3)	1266 (183.8)	16.4	26.8	34.6	68.9
01B42P1	−25	−13	422 (61.2)	367 (53.3)	593 (86.1)	1269 (184.2)	16.1	25.4	32.4	69.6
04B41P1	0	32	407 (59.1)	366 (53.1)	582 (84.4)	1234 (179.1)	17.5	28.5	37.1	69.7
03B41P1	20	68	362 (52.5)	353 (51.3)	551 (79.9)	1197 (173.7)	14.7	24.7	32.2	71.5
02B41P1	50	122	389 (56.5)	342 (49.7)	528 (76.7)	1152 (167.2)	14.6	23.6	30.4	71.0
01B41P1	100	212	372 (54.0)	338 (49.0)	515 (74.7)	1169 (169.6)	13.0	21.6	28.1	72.1
01B51P1	150	302	325 (47.1)	307 (44.6)	501 (72.7)	1045 (151.6)	13.0	21.1	27.2	67.6
02B52P1	200	392	289 (42.0)	279 (40.5)	502 (72.8)	1109 (161.0)	13.6	21.0	26.6	67.8
03B51P1	250	482	282 (41.0)	270 (39.2)	528 (76.6)	1021 (148.2)	12.5	19.5	24.8	62.1

Table B-4. Tensile Test Results, A-537 Class 1 (P1), Longitudinal Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
							Uniform	Total		
	(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture		*L/D* = 7	*L/D* = 4	
16B62P1	−196	−320	861 (125.0)	821 (119.1)	1007 (146.2)	1505 (218.4)	16.0	23.2	28.6	46.4
15B62P1	−150	−238	682 (99.0)	626 (90.9)	807 (117.2)	1545 (224.2)	18.3	30.3	39.3	63.0
16B61P1	−125	−193	558 (81.0)	500 (72.5)	694 (100.7)	1376 (199.7)	17.3	28.4	36.7	66.5
15B61P1	−50	−58	434 (63.0)	407 (59.1)	643 (93.3)	1338 (194.2)	17.5	28.1	36.0	69.3
14B61P1	20	68	373 (54.1)	351 (51.0)	562 (81.5)	1142 (165.8)	15.7	26.6	34.8	69.6
13B61P1	100	212	369 (53.6)	320 (46.5)	513 (74.5)	1208 (175.3)	14.3	23.4	30.2	73.5
13B62P1	150	302	320 (46.4)	292 (42.4)	488 (70.9)	1069 (155.2)	14.6	23.0	29.3	70.2
14B62P1	200	392	283 (41.1)	269 (39.0)	496 (72.0)	1081 (156.9)	13.5	21.3	27.1	68.2

Table B-5. Tensile Test Results, A-537 Class 1 (P2), Transverse Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
							Uniform	Total		
	(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture		*L*/*D* = 7	*L*/*D* = 4	
01B52P2	−196	−320	938 (136.1)	860 (124.8)	966 (140.2)	1614 (234.2)	15.2	22.7	28.3	52.0
04B51P2	−150	−238	737 (107.0)	658 (95.5)	836 (121.4)	1509 (219.0)	17.5	26.8	33.8	58.7
04B42P2	−125	−193	648 (94.1)	542 (78.6)	741 (107.5)	1447 (210.0)	17.1	29.0	37.9	65.6
03B42P2	−100	−148	587 (85.2)	489 (71.0)	699 (101.5)	1448 (210.1)	17.3	28.4	36.7	68.1
02B42P2	−50	−58	472 (68.5)	422 (61.3)	619 (89.9)	1361 (197.5)	15.9	25.8	33.2	71.0
01B42P2	−25	−13	469 (68.1)	409 (59.3)	609 (88.4)	1344 (195.0)	14.8	24.1	31.1	71.6
04B41P2	0	32	453 (65.8)	392 (56.9)	588 (85.3)	1362 (197.7)	14.7	24.5	31.9	73.3
03B41P2	20	68	443 (64.3)	378 (54.9)	554 (80.4)	1297 (188.3)	15.3	25.7	33.5	73.9
02B41P2	50	122	398 (57.7)	374 (54.3)	543 (78.8)	1264 (183.4)	13.9	24.9	33.2	73.9
01B41P2	100	212	385 (55.9)	365 (53.0)	521 (75.6)	1177 (170.8)	13.3	22.2	28.9	72.2
01B51P2	150	302	363 (52.7)	343 (49.8)	513 (74.5)	1184 (171.8)	12.1	20.4	26.6	71.1
C2B51P2	200	392	329 (47.8)	315 (45.7)	519 (75.3)	1123 (163.0)	12.7	20.6	26.5	68.4
C3B51P2	250	482	303 (44.0)	293 (42.5)	546 (79.2)	1744 (253.1)	13.5	20.3	25.4	75.9

