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Final Report on 3 Cr–1.5 Mo Steels for Gasifier Pressure Vessel Construction

R. W. Swindeman
J. F. King
R. K. Nanstad

Research supported by the Morgantown Energy Technology Center, U.S. Department of Energy

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METALS AND CERAMICS DIVISION

FINAL REPORT ON 3 Cr—1.5 Mo STEELS FOR GASIFIER PRESSURE VESSEL CONSTRUCTION

R. W. Swindeman, J. F. King, and R. K. Nanstad

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FINAL REPORT ON 3 Cr–1.5 Mo STEELS FOR GASIFIER PRESSURE VESSEL CONSTRUCTION*

R. W. Swindeman, J. F. King, and R. K. Nanstad

ABSTRACT

This report provides results from an experimental program to evaluate the potential of 3 Cr–1.5 Mo steels for construction of large gasifier vessels for service at metal temperatures of 316°C and pressures to 8 MPa. Information starts with processing data for three commercial heats with different elements added for hardenability and strength. This is followed by a description of welding practices, which included submerged arc and shielded metal arc methods. Hardenability data are provided along with information on tempering and postweld heat treating. The mechanical properties compiled included tensile and impact strength, fracture toughness, fatigue, and embrittlement. The steels were found to be very promising and competitive with the best of the new steels being developed for petrochemical and petroleum applications.

INTRODUCTION

This report provides a data compilation and final assessment of the potential of 3 Cr–1.5 Mo steels for gasifier pressure vessel construction. The work summarized in this report represents the culmination of research on pressure vessel steels that began in the late 1970s in response to a perceived need for steels to construct heavy-walled, large-diameter gasifiers for high-Btu coal gasification plants.[1–9] As the fuels crisis abated, government involvement in surface gasification projects lessened, and the gasification schemes promoted by industry became less ambitious. Plant designs were modeled on extensions of existing capabilities, and the scale of the plants was substantially reduced. Concomitant with this

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reduction in scale was a reduction in the materials requirements for gasifier pressure vessel construction. The steels currently approved by the ASME Boiler and Pressure Vessel Code will meet all of the near-term requirements for vessel construction. This situation will persist as long as there is no urgent need to establish a synfuels industry.

The lessons learned in the late 1970s suggest that there are benefits in having advanced pressure vessel materials that provide the plant designers with the options for plant optimization, should the need for a rapidly expanding synfuels industry arise. Typical options in regard to process vessels include whether to design for (1) one large field-fabricated vessel or several parallel and smaller shop-fabricated vessels, (2) multilayer or monolithic vessels, and (3) hot-wall or cold-wall service. Whatever options are selected, there will be a distinct advantage to having an easily fabricated pressure-vessel steel available that will exceed the strength and corrosion resistance available in the steels currently in the ASME Code.

An assessment was undertaken in 1982 that identified the criteria for evaluating advanced steels and outlined a program to produce the data needed to select a candidate for eventual codification.[9] The criteria included sufficient fabricability to produce rolled plate and forged rings, full hardenability in section thicknesses to 300 mm, weldability by all commercial shop and field practices, strength equivalent to the best steels in the Code today (such as SA-533 grade B), flexibility in tempering and postweld heat treatment (PWHT) schedule, sufficient resistance to temper embrittlement to allow 54-J Charpy V-notch energy at −18°C after slow cooldown from the PWHT, and sufficient resistance to hydrogen embrittlement to permit safe operation of the vessel in hydrogen-bearing environments at 8 MPa pressure and 316°C metal temperature. It was mandatory that the steel be amenable to the production capability of the steel industry in the United States.

On the basis of the criteria identified above, several potential alloy compositions were evaluated for DOE.[10] Two steels were recommended for additional examination: 2.25 Cr—1 Mo steel quenched and tempered to meet the ASTM A 542 class 3 specification, and 3 Cr—1.5 Mo steel normalized

and tempered to meet properties similar to the A 542 class 3 range. Work proceeded on the 2.25 Cr–1 Mo alloy with special emphasis on determining whether the material could be welded and heat treated to bring different heats and weld metals within the desired strength range while maintaining adequate toughness.[10] It was concluded that the alloy design criteria could be met with proper care of fabrication procedures. While this work was under way, a code case was approved, at the request of a foreign steel producer, that permitted pressure vessels to be constructed from material meeting the ASTM A 542 specification.[11] Allowable stresses were approved for service to 427°C (800°F) under Sect. VIII, Div. 1 and Div. 2 rules.[12] With the approval of this code case, and the additional development of quenched and tempered 2.25 Cr–1 Mo steel for heavy-walled vessel construction by The Metal Properties Council (MPC) for the American Petroleum Institute, the need for the DOE-sponsored work on 2.25 Cr–1 Mo steel was no longer justified.[10,13] However, the work under way on the 3 Cr–1.5 Mo steel was not duplicative of any industry effort in the United States, and the potential of this alloy group appeared to be greater than that for 2.25 Cr–1.5 Mo steel. In order to assess the potential of these alloys relative to the 2.25 Cr–1.5 Mo steel, the DOE-sponsored work was extended for an additional year. This report provides the results of that work.

PROGRAM PLAN

The approval of a new alloy in the ASME Code is often a long and expensive process. The requirements are provided in Code documents, e.g., Appendix 16 of Sect. VIII, Div. 2, but they are flexible and subject to different interpretations. In planning the work on advanced 3 Cr–1.5 Mo steels, we assumed that the development should proceed along the lines sketched in Fig. 1. Here it is necessary to begin with the basic principles of alloy design and examine a range of compositions as small laboratory heats. These heats, usually produced in the 10- to 50-kg size, are then heat treated to simulate heavy-section alloy fabrication procedures and studied with respect to phase identification, strength, toughness, and corrosion resistance. Analysis of the data then leads to the identification

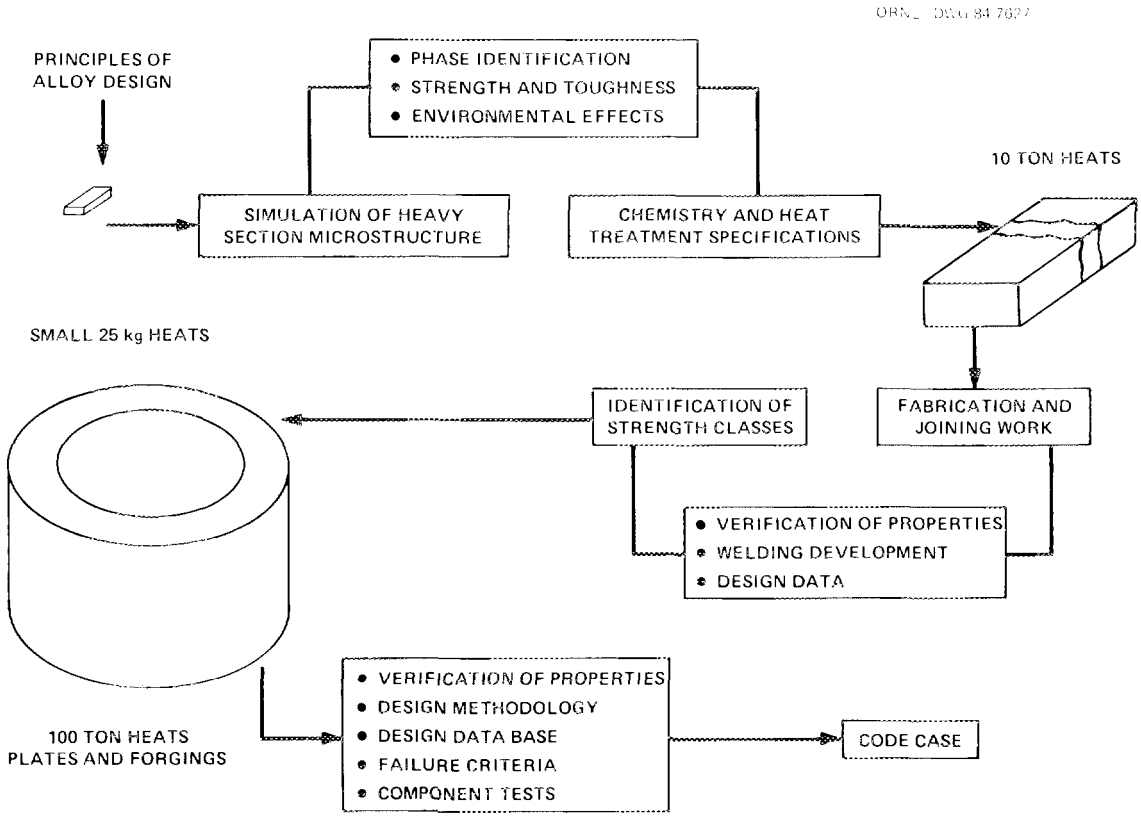

Fig. 1. Development of advanced pressure vessel materials.

of the most promising chemical and heat treatment specifications and the procurement of a small commercial heat of 8 to 12 tons. The small heat is fabricated into moderate section thicknesses and used to demonstrate fabricability and weldability. Depending on the initial success, one or more additional small heats may be produced. Data produced from tests on small heats are acceptable as part of the information package submitted to the code body; however, it is necessary to produce at least one large heat in the product form required for vessel fabrication. Data produced from tests on this product form are an important part of the code information package.

In Japan, the advanced pressure vessel steels have progressed through all of the developmental steps sketched in Fig. 1 to the production of large heats of heavy-section plates and ring forgings. Specific examples

include 2.25 Cr—1 Mo—V—Ti—B and 3 Cr—1 Mo—V—Ti—B.[14-16] Data suggest that these steels could meet all of the criteria selected for gasifier pressure vessel construction, with the possible exception of meeting the capability for production by the United States steel industry. The problem is a limited capacity in the United States for producing steels that contain boron. The boron is present in the Japanese steels for hardenability, and alternate methods for promoting hardenability are available. In the United States, laboratory heats of steels containing increased amounts of hardenability-promoting elements such as nickel, manganese, chromium, and molybdenum have been examined, and those developmental steels were a keystone in our program plan.[9,17-22] The most promising compositions were identified, and the DOE Surface Gasification Materials Program (SGMP) and the Advanced Research and Technology Development (AR&TD) Fossil Energy Materials Program supported the procurement of small commercial heats.[23,24] These heats were examined with respect to fabricability, weldability, and response to tempering.[20,24-26] Preliminary results were sufficiently promising to encourage the Nippon Kokan Steel Company to produce a large commercial heat.[27] Portions of the heats were provided to industrial laboratories and AR&TD subcontractors for further evaluation. Many of these evaluations are in progress, and the results and conclusions are tentative. However, this report will summarize some of the results of this research when pertinent to the issues being discussed.

MATERIAL AND PROCESSING

The work reported here involved three heats of 3 Cr—1.5 Mo steel that differed in content of important alloying elements such as carbon, vanadium, manganese, and nickel. Typical compositions are provided in Table 1. In each case the commercial heat was produced after the collection and analysis of data on small laboratory heats. Because those data are also important to the understanding of the alloys, the chemical compositions and processing of the laboratory heats are described in this section.

Table 1. Chemical compositions

Material identification	MP[a]	Wt % of indicated elements													
		C	Mn	Si	Ni	Cr	Mo	V	S	P	Al	N	Sn	Sb	Cu
3 Cr–1.5 Mo–V (aim)		0.10	0.90	0.20	0.20	3.0	1.45	0.10	≤0.010	≤0.012	≤0.025	≤0.020	≤0.020	≤0.007	≤0.12
ht 2905	IV	0.103	0.86	0.21	0.11	2.97	1.45	0.13	0.009	0.006	0.005	0.009			
ht A9349	E/AOD	0.12	0.84	0.27	0.14	2.86	1.48	0.09	0.002	0.011	0.004	0.004	0.002	<0.001	0.06
ww 6672	IV	0.072	0.94	0.28	0.19	3.02	1.44	0.076	0.0034	0.003	0.016	0.006	<0.001	<0.001	0.005
ww 6673	IV	0.071	0.94	0.26	0.19	2.97	1.47	0.076	0.0032	0.003	0.016	0.007	<0.001	<0.001	0.005
ww 6685	IV	0.073	0.9	0.23	0.20	3.01	1.46	0.79	0.0044	0.0043	0.013	0.009	<0.001	<0.001	0.003
WAMAX	SAW	0.054	1.10	0.34	0.18	2.98	1.40	0.082	0.0018	0.005	0.014	0.010	<0.001	<0.001	0.006
JFK 328	SAW	0.050	0.91	0.25	0.19	3.06	1.40	0.074	0.003	0.005	0.011	<0.01	<0.001		0.005
JFK 329	SAW	Same as JFK 328													
USW 21414		0.10	0.90	0.25	0.28	2.90	1.38	0.12	0.003	0.010	0.01	0.011	0.01		0.03
JFW 342	SAW	0.084	0.84	0.21	0.27	3.16	1.41	0.092	0.002	0.004	0.01	0.008	0.001		0.02
M10552		0.090	0.70	0.17	0.01	2.90	1.41	0.097	0.007	0.007					
BF	SMAW	0.091	0.72	0.19	0.02	2.95	1.42	0.092	0.007	0.007					
M10556		0.075	0.69	0.16	0.01	3.03	1.42	0.075	0.008	0.007					
BG	SMAW	0.070	0.70	0.17	0.01	3.05	1.42	0.074	0.008	0.007					
M10557		0.057	0.63	0.12	0.01	2.92	1.42	0.035	0.009	0.007					
BH	SMAW	0.057	0.67	0.17	0.01	2.99	1.42	0.037	0.008	0.007					
ht 6647	IA	0.11	0.85	0.14	0.20	3.02	1.54	0.088	0.013	0.003	0.013	0.014			
3 Cr–1.5 Mo–Ni (aim)		0.15	0.50	0.20	0.50	3.0	1.5		≤0.01	≤0.012	≤0.025	≤0.020	≤0.020	≤0.010	≤0.10
UCB D	IV	0.15	0.47	0.22	0.50	3.0	1.50		0.0036	0.006	0.008				
A9749	E/AOD	0.15	0.51	0.25	0.55	3.03	1.52		0.003	0.012	0.01	0.008	0.006	<0.01	0.10
JFK 323	SAW	0.12	0.62	0.28	0.50	3.02	1.50	0.008	0.002	0.012	0.007	0.006	<0.001		0.12
JFK 344	SAW														
3 Cr–1.5 Mo–V NKK	BOF	0.14	0.55	0.07		3.11	1.50	0.096	0.001	0.004	0.018	0.011	0.002	<0.001	
UCB E	IA	0.14	0.49	0.22	0.50	2.95	1.50	0.21	0.0034	0.006	0.008				
CE 3797	ESR	0.13	0.44	0.34	0.53	3.10	1.39	0.22	0.001	0.005	0.043		<0.001		0.002
3 Cr–1 Mo–V WCM3V[b]		0.10	0.63	0.04		2.9	1.0	0.27	0.003	0.009					

[a]MP = melting practice, IV = induction vacuum, IA = induction argon, E/AOD = electric furnace argon/oxygen decarburization, SAW = submerged arc weld, SMAW = shielded metal arc weld, BOF = basic oxygen vacuum arc degassing, ESR = electroslag remelt.

[b]0.1% Ti.

3 Cr–1.5 Mo–V STEEL

The development of the 3 Cr–1.5 Mo steels was started in the late 1970s by Wada and co-workers.[18] Over the years, at least 18 vacuum-melted and four air-melted laboratory heats were produced in order to develop specifications for the optimum carbon, manganese, silicon, nickel, vanadium, and nitrogen contents.[19,20] The maximum allowable phosphorus and sulfur contents were also established. The vacuum-melted heats were 25 kg each and the air-melted heats were 57 kg each. All heats were aluminum killed. The ingots were forged to 50-mm-thick billets and hot rolled to 16-mm plates for subsequent examination. The compositions for the materials studied at AMAX Research Laboratory are provided in Table 1. They ranged from 0.068 to 0.12% C, 0.56 to 1.48% Mn, 0 to 0.49% Ni, and 0.05 to 0.15% V. A typical grain size is reported to be ASTM No. 7. Some of this material (heat P2904) was provided to the University of Tennessee for studies of weldability.

The selection of the aim chemical composition for the commercial heat of 3 Cr–1.5 Mo–V steel was based on the evaluation of the performance of the laboratory heats. Carpenter Technology, Inc., melted the heat in a scrap-charged electric furnace. The heat (Cartech heat 50580) was argon-oxygen decarburized (AOD) and bottom poured into two molds 145 by 35 cm in cross section. The ingots were shipped to Lukens Steel Company for further processing, where they were renumbered as heat A9349 (refs. 23, 24). These ingots were conditioned, heated, and rolled to 100-mm (4-in.) plate by standard plate rolling practice. The final plate dimension was 10 by 170 by 340 cm before pattern cutting. Figure 2 shows a typical plate being processed by Lukens Steel. Two lots were produced from the plate. Lot 1 was austenitized at 955°C for 2 h, air cooled, and tempered at 566°C for 2 h. This material was identified as heat A9349 (NT). Lot 2 was austenitized at 955°C for 2 hr, water quenched, and tempered at 566°C for 2 h. This material was identified as heat A9349 (QT). The NT material had a grain size near ASTM No. 5 and the QT material near ASTM No. 8, as shown in Fig. 3.

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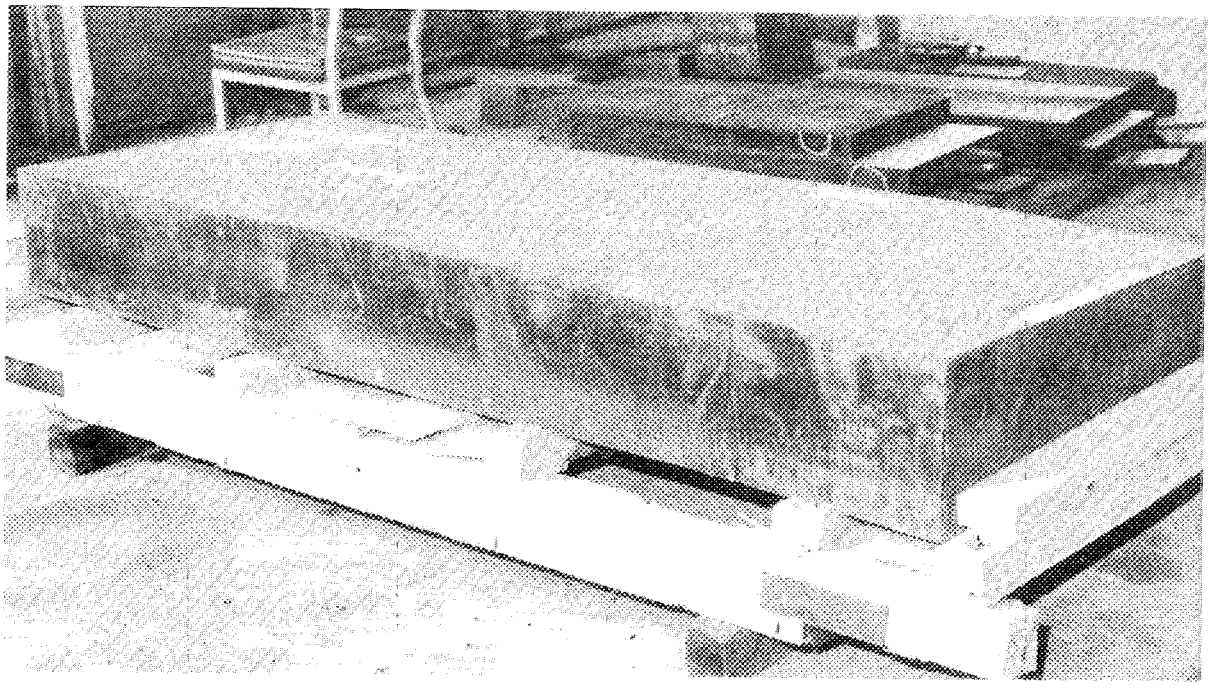

(*a*)

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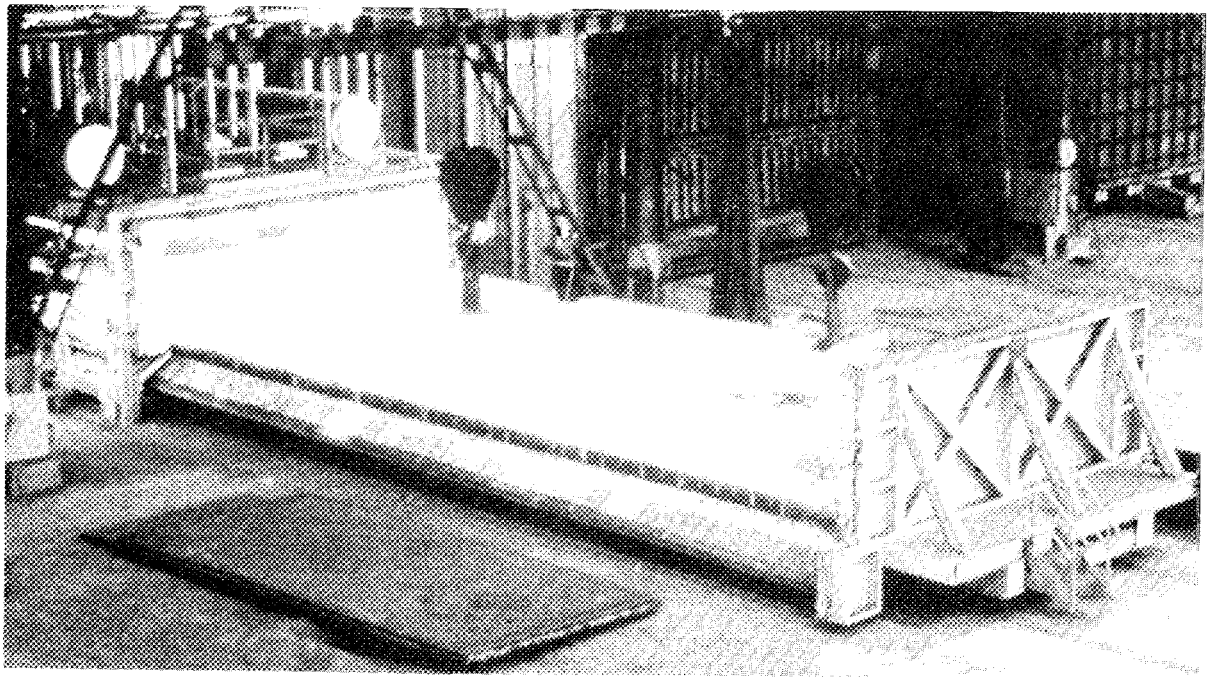

(*b*)

Fig. 2. (*a*) Heat treating facility used by Lukens Steel Company for 100-mm plate of 3 Cr-1.5 Mo steel. (*b*) NKK heat of 3 Cr-1.5 Mo steel.

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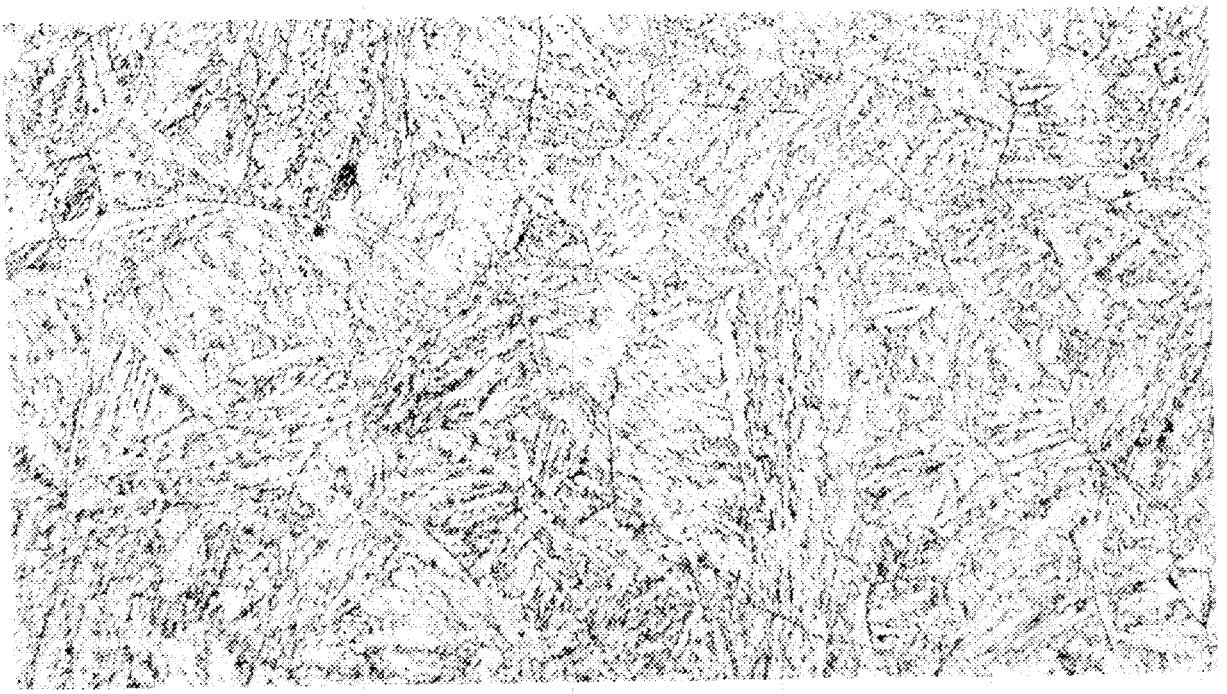

(*a*) 50 μm

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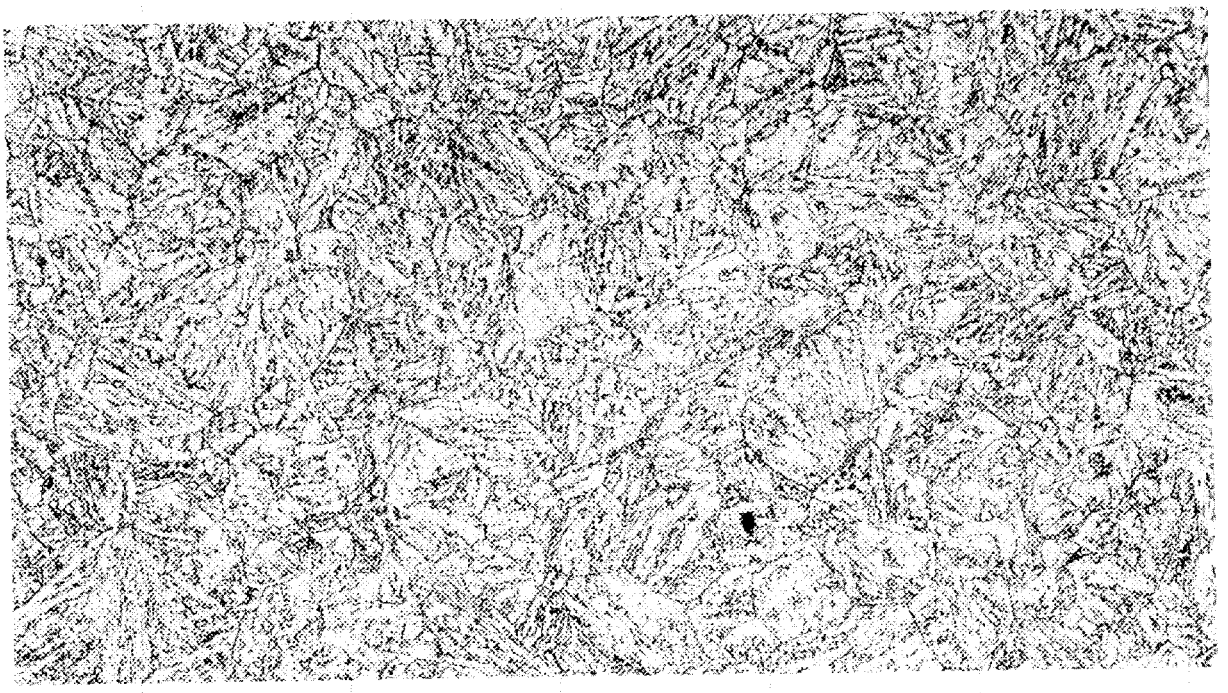


(*b*) 50 μm

Fig. 3. Microstructures in as-received 3 Cr—1.5 Mo—V steel. (*a*) Heat A9349 (NT). (*b*) Heat A9349 (QT).