Table B-6. Tensile Test Results, A-537 Class 1 (P2), Longitudinal Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
	(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture	Uniform	Total L/D = 7	Total L/D = 4	
16B62P2	−196	−320	916 (133.0)	842 (122.2)	952 (138.2)	1638 (237.8)	16.3	24.9	31.3	54.4
15B62P2	−150	−238	700 (101.6)	658 (95.5)	826 (119.9)	1585 (230.0)	19.0	30.8	39.6	64.1
16B61P2	−125	−193	615 (89.3)	520 (75.5)	730 (106.0)	1447 (210.0)	16.7	29.4	38.9	66.2
15B61P2	−50	−58	467 (67.8)	411 (59.7)	619 (89.9)	1365 (198.1)	15.1	25.1	32.6	71.6
14B61P2	20	68	420 (61.0)	366 (53.2)	552 (80.1)	1294 (187.8)	14.2	24.5	32.2	74.1
13B61P2	100	212	389 (56.4)	344 (49.9)	513 (74.4)	1182 (171.5)	13.9	23.3	30.3	73.1
13B62P2	150	302	333 (48.4)	323 (46.9)	515 (74.8)	1177 (170.8)	13.2	21.6	27.9	71.9
14B62P2	200	392	309 (44.3)	298 (43.3)	511 (74.2)	1132 (164.3)	12.7	20.0	25.5	68.7

Table B-7. Tensile Test Results, A-537 Class 2 (P4), Transverse Orientation, 1/4 *t* Depth

Specimen	Test Temperature (°C)	Test Temperature (°F)	Stress, MPa (ksi) Upper Yield	Stress, MPa (ksi) Lower Yield	Stress, MPa (ksi) Ultimate	Stress, MPa (ksi) True Fracture	Elongation, % Uniform	Elongation, % Total *L/D* = 7	Elongation, % Total *L/D* = 4	Reduction of Area (%)
01B52P4	−196	−320	976 (141.6)	885 (128.5)	977 (141.8)	1722 (249.9)	15.2	24.2	31.0	57.2
04B51P4	−150	−238	759 (110.2)	711 (103.2)	853 (123.8)	1636 (237.4)	14.6	27.1	36.5	64.9
04B42P4	−125	−193	665 (96.5)	560 (81.3)	754 (109.5)	1535 (222.8)	16.6	28.8	38.0	68.1
03B42P4	−100	−148	601 (87.3)	525 (76.2)	705 (102.3)	1483 (215.3)	13.5	24.4	32.6	70.1
02B42P4	−50	−58	498 (72.3)	442 (64.1)	629 (91.3)	1403 (203.7)	14.9	26.7	35.6	73.6
01B42P4	−25	−13	460 (66.7)	425 (61.7)	607 (88.1)	1405 (203.9)	14.4	26.2	35.1	74.1
04B41P4	0	32	470 (68.2)	414 (60.1)	593 (86.1)	1370 (198.9)	13.1	23.7	31.7	74.2
03B41P4	20	68	457 (66.4)	404 (58.6)	571 (82.9)	1308 (189.9)	13.0	23.6	31.6	75.0
02B41P4	50	122	433 (62.9)	400 (58.0)	556 (80.7)	1299 (188.6)	12.8	23.2	31.0	74.9
01B41P4	100	212	430 (62.4)	382 (55.5)	534 (77.5)	1323 (192.0)	11.7	21.1	28.2	76.7
01B51P4	150	302	380 (55.1)	371 (53.4)	532 (77.2)	1166 (169.3)	11.0	19.8	26.4	72.4
02B51P4	200	392	364 (52.8)	347 (50.3)	537 (77.9)	1237 (179.5)	11.4	20.1	26.6	73.5
03B51P4	250	482	345 (50.0)	333 (48.4)	562 (81.6)	1257 (182.5)	11.6	20.0	26.3	72.4