Material from this heat was shipped to the Westinghouse Electric Corporation Research and Development Center (WRC), the University of Tennessee, Combustion Engineering, Inc. (CE), Chicago Bridge and Iron (CBI), Cornell University, and AMAX for additional investigations.

3 Cr–1.5 Mo–Ni STEEL

The 3 Cr–1.5 Mo–Ni steel was selected from a group of experimental alloys under investigation by Todd and co-workers at the University of California for the AR&TD program.[21,22] The laboratory heats of the steels were produced by AMAX using vacuum induction melting and casting under argon. Procedures were identical to those followed for the 3 Cr–1.5 Mo–V steels.[20] See Table 1 for the chemical composition. The 55-kg ingot was upset forged and rolled to produce a 30-mm-thick plate that was austenitized at 980°C for 1 h. Both oil quenching and slow cooling were used to examine hardenability. The grain size of the experimental heat was estimated as ASTM No. 6.

A 30-kg laboratory heat of 3 Cr–1.5 Mo–Ni steel was produced by Pickering at the Combustion Engineering, Inc., Metallurgical Laboratory.[28] This heat was electroslag remelted to a 125-mm-diam ingot, hammer forged, and rolled to a plate 62 by 75 mm in cross section. After production, the plate was provided to the University of California for further processing and examination. Chemical composition is provided in Table 1.

The commercial heat of 3 Cr–1.5 Mo–Ni steel was melted by the Electralloy Corporation and identified as heat 15105. The ingots were shipped to Lukens Steel Company for rolling and the heat was renumbered as A9749. Fabrication procedures were identical to those described for heat A9349, except that two plate thicknesses (25 and 100 mm) were produced.[26] The 100-mm-thick plate was austenitized at 955°C for 4 h, air cooled, and tempered at 607°C for 4 h. The 25-mm-thick plate was austenitized at 955°C for 1 h, air cooled, and tempered at 607°C for 1 h. The grain size of the 100-mm-thick plate was near ASTM No. 6, as shown in Fig. 4. Material from this heat was shipped to the University of California, the AMAX Corporation Research Laboratory, the Westinghouse Electric Corporation R&D Center, and the University of Tennessee.

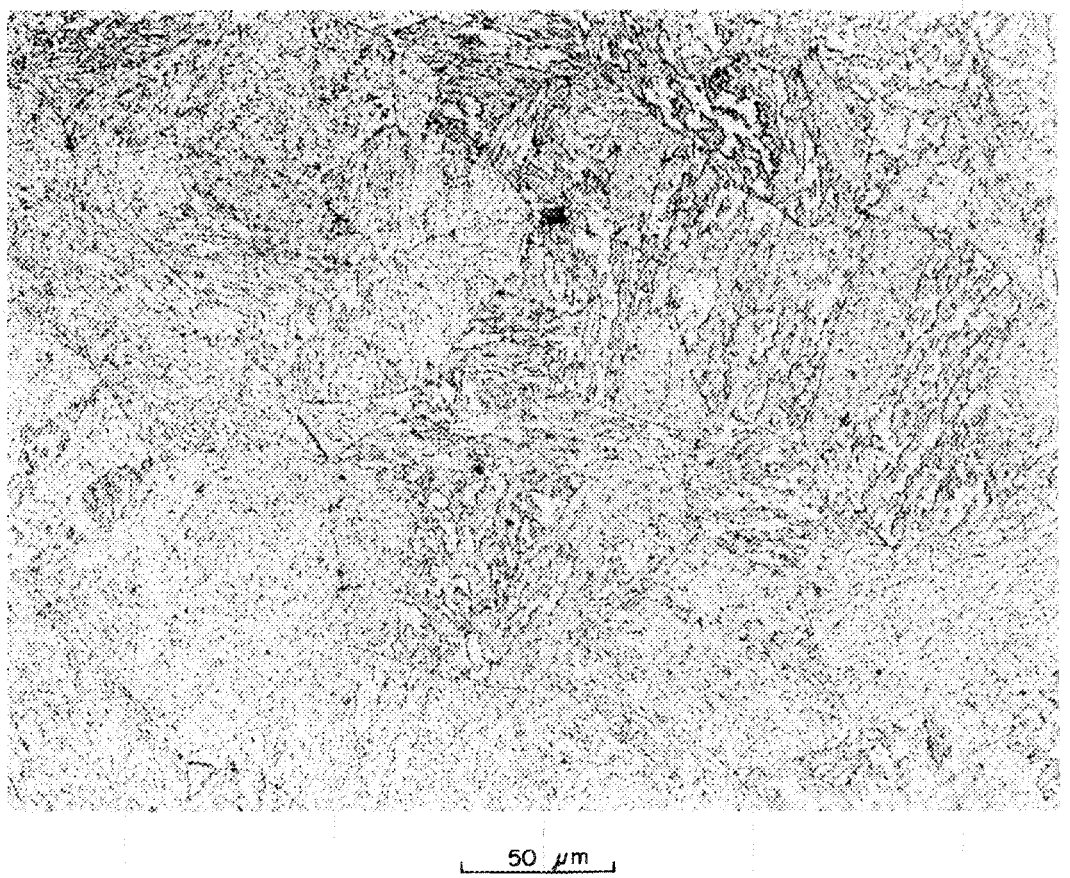


Fig. 4. Microstructure of 3 Cr–1.5 Mo–Ni steel (heat A9749) after tempering at 690°C for 16 h.

NKK 3 Cr–1.5 Mo–V STEEL

The NKK heat of 3 Cr–1.5 Mo steel was produced as a result of technical interactions between AMAX and the Nippon Kokan Company of Kawasaki, Japan.[27] The steel represents a combination of the best features of the compositions designed by AMAX, the University of California, and the researchers at NKK. The 40-ton heat was produced by the LD converter vacuum arc degassing process, molded as a unidirectional solidified ingot, and rolled to a plate thickness of 250 mm. It was austenitized at 950°C for 3 h, roller quenched, and tempered at 690°C for 2 h. (See Fig. 5 for a typical microstructure.) The material was provided to both AMAX and ORNL for examination. The welds produced in the material were supplied to the University of Tennessee for evaluation.

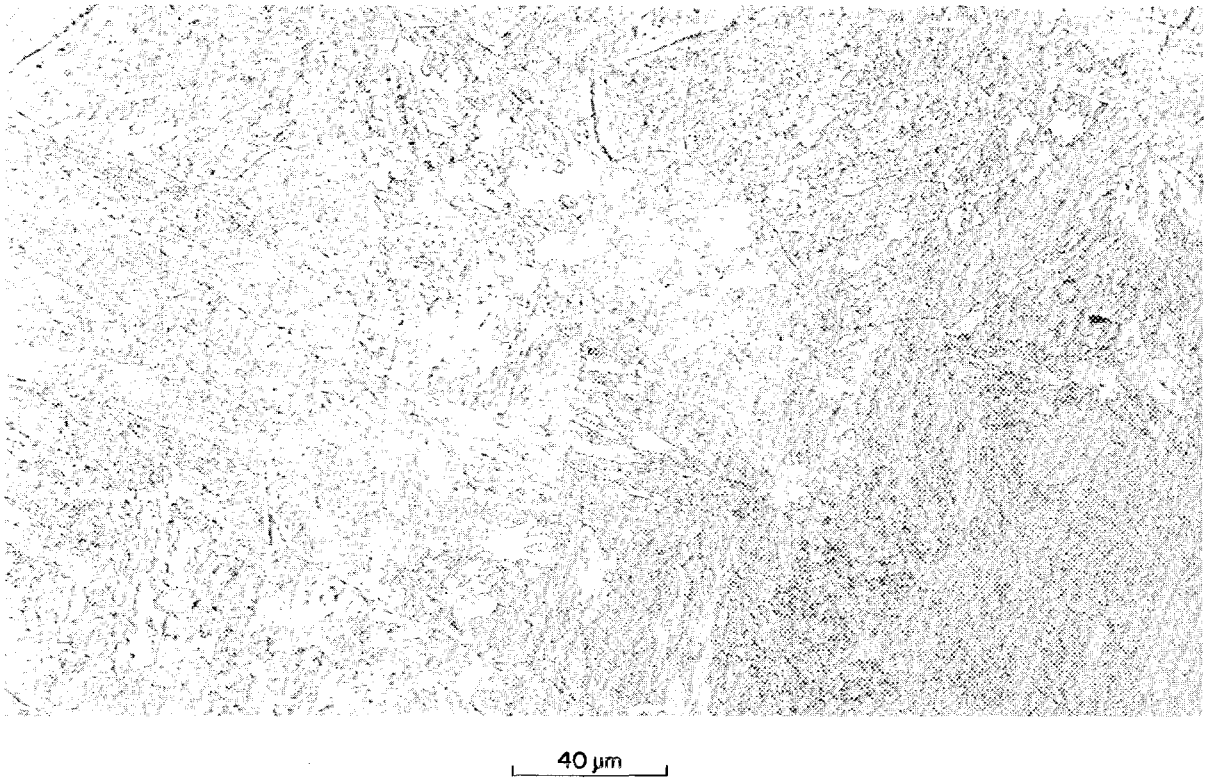


Fig. 5. Microstructure of 3 Cr–1.5 Mo–V steel (heat NKK), near quarter thickness of 250-mm plate.

In summary, several compositions of 3 Cr–1.5 Mo steels were produced, varying in composition of elements that affect hardenability: carbon, manganese, and nickel. The vanadium content was also varied. The melting processes included induction, electric, electroslag, and basic oxygen, and several refining procedures were included. The heat sizes ranged from 25 kg to 40 tons. No problems were encountered in meeting the desired chemical compositions or fabrication schedules.

WELDABILITY AND WELDMENTS

Weldability and weldment properties are of major concern in the development of low-alloy steels containing chromium, molybdenum, nickel, and vanadium, and a high priority was placed on examining the behavioral

features of the 3 Cr–1.5 Mo steels. However, the delays in the arrival of some of the steels included in the SGMP project reduced the amount of work that we could complete on these subjects. Because of scheduling problems this final report does not include a full discussion of all of the data on weldability and weldments that we produced, but it does identify the important issues that need to be resolved before the steels are commercialized.

3 Cr–1.5 Mo–V STEEL

Wada and co-workers examined the properties of the heat-affected zone (HAZ) in the developmental 3 Cr–1.5 Mo steels after welding by the shielded metal arc (SMA) and submerged arc (SA) processes.[20] The SMA welds were produced in 16-mm plate with E9018-B3 (2.25 Cr–1 Mo) electrodes in order to examine the cold cracking susceptibility. The details of the welding process are provided in Table 2, and the welded plate configuration is illustrated in Fig. 6. The welds were approximately 200 mm long, including both the anchor welds and test weld section. Examination of the test section of the Y-groove revealed no cracking. This was interpreted to indicate adequate resistance to cold cracking.

AMAX also welded the commercial heat (A9349) by the SMA process in order to examine the cold cracking susceptibility. The evaluation involved the Lehigh self-restraint test with the weld configuration sketched in Fig. 7. In this case, the plate was 28.6 mm thick, produced by rolling down the 100-mm-thick plate. The weld was 12.7 mm long and was produced by the SMA process using E9018-B3 electrodes. The welding procedure was slightly different from that used on the developmental alloys, as indicated in Table 2, but the results were essentially the same and indicated no tendency for cold cracking in this steel.

The weld wire used by Wada and Cox for the SA welds on laboratory heats was 2.25 Cr–1 Mo steel. Because the purpose of the welding was to examine the tendency for stress relief (SR) cracking in the HAZ as a result of embrittlement due to exposure to a weld thermal cycle, welding with 3 Cr–1.5 Mo steel wire was not necessary. The weldment that was produced

Table 2. Summary of shielded metal arc welds in 3 Cr–1.5 Mo steels

Material	Type joint	Electrode	Preheat (°C)	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)	Reference
3 Cr–1.5 Mo–V 16-mm plate	Y-groove	E 9018-B3 (2 1/4 Cr–1 Mo)	95–150	160 dc	22	14.6	14.6	AMAX
3 Cr–1.5 Mo–V 28.6-mm plate	Lehigh double U-groove	E 9018-B3	95–150	160 dc	22	12.4	17.0	AMAX
3 Cr–1.5 Mo–V 25-mm plates	Butt	M-10552 M-10556 M-10557	165	180 dc	24			Combustion Engineering
3 Cr–1.5 Mo–V 25-mm plates	V-groove	M-10552	117	150 dc	22			ORNL
3 Cr–1.5 Mo–V 25-mm plates	V-groove	M-10552	177	150 dc	22			University of Tenn.

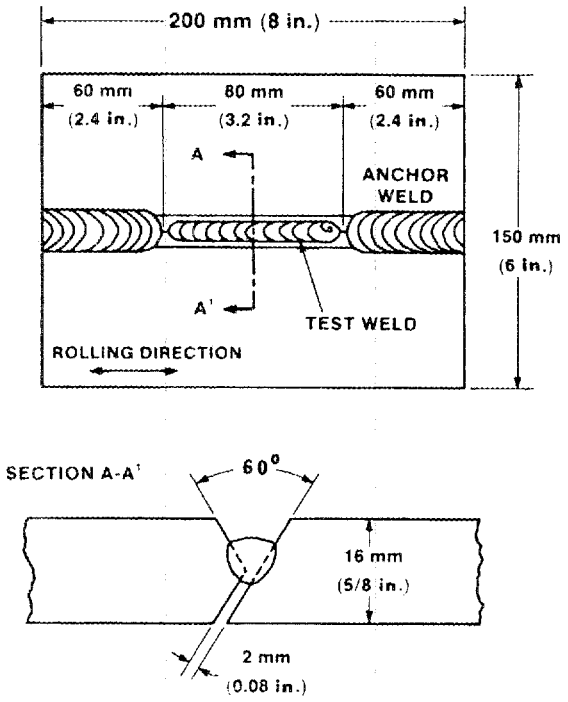


Fig. 6. Assembly for the Y-groove weld cracking test (shielded metal arc weld). *Source*: T. Wada and T. B. Cox, "A New 3 Cr—1.5 Mo Steel for Pressure Vessel Applications," pp. 77—97 in *Research on Chrome-Moly Steels*, MPC 21, American Society of Mechanical Engineers, New York, 1984.

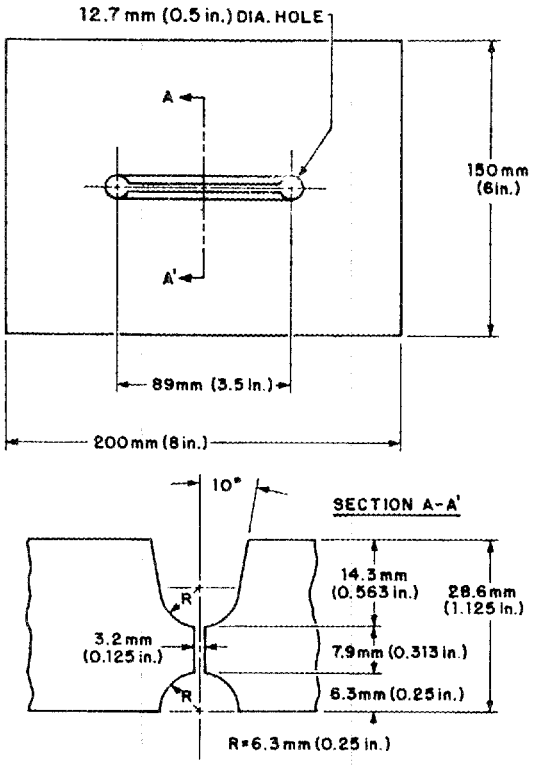


Fig. 7. Lehigh self-restraint cracking test specimen (shielded metal arc weld). *Source*: T. Wada and T. B. Cox, "A New 3 Cr—1.5 Mo Steel for Pressure Vessel Applications," pp. 77—97 in *Research on Chrome-Moly Steels*, MPC 21, American Society of Mechanical Engineers, New York, 1984.

is sketched in Fig. 8, and the details of the welding procedure are provided in Table 3. Here the weld, approximately 400 mm long, was placed in a 16-mm plate. Penetration was only enough to fuse implant specimens to the weld bead. The implant specimens were removed, heated to 620°C, and creep tested to failure to examine the failure mode and ductility. No brittle creep failures were observed in the HAZ, leading the researchers to conclude that the 3 Cr–1.5 Mo–V steel was highly resistant to SR cracking.

AMAX produced 70 kg of SA weld wire for use in the examination of the weldability and weldment properties of 3 Cr–1.5 Mo–V steel.[29] The specified weld metal composition was a result of technical discussions between AMAX personnel, ORNL, and a consultant, R. D. Thomas, and required a reduced level of carbon and vanadium in order to avoid cracking problems during welding of 100-mm plate. Both the carbon and vanadium specifications were reduced from 0.10% (±0.02%) in the base metal to 0.07% (±0.02%)

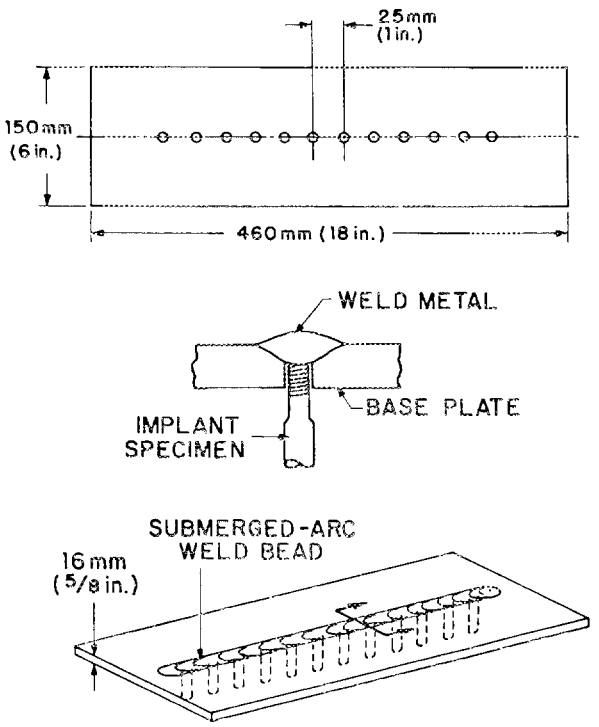


Fig. 8. Weldment with implant specimens for testing stress-relief embrittlement of the heat-affected zone. *Source:* T. Wada and T. B. Cox, "A New 3 Cr–1.5 Mo Steel for Pressure Vessel Applications," pp. 77–93 in *Research on Chrome-Moly Steels*, MPC 21, American Society of Mechanical Engineers, New York, 1984.

Table 3. Summary of submerged metal arc welds in 3 Cr–1.5 Mo steels

Material	Type joint	Wire	Flux	Preheat (°C)	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)	Passes	Reference
3 Cr–1.5 Mo–V 12-mm plate	Implant bars	2 1/4 Cr–1 Mo			460–500	30 dc e+	46	19	1	AMAX
3 Cr–1.5 Mo–V 100-mm plate	U-groove	ht 6673	Thyssen UV420TTR	150–205	475	30 dc e+	40	21	79	AMAX
3 Cr–1.5 Mo–V 100-mm plate	V-groove	ht 6672	Oerlikon OP-76	175–260	400–450	31 ac sq wave	35	22	116	ORNL
3 Cr–1.5 Mo–V 100-mm plate	V-groove JFK 342	ht USW21414	Oerlikon OP-76	204	400	32 ac sq wave	25	30.5	88	ORNL
3 Cr–1.5 Mo–Ni 100-mm plate	V-groove JFK 343 JFK 344	ht A9749	Oerlikon OP-76	260	400	35 ac sq wave	25	33.6	75	ORNL
3 Cr–1.5 Mo–V 100-mm plate	V-groove JFK 345	hw-CM3V	B3CM	204	540	35 dc e+	30	35	42	ORNL

in the SA weld wire. Three heats of 3.2-mm-diam weld wire were produced, all within the required chemical composition. Chemical composition data are presented in Table 1.

Submerged arc welds were produced in the 100-mm plate after tempering at 565°C for 2 h. Similar procedures were used by AMAX and ORNL.[25,29] The SA welding system at AMAX is shown in Fig. 9, which shows a plate 915 mm long by 457 mm wide in position for welding. The weld preparation contour was a single U-groove, 35 mm wide at the crown. The plate was fully restrained and preheated in the range from 175 to 205°C during welding. The weld pass sequence is diagrammed in Fig. 10, which also shows the macroetched cross section. More details of the welding procedure are provided in Table 3 and the chemical composition of the weld deposit is provided in Table 1. Inspection of the weldment revealed no plate distortion nor any evidence of cold cracking. After sectioning into two pieces, the weldment was stress relieved at 635°C for 4 h. One half was retained by AMAX for testing, and the other half was shipped to ORNL for evaluation.

Three SA welds were produced at ORNL, each about 500 mm long. The first weld, JFK 328, was in the 100-mm plate that was in the NT condition (565°C for 2 h). This material was identical to that used by AMAX. The weld joint was a single V-groove with a 20° included angle and a 10-mm root gap. The plate was fully restrained and preheated in the range from 177 to 260°C. The weld was wider than that produced by AMAX and required 116 passes. The details of the welding procedure and the chemical composition of the deposit are provided in Tables 3 and 1, respectively. The plate was stress relieved at 621°C for 2.5 h after welding. Inspection of the plate after welding revealed a small crack in the centerline of the root pass that appeared to be related to incomplete penetration into the backing plate at the start of the weld. No other cracks were found. The plate was stress relieved at 621°C for 2.5 h, sectioned, and evaluated at ORNL and the University of Tennessee.

The second ORNL weld, JFK 329, was produced in the QT plate tempered at 565°C for 2 h. The welding procedure was essentially the same as that used for JFK 328. A sound weld was produced that was stress relieved at

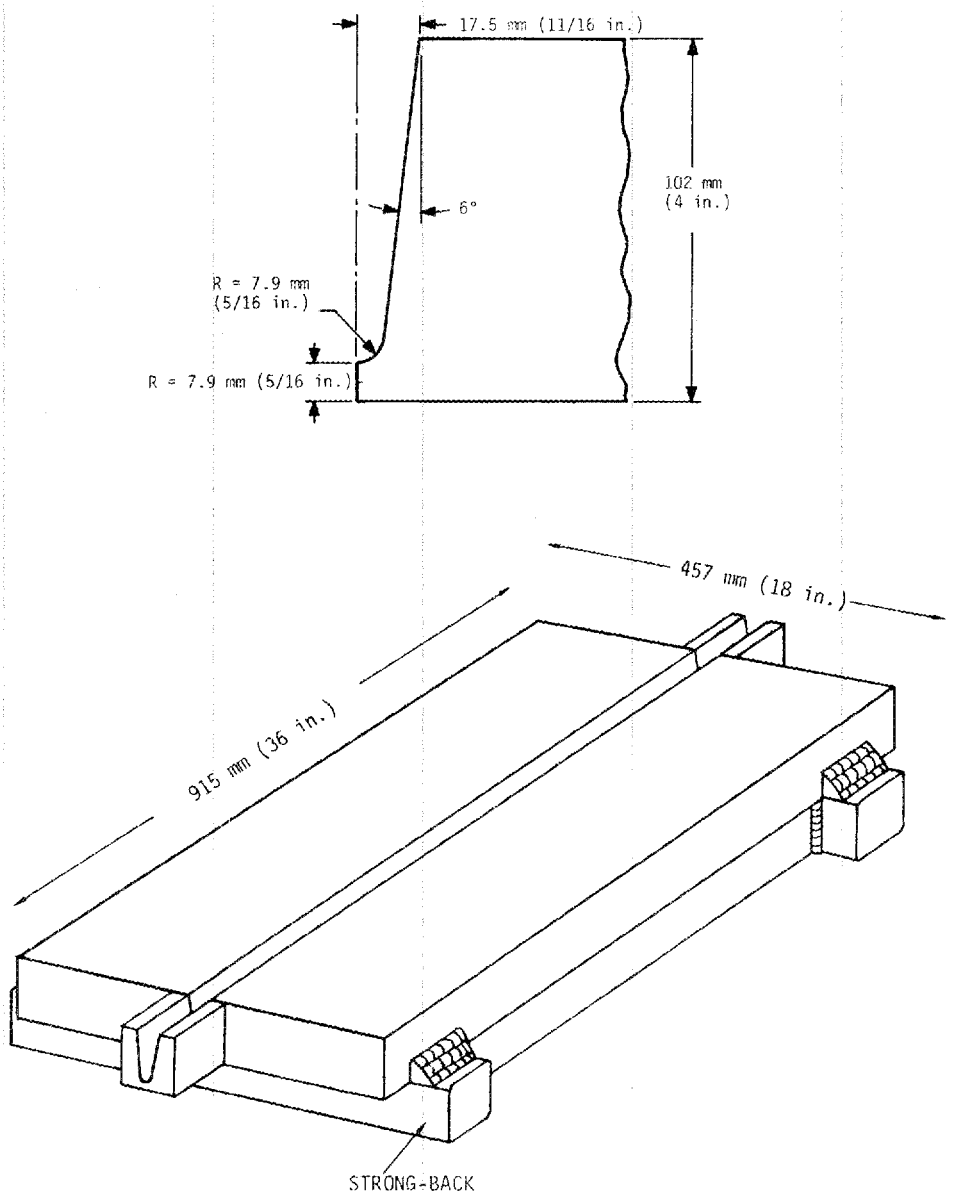


Fig. 9. The 100-mm plate of 3 Cr–1.5 Mo–V steel ready for welding by the submerged arc process. *Source*: D. P. Edmonds et al., *Evaluation of 3 Cr–1.5 Mo–0.1 V Steel as a Gasifier Pressure Vessel Alloy*, ORNL-6106, January 1985.