Table B-8. Tensile-Test Results, A-537 Class 2 (P4), Longitudinal Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Stress, MPa (ksi)				Elongation, %			Reduction of Area (%)
								Total		
	(°C)	(°F)	Upper Yield	Lower Yield	Ultimate	True Fracture	Uniform	L/D = 7	L/D = 4	
16B62P4	−196	−320	979 (142.1)	897 (130.2)	983 (142.7)	1730 (251.1)	14.0	22.6	29.1	56.1
15B62P4	−150	−238	775 (112.5)	718 (104.3)	850 (123.4)	1644 (238.6)	14.1	28.7	39.6	66.7
16B61P4	−125	−193	608 (88.3)	574 (83.3)	751 (109.0)	1718 (249.3)	14.6	25.8	34.2	72.8
15B61P4	−50	−58	502 (72.9)	445 (64.6)	641 (93.0)	1403 (203.7)	14.6	24.6	32.1	73.0
14B61P4	20	68	451 (65.4)	396 (57.5)	565 (82.2)	1186 (172.2)	12.2	24.0	32.8	73.4
13B61P4	100	212	403 (58.5)	378 (54.9)	532 (77.2)	1293 (187.7)	11.7	21.7	29.2	76.5
13B62P4	150	302	396 (57.5)	365 (53.0)	523 (76.7)	1155 (167.7)	10.4	19.1	25.6	72.9
14B62P4	200	392	367 (53.3)	340 (49.3)	533 (77.4)	1298 (188.4)	11.7	20.5	27.1	76.1

APPENDIX C

Tables of Charpy Impact Test Results

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Table C-1. Charpy Impact Test Results, A-508 Class 1 (F1), AC Orientation

Specimen	Depth Location	Test Temperature (°C)	Test Temperature (°F)	Dial Energy (J)	Dial Energy (ft-lb)	Drop in Load (ΔP) (%)	Lateral Expansion (mm)	Lateral Expansion (mils)	Fracture Appearance (% Shear)
12C2F1	1/4 $t \times t$	−101	−150	15	11	100	0.21	8.1	1
09C7F1	1/4 $t \times t$	−101	−150	12	9	100	0.13	5.0	1
06C7F1	1/4 $t \times t$	−73	−100	97	71	89	1.55	61.2	25
06C2F1	1/4 $t \times t$	−73	−100	51	37	97	0.74	29.3	10
03C6F1	0.3 $t \times t$	−23	−10	133	98	59	1.61	63.5	45
15C3F1	0.3 $t \times t$	−23	−10	109	80	58	1.47	58.0	25
03C2F1	1/4 $t \times t$	−18	0	165	122	43	1.84	72.3	60
03C7F1	1/4 $t \times t$	−18	0	175	129	42	1.89	74.6	60
09C2F1	1/4 $t \times t$	10	50	202	149	0	2.00	78.7	100
15C2F1	1/4 $t \times t$	20	68	246	181	0	1.38	54.5	100
12C7F1	1/4 $t \times t$	50	122	300	221	0	1.45	57.0	100
15C7F1	1/4 $t \times t$	75	167	262	193	0	1.35	53.0	100
06V1F1	1/4 $t \times t$	100	212	291	214	0	1.18	46.5	100
02N4F1	0.4 $t \times t$	125	257	274	202	0	1.35	53.3	100
09V1F1	1/4 $t \times t$	150	302	317	233	0	No break		100
04N3F1	0.3 $t \times t$	175	347	313	231	0	No break		100
02N6F1	0.3 $t \times t$	200	392	318	234	0	No break		100
04N6F1	0.3 $t \times t$	225	437	310	228	0	No break		100
06N6F1	0.3 $t \times t$	250	432	295	218	0	No break		100
13C1F1	3/4 × 1 1/4 in.	−129	−200	7.5	5.5	100	0.04	1.5	0
07C1F1	3/4 × 1 1/4 in.	−101	−150	39	28.5	100	0.52	20.5	5
01C8F1	3/4 × 1 1/4 in.	−101	−150	15	11	100	0.12	4.8	1
04C8F1	3/4 × 1 1/4 in.	−73	−100	70	52	94.5	1.10	43.4	25
04C1F1	3/4 × 1 1/4 in.	−73	−100	65	48	No trace	0.98	38.5	25
07C8F1	3/4 × 1 1/4 in.	−46	−50	144	106	55	1.88	74.2	40
01N1F1	3/4 × 1 1/4 in.	−23	−10	136	100	52	1.78	70.0	45
01N8F1	3/4 × 1 1/4 in.	−23	−10	206	151	0	1.29	50.7	100
01C1F1	3/4 × 1 1/4 in.	−18	0	201	148	0	2.18	85.9	100
10C1F1	3/4 × 1 1/4 in.	10	50	186	137	25	2.10	82.5	80
10C8F1	3/4 × 1 1/4 in.	38	100	240	177	0	1.90	74.8	100