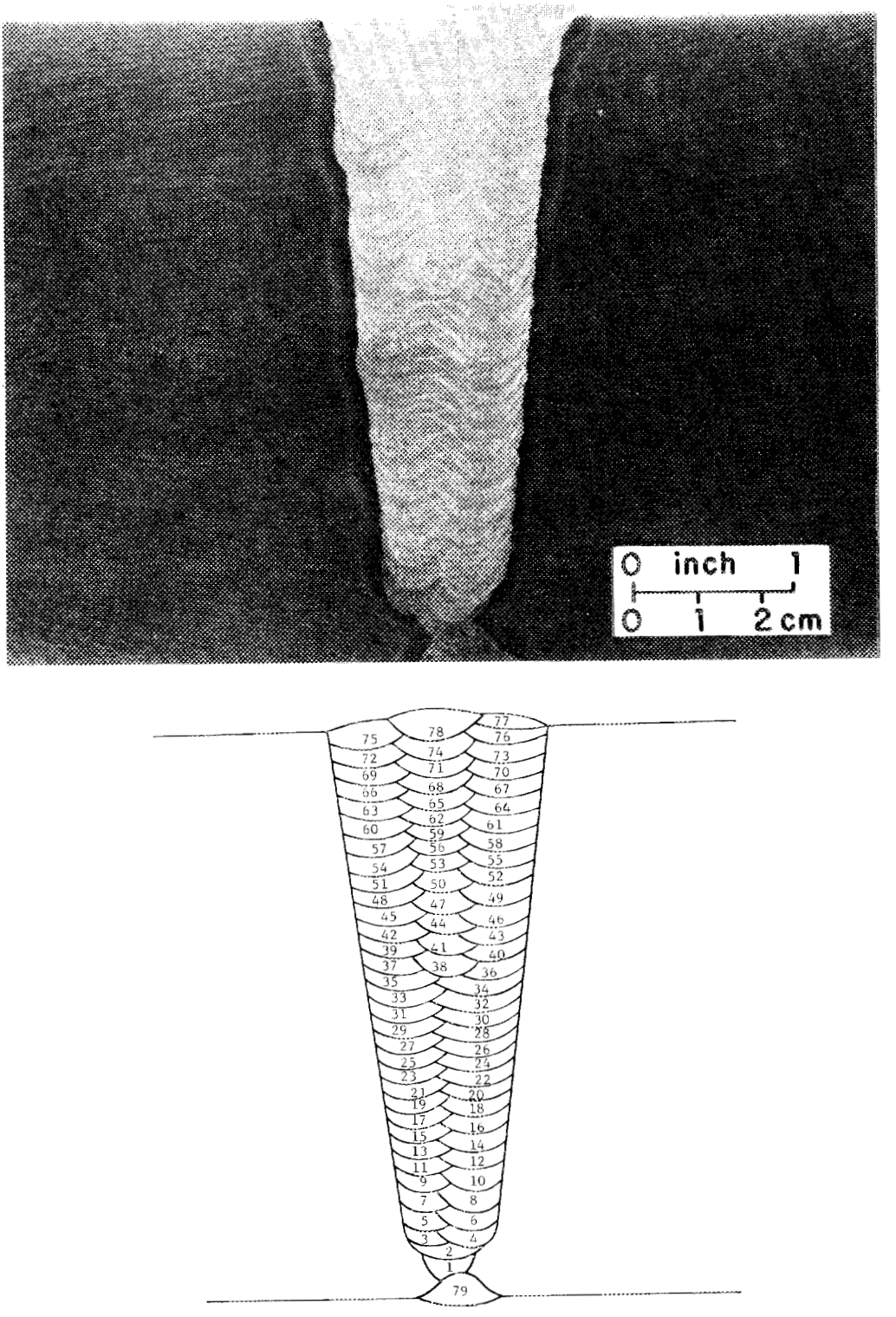


Fig. 10. Section of the submerged arc weld joint in the 100-mm plate of 3 Cr–1.5 Mo–V steel. *Source*: D. P. Edmonds et al., *Evaluation of 3 Cr–1.5 Mo–0.1 V Steel as a Gasifier Pressure Vessel Alloy*, ORNL-6106, January 1985.

621°C, sectioned, and distributed for mechanical properties studies. Chemical compositions and welding procedures are provided in Tables 1 and 3.

The third SA weld made at ORNL was in a 100-mm plate of the QT material, but with weld wire produced by U.S. Welding (heat 21414) with higher carbon and vanadium content. The carbon and vanadium were increased when it became clear the SA weld material did not possess the desired strength and that higher levels could be tolerated without cracking problems. The initial attempt at producing the weldment resulted in cracking after 12 passes. No cause was identified. The plates were remachined with a 15° included angle V-groove and a 16-mm root opening. A successful weld was made with a preheat of 204°C, a maximum interpass temperature of 260°C, and 88 passes. No cracking was observed. After inspection, the weld was stress relieved at 621°C for 2.5 h. More details of the welding wire composition and welding procedures are provided in Tables 1 and 3. A photograph of the weld, JFK 342, is provided in Fig. 11. The weldment was used for additional mechanical properties testing at ORNL.

As mentioned above, the SMA welding studies at AMAX were performed with 2.25 Cr–1 Mo steel electrodes, and they demonstrated the ease of welding the developmental alloy. The 3 Cr–1.5 Mo steel electrodes for SMA welding were produced by Pickering at Combustion Engineering, Inc., under subcontract to the AR&TD program.[28] This activity involved the investigation of the effect of increasing weld metal carbon and vanadium content on the weldability and weldment mechanical properties. Three levels of carbon and vanadium were examined: nominally 0.10, 0.07, and 0.05%. Actual compositions are provided in Table 1. Butt welds were made in 25-mm plates sawed from the 100-mm plate of heat A9349 (NT), and welding was performed with the setup and conditions identified in Fig. 12. No difficulties were encountered in producing any of the welds. No cold cracking was observed nor was there any evidence of microcracking or stress relief cracking during subsequent PWHT. The tensile and impact properties of the three weld compositions were determined by CE. Also, 22 kg of electrodes from heat M-10552 were provided to ORNL for additional

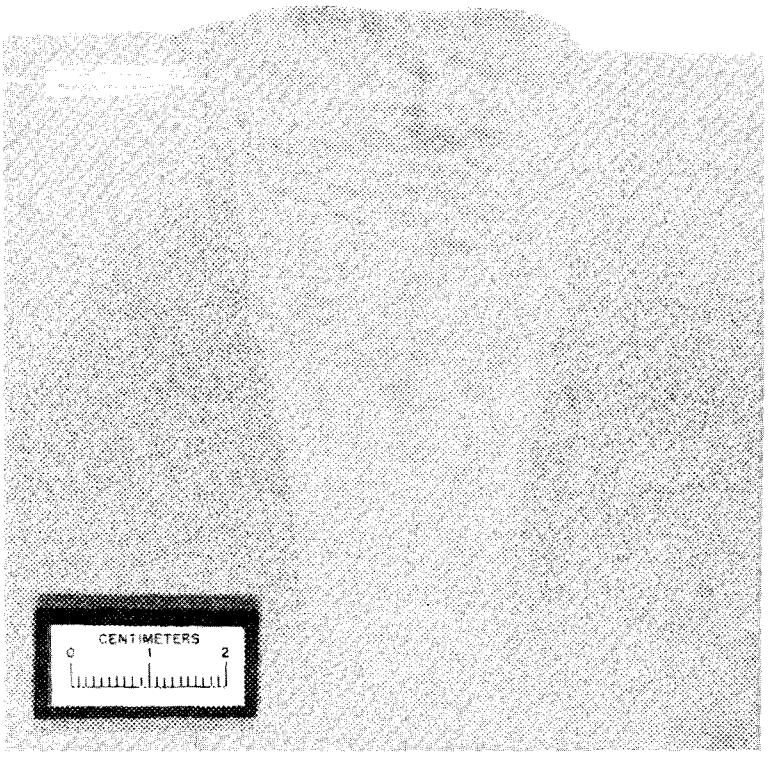
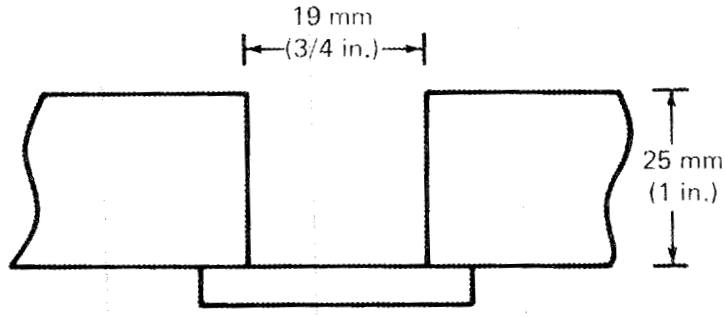


Fig. 11. Cross-section microstructure of submerged arc weld JFK 342 (heat A9349 QT).

evaluation. This material contained 0.09% carbon and 0.097% vanadium. Subsequent SMA welds were made at ORNL and the University of Tennessee, and no welding problems were encountered.

In addition to the SA and SMA welds, autogenous gas tungsten-arc (GTA) welds were made at the University of Tennessee in both the laboratory heat (P2904) and the commercial heat (A9349) of 3 Cr—1.5 Mo—V steel. They were made to examine the susceptibility of weldments to cold cracking by means of the University of Tennessee-modified hydrogen sensitivity test.[30] Here GTA welds were produced in small samples according to the conditions identified in Fig. 13. Various levels of preheating were examined, and 5% hydrogen was added to the argon shielding

ORNL–DWG 85-14741



WELD PLATE CONDITIONS

WELDING POSITION	FLAT
POWER SOURCE	DC, e^+
AMPERAGE	180
VOLTAGE	24
PREHEAT	165°C (325°F)
INTERPASS	165–190°C (325–375°F)

Fig. 12. Dimensions of the plate weld and welding conditions for SMA welds in heat A9349.

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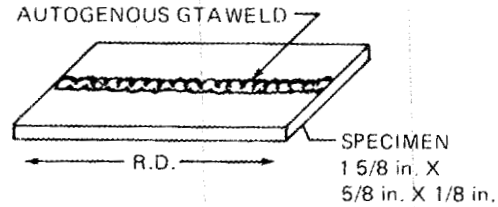
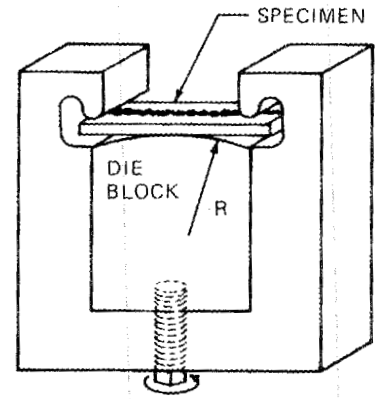


CURRENT	80–100 amps
VOLTAGE	10 v
TRAVEL SPEED	5 ipm
SHIELDING GAS	5% H_2 95% Ar, FLOW RATE 30 CFH
ELECTRODE	2% THORIATED TUNGSTEN 1/16 in. diam.

UT-MODIFIED HYDROGEN SUSCEPTIBILITY TEST SPECIMEN



SCHEMATIC DIAGRAM OF APPARATUS USED TO STRAIN SPECIMEN*

*AFTER SAVAGE et. al.

Fig. 13. Autogenous GTA welds in 3 Cr–1.5 Mo steel.

gas to saturate the fusion zone with hydrogen.[31] Subsequent testing of the specimens for hydrogen-assisted cracking revealed that both heats performed well, relative to other pressure vessel steels, provided that the preheat was in the range specified for welding low-alloy steels.

Finally, under work supported by the DOE Basic Energy Sciences program, electron beam welds were produced in a 100-mm plate of heat A9349 (QT).[32] (See Fig. 14.) No difficulties were encountered in producing sound welds that were subsequently evaluated for strength and toughness. The strength of the weld metal was found to exceed that of the base metal, and the Charpy impact properties were nearly identical to the base metal properties after a PWHT of 590°C for 5 h.

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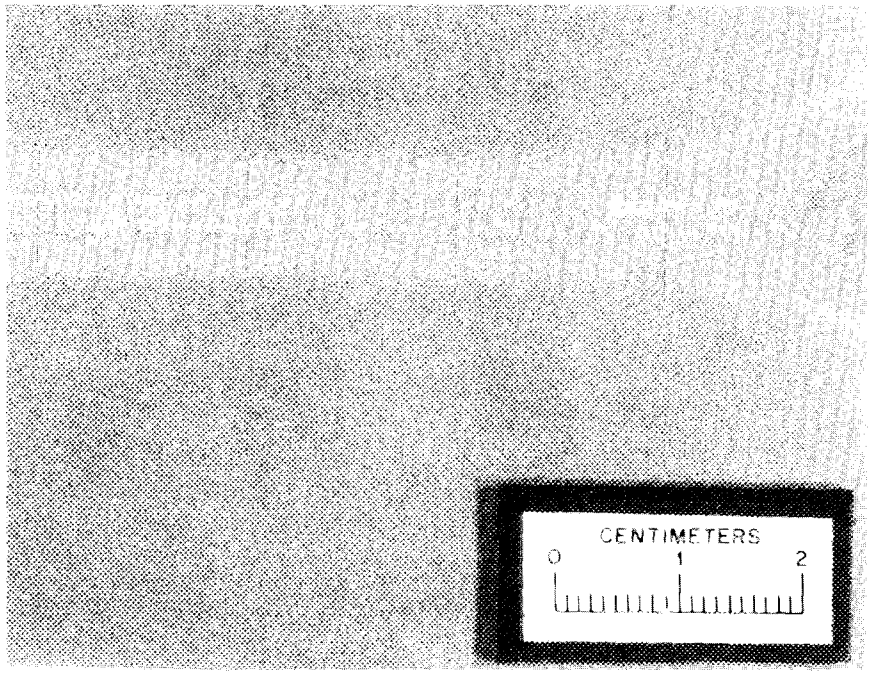

Fig. 14. Cross-section microstructure of electron beam weld in heat A9349 QT.

3 Cr-1.5 Mo-Ni STEEL

On the basis of the experience with 3 Cr-1.5 Mo-V steel, SA welding wire for the 3 Cr-1.5 Mo-Ni steel was produced with a composition identical to that of the base metal. This was done by cutting bars of square cross

section from the 25-mm plate of heat A9749 and rolling them to a size convenient for wire production. Approximately 90 kg of wire was produced by CE and supplied to ORNL. A weld was produced in the 100-mm plate and tempered at 704°C for 4 h, following procedures identical to those used previously for the 3 Cr–1.5 Mo–V steel. A cross section of the 170-mm-long weldment is shown in Fig. 15, and the chemical composition of the deposit is provided in Table 1. Detailed welding procedures are presented in Table 3. The weld was inspected, found to be sound, and stress relieved at 621°C for 2.5 h before sectioning and further evaluation. Additional testing was performed at ORNL, the University of California, the University of Tennessee, and the Westinghouse Electric Corporation R&D Center.

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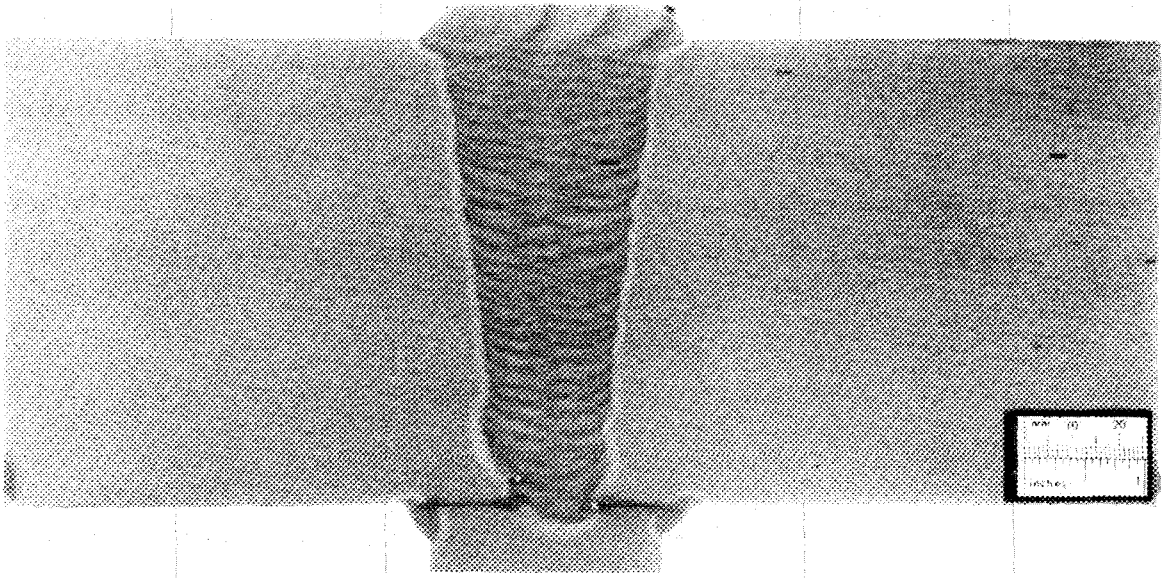


Fig. 15. Cross section of submerged arc weld in 3 Cr–1.5 Mo–Ni weld JFK 343.

Autogenous GTA welds were produced in a 25-mm plate of 3 Cr–1.5 Mo–Ni steel at the University of Tennessee in order to examine the cold cracking susceptibility.[31] Procedures were identical to those reported earlier for the 3 Cr–1.5 Mo–V steel. It was found that this steel was highly resistant to hydrogen-induced cracking and could be welded in the presence of hydrogen with very low preheat.

NKK 3 Cr–1.5 Mo–V STEEL

Submerged arc welds were produced in the 3 Cr–1.5 Mo–V steel with 3 Cr–1 Mo–V steel wire and flux supplied by Japan Steel Works. A submerged arc weldment was made in 100-mm-thick plate of the 3 Cr–1.5 Mo–0.1 V steel with filler metal having a composition of 3 Cr–1 Mo–0.27 V–0.1 Ti. The filler wire has a trade designation of W-CM3V, and the flux is designated as B-3CM. The fully restrained weld plates were preheated to 204°C before welding. Welding was initiated with alternating current, but difficulties were encountered with arc stability and weld bead configuration. The process was changed to welding with direct current, which eliminated the stability and configuration problems.

SUMMARY

In summary, welds were produced in three commercial heats and several laboratory heats of 3 Cr–1.5 Mo steels by using SMA, SA, GTA, and EB methods. No significant problems were encountered when careful but standard welding procedures were followed. Additional work is needed to demonstrate that heavy-gage plates and forgings can be welded, and other practices such as gas metal-arc (GMA) and electroslag (ES) welding should be investigated.

HARDENABILITY AND HEAT TREATMENTS

In the assessment report it was concluded that the 3 Cr–1.5 Mo steels offered a distinct advantage over 2.25 Cr–1 Mo steel in regard to thick-section hardenability and subsequent tempering response.[9] This point was further discussed in a recent report on the metallographic examination of the 3 Cr–1.5 Mo alloys.[26] The need for good hardenability may be understood by superimposing the cooling trends in heavy-gage plates on the continuous cooling transformation (CCT) diagram. In Fig. 16 the average cooling rates from the austenitizing temperature are shown for plates of different thicknesses.[33] Three cooling methods are included, labeled air cooled, fan cooled, and water quenched. A fourth curve provides an indication of the variation in the cooling rate between the quarter thickness

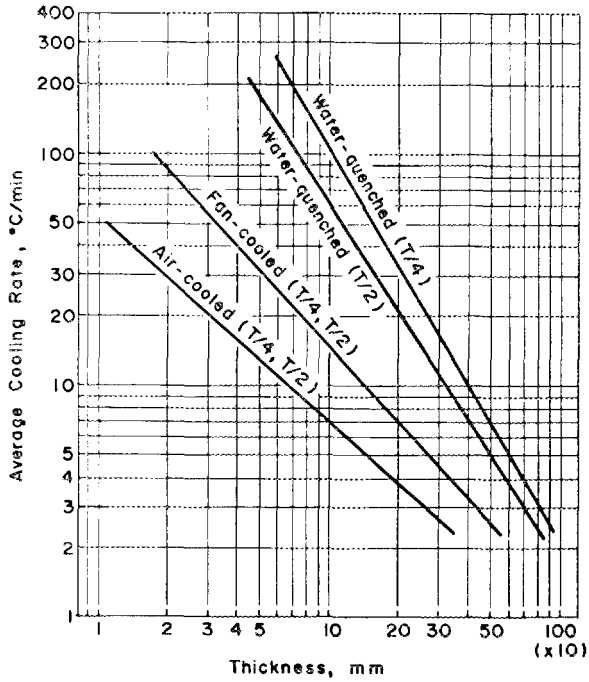
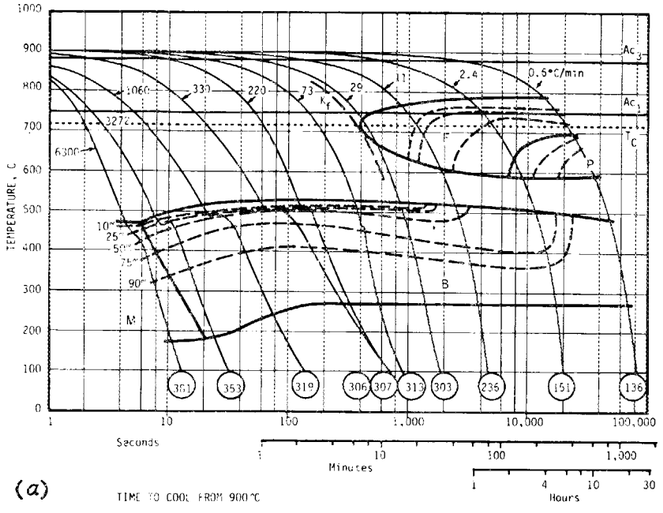
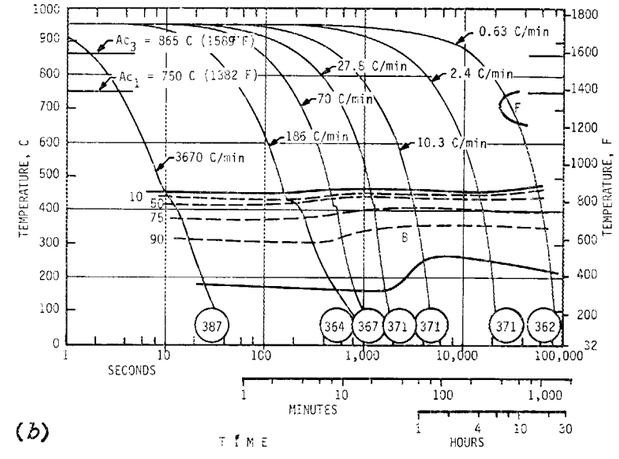


Fig. 16. Average cooling rates between the austenitizing temperature and 450°C for various cooling methods. *Source*: Y. Murakami, T. Nomura, and J. Watanabe, "Heavy-Section 2.25 Cr–1 Mo Steel for Hydrogenation Reactors," pp. 383–417 in *Application of 2.25 Cr–1 Mo Steel for Thick-Wall Pressure Vessels*, ed. G. S. Sangdahl and M. Semchyshen, STP 755, American Society for Testing and Materials, Philadelphia, 1982.

(T/4) and the half thickness (T/2) for water quenching. The air-cooled 100-mm plates of heats A9349 (NT) and A9749, for example, were subjected to a cooling rate of 7°C/min, while the water-quenched 100-mm plate of heat A9349 (QT) cooled at a rate of 100°C/min at T/4. When these curves are superimposed on the CCT diagrams shown in Fig. 17, the microconstituents produced on cooling may be estimated. In the case of 2.25 Cr–1 Mo steel, all these cooling curves would pass through regions of the CCT diagram that indicate transformation to proeutectoid ferrite and pearlite followed by transformation of the remaining austenite to bainite at temperatures starting in the 450 to 550°C range.[34] The percentages of these constituents depend on cooling rate for a given composition and grain





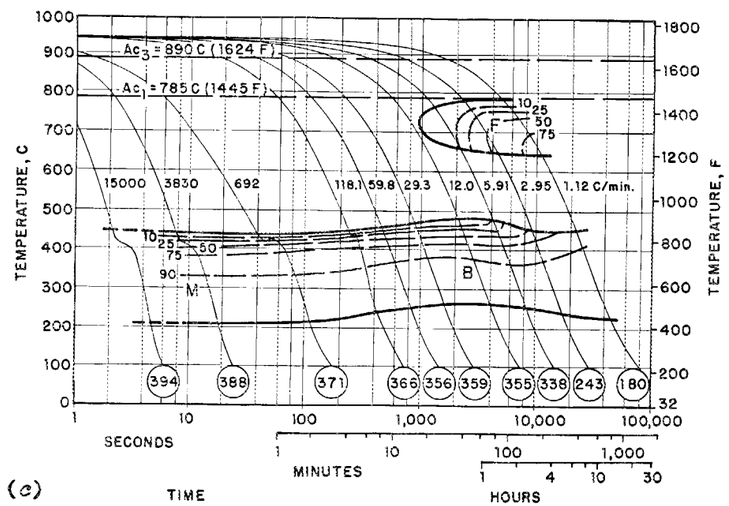


Fig. 17. Continuous-cooling transformation diagrams. (*a*) 2.25 Cr—1 Mo steel. (*b*) 3 Cr—1.5 Mo —V steel (heat P2074) with 1.4 % Mn. (*c*) 3 Cr—1.5 Mo—V steel (heat A9349). *Source*: T. Wada and T. B. Cox, "3 Cr—1.5 Mo Steel for Pressure Vessels in Hydrogen Service," pp. 81—98 in *Advanced Materials for Pressure Vessel Service with Hydrogen at High Temperatures and Pressures*, MPC 18, ed. M. Semchyshen, American Society of Mechanical Engineers, New York, 1982; T. Wada and T. B. Cox, "A New 3 Cr—1.5 Mo Steel for Pressure Vessel Applications," pp. 77—93 in *Research on Chrome-Moly Steels*, MPC 21, American Society of Mechanical Engineers, New York, 1984.

size. Proeutectoid ferrite increases with decreasing cooling rates. When present in large percentages, ferrite produces low tensile strength and poor toughness, which are undesirable properties for heavy-wall vessels. Bainite is preferred because of its excellent strength and toughness after tempering. Although not shown in the CCT diagram, the bainite changes in character, depending on the temperature at which it is formed. The granular and dislocated lath forms are discussed in some detail by Parker and co-workers, by Ritchie and co-workers, Richey, and by Klueh and Nasreldin in their investigations of microstructures in 3 Cr—Mo steels.[21,22,31,35]

BASE METAL HARDENABILITY

The CCT diagram determined by AMAX on a developmental heat of 3 Cr—1.5 Mo—V steel (heat P2074) containing 1.4% Mn is shown in Fig. 17(*b*).[20] Here it may be seen that for a fine-grained material (ASTM No. 7), in which ferrite formation would most likely occur, the material transforms to the desired bainitic microconstituent at cooling rates as low as 2.4°C/min. This excellent hardenability would allow heavy-section plates to be produced with fully bainitic microstructures.

The commercial heat of 3 Cr—1.5 Mo—V steel also indicated good hardenability on the basis of the Jominy bar test,[23] but the CCT determined by AMAX on this heat [Fig. 17(*c*)] indicated that some proeutectoid ferrite could be produced for cooling rates approaching 12°C/min, in spite of the coarser grain size (ASTM No. 5). The CCT diagram in Fig. 17(*c*) contains details regarding the percentage ferrite within the ferrite nose. Also, martensite is shown to be produced for cooling rates in excess of 100°C/min. It appears that the steel is completely transformed by the time the temperature drops below 200°C, and there is no evidence of retained austenite. Commercial heat A9349 produced lower diamond pyramid hardness (DPH) values for the same cooling rate than did laboratory heat P2074. These DPH values are circled in Fig. 17(*b*) and (*c*). This difference in hardenability and as-cooled hardness is probably due to the lower manganese content of the commercial heat. Referring back to Fig. 16, it may be seen

that, to avoid the nose of the ferrite transformation which occurs at 12°C/min for a grain size near ASTM No. 5, it will be necessary to water quench plates thicker than 200 mm.

The CCT curve for the 3 Cr–1.5 Mo–Ni steel has not been determined. However, Ritchie et al. examined the microstructures in the laboratory heats after oil quenching (1200°C/min) and slow cooling (8°C/min).[22] They observed 100% bainite by light microscopy, granular character to the bainite when viewed in the scanning electron microscope, and some retained austenite between the bainite laths when examined by transmission electron microscopy. High-resolution optical microscopy of heat A9749 air cooled at a rate of 7°C/min also indicated a fully bainitic microstructure.

Optical microscopy of the NKK heat of 3 Cr–1.5 Mo–V steel revealed a fully bainitic microstructure throughout the 250-mm thickness. This plate was roller quenched with cooling rates exceeding 10°C/min, so a fully bainitic microstructure would be expected if the CCT diagram shown in Fig. 17(*c*) were representative of the steel.

TRANSFORMATIONS IN WELDING

Because of the high cooling rates associated with most welding processes, weld metal deposits should develop microstructures typical of rapid cooling from the austenitizing temperature. For this reason, hardenability is not of great concern in weldments, and elements added for hardenability in the base metal are not needed in the weld metal. Therefore, either 2.25 Cr–1 Mo or 3 Cr–1.5 Mo steel could be used to weld the 3 Cr–1.5 Mo steels for service conditions where hydrogen attack is not a problem. The microstructures of the deposited weld metals confirm the fully bainitic microstructure in the 3 Cr–1.5 Mo–V steel.

The very rapid thermal excursion through the critical transformation temperatures that occurs during welding can produce microstructures in the weldments that are considerably different from those observed in heavy-section plates, which cannot be rapidly heated and cooled. The details of the transformation kinetics of all three commercial 3 Cr–1.5 Mo steels are under investigation at the University of Tennessee and the University of California.[22,31] Gleeble thermomechanical simulators are used to simulate

welding thermal cycles. The dilatometer on the Gleeble unit allows the critical transformation temperatures to be determined on heating and cooling. Data produced in this way permit the construction of CCT diagrams that apply to regions of the HAZ that pass through the critical temperatures and into the austenite region. A typical set of curves produced from Gleeble experiments on 3 Cr–1.5 Mo–V is shown in Fig. 18. These show the temperature versus log time trend for a series of welding heat input values ranging from 7 to 59 kJ/cm. Included in the curves are the temperatures for the bainite start, the bainite finish, and the resulting DPH hardness values. The high DPH data are consistent with the very high cooling rates indicated in Fig. 17(*c*). Similar curves have been produced for the 3 Cr–1.5 Mo–Ni steel (heat A9749). The microstructures produced by the rapid thermal transients are under intense study because they control the response to tempering of the HAZ. This region is the weakest link in nearly all low-alloy steels. Further work is needed to determine if the Gleeble simulations truly represent the microstructures in the HAZ of the heavy-section weldments. Such work is under way for the three

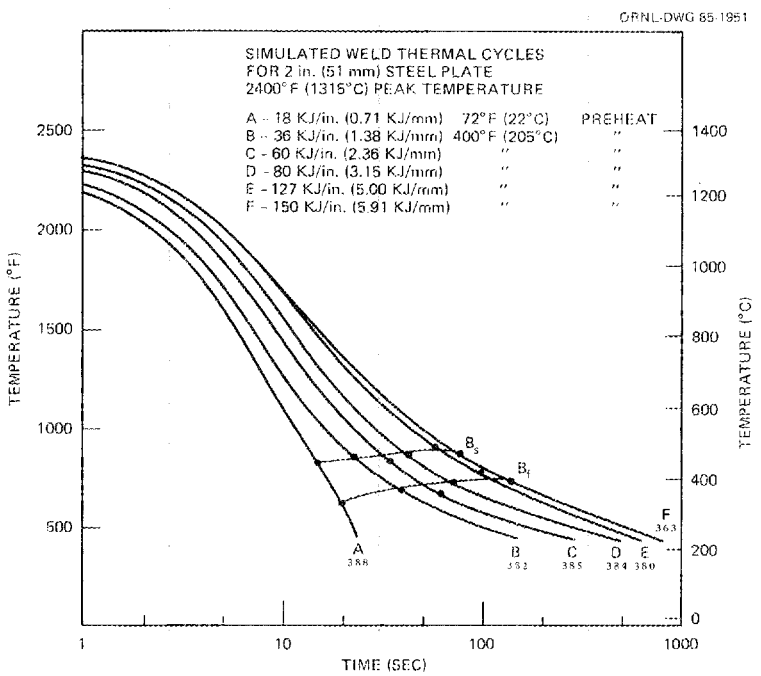


Fig. 18. Continuous-cooling transformation diagram for 3 Cr–1.5 Mo–V steel (heat A9349) obtained by Gleeble simulation of weld thermal cycles.

commercial heats under the sponsorship of the AR&TD program. It should be recognized that the heat input varies considerably from one welding process to another, and that the CCT diagrams produced by the Gleeble simulations are helpful in determining the microstructures and needed PWHT as a function of the welding process.

TEMPERING AND POSTWELD HEAT TREATMENT

The purpose of the tempering and PWHT is to temper the hard bainitic or martensitic microstructures for improved toughness and resistance to hydrogen embrittlement and hydrogen attack. Also, the residual stresses produced in thick-section weldments will be relieved while heating to the tempering conditions or during the tempering process. Much was written about the tempering response of the 3 Cr—1.5 Mo steels in the assessment report and in subsequent reports.[9,20,22,25,26,35] In the next section of this report the mechanical properties will be correlated with the tempering conditions.

The tempering studies on the 3 Cr—1.5 Mo steels were performed on both the commercial product forms and on small specimens machined from the products. In the construction of Code-approved pressure vessels, it is accepted practice to take samples from the tempered product at the T/4 location and well away from any edges that would experience cooling or heating conditions not representative of the product. This is particularly important for materials of low hardenability, such as 2.25 Cr—1 Mo steel, where the microstructure and properties may vary considerably through the thickness. The small laboratory heats and 100-mm-thick commercial plates of the 3 Cr—1.5 Mo steels exhibited uniform through-thickness microstructures, however, so that studies could be performed on either samples cut from tempered products or samples cut from untempered products that were subsequently tempered. Both procedures were used. Issues of some importance in the tempering response studies were the rate of heating to the tempering condition and the rate of cooling after tempering. In most cases the heating and cooling of specimens were performed at rates that were typical of thick-section tempering; i.e., the samples were furnace heated and furnace cooled.

Although the 3 Cr–1.5 Mo steels were known to temper more rapidly than 2.25 Cr–1 Mo steel, the strength for any tempering condition was expected to be greater for the 3 Cr–1.5 Mo steels, and, after an initial reduction in strength and gain in toughness, it was expected that further reduction in strength with tempering would be slower.[9,20] Thus it was expected that the 3 Cr–1.5 Mo steel would have a larger tempering window, and this feature would reduce the cost of construction of large, heavy-wall vessels fabricated from 3 Cr–1.5 Mo steel relative to 2.25 Cr–1 Mo steel (SA-542 class 3).

The steels were usually stress relieved after normalizing. Typically, these stress reliefs were at temperatures in the range from 566 to 621°C, which was well below the range for tempering and PWHT. The tempering severity is quantified by the value of the tempering parameter (TP) developed by Hollomon and Jaffee many years ago:[36]

$$TP = T(C + \log t)/1000 \ ,$$

where T is absolute temperature (K or R), t is time in hours at temperature, and C is a constant. Often, C is taken to be 20, which was the number proposed by Larson and Miller to correlate creep-rupture data rather than tempering response.[37] Nevertheless, when C is replaced by 20 in the above equation, the TP is often called the Larson-Miller parameter.

The temperatures examined in the tempering studies ranged from 663 to 700°C and the time from a few hours to 1000 h. In the construction of a vessel, of course, the times are kept to a minimum, but after several welding and welding repair cycles, some sections of a vessel may accumulate up to 40 h of tempering and PWHT. No studies were undertaken to examine the influence of multiple heat-treating cycles or the use of different time-temperature combinations for tempering base metal and PWHT of weldments. Such studies should follow if the work on weldments shows it to be necessary.

The detailed metallurgical changes that occur during the tempering process will not be discussed in this report, but information on the process for the 3 Cr–1.5 Mo steel may be found in reports previously cited and in the work of Shaw that was supported by the AR&TD program.[38]

Finally, the HAZ of weldments is essentially a tempered zone at the completion of the welding process. As each weld pass is laid down, the nearby material experiences a thermal cycle that depends on its distance from the pass, the heat input, and the welding speed. Thus, some regions of the weldment may experience virtually no tempering and other regions may be overtempered before the PWHT. Some studies have been performed on this problem but more work remains.[25,31]

An earlier section of this report mentioned that creep experiments were performed on samples of 3 Cr–1.5 Mo–V steel welded to a plate by the SA process in order to examine the tendency toward stress relief cracking during PWHT at temperatures in the range from 600 to 700°C.[20] The HAZ material of the SA weld, of course, included all the different tempered regions of a heavy-section weldment, and samples failed in the base metal in a ductile manner. The test actually evaluated strength, rather than ductility of the strongest but most brittle region, and was but one of several types of tests that have been developed to evaluate the tendency toward stress relief cracking. Another type of test performed at the University of Tennessee involved the simulation of the HAZ microstructure by the Gleeble followed by a creep test at temperatures in the range anticipated for the PWHT.[31] (See Fig. 19.) In this test essentially all of the material in the specimen has the same HAZ microstructure, whereas in the SA-welded specimens tested by Wada and co-workers only a small region contained a strongly embrittled HAZ microstructure.

Tests revealed that the laboratory heat of 3 Cr–1.5 Mo–V (P2904) had excellent ductility and was ranked above 2.25 Cr–1 Mo steel in resistance to SR cracking. Heat A9349 exhibited very poor creep ductility and ranked with the nuclear pressure vessel steel A302B, which has poor resistance to SR cracking. Similar examination of the 3 Cr–1.5 Mo–Ni steel revealed that this material was outstanding among the low-alloy steels in regard to resistance to SR cracking. The reason for these differences is unknown, and much work remains before answers are available. Work on the nuclear pressure vessel steels linked the propensity for SR cracking to the increased chromium, molybdenum, and vanadium content, but this is an inappropriate argument for alloys with greater than 1% chromium.[39] In fact, high-chromium

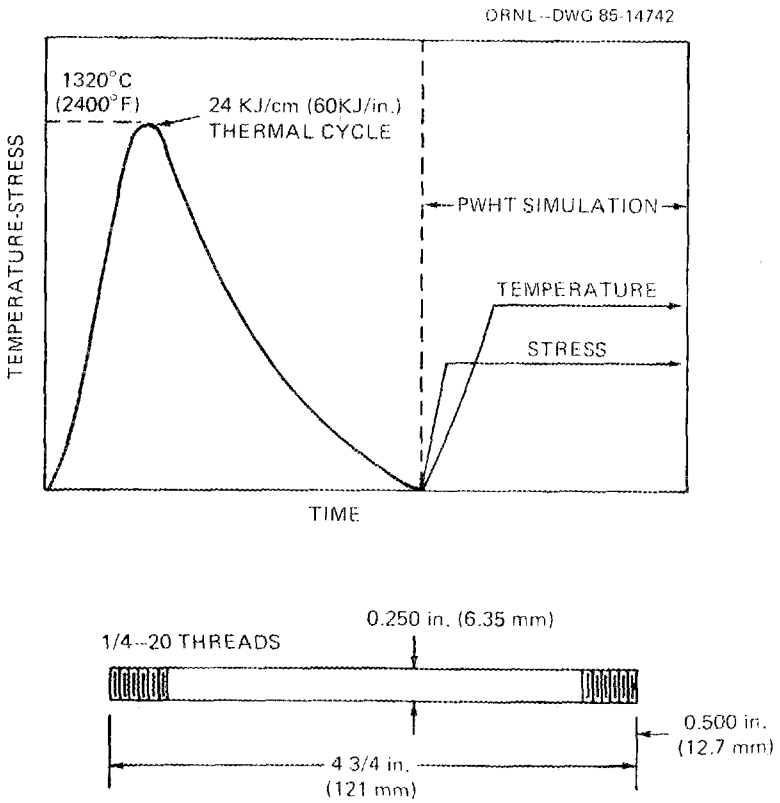


Fig. 19. (*a*) Schematic representation of the thermal treatment and stress cycle employed in SRC determination. (*b*) Gleeble sample employed in SRC evaluation. *Source*: M. W. Richey, *The Weldability of Cr-Mo Steels for Fossil Energy Applications*, M.S. Thesis, University of Tennessee, March 1984.

steels appear to be immune to SR cracking, as indicated in Table 4. High levels of phosphorus have also been blamed, but the differences in the phosphorus level of the 3 Cr-1.5 Mo steels is not great enough to explain the differences in behavior. On the positive side no SR cracking was observed in any of the weldments produced in the 3 Cr-1.5 Mo steel.

SUMMARY

In summary, CCT diagrams have been obtained from experiments on 3 Cr-1.5 Mo-V and 3 Cr-1.5 Mo-Ni steels. Similar information has been produced on simulated HAZ microstructures in these same steels. Data confirm excellent hardenability. The microstructural constituents consist of different forms of bainite, with some retained austenite for slow cooling or martensite for very rapid cooling. The steels have good

Table 4. Stress-rupture test results for 3 Cr–1.5 Mo and 2.25 Cr–1 Mo steels

Material	Postweld heat treatment (°C)	Postweld heat treatment (°F)	Reduction of area (%)
Berkeley 3 Cr–1.5 Mo–0.5 Ni	680	1250	27
	620	1150	24
P2904 3 Cr–1.5 Mo	680	1250	27
	620	1150	20
BP3 2.5 Cr–1 Mo–0.10 C	680	1250	25
	620	1150	13
646363-D 2.25 Cr–1 Mo–0.10 C	680	1250	22
	620	1150	8
3443 2.25 Cr–1 Mo–0.12 C	680	1250	19
	620	1150	3
JSW 3 Cr–1 Mo–V–Ti–B	680	1250	12
	620	1150	7
SA-533	620	1150	8
A517F[a]	620	1150	1.5
A9349-1A 3 Cr–1.5 Mo	680	1250	1.4
SA-508[a]	620	1150	0.5

[a]Known to have a significant susceptibility to stress relief cracking.

resistance to cold cracking, and no difficulty with stress relief cracking was encountered during the PWHT of weldments in 100-mm plates of 3 Cr–1.5 Mo–V steels. This is despite the poor performance of the commercial heat (A9349) in tests designed to establish the propensity for SR cracking. The 3 Cr–1.5 Mo–Ni steel weldment exhibited excellent response to PWHT, and the base metal of the commercial heat (A9749) was outstanding in the simulated SR cracking test. Additional work is needed to confirm these findings for heavy-section weldments.

MECHANICAL PROPERTIES

The mechanical properties of most interest in examining the potential of a new steel for gasifier construction are those that are required for setting the allowable design stresses in Sect. VIII, Divs. 1 and 2, of the ASME Code. For service to 316°C and Code approval to 371°C, the allowable stresses will most certainly be based on tensile properties, with the ultimate tensile strength (UTS) controlling. The properties reported below reflect this emphasis. The other properties are important, however, and are needed to assure Code groups that the steel's behavioral features are similar to those of other structural steels in the same general grouping. The supplementary data include impact properties, fracture toughness, fatigue, and performance in the service environment.

TENSILE PROPERTIES

The tensile and impact data for heavy-gage plate are determined at locations at least one-fourth of the thickness (T/4) from any cooled edge and at a depth of T/4 from the cooled surfaces. This rule assures that the test location will have properties that are more or less typical of the plate, should the microstructure and properties be cooling-rate dependent. The laboratory heats and small commercial heats of the 3 Cr–1.5 Mo steels exhibited through-thickness hardenability, and no differences were observed with respect to microstructure and mechanical properties of specimens machined from different locations. All samples from the 25-mm-thick laboratory heats were taken from the centerline (T/2) location. Samples from the 100-mm-thick plate (heat A9349) tested by Swift were also taken from the centerline[23,24] location. Specimens from the 100-mm-thick plates (heats A9349 and A9749) tested at ORNL were taken from five through-thickness locations that are identified in the data tables in Appendix A. Specimens were machined perpendicular to the plate rolling direction or welding direction. Testing methods used by all investigators conform to ASTM practice E-21; however, strain rate was a variable and ranged from 0.005 to 0.02/min, depending on the investigator. More than 200 tensile

tests were performed by the investigators to examine the effect of composition, TP, welding, and test temperature on the strength and ductility of the 3 Cr–1.5 Mo steels. A complete listing of the data is provided in Appendix A, and the trends for these data are summarized below.

The dependence of the room-temperature yield strength (YS), ultimate tensile strength (UTS), elongation (El), and reduction of area (RA) on the TP are shown in Figs. 20 and 21 for the different steels. As expected, the YS and UTS decreased and the El increased with increasing TP. To meet the alloy design criteria described earlier in the report, it is necessary to temper the alloys to UTS values in the range from 580 to 760 MPa. These levels are indicated on the right margins of the figures. Virtually all of the data indicate that this strength range can be achieved by tempering to TP in the range from 19.5 to 21. Two exceptions were noted. The data reported by AMAX on heat A9349 NT[29] indicated strength levels considerably below all others, and the singular test on the laboratory heat of 3 Cr–1.5 Mo–Ni steel[22] produced very high strength. Examination of testing strain rate and grain size effects revealed no strong influence on the UTS, although in one case some unexplained low YS data were obtained on heat A9349 NT [Fig. 20(*b*)].

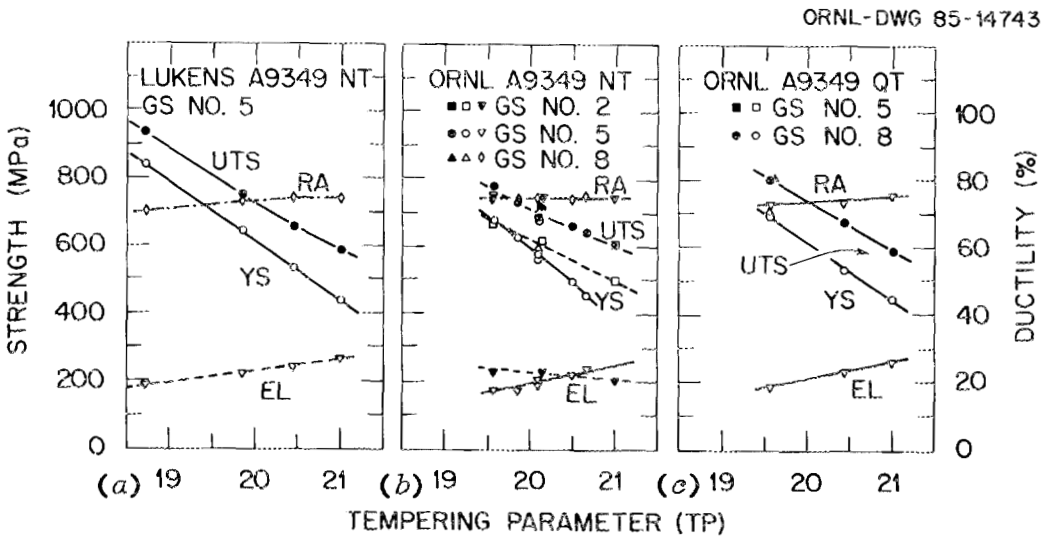


Fig. 20. Data on ultimate tensile strength (UTS), yield strength (YS), reduction of area (RA), and elongation (El) versus tempering parameter (TP) for a commercial heat of 3 Cr–1.5 Mo–V steel (heat A9349).

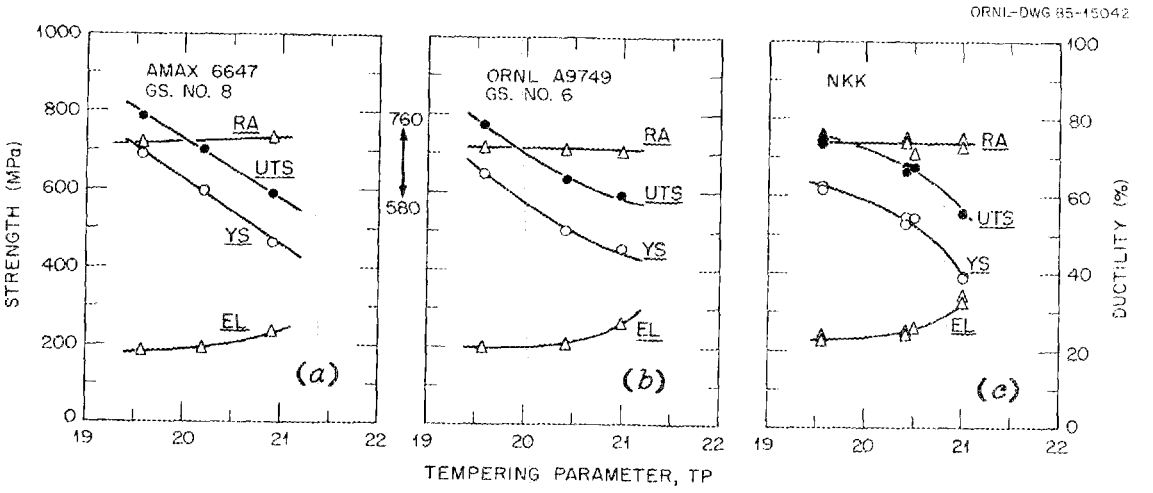


Fig. 21. Data on ultimate tensile strength (UTS), yield strength (YS), reduction of area (RA), and elongation (El) versus TP for 3 Cr–1.5 Mo steels. (*a*) 3 Cr–1.5 Mo–V (heat 6647). (*b*) 3 Cr–1.5 Mo–Ni (heat A9749). (*c*) 3 Cr–1.5 Mo–V (heat NKK).

The tempering curves from the UTS versus TP data are collected in Fig. 22 after discarding the anomalous data mentioned above. The data in Fig. 22 indicate that the tempering window is quite broad, with a TP of 19.8 required to bring the strongest heat to below 760 MPa and a TP up to 20.95 allowing the weakest heat to maintain its strength above 580 MPa. For a total of 24 h accumulated tempering time, the allowed temperatures would be from 653 to 707°C. This range is more than adequate for vessel fabricators and represents an improvement over the allowable tempering range for 2.25 Cr–1 Mo steel.