Table C-2. Charpy Impact Test Results, A-508 Class 1 (F1), CA Orientation

Specimen	Depth Location	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
		(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
10B2F1	1/4 $t \times t$	–101	–150	8	6	100	0.07	2.6	0
10A7F1	1/4 $t \times t$	–101	–150	12	9	99	0.09	3.6	1
11A7F1	1/4 $t \times t$	–87	–125	25	18.5	100	0.32	12.6	5
11B2F1	1/4 $t \times t$	–87	–125	14	10.5	98	0.15	5.8	5
12A2F1	1/4 $t \times t$	–73	–100	120	88	85	1.71	67.4	25
10B7F1	1/4 $t \times t$	–73	–100	159	117	73	2.34	92.3	35
12A7F1	1/4 $t \times t$	–59	–75	259	190	0	2.10	82.5	100
12B2F1	1/4 $t \times t$	–59	–75	83	61	96	1.28	50.2	25
11A2F1	1/4 $t \times t$	–46	–50	317	233	No trace	1.51	59.5	100
11B7F1	1/4 $t \times t$	–46	–50	175	129	59	2.32	91.2	40
10A2F1	1/4 $t \times t$	–7	20	325	240+	0	No break		
12B7F1	1/4 $t \times t$	–7	20	325	240+	0	No break		
03A1F1	3/4 × 1 1/2 in.	–101	–150	13	9.5	No trace	0.09	3.7	1
02A2F1	3/4 × 1 1/2 in.	–101	–150	12	9	98	0.05	2.0	1
03B1F1	3/4 × 1 1/2 in.	–87	–125	130	95.5	82	1.91	75.2	25
03A8F1	3/4 × 1 1/2 in.	–73	–100	120	88	87	1.78	70	30
02B7F1	3/4 × 1 1/2 in.	–59	–75	130	96	80	1.87	73.8	30
02B2F1	3/4 × 1 1/2 in.	–46	–50	178	131	51	2.32	91.5	45