The effects of temperature variations on strength and ductility properties are shown in Figs. 23, 24, and 25 for the TP values around 19.56, 20.44, and 21.0, respectively. The steels lose about 100 MPa of their UTS as the temperature increases from 25 to 316°C. The exception is the 3 Cr–1.5 Mo–Ni steel, which retains more of its strength than the others. Above 400°C there appears to be a substantial variation in the strength and ductility data from heat to heat that may be due to either testing variables or actual differences from one steel to another. Considerably more data are needed to define the strength properties for temperatures

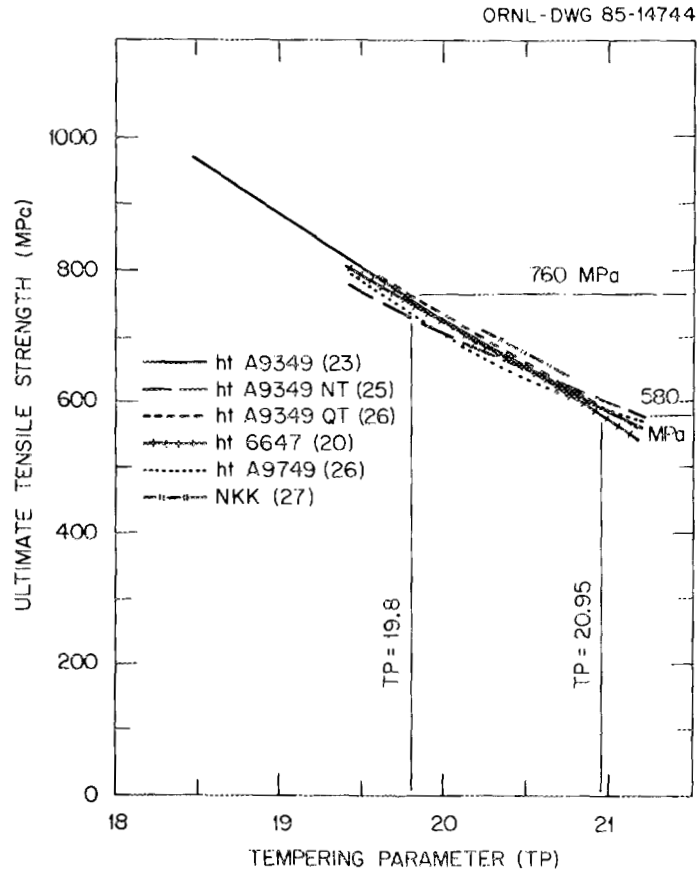


Fig. 22. Comparison of ultimate tensile strength (UTS) versus tempering parameter (TP) for various heat treatments of 3 Cr–1.5 Mo steels.

above 400°C. Additional work is also needed before the ratio of elevated-temperature strength to room-temperature strength can be established with any degree of confidence. Results from preliminary estimations have been reported, however, and form the basis for estimating the strength levels that might be provided as part of a Code information package.[29]

All the ductility indices appear to be satisfactory, including the uniform strain. The available data for this ductility index are provided in the tables in Appendix A.

As mentioned in the previous section of this report, the carbon and vanadium levels of the initial SA weld wire and SMA electrodes were selected to be less than those of the base metal in order to avoid problems with weldability. In hindsight, these precautions were not

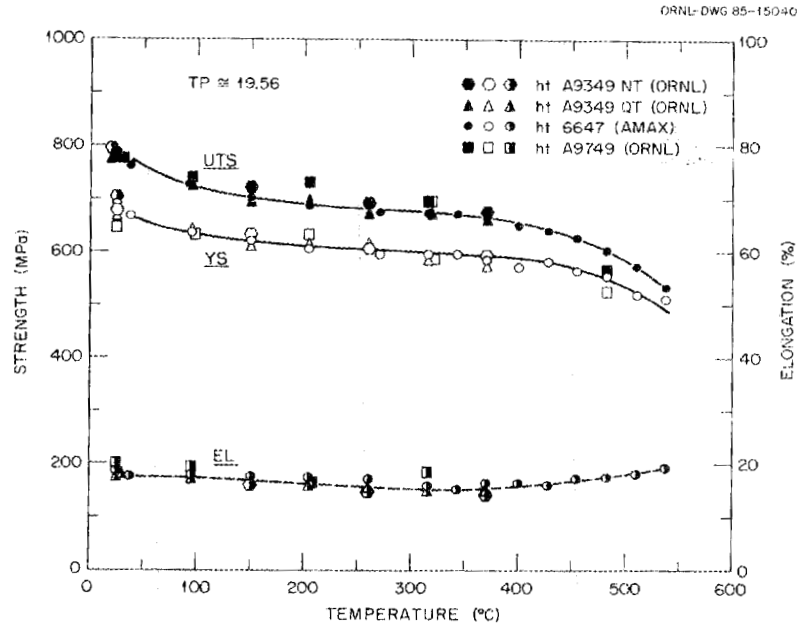


Fig. 23. Data on ultimate tensile strength (UTS), yield strength (YS), and elongation (El) versus temperature for 3 Cr—1.5 Mo steels tempered to TP of 19.56.

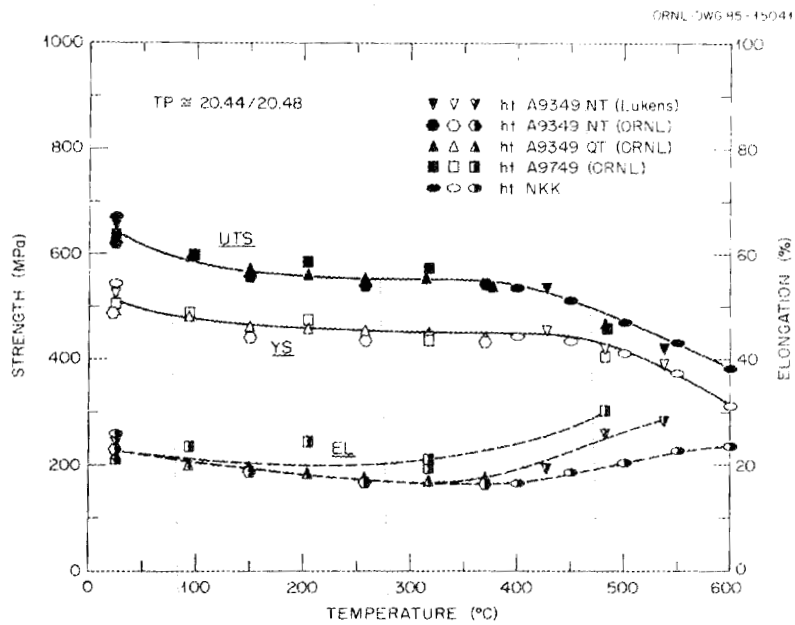


Fig. 24. Data on ultimate tensile strength (UTS), yield strength (YS), and elongation (El) versus temperature for 3 Cr—1.5 Mo steels tempered to TP of 20.44 to 20.48.

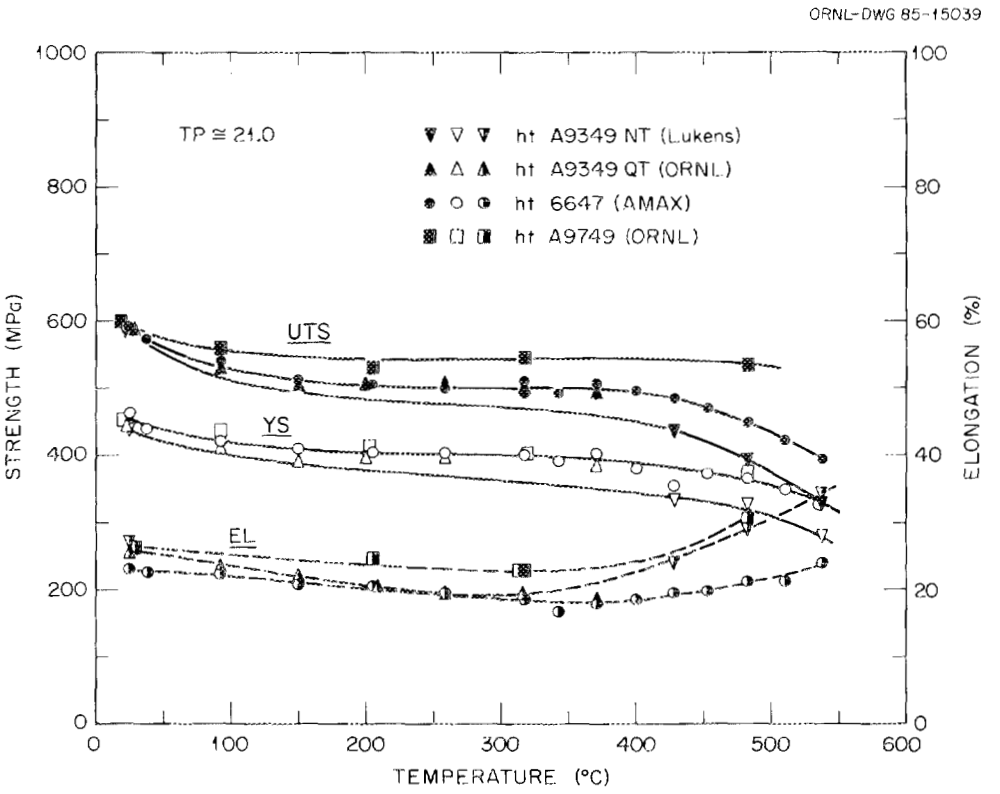


Fig. 25. Data on ultimate tensile strength (UTS), yield strength (YS), and elongation (El) versus temperature for 3 Cr–1.5 Mo steels tempered to TS of about 21.0.

necessary and only served to produce low strength in the deposited weld metal. The tensile properties of SA weld metal are provided in Fig. 26, and similar data for SMA weld metal are provided in Fig. 27. Other data are tabulated in Appendix A, including the results of exploratory testing of material containing the HAZ. Trends for the SA weld metal in Fig. 26 suggest that the weld metal is weaker than the base metal for the same value of the TP. However, the strength increases with carbon level, as may be seen by comparing the data in Fig. 26(*b*) with Fig. 26(*c*). To bring the strength of the SA weld metal within the range expected for base metal, it will be necessary to specify a SA weld wire composition that would increase the deposited carbon content in the weld deposit to levels near the base metal. Another option would be to reduce the PWHT conditions to TP values in the 19.0 to 20.0 range. Such a course of action would also avoid overtempering of the material in the HAZ that does not pass through

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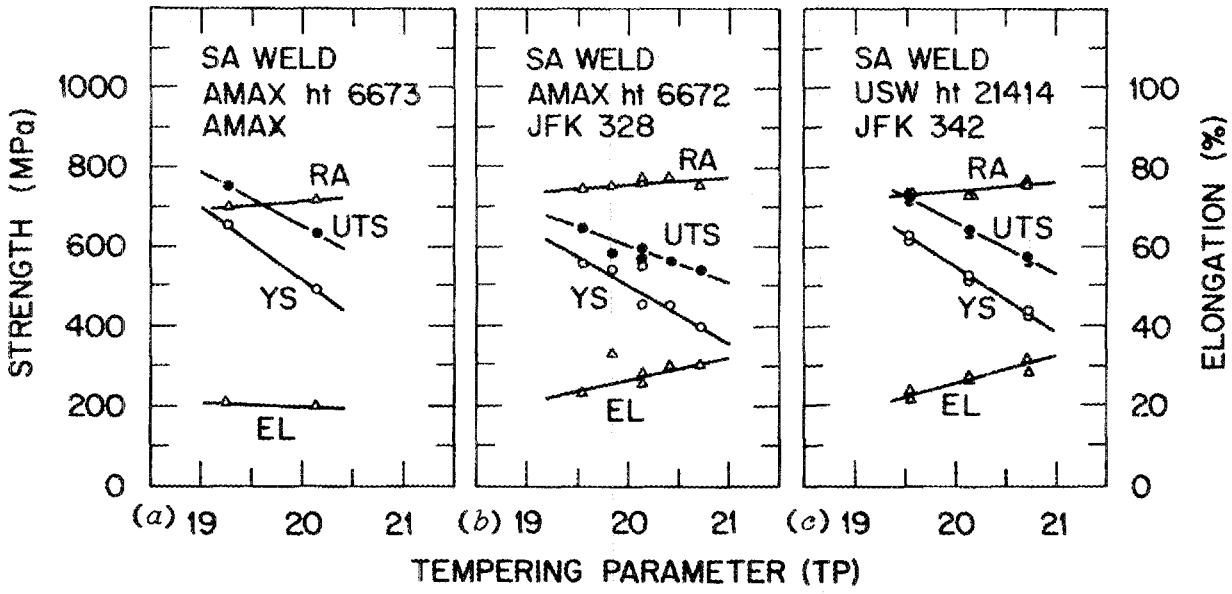

Fig. 26. Data on ultimate tensile strength (UTS), yield strength (YS), reduction of area (RA), and elongation (El) versus TP for submerged arc welds in 3 Cr–1.5 Mo steels.

the transformation temperature during the weld thermal cycle. Either method is feasible, but further work would be needed to confirm our expectation that the weld metal strength can be matched to the base metal for all heats.

The tensile properties of the SMA welds were found to be rather erratic, as indicated by the data plotted in Fig. 27. Here only a narrow range of TP values was examined and large variations in strength were observed. The strongest of the SMA welds approached the strength of the base metals. Reasons for the variations in response are several and stem from the fact that the SMA process is a manual process that inherently produces more variation in the chemical composition and microstructure of the weld metal deposit and nearby HAZ. Also, the SMA weld is narrow and more difficult to test in a direction transverse to the welding direction. Base metal, HAZ, and weld metal may be present in the test section.

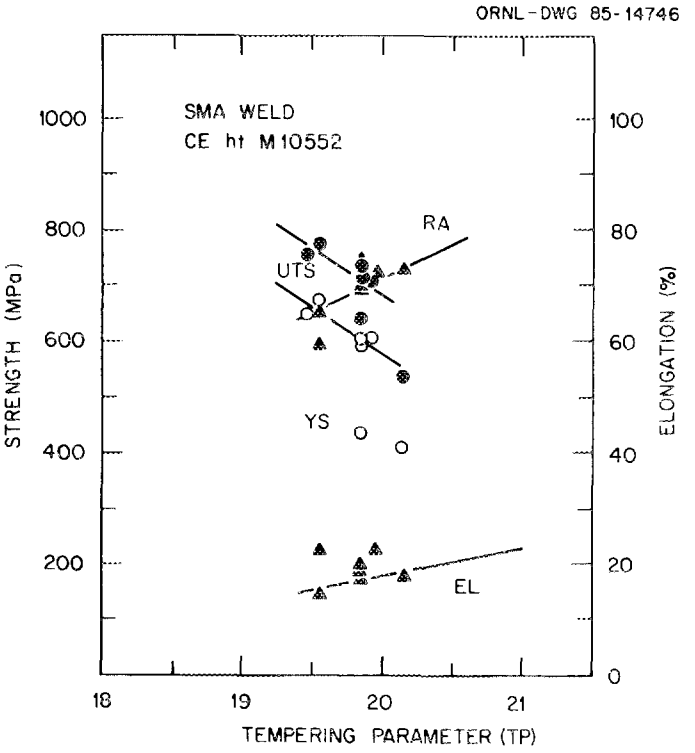

Fig. 27. Data on ultimate tensile strength (UTS), yield strength (YS), reduction of area (RA), and elongation (El) for shielded metal arc welds in 3 Cr–1.5 Mo–V steel.

Before commercialization of the 3 Cr–1.5 Mo steels, more work needs to be performed on SMA welds to optimize electrode compositions and PWHT for strength and consistency. Again, the excellent hardenability of the 3 Cr–1.5 Mo steels is not needed for the success of the SMA welding process. Possibly, 2.25 Cr–1 Mo steel electrodes could be used and the PWHT conditions reduced accordingly.

The effects of temperature variations on the strength and ductility of SA and SMA weld metals are illustrated in Figs. 28 and 29 for two values of the TP, and data are provided in Appendix A. The strength data at high temperature are as erratic as those produced at room temperature and suggest that more testing of weldments is needed to better define weldment performance. Trends for the higher carbon weld deposits are similar to those observed for base metal, but additional testing of the HAZ under tensile loading is needed to assure that the overtempered region of the HAZ will present no problems.

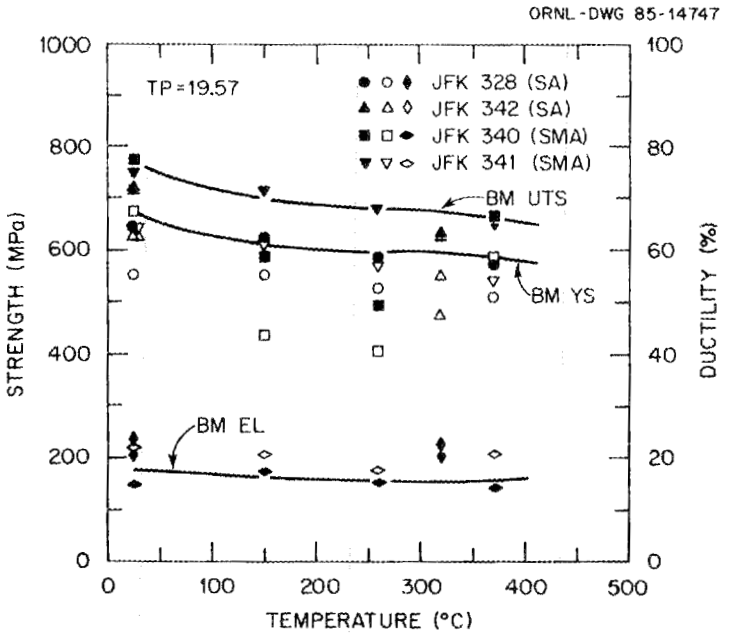

Fig. 28. Data on ultimate tensile strength (UTS), yield strength (YS), and elongation (El) versus temperature for base metal (BM) and for submerged arc and shielded metal arc welds in 3 Cr–1.5 steels for TP of 19.57.

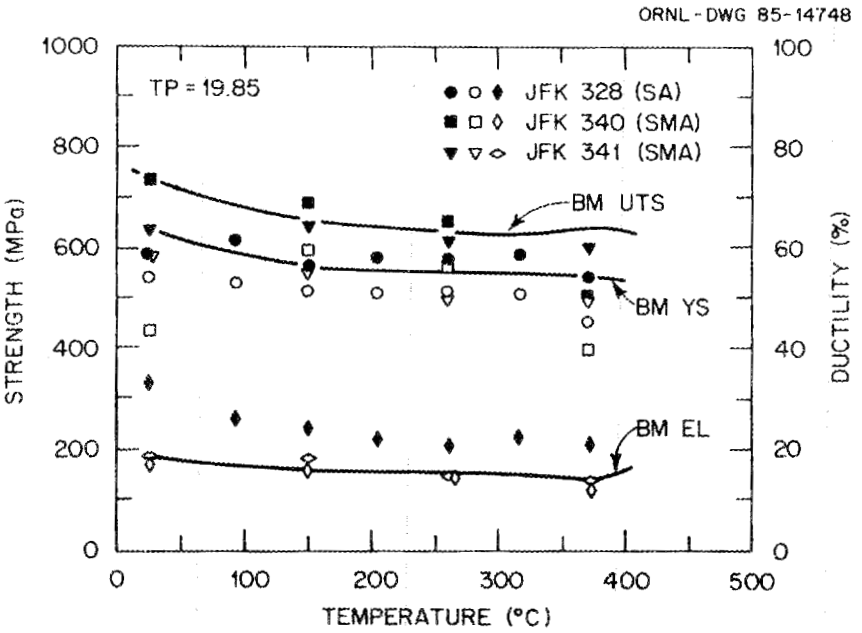

Fig. 29. Data on ultimate tensile strength (UTS), yield strength (YS), and elongation (El) versus temperature for base metal (BM) and for submerged arc and shielded metal arc welds in 3 Cr–1.5 Mo steels for TP of 19.85.

Summarizing the results of the tensile testing work, it appears that the 3 Cr–1.5 Mo steels are not very sensitive to composition, melting practice, cooling rate, and heat or product size. Data indicate that the steels may be tempered over a broad range of conditions to produce high strength and adequate ductility. Weld metal must match the base metal in regard to carbon content, or the PWHT for weldments must be at lower values of the TP than recommended for base metals in order to meet base metal strength. More mechanical testing of weldments is needed to establish a data base for Code action.

CHARPY V-NOTCH IMPACT PROPERTIES

Although the Charpy V-notch (CVN) impact properties do not enter directly into vessel design, minimum properties are specified in the ASME Code, Part AM of Sect. VIII, Div. 2, and they influence procurement specifications, fabrication procedures, heat treating schedules, vessel testing procedures, and vessel operation. Depending on the UTS range, low-alloy steels may have to meet minimum Charpy-V impact energy levels at the minimum operating temperature of the vessel, or, in the case of high-strength low-alloy steels, exhibit more than a minimum lateral expansion in the Charpy test. Vessel fabricators generally go well beyond the minimum requirements in the Code and evaluate the steels on the basis of several toughness indices derived from Charpy and fracture mechanics testing. In the data described below, we provide, when available, the full curves of Charpy-V impact energy (CVE) versus temperature, and derived properties such as the 54-J transition temperature (TT54), the 50% ductile fracture appearance transition temperature (FATT), the mid-energy transition temperature (METT), the room temperature CVE, and the upper shelf energy (USE). Because of the large data base, the information includes only test data for the commercial steels. Those derived properties are often correlated against the TP or the UTS as a correlating parameter; in this section, the UTS is used for that purpose. Further, in the design and selection of alloy compositions only one toughness criterion was chosen: at least 54-J CVE at –18°C. Thus, the TT54 was of most concern, even

though the lateral-expansion data are required by the Code for the high-strength steels. The TT54 criterion represents the state of the art in low-alloy steel production in the petroleum and petrochemical industries.

The Charpy curves for the steel are provided in Figs. 30 and 31. Data reveal the general range of scatter typical of Charpy curves and also indicate a gradual rise from low CVE at low temperatures to the upper shelf. This transition occurs over a temperature interval from 100 to 200°C. Most of the curves drawn through the data represent a least-squares fit to a hyperbolic tangent function (25). As expected, the curves shift to higher energies and lower temperatures with increasing TP or decreasing UTS, and all indicate excellent upper shelf energies in the stress-relieved condition before tempering.

The various toughness indices are plotted against the UTS in Fig. 32. The correlation of the TT54 with UTS, for example, is shown in Fig. 32(*a*). Here in the UTS range of interest (580 to 760 MPa) all the steels exhibit

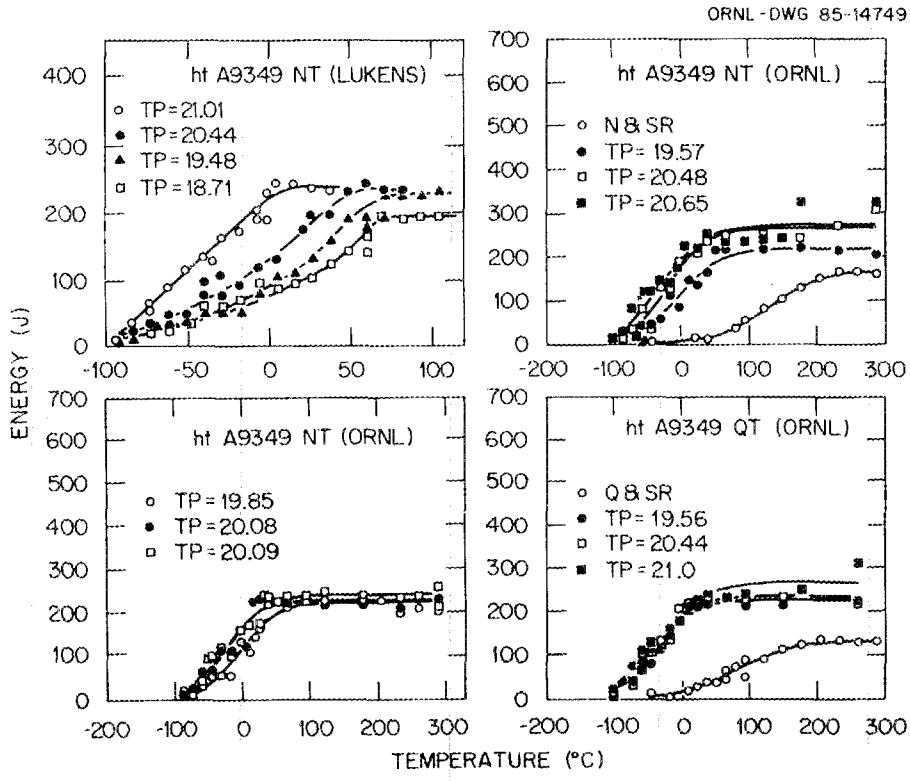

Fig. 30. Data on Charpy-V impact energy (CVE) versus temperature for 3 Cr–1.5 Mo–V steel (heat A9349).

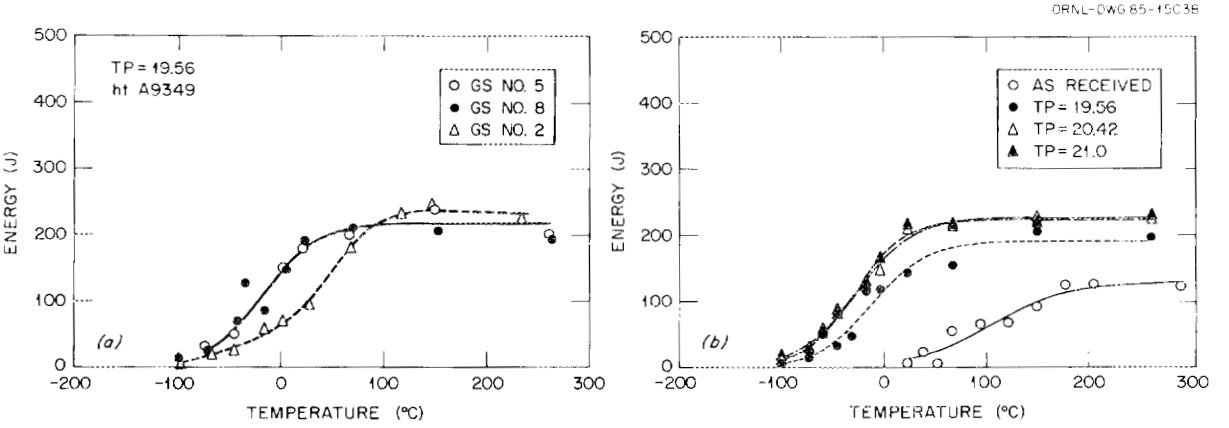

Fig. 31. Data on Charpy-V impact energy (CVE) versus temperature for 3 Cr—1.5 Mo steels. (*a*) Grain size effects in heat A9349. (*b*) TP effects in heat A9749.

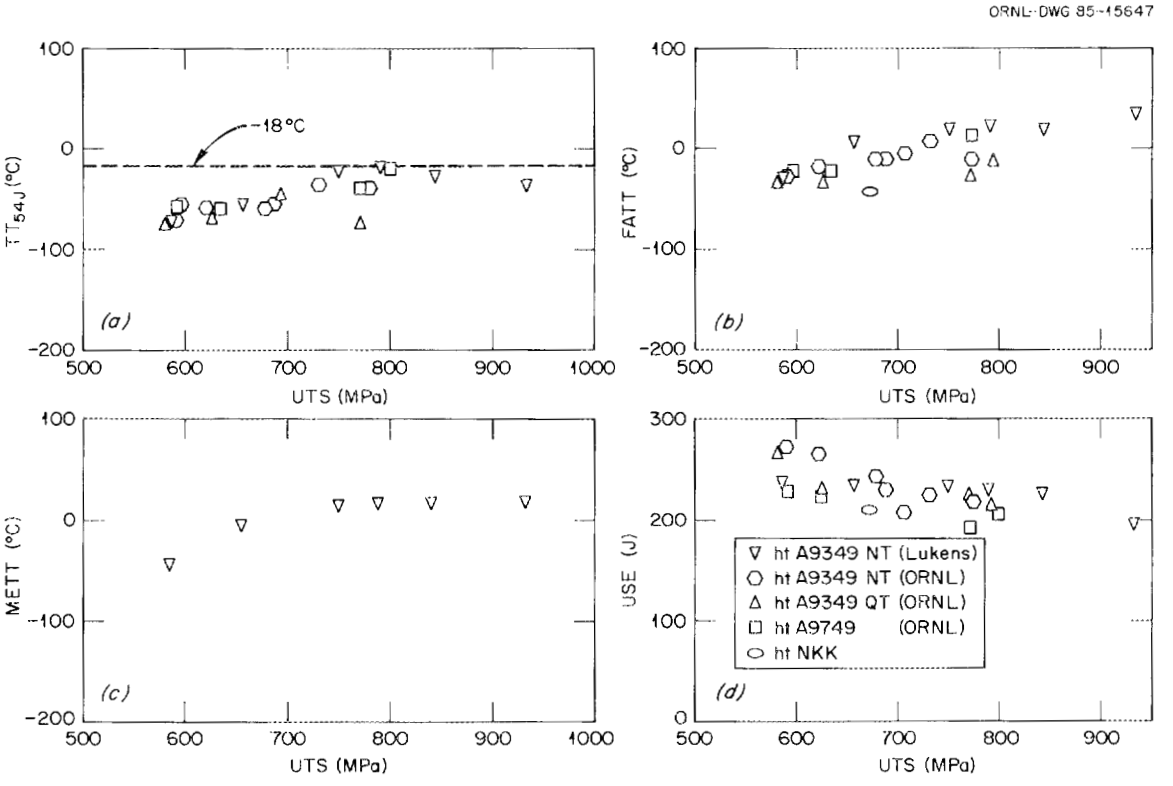

Fig. 32. Variation of (*a*) 54-J transition temperature (TT54), (*b*) fracture appearance transition temperature (FATT), (*c*) mid-energy transition temperature (METT), and (*d*) upper shelf energy (USE).

similar behavior and increase their TT54 values with increasing UTS. All steels meet the criterion of a TT54 below −18°C, even at UTS levels well above 760 MPa. Thus, the impact properties of the steels are excellent. The FATT and METT data are plotted against UTS in Fig. 32(*b*) and (*c*). These data also show rising values with increasing UTS, but they indicate acceptable impact resistance in the UTS range of interest for a new steel. Indeed, the 3 Cr–1.5 Mo steels appear to be superior to 2.25 Cr–1 Mo steel in regard to impact resistance, as reported earlier.[9,18] The USE data are plotted against UTS in Fig. 32(*d*). These data indicate excellent toughness at all UTS levels. Because of the inherent variability of CVN data, no significance is attached to differences in the data for the different steels, and impact properties of all the 3 Cr–1.5 Mo steels are judged to be equally good. More details of the correlation of CVN data with TP, UTS, and microstructure are available in several of the references.[1,14–26]

The CVE versus temperature curves for SA weld metals are provided in Figs. 33 and 34. The data in Fig. 33 are for tests performed by AMAX and

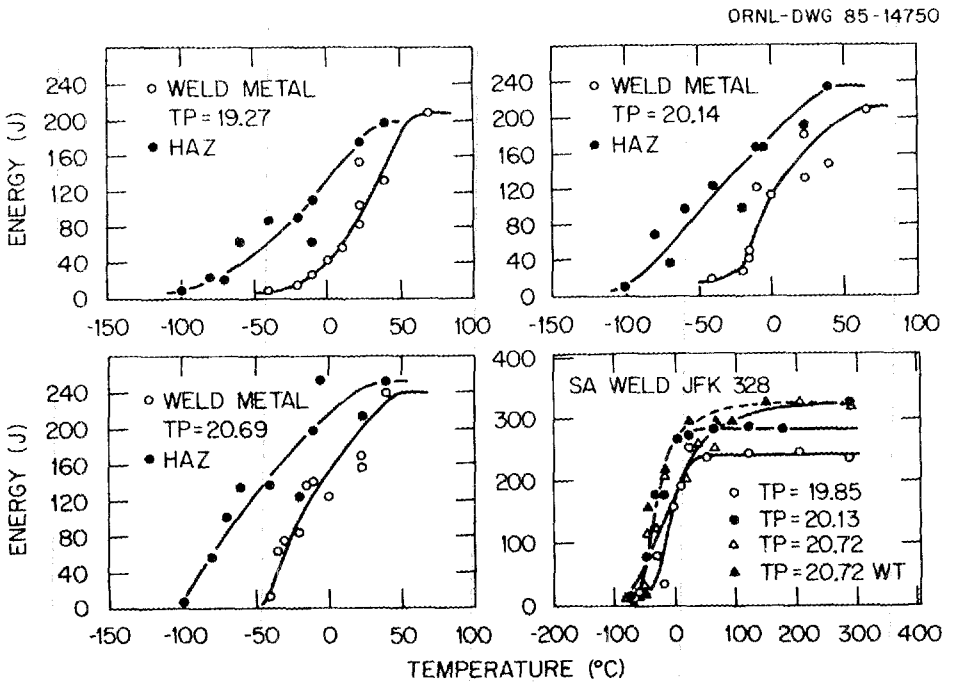

Fig. 33. Data on Charpy-V impact energy versus temperature for 3 Cr–1.5 Mo–V (heat A9349) submerged arc weld metals. *Source*: T. Wada and T. B. Cox, *Preparation and Evaluation of Submerged-Arc Weld in 4 In. Thick 3 Cr–1.5 Mo–0.1 V Steel Plate*, Report CP-253, AMAX Research Laboratory, Ann Arbor, Mich., December 15, 1983.

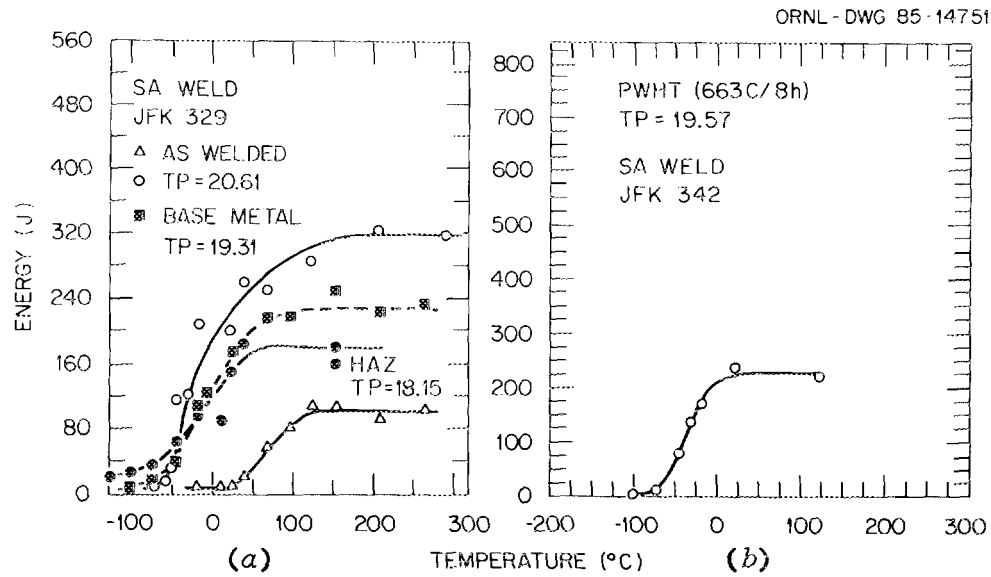

Fig. 34. Data on Charpy-V impact energy versus temperature for submerged arc welds (*a*) JFK 329 and (*b*) JFK 342 in 3 Cr–1.5 Mo–V steel (heat A9349).

ORNL on SA welds of heat A9349 NT (welds WAMAX and JFK 328). Included in the AMAX work were tests on both weld metal and HAZ material after three TP values. In the AMAX examination the weld metal had a higher TT54 than the HAZ material and did not meet the goal of −18°C or below for the two lower TP values. The CVN properties of the HAZ material were very good. The SA weld produced at ORNL exhibited excellent CVN properties at all values of the TP, and only one sample at the TP of 19.85 fell below the desired energy level. Additional Charpy data for SA welds are provided in Fig. 34. The first set of curves in Fig. 34(*a*) show the results of some tests, on weldment JFK 329 in heat A9349 NT, which included evaluation of the base plate, the weld metal in the stress-relieved and tempered conditions, and HAZ material. The low TP for the base metal (19.31) represents material in a stress-relieved condition (663°C for 2.5 h), while the low value of the TP for the HAZ represents another stress-relief condition (621°C for 2.5 h) before PWHT. All data, except for the as-welded weld metal, indicate excellent CVN properties. The higher carbon- and vanadium-bearing weld metal in weldment JFK 342 (heat A9349 NT) also had good CVN properties at the only value of the TP that was examined [see Fig. 34(*b*)].

Thus, although only a small number of SA welds and tempering conditions were examined, the CVN data for the SA welds in the 3 Cr—1.5 Mo steels are adequate for assessing the potential of the alloy group. The shapes of the curves for the SA welds show trends similar to those of base metal, and the derived data can be obtained readily.

The TT54, FATT, and USE data are plotted as a function of the UTS in Fig. 35. Here, the first weld produced in heat A9349 (the AMAX weld) did not meet the criterion of TT54 at −18°C, except for the highest TP condition, which also produced an undesirably low strength. The ORNL weld JFK 328 and the higher carbon level in JFK 342 solved this problem, and it appears that the SA welds can be produced with excellent impact properties. The other derived impact properties provided in Fig. 35 (the FATT and USE) are considered to be satisfactory.

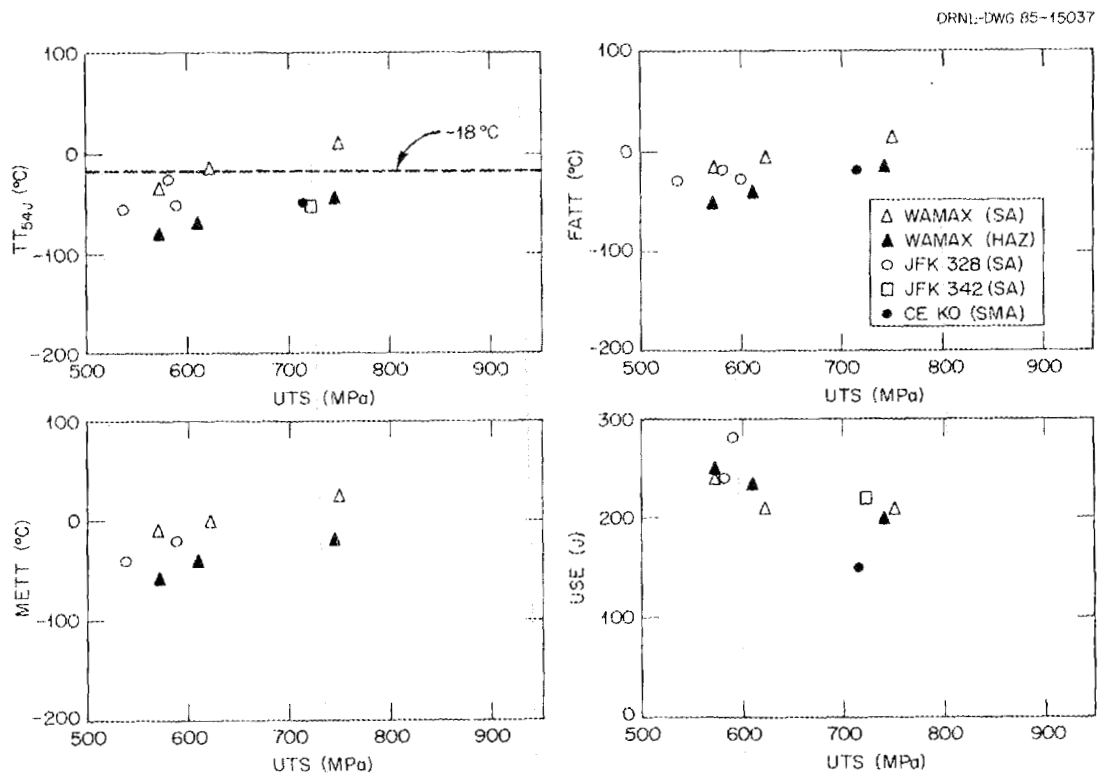

Fig. 35. Data on TT54, FATT, METT, and USE versus UTS for submerged arc and shielded metal arc welds in 3 Cr—1.5 Mo steels.

The CVN impact properties of the SMA welds were excellent and are summarized in Fig. 36. The work at CE showed that there was no sacrifice in impact properties with increasing carbon and vanadium levels in the 3 Cr–1.5 Mo steel (heat A9349), and that good values for the TT54, FATT, and USE could be produced at low values of the TP. This observation is important if the PWHT is to be at lower TP values than those for base metal. Clearly, more work needs to be performed on SMA welds for the 3 Cr–1.5 Mo–Ni and NKK steels.

The CVE versus temperature curves for EB welds in heat A9349 are shown in Fig. 37. Again, these curves indicated excellent impact resistance for weldments made with this process.[32]

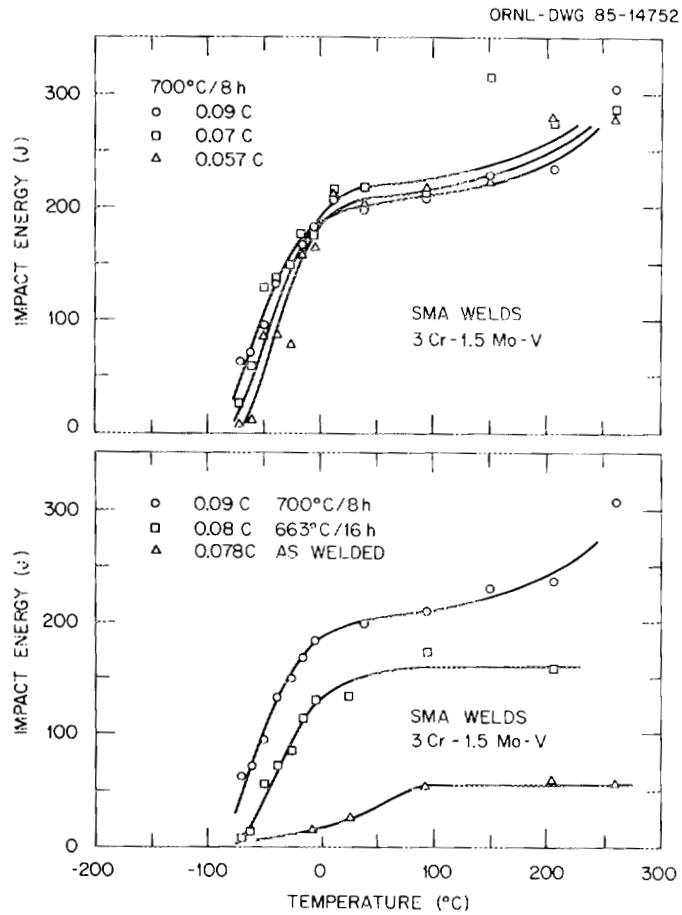

Fig. 36. Data on Charpy-V impact energy versus temperature for shielded metal arc welds in 3 Cr–1.5 Mo–V steel (heat A9349).

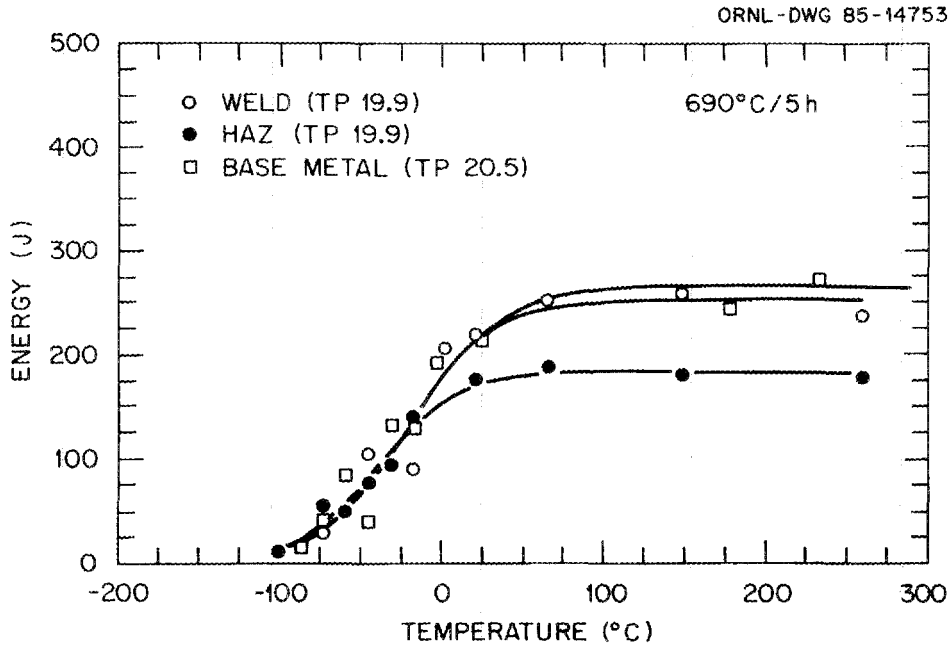

Fig. 37. Data on Charpy-V impact energy versus temperature for electron beam welds in 3 Cr–1.5 Mo–V steel (heat A9349 QT).

The exploration of the impact properties of the HAZ in SA welds by AMAX and ORNL for heat A9349 (refs. 25, 29) needs to be extended to the other steels. Although data trends suggest no problem with the HAZ, current information suggest that the HAZ is composed of a very complicated metallurgical structure of varying hardness and toughness relative to the weld metal and base metal. In a typical Charpy specimen it is difficult to locate the notch in the most brittle region and assure propagation in that plane. Additional studies of the HAZ CVN properties must continue as the welding consumables, procedures, and PWHT are being finalized.

In summary, the Charpy impact properties of the 3 Cr–1.5 Mo steels are excellent for base metals, weld metals, and HAZ materials. The data base needs to be extended to demonstrate that increasing the weld metal strength by increasing the deposited carbon content or reducing the PWHT will not reduce the CVN properties below the acceptable levels.

FRACTURE TOUGHNESS

As a preliminary investigation of fracture toughness, 25.4-mm-thick compact specimens were tested at room temperature to determine J-integral

tearing resistance (J-R) behavior. Two specimens were tested for each of three tempering parameters, 19.56, 20.44, and 21.0, for the quenched and tempered steel.

Testing of compact specimens was performed by the single specimen compliance (SSC) technique. All compact specimens were side-grooved on each side by 10% of the specimen thickness. The SSC technique provides a method to determine the amount of specimen crack extension by means of small unloadings (<15% of maximum load) conducted at regular intervals throughout the test.

Values of the J-integral were calculated by using the modified version of the J-integral, known as J_M, proposed by Ernst.[40] J_M is given by:

$$J_M = J_D - \int_{a_0}^{a} \frac{\partial [J_D - G]}{\partial a} \bigg|_{\delta_{pl}} da \ , \qquad (1)$$

where

J_D = deformation theory J,

G = Griffith linear elastic energy release rate = $K_I^2(1 - \nu^2)/E$,

a_0, a = the initial and current crack lengths,

$J_D - G = J_{pl}$, the plastic part of the deformation theory J,

δ_{pl} = the plastic part of the displacement,

ν = Poisson's ratio.

Deformation theory J (J_D) contained in Eq. (1) is the formulation of the J-integral specified for use in the ASTM Standard Test for J_{Ic}, A Measure of Fracture Toughness, E813-81, and in the tentative ASTM J-integral resistance (J-R) curve test procedure described by Albrecht et al.[41] Modified J (J_M) was used in this study because Ernst has shown it to be more specimen-size independent when the crack extension exceeds the J-controlled crack growth regime.

A typical R curve produced with the SSC technique is illustrated in Fig. 38. The R curve format of Fig. 38 is in accordance with that of ASTM Standard E813, i.e., J_{Ic}, the initiation elastic-plastic fracture

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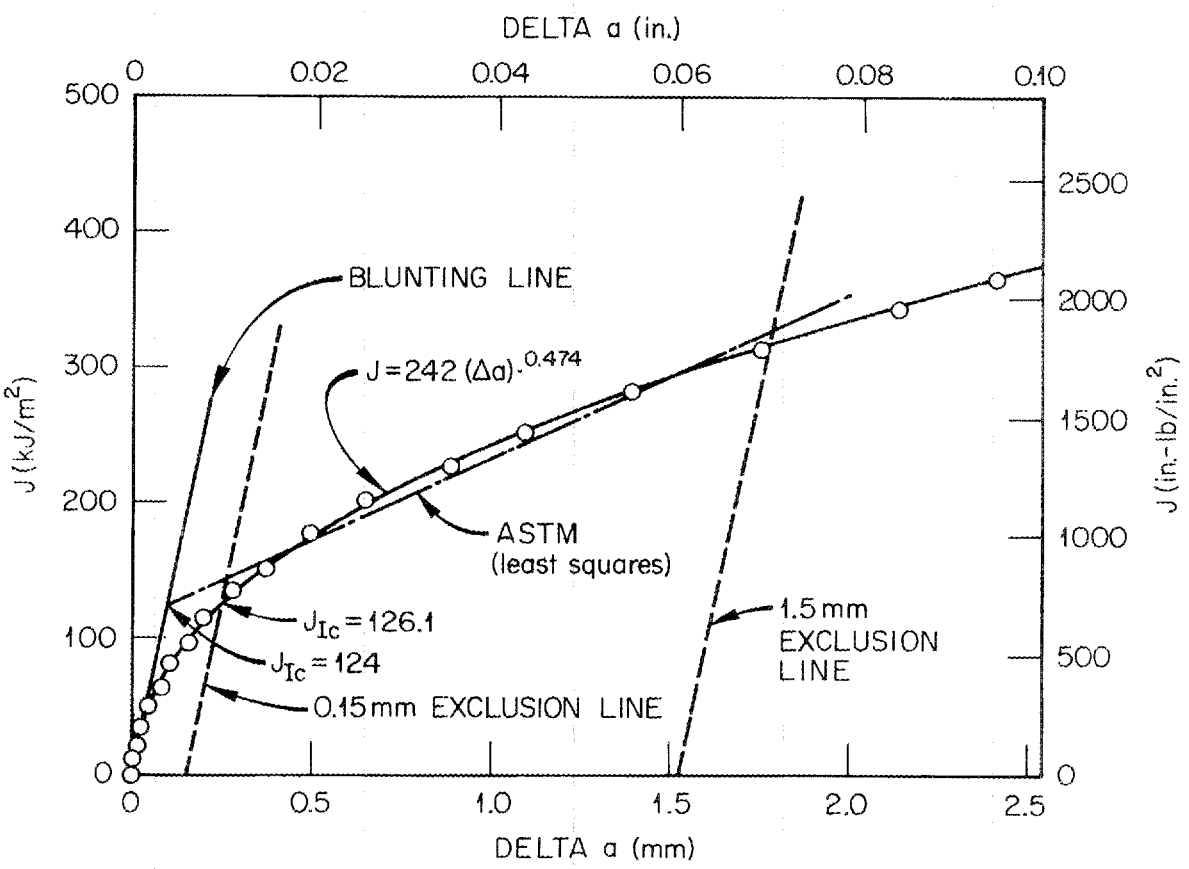

Fig. 38. Power law representation of the J–R curve using the single specimen compliance (SSC) test technique, and comparison with the ASTM E813 procedure.

toughness, is defined by the intersection with the blunting line of the linear regression fit to the data between the 0.15- and 1.5-mm exclusion lines. The use of linear least-squares fit stems from the multispecimen nature of ASTM E813, where a minimum of only four data points is required. Thus, with only a few data points, the nonlinear nature of the R curve cannot be evaluated. For this study, we also used the procedure proposed by Loss,[42,43] whereby a power law, $J = C(\Delta a)^N$, is fit to the data between the 0.15- and 1.5-mm exclusion lines with the constants C and N chosen to optimize the curve fit. The initiation fracture toughness, J_{Ic}, is defined with this procedure as the intersection of the power law

R curve with the 0.15-mm exclusion line as indicated in Fig. 38. In addition to more closely describing the nonlinear behavior of the R curve, the power law J_{Ic} definition provides a consistent means for determining the initiation toughness when fast fracture, i.e., brittle fracture by a cleavage micromode, occurs before development of a full R curve.