Table C-3. Charpy Impact Test Results, A-537 Class 1 (P1), TL Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
	(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
04B02P1	−100	−148	4.1	3	100	0.01	0.2	0
03B02P1	−75	−103	15.6	11.5	100	0.11	4.4	1
02B02P1	−50	−58	22.4	16.5	99	0.38	14.9	0
01B02P1	−25	−13	69.8	51.5	94	1.03	40.6	0
04C83P1	−7	20	98	72	62	1.29	50.7	0
05C83P1	−7	20	84	62	71	1.14	45.0	5
04B01P1	0	32	102	75	66	1.50	59.2	0
01B01P1	21	70	142	105	56	1.94	76.5	0
02B01P1	50	122	170	125	0	2.15	84.5	100
03B01P1	75	167	161	118	0	2.15	84.5	100
01B22P1	100	212	169	124	0	2.06	81.0	100
02B22P1	125	257	190	140	0	2.11	83.2	100
02B32P1	150	302	168	124	0	1.82	71.7	100
02B21P1	150	302	228	168	0	2.07	81.3	100
04B22P1	175	347	156	115	0	1.69	66.5	100
03B32P1	175	347	172	127	0	1.82	71.5	100
03B21P1	175	347	170	125	0	1.98	78.0	100
01C83P1	200	392	161	119	0	1.73	68.0	100
04B32P1	225	437	185	136	0	1.57	61.8	100
02C83P1	225	437	177	130	0	1.73	68.2	100
03B22P1	225	437	255	188	0	1.20	47.4	100
04B21P1	275	527	186	137	0	1.52	60.0	100

Table C-4. Charpy Impact Test Results, A-537 Class 1 (P1), LT Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
	(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
08B61P1	–100	–148	4.1	3	100	0.09	0.3	0
07B61P1	–75	–103	11.5	8.5	97	0.14	5.6	1
06B61P1	–50	–58	45	33	99	0.57	29.5	10
05B61P1	–25	–13	102	75.5	88	1.50	59.2	30
04B61P1	0	32	149	110	44	1.91	75.0	70
01B61P1	21	70	167	123	31	2.07	81.5	80
02B61P1	50	122	201	148	0	2.19	86.2	100
03B61P1	75	167	199	146	0	2.14	84.2	100
09B61P1	100	212	201	148	0	2.15	84.7	100
10B61P1	125	257	226	166	0	2.18	85.8	100
11B61P1	150	302	241	178	0	1.88	74.0	100
10B62P1	175	347	222	164	0	1.45	57.1	100
12B61P1	175	347	258	190	0	1.74	68.7	100
11B62P1	225	437	267	197	0	1.23	48.6	100
09B62P1	225	437	298	220	0	No break		
12B62P1	275	527	247	182	0	1.07	42.0	100

Table C-5. Charpy Impact Test Results, A-537 Class 1 (P2), TL Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
	(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
01B21P2	−125	−193	4.1	3	100	0.03	1.0	0
04B02P2	−100	−148	17	13	99	0.09	3.7	1
03B02P2	−75	−103	41	30.5	98	0.56	22.1	5
04A01P2	−59	−75	77	57	95	1.11	43.7	10
02B02P2	−50	−58	98	72	92	1.32	52.0	25
03A01P2	−46	−50	81	60	93	1.26	49.6	15
02A01P2	−32	−25	112	83	80	1.52	59.8	30
01B02P2	−25	−13	101	74.5	70	1.42	56.1	30
01A01P2	−12	10	125	92.5	59	1.61	63.5	40
01C81P2	−12	10	150	110	53	1.95	76.8	45
02C81P2	−12	10	134	98	50	1.80	70.7	40
04B01P2	0	32	148	109	42	1.93	76.0	70
05A01P2	4	40	159	117	40	1.98	78.0	65
01A11P2	20	68	197	145	No trace	2.17	85.5	100
03B22P2	20	68	188	138	0	2.02	79.5	100
01B01P2	20	68	200	147	0	2.24	88.2	100
02B01P2	50	122	199	147	0	2.14	84.4	100
03B01P2	75	167	213	157	0	2.15	84.5	100
02B21P2	100	212	197	145	0	2.03	80.0	100
03B21P2	125	257	241	178	0	1.87	73.5	100
01B31P2	125	257	195	143	0	1.92	75.5	100
05A11P2	150	302	195	143	0	1.83	72.0	100
02B31P2	150	302	202	149	0	1.78	70.0	100
01B32P2	175	347	235	173	0	1.52	59.7	100
03B31P2	175	347	209	154	0	1.58	62.1	100
04B31P2	200	392	195	144	0	1.68	66.2	100
01B22P2	200	392	256	188	0	1.20	47.2	100
04B21P2	200	392	266	196	0	1.50	59.0	100
02B22P2	225	437	281	207	0	1.21	47.5	100
04B22P2	225	437	286	211	0	No break		
04A11P2	250	482	255	188	0	1.29	50.8	100
03B32P2	250	482	289	213	0	No break		
02B32P2	275	527	283	208	0	No break		