Another effect resulting from the nonlinear nature of the R curve is that the tearing modulus[44] is not constant as was originally envisioned by ASTM E813. For comparison purposes and consistency with ASTM E813, a single value for the tearing modulus (T_{avg}) can be computed from the power law equation for R curves. The tearing modulus is defined as:

$$T = \frac{E}{\sigma_f^2} \frac{dJ}{da} , \quad \text{(ref. 44)} \tag{2}$$

where σ_f = (yield strength + ultimate strength)/2.

To obtain an average value for the slope of the power law R curve, the power law equation is fit in closed form with a linear regression of the form $J = J_o + (dJ/da)\Delta a$ to that part of the curve lying between the exclusion lines. This technique is directly analogous to the E813 method of fitting a linear line to the discrete data points. However, fitting the power law equation has the effect of including an infinite number of points. Little difference in magnitude is observed between the values of T obtained by the two techniques.

The power law and E813 methodologies produce similar results in regions covered by the E813 standard.[45,46] According to Hawthorne[45] and Hiser,[46] the power law method also provides a means to obtain values for the linear elastic fracture toughness (K_{Ic}) that are generally within 10 to 15% of those using the procedures of ASTM Standard E399. The procedure is to convert the elastic-plastic J_{Ic} power law initiation toughness to a quasielastic K_{Jc} value using the following relationship:

$$K_{Jc} = [EJ_{Ic}]^{0.5} . \tag{3}$$

Equation (3) is identical to the E813 equation. Some researchers include a plane-strain term in the equation. A plane-strain term was not included here because specimens experienced net section yielding. Such behavior is closer to plane stress than it is to plane strain.

The results of the J-R tests are summarized in Table 5 and shown graphically in Figs. 39 through 41. Figure 39 shows that both the initiation fracture toughness, J_{Ic}, and the tearing modulus, T, increase with an increasing amount of tempering. The effect is most dramatic in the case of the tearing modulus and emphasizes the observation that increased tempering of this steel significantly increases its resistance to ductile tearing. Even though the specimens at the lowest tempering parameter failed by ductile-dimple processes, the increased tempering resulted in much higher energy impact to achieve the same degree of crack growth. Since the elastic modulus does not change appreciably with tempering, changes in K_{Jc} are the same as those for J_{Ic}. It is interesting to compare the J-R test behavior with that of Charpy impact tests, and Fig. 41 shows a plot of K_{Jc} versus Charpy upper-shelf energy. As can be seen, the K_{Jc} increases with increasing upper-shelf energy and, by inference, one can observe that all the ductile toughness measurements discussed have increased with the tempering parameter.

Table 5. Results for J-R tests of 3 Cr—1.5 Mo—0.1 V steel at room temperature

(All specimens are 25.4-mm-thick compact specimens with 10% side grooves on each face)

Temper parameter	J_{Ic} (kJ/m^2)		K_{Jc} (MPa$\sqrt{m}$)	
	Power law	E813	T_{avg}	Power law
19.56	176	180	110	190
19.56	203	195	113	204
20.44	220	175	273	213
20.44	217	152	285	212
21.0	275	254	375	238
21.0	428	325	393	297

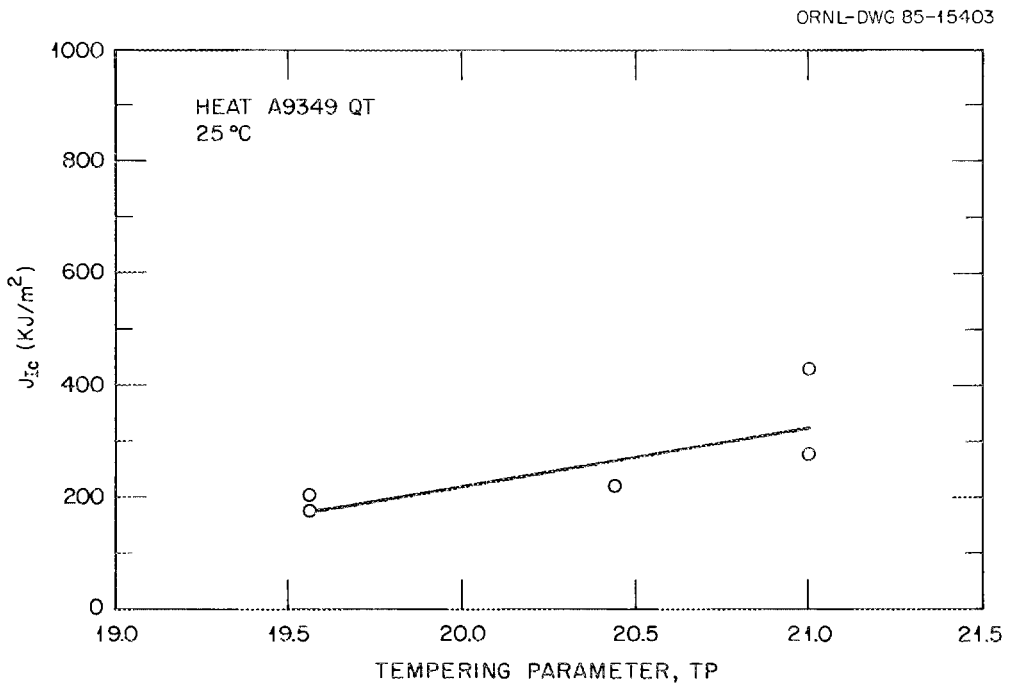

Fig. 39. Variation of J_{Ic} with the tempering parameter for heat A9349 QT.

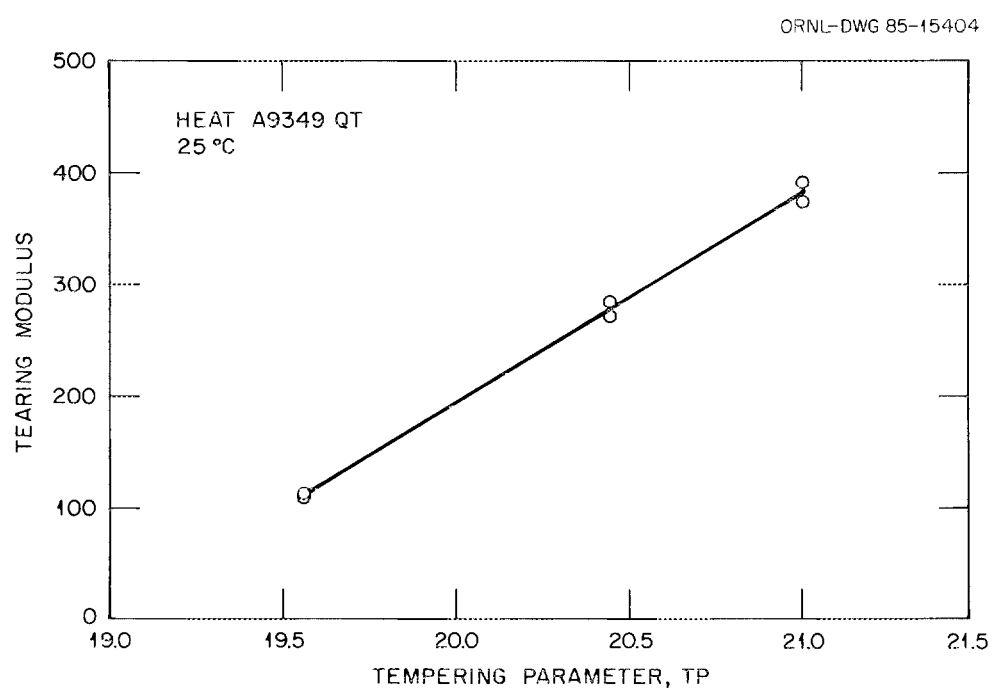

Fig. 40. Variation of the tearing modulus with tempering parameter for heat A9349 QT.

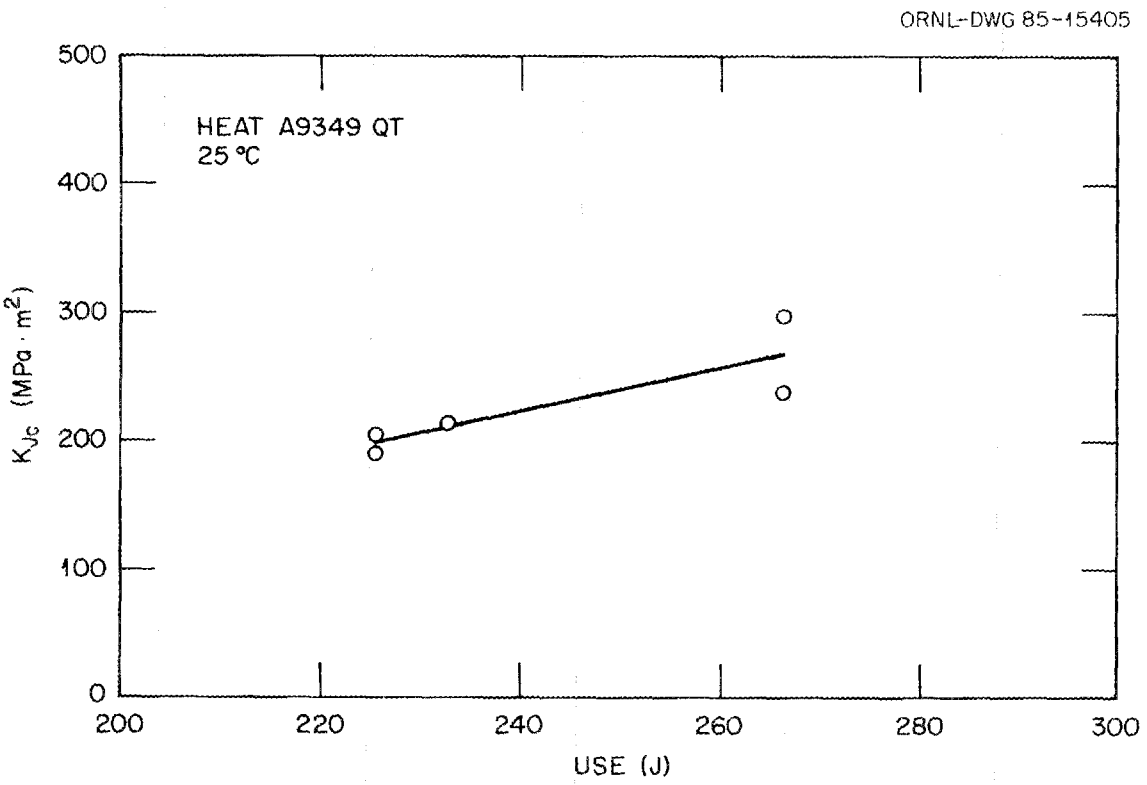

Fig. 41. Variation of K_{Jc} with the upper-shelf energy for heat A9349 QT.

FATIGUE

The purpose of fatigue testing was to assure that the 3 Cr—1.5 Mo steels would behave in a manner typical of the steels used to establish the basis for the fatigue analysis in Sect. VIII, Div. 2, of the ASME Code. Samples from the 3 Cr—1.5 Mo—V steel (heat A9349 NT) were tempered to three levels of the TP (19.56, 20.42, and 20.98) and tested at 25, 316, and 482°C under strain control with an imposed strain rate of 0.001/s. Both hourglass and uniform gauge section samples were examined, in case the work softening tendency of the steels would influence the cyclic life. The test methods conformed to ASTM recommended practice E606, and the complete set of test data is provided in Appendix D. A set of curves is provided in Fig. 42 to show the change in stress range with cycles at 0.6% strain range. Cyclic softening occurs at all temperatures, which is typical of the bainitic steels.[39] Fatigue cracks tended to nucleate on

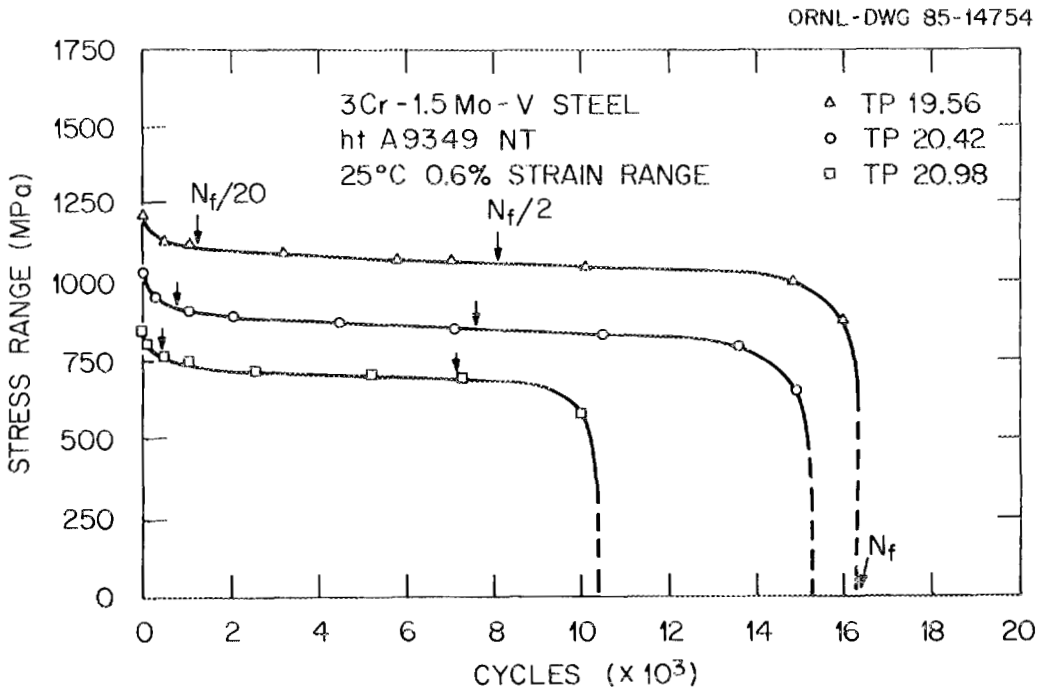

Fig. 42. Stress range versus cycles for 3 Cr–1.5 Mo–V steel, heat A9349 NT, at room temperature and 0.6% strain range.

planes normal to the applied stress but go into a shear mode while still small. The failure definition (N_f) in terms of a stress drop was difficult because of the superposition of stress decrements due to cyclic softening and the slowly growing fatigue crack in shear. Total separation was selected as the failure criterion. Cyclic hardening curves are provided in Fig. 43. They are based on the cyclic strength at $N_f/20$, which is one of the limiting criteria for developing design curves for fatigue. In Fig. 43(*a*) the cyclic strength is plotted against the cyclic strain for the three tempered conditions and at 316°C. Data indicate that the strength differences produced by the different tempers are preserved during the first 5% of cyclic life. The influence of temperature on the cyclic strength is shown in Fig. 43(*b*). Again, the trends shown for the temperature variation of tensile strength are reflected in the cyclic strength data.

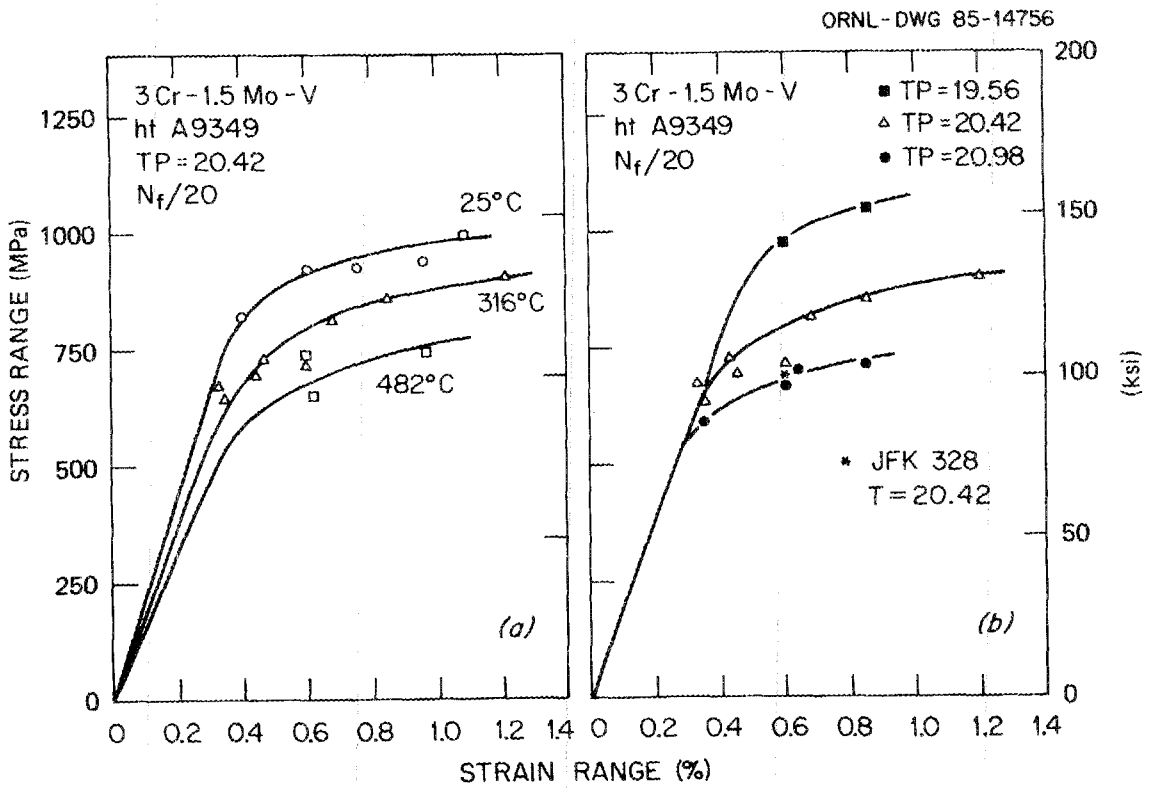

Fig. 43. Cyclic hardening curves for 3 Cr–1.5 Mo–V steel, heat A9349 NT.

Strain range versus cyclic life data are summarized in Fig. 44 and are compared with the design curve from Sect. VIII, Div. 2, of the ASME Code. For all TP values, a satisfactory margin exists between actual data and the design curve.

A few tests were performed on samples machined from the SA weldment of heat A9349 NT, and they also indicated adequate fatigue resistance. Data are provided in Appendix D.

EMBRITTLEMENT

Embrittlement in low-alloy steels for pressure vessel service has attracted a great deal of attention over the years, and the 3 Cr–1.5 Mo steels have been designed to provide maximum strength with minimum sacrifice of embrittlement resistance. Actually, there are several causes for embrittlement as summarized in Fig. 45. Included are such damaging

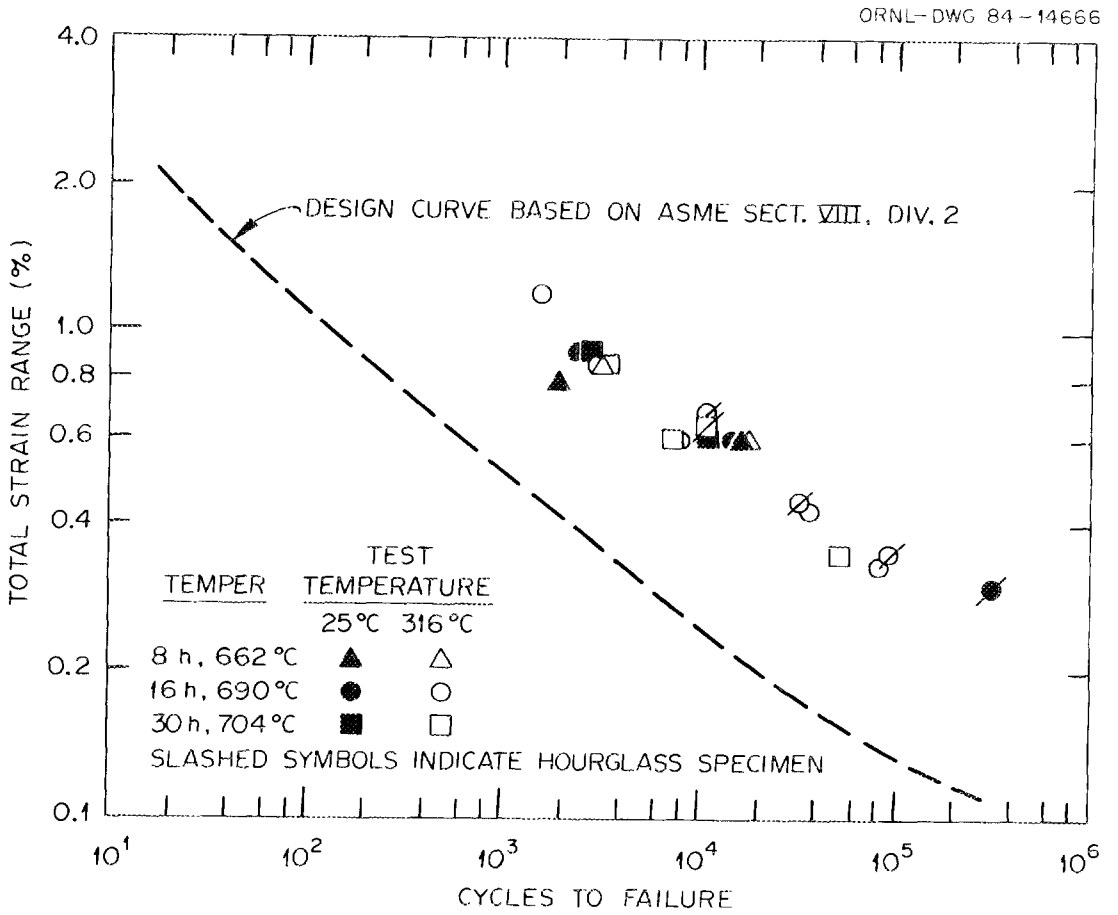

Fig. 44. Total strain range versus cycles to failure for 3 Cr–1.5 Mo–V steel, heat A9349 NT.

mechanisms as creep embrittlement, hydrogen attack, fatigue and creep-fatigue cracking, disbonding of the austenitic stainless steel cladding from the base metal, temper embrittlement (TE), and hydrogen embrittlement (HE). Each of these damage mechanisms has been considered in the development of the 3 Cr–1.5 Mo steels that are intended for hydrogen service up to 500°C. For gasifier pressure vessels that operate at lower temperatures, however, the primary concerns are limited to TE, HE, and synergistic interactions between the two. These subjects have been discussed at some length in other reports,[1,9] which reference work indicating that TE can be controlled by specification of the proper chemical composition and that HE can be controlled by the specification of an upper limit to the UTS, say 770 MPa,

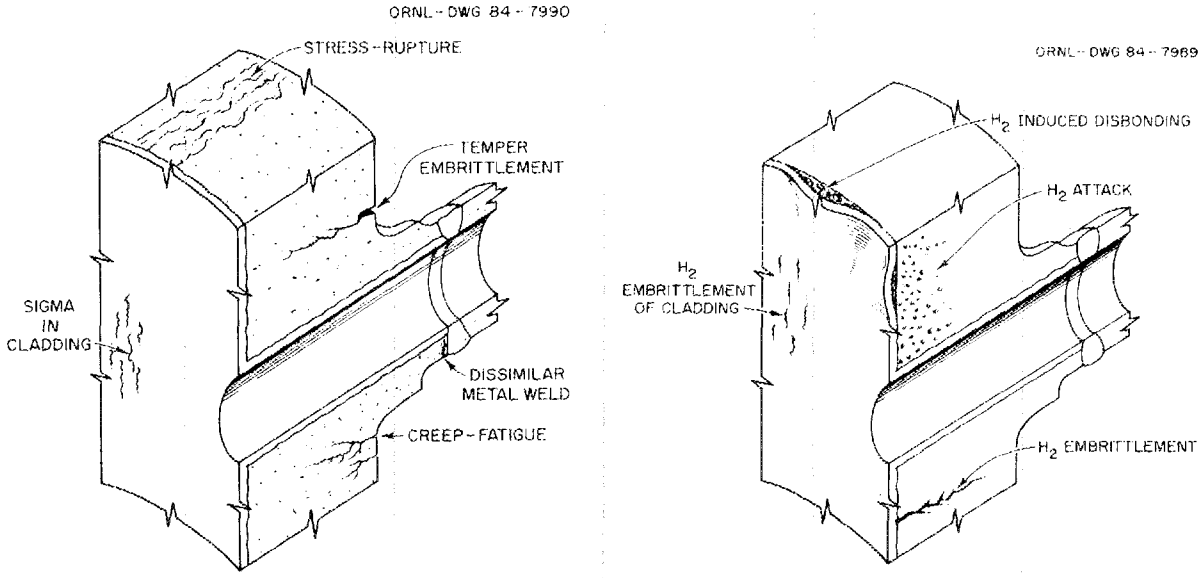

Fig. 45. Embrittlement mechanisms in high-temperature, high-pressure hydrogen service.

and by proper operation of the vessel in regard to cooling, depressurization, and purging of hydrogen-bearing gases. The 3 Cr—1.5 Mo steels are relatively new, and the data base relating to TE and HE is sparse.

Wada and Cox report the results of their studies of the 3 Cr—1.5 Mo—V steels in which the temper embrittlement tendency was assessed by determining the shifts in the TT54 and the FATT, or the decrease in the USE, after a step cooling.[20] See Fig. 46 for a typical cooling schedule. They report shifts in the TT54 and FATT of the order of 10 to 20°C, depending on the manganese content. Heat A9349, which has 0.84% Mn, exhibited a shift of 10°C. Such a shift is judged to be acceptable, especially for gasifier vessels that experience low-temperature service where the rate of TE is very low.