Table C-6. Charpy Impact Test Results, A-537 Class 1 (P2), LT Orientation, 1/4 *t* Depth

Specimen	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
	(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
09B61P2	−125	−193	4.1	3	100	0.01	0.5	0
08B61P2	−100	−148	20	15	99	0.12	4.6	1
07B61P2	−75	−103	32	24	99	0.39	15.2	10
06B61P2	−50	−58	90	66.5	92	1.26	49.8	25
05B61F2	−25	−13	151	111	57	1.98	78.1	45
04B61F2	0	32	214	158	0	2.19	86.4	100
01B61F2	20	68	218	161	0	2.17	85.4	100
02B61F2	50	122	228	168	0	2.03	79.9	100
03B61F2	75	167	226	167	0	2.00	78.6	100
10B61F2	100	212	268	198	0	1.83	72.0	100
12B61F2	125	257	264	194	0	1.29	50.7	100
11B61F2	125	257	307	226	0	No break		
12B62F2	175	347	279	205	0	No break		
08B62F2	200	392	283	208	0	No break		

Table C-7. Charpy Impact Test Results, A-537 Class 2 (P4), TL Orientation, 1/4 t Depth

Specimen	Test Temperature		Dial Energy		Drop in Load (ΔP) (%)	Lateral Expansion		Fracture Appearance (% Shear)
	(°C)	(°F)	(J)	(ft-lb)		(mm)	(mils)	
02B21P4	−125	−193	11.5	8.5	100	0.04	1.5	0
04B02P4	−100	−148	23	17	98	0.21	8.4	1
03B02P4	−75	−103	43	31.5	99	0.54	21.2	10
02B02P4	−50	−58	142	105	72	1.90	74.8	40
01B02P4	−25	−13	237	174	0	2.13	83.9	100
01E3104	−18	0	177	130	40	1.98	78.0	80
02E31P4	−18	0	158	116	48	1.87	73.5	60
04B01P4	0	32	237	174	0	2.26	89.0	100
01B01P4	20	68	224	165	0	2.08	81.7	100
02B01P4	50	122	234	172	0	2.02	79.6	100
03B01P4	75	167	294	217	0	1.60	63.0	100
02B32P4	75	167	309	228	0	1.33	52.5	100
01B21P4	100	212	284	209	0	1.81	71.4	100
04B21P4	100	212	307	226	0	1.38	54.2	100
01B32P4	100	212	306	226	0	1.20	47.2	100
03B21P4	150	302	325	240+	0	No break		No break
02B31P4	150	302	319	235	0	No break		No break
01B31P4	150	302	315	232	0	No break		No break
03B31P4	200	392	318	234	0	No break		No break
03B32P4	200	392	319	235	0	No break		No break
04B32P4	250	482	320	236	0	No break		No break

Table C-8. Charpy Impact Test Results, A-537 Class 2 (P4), LT Orientation, 1/4 *t* Depth

Specimen	Test Temperature (°C)	Test Temperature (°F)	Dial Energy (J)	Dial Energy (ft-lb)	Drop in Load (ΔP) (%)	Lateral Expansion (mm)	Lateral Expansion (mils)	Fracture Appearance (% Shear)
09B61P4	−125	−193	8.1	6	100	0.14	5.4	1
08B61P4	−100	−148	30	22.5	97	0.38	15.1	5
07B61P4	−75	−103	121	89	85	1.66	65.3	25
06B61P4	−50	−58	105	77.5	81	1.43	56.3	30
05B61P4	−25	−13	254	187	0	2.19	86.3	100
04B61P4	0	32	230	170	0	2.19	86.4	100
01B61P4	20	68	258	190	0	1.94	76.5	100
02B61P4	50	122	315	232	0	1.49	58.7	100
03B61P4	75	167	325	240+	0	No break		
09B62P4	150	302	323	238	0	No break		
10B62P4	200	392	321	237	0	No break		

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