Ritchie and coworkers used a procedure similar to that of Wada and Cox in examining the TE tendency in the 3 Cr—1.5 Mo—Ni steels.[21,22] They found that the shift in the TT54 of the laboratory heat was upward by 45°C, and the USE dropped by approximately 25 J. These results, which are in qualitative agreement with results of Wada and Cox, indicate that care must be taken to avoid long-time exposure at high temperatures with these steels.

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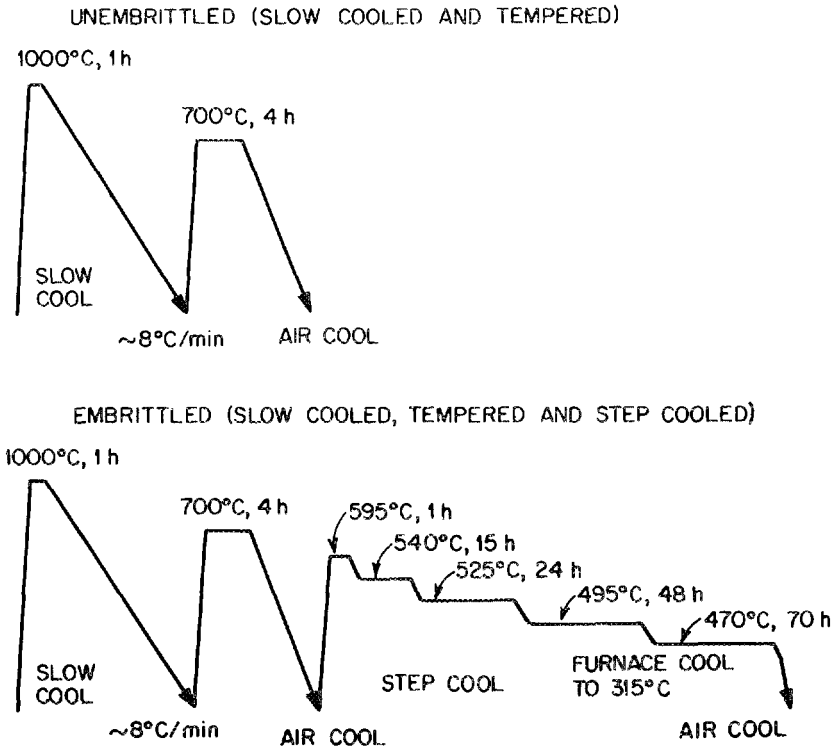

Fig. 46. Schematic representation of the heat treatments used to assess susceptibility to temper embrittlement.

The work of Shaw is of particular significance to the assessment of the 3 Cr–1.5 Mo steels for gasifier applications.[47,48] Shaw has developed a model that relates the TE and HE tendency to the composition and microstructure. Also, he is testing the commercial heats of 3 Cr–1.5 Mo–V steel and 3 Cr–1.5 Mo–Ni steel in simulated gasifier atmospheres that permit TE, HE, and their synergistic effects to be examined on the basis of fracture mechanics data.

In the model for the shift in the TT54, Shaw finds that for high-strength alloys the shift (ΔTT54) is correlated by the expression:

$$\Delta TT54 = 5(-790 + 230\ Cr + 58.8\ Cr^2 + 4006\ C + 11338\ C^2 + 89.4\ Si^2 + 33.6\ Mo\ Cr + 6400\ Mn\ P)/9\ ,$$

where the element compositions are in percent.

Similarly, the shift in the FATT is given by:

$$\Delta FATT = 5(-110 + 739\ Cr\ C + 469\ Mo\ C + 4423\ Si\ P + 71\ Mn^2 - 5967\ C^2 - 13.3\ Cr^2/9\ .$$

The elements contributing to the embrittlement are principally silicon, manganese, phosphorus, and molybdenum. These equations were used to estimate the TE tendencies of the 3 Cr–1.5 Mo alloys. They tend to overestimate the degree of embrittlement based on the step cooling evaluation method (see Table 6).

Shaw's evaluation of the HE tendency of the 3 Cr–1.5 Mo steel is now in progress. Current data indicate that the steels are more sensitive to TE and HE than standard 2.25 Cr–1 Mo steel (see Table 6). Part of the reason for this behavior is associated with the higher strength levels produced in the 3 Cr–1.5 Mo steels. In any event, the toughness of these steels, even in the embrittled condition, is excellent and would present no problem for safe operation in hydrogen service.

Table 6. Comparison of temper and hydrogen embrittlement data for 2 1/4 Cr–1 Mo steel with those for 3 Cr–1.5 Mo–V steel (heat A9349 QT) at three tempering levels

Property	Steel			
	2 1/4 Cr–1 Mo SA-387 gr 22 cl 2	3 Cr–1.5 Mo–V		
		TP[a] 19.56	TP 20.42	TP 20.98
As tempered TT54 (°C)	−73	−29	−73	−59
Temper embrittled TT54 (°C)	−79	32	−21	−40
K_{Ic} at 316°C in air (MPa$\sqrt{m}$)	220	227	231	277
K_{Ic} at 316°C in H_2 + 1% H_2S (MPa$\sqrt{m}$)	211	68	98	189

[a]Tempering parameter.

COMPARISON WITH OTHER STEELS

Because of the very aggressive low-alloy steel research programs now under way worldwide, it is difficult to compare the 3 Cr–1.5 Mo steels with other new steels. Many of these steels are in various stages of development, and each time one steel appears to offer a distinct advantage over others, competitive steel companies modify their compositions or heat treatments to meet the challenge. Certainly, the 3 Cr–1.5 Mo steels described in this report offer advantages over the steels currently in the ASME Code that were used to establish the alloy design criteria mentioned in the introduction of this report and in the assessment report.[9] The 3 Cr–1.5 Mo steels, however, are the only new steels currently being developed in the U.S. to meet the melting and fabrication practices of the U.S. industry. In comparing the 3 Cr–1.5 Mo steels with the new steels being produced in Japan, one must recognize that the Japanese steels are much cleaner and contain lower tramp elements. This results in better toughness properties. Further, most of the Japanese companies have the capability of producing large heats of boron-containing steels. This allows them to develop good hardenability without additions of manganese or nickel. Low manganese content, in combination with low sulfur and silicon, produces excellent resistance to TE and HE.

Comparison of the data for the 3 Cr–1.5 Mo steels with data produced for the 3 Cr–1 Mo–V steels reveals equivalent or superior strength and toughness in the 3 Cr–1.5 Mo steels. Such a comparison, taken from the work of Ritchie and co-workers, is shown in Fig. 47. However, data for all the new steels are insufficient to establish the heat-to-heat variability of the tempering response, and much more needs to be learned before the steels are ready for commercialization. This is particularly true for the higher vanadium-containing Japanese steels. Further, the properties of weldments and the development of welding procedures for use by the United States industry needs a great deal of additional attention. The capability of welding heavy sections of the candidate steels has been demonstrated by the Japanese, but to date the only work in the United States has been with the 100-mm sections of the 3 Cr–1.5 Mo steel.

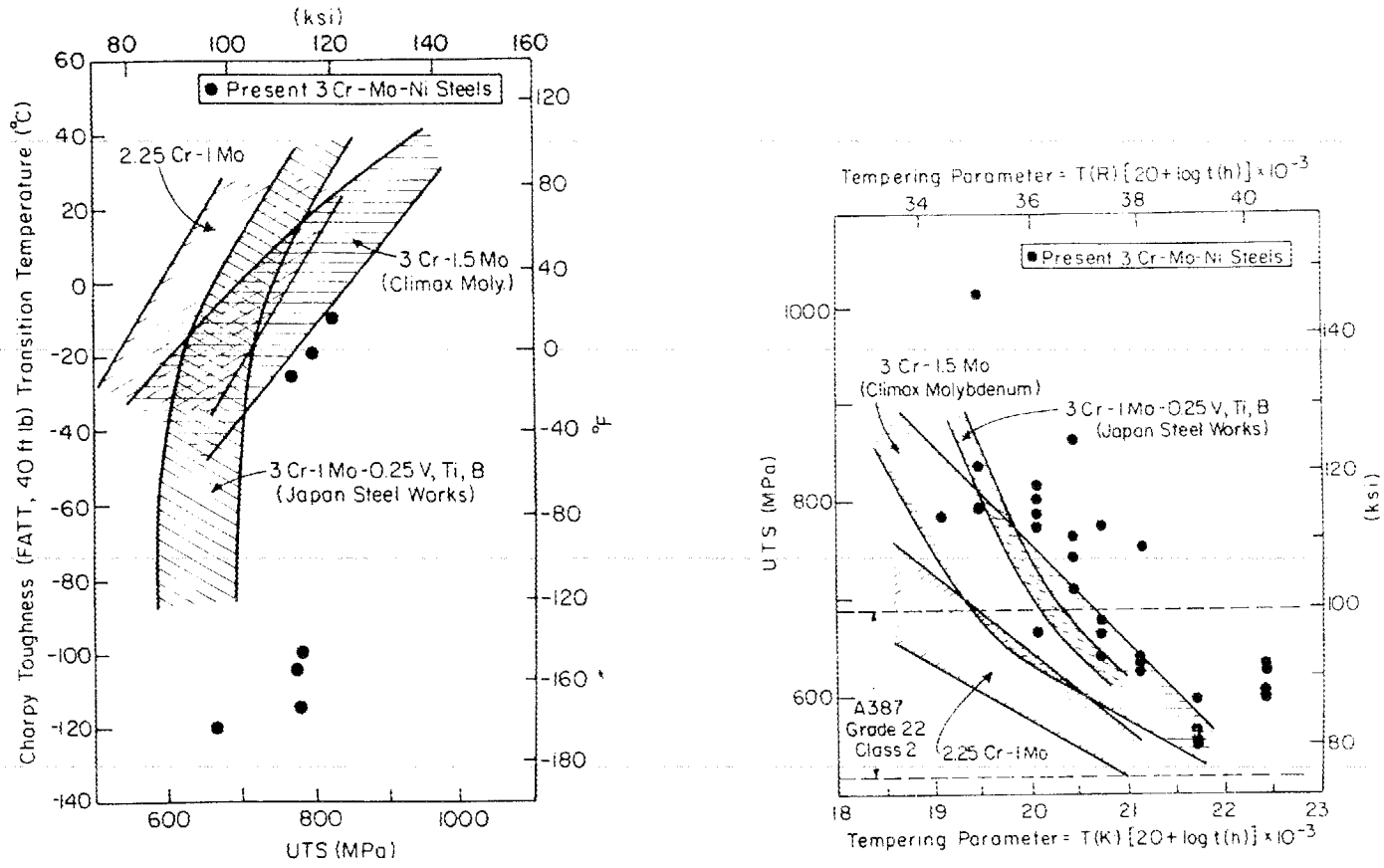

Fig. 47. Comparison of strength and toughness of 3 Cr–1.5 Mo steels with other candidate pressure vessel steels. *Source*: R. O. Ritchie et al., "A New Series of Advanced 3 Cr–Mo–Ni Steels for Thick Section Pressure Vessels in High Temperature and Pressure Hydrogen Service," *J. Mater. Energy Sys.* **6**(3), 151–62 (1984).

SUMMARY AND RECOMMENDATIONS

Several modifications of 3 Cr–1.5 Mo steels have been produced as laboratory and commercial heats ranging in size from 25 kg to 40 tons. No problems have been experienced in meeting aim compositions with standard melting practices available to United States industry.

The steels are readily fabricable and exhibit good workability and excellent hardenability.

The steels are weldable by standard welding practices, including submerged arc, shielded metal arc, and electron beam.

Mechanical properties of the steels vary as a function of the tempering parameter, with strength decreasing and ductility increasing with increasing TP. The steels meet or exceed the expectations for mechanical properties of the base metals.

Further work needs to be performed to demonstrate the heavy-section weldability and to define the optimum PWHT.

Work currently supported by the AR&TD Fossil Energy Materials Program will identify any further needs for research and will provide the additional data needed by industry to determine whether or not to proceed with commercialization.

ACKNOWLEDGMENTS

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Appendix A

TENSILE DATA

MATERIAL: A9349 NT
ASTM GS NO. 5 LUKENS DATA
TEMPER: TP=18.71/ 19.02/ 19.43

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
1	25	839	932	NA	19	70
2	25	745	842	NA	20	73
3	25	688	789	NA	21	73

MATERIAL: A9349 NT
ASTM GS NO. 5 LUKENS DATA
TEMPER: TP=19.84

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
4	25	643	749	NA	22	73
5	427	518	590	NA	19	76
6	482	493	528	NA	20	82
7	538	461	486	NA	24	87

MATERIAL: A9349 NT
ASTM GS NO. 5 LUKENS DATA
TEMPER: TP=20.44

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
8	25	529	656	NA	24	74
9	427	453	532	NA	19	74
10	482	420	469	NA	26	81
11	538	391	421	NA	28	88

MATERIAL: A9349 NT
ASTM GS NO. 5 LUKENS DATA
TEMPER: TP=21.01

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
12	25	438	586	NA	27	74
13	427	332	438	NA	24	74
14	482	327	391	NA	29	83
15	538	282	327	NA	34	91

MATERIAL: A9349 NT GS NO.5
TEMPER: 663C/8H TP=19.57

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN53	-4	688	799	6.2	18.7	74.5
AN58	-4	686	796	6.0	18.1	73.7
AN49	23	677	775	5.8	18.0	75.4
AN54	23	673	772	5.5	174	74.2
AN50	149	637	720	4.5	16.3	75.3
AN55	149	634	719	4.2	15.4	73.9
AN51	260	609	694	3.9	14.3	73.5
AN56	260	605	689	3.9	14.5	73.3
AN52	371	591	674	3.6	14.9	68.4

MATERIAL: A9349 NT GS NO. 5
TEMPER: 663C/16H TP= 19.85

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN8	-4	618	742	6.9	19.4	73.1
AN16	-4	633	753	6.5	18.8	71.3
AN1	23	615	722	5.8	17.9	73.3
AN9	23	634	740	5.8	17.5	73.0
AN2	93	607	698	5.0	17.3	75.0
AN10	93	586	678	5.2	17.4	74.6
AN3	149	566	658	4.9	16.3	75.0
AN11	149	565	657	4.9	16.2	73.3
AN4	204	544	635	4.8	16.3	74.2
AN12	204	568	653	4.3	15.6	73.5
AN5	260	571	658	4.2	14.7	73.2
AN13	260	535	627	4.3	15.4	72.4
AN6	316	533	624	4.2	13.9	68.4
AN14	316	527	624	4.1	14.4	69.8
AN7	371	546	637	3.8	13.6	66.7
AN15	371	563	650	3.9	13.6	67.0

MATERIAL: A9349 NT GS NO. 5
TEMPER: 674C/16H TP=20.08

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN63	-4	590	712	6.6	19.5	73.9
AN68	-4	579	709	7.2	19.9	72.8
AN59	23	578	687	6.1	19.4	74.2
AN64	23	572	687	6.6	19.1	73.9
AN60	149	535	631	5.0	17.0	75.0
AN65	149	533	628	5.4	17.0	72.6
AN61	260	517	610	4.3	15.3	73.9
AN66	260	505	601	4.6	15.4	72.1
AN62	371	506	597	4.2	14.3	66.2
AN67	371	499	593	4.2	14.2	67.2

MATERIAL: A9349 NT GS NO. 5
TEMPER: 688C/8H TP=20.09

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN24	-4	594	719	7.5	20.6	74.6
AN32	-4	577	703	7.3	20.1	75.0
AN17	23	569	685	6.8	19.5	74.6
AN25	23	550	671	7.2	20.8	74.5
AN18	93	527	630	5.8	18.4	72.6
AN26	93	526	632	5.9	18.3	74.7
AN19	149	511	612	5.5	18.6	75.8
AN27	149	535	630	5.1	17.4	75.0
AN20	204	501	599	5.0	17.0	73.3
AN28	204	503	603	5.2	16.9	72.9
AN21	260	493	593	4.8	15.7	74.1
AN29	260	514	613	4.5	15.2	73.1
AN22	316	495	594	4.7	15.4	70.5
AN30	316	486	588	4.8	15.4	67.8
AN23	371	475	583	4.9	15.4	68.2
AN31	371	478	583	4.9	14.9	67.8

MATERIAL: A9349 NT GS NO. 5
TEMPER: 693C/16H TP=20.48

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN73	-4	499	644	9.7	23.9	74.2
AN78	-4	516	654	9.4	22.7	73./9
AN69	22	491	621	7.8	22.2	73.7
AN74	22	491	621	7.9	21.7	73.8
AN70	149	428	551	6.5	19.0	74.8
AN75	149	452	561	6.1	18.7	75.3
AN76	260	426	536	5.7	17.1	73.0
AN72	371	428	539	5.8	16.3	69.6
AN77	371	439	547	5.6	16.5	68.9

MATERIAL: A9349 NT GS NO. 5
TEMPER: 701C/16H TP=20.65

SPEC NO	TEMP (C)	YLD (MPA)	ULT (MPA)	UE (%)	EL (%)	RA (%)
AN40	-4	462	615	9.8	24.9	74.9
AN48	-4	476	626	10.3	24.6	74.0
AN35	23	452	589	9.2	23.7	74.7
AN41	23	453	590	9.7	23.7	75.1
AN33	93	441	557	7.2	20.6	75.9
AN42	93	440	560	7.1	20.5	75.3
AN34	149	419	536	7.3	20.3	75.0
AN43	149	423	538	7.0	19.4	72.1
AN36	204	416	528	6.7	19.3	75.3
AN44	204	412	527	6.8	19.9	74.9
AN37	260	397	5151	6.5	18.3	73.9
AN45	260	421	532	5.8	17.3	73.0
AN46	316	407	525	6.4	17.4	71.5
AN39	371	399	520	6.7	17.0	70.2
AN47	371	394	521	7.2	17.8	68.1

MATERIAL: A9349 QT
ASTM GS NO. 8
TEMPER: TP=704C/30H TP=20.98

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
W1A10	25	65.9	87.7	11.6	26.5	71.9
W1A16	72	63.9	84.3	10.2	25.7	74.3
W1A18	200	60.3	77.7	9.2	23.6	74.7
W1A14	300	57.4	73.6	8.3	22.1	74.6
W1A11	400	57.9	73.9	7.0	20.3	76.5
W1A13	500	57.1	73.4	7.0	19.6	74.8
W1A15	600	55.0	72.7	7.7	19.0	70.7
W1A19	700	55.4	71.9	7.0	18.1	70.6

MATERIAL: A9349 QT
ASTM GS NO. 8
TEMPER: TP=690C/16H TP=20.44

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
W2A20	25	76.6	96.7	8.5	22.7	72.5
W2A28	72	72.0	90.8	8.5	23.2	74.3
W2A27	200	70.6	86.3	6.3	20.1	74.5
W2A23	300	67.8	83.2	6.5	19.4	74.3
W2A21	400	66.8	81.5	5.5	18.2	74.3
W2A24	500	65.7	80.1	5.4	17.3	74.5
W2A25	600	65.1	80.4	5.3	17.0	74.6
W2A16	700	63.2	78.7	5.6	17.2	70.3

MATERIAL: A9349 QT
ASTM GS NO. 8
TEMPER: TP=663C/8H TP=19.54

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
W3A30	25	100	115.5	6.0	18.2	72.1
W3A31	72	95.5	117.7	6.3	18.4	74.3
W3A33	200	92.4	105.1	4.6	17.4	74.1
W3A34	300	88.6	101.0	4.5	16.9	75.6
W3A35	400	88.9	100.6	4.3	15.9	74.3
W3A36	500	89.0	97.1	3.3	15.4	74.4
W3A38	600	84.8	97.5	4.0	15.3	72.4
W3A39	700	82.7	95.4	3.4	15.0	70.7

MATERIAL: A9349 NT
ASTM GS NO. 2
TEMPER: TP=19.57/ 20.13/ 20.98
(663C/8H 690C/8H 704C/30H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
CG48	25	665	763	6.8	23.1	74.0
CG46	25	616	720	6.5	23.1	74.0
CG40	25	497	606	5.8	20.0	74.3

MATERIAL: A9349
NQ1 AND NQNT1 GS NO.5/ NTNQ1 GS NO. 7
TEMPER: TP=17.03/ 20.09/ 19.56
(566C/2H 690C/8H 663C/8H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
NQ1	25	1079	1262	NA	NA	NA
NQNT1	25	594	707	NA	NA	NA
NTNQ1	25	699	792	NA	NA	NA

MATERIAL: 3CR-1.5MO-NI
ASTM GS NO. 7
TEMPER: TP=17.03 (566C/4H)
STRAIN RATES 0.02/MIN/ 0.02/MIN/ 0.005/MIN

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
BC18	25	1029	1161	5.1	15.5	66.9
BC40	25	994	1170	5.3	22.0	68.8
BC33	25	966	1187	4.9	15.4	65.8

MATERIAL: 3CR-1.5MO-NI
ASTM GS NO. 7
TEMPER: TP=19.57 (663C/8H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
BC6	25	646	771	7.4	20.0	71.5
BC17	93	635	740	5.8	19.4	70.5
BC39	204	630	730	4.4	16.6	73.0
BC45	316	585	694	3.8	28.4	67.8
BC10	316	570	699	4.0	18.6	66.3
BC13	482	523	564	1.7	29.6	78.7
BC8	482	521	569	2.8	22.4	77.7

MATERIAL: 3CR-1.5MO-NI
ASTM GS NO. 7
TEMPER: TP=20.42 (690C/16H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
BC9	25	501	633	7.6	20.8	71.0
BC16	93	485	599	6.4	23.6	74.2
BC38	204	476	584	6.5	22.1	71.7
BC14	316	438	549	6.5	19.3	69.9
BC19	316	447	572	5.3	20.9	66.8
BC11	482	402	461	2.8	31.0	81.7
BC41	482	403	473	4.0	25.0	77.0

MATERIAL: 3CR-1.5MO-NI
ASTM GS NO. 7
TEMPER: TP=20.98 (704C/30H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
BC22	25	454	593	10.0	26.0	70.2
BC32	93	439	559	7.5	25.7	75.1
BC27	204	412	531	7.4	24.6	72.9
BC30	316	395	511	5.3	22.9	69.5
BC15	316	400	544	7.4	23.2	64.2
BC3	482	378	536	3.2	31.0	81.1
BC35	482	364	440	5.6	28.9	77.0

MATERIAL: NKK 3CR-1.5MO-V
ORNL DATA
TEMPER: TP=19.54 (663C/8H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
663-5	25	620	748	6.5	22.7	74.4
663-4	25	622	742	6.7	23.7	75.2
663-10	204	575	676	5.0	21.9	76.2
663-3	316	554	653	4.9	20.3	72.5

MATERIAL: NKK 3CR-1.5MO-V
ORNL DATA
TEMPER: TP=20.44 (690C/16H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
690-1	25	542	673	7.7	24.7	74.2
690-9	25	524	658	7.5	25.1	75.3
690-7	204	487	592	5.5	22.6	70.1
690-3	316	477	587	4.8	20.3	72.4

MATERIAL: NKK 3CR-1.5MO-V
ORNL DATA
TEMPER: TP=20.98 (704C/30H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
704-5	25	394	555	13.2	32.8	75.6
704-9	25	390	555	12.7	34.7	24.5
704-8	204	362	488	8.2	27.7	75.9
704-4	316	353	488	7.9	24.0	74.8

MATERIAL: NKK 3CR-1.5MO-V
NKK DATA AT T/4
TEMPER: TP=20.5 (690C/20H)

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
NKK1	25	542	672	NA	26	71
NKK2	400	442	537	NA	16	71
NKK3	450	438	512	NA	18	73
NKK4	500	413	471	NA	20	78
NKK5	550	375	434	NA	23	84
NKK6	600	313	382	NA	28	88

MATERIAL: WAMAX SA WELDMENT
SPECIMEN LOCATION: WELD
TEMPERS: 704C/16H, 677C/16H, & 649C/8H

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	EL (%)	RA (%)	TP (K)
AXL11	25	400	572	22.0	73.5	21.69
AXL21	25	490	622	19.5	71.5	20.14
AXL32	25	653	750	20.5	69.5	19.27

MATERIAL: WAMAX SA WELDMENT
SPECIMEN LOCATION: HAZ
TEMPERS: 704C/16H, 677C/16H, & 649C/8H

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	EL (%)	RA (%)	TP (K)
AXL12	25	400	572	22.0	73.5	21.69
AXL22	25	467	610	23.0	72.5	20.14
AXL32	25	467	710	23.0	72.5	20.14

MATERIAL: WAMAX SA WELDMENT
SPECIMEN LOCATION: BASE METAL
TEMPERS: 704C/16H, 677C/16H, & 649C/8H

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	EL (%)	RA (%)	TP (K)
AXL10	25	373	554	32.0	75.0	21.69
AXL21	25	458	609	29.0	73.0	20.14
AXL30	25	652	758	24.0	71.5	19.27

Tensile properties of 3 Cr—1.5 Mo—V submerged arc weld metal (weld JFK 328) after postweld heat treatment

Postweld heat treatment[a]			Test temperature		0.2% Offset yield strength[b]		Ultimate strength[b]		Ductility (%)	
(h)	(°C)	(°F)	(°C)	(°F)	(MPa)	(ksi)	(MPa)	(ksi)	Total elongation	Reduction of area
			260	500	528	76.6	588	85.2	23.9	75.5
			371	700	510	73.9	574	83.2	20.9	73.9
16	663	1225	24	75	556	80.6	630	91.4	33.2	74.8
			93.3	200	528	76.6	616	89.3	26.0	75.5
			149	300	516	74.9	562	81.5	24.3	75.1
			204	400	509	73.8	578	83.9	22.0	75.5
			260	500	513	74.4	576	83.5	20.9	73.5
			316	600	507	73.5	584	84.7	22.0	73.5
			371	700	456	66.2	541	78.4	21.1	72.7
16	677	1250	24	75	517	75	591	85.7	25.9	77.3
			149	300	507	63.5	549	79.6	25.2	75.0
			260	500	471	68.3	520	75.4	20.9	63.0
			371	700	432	62.6	515	74.7	22.9	72.7
8	690	1275	24	75	510	74	601	87.2	28.1	75.9
			93.3	200	459	66.6	454	79.1	29.2	75.5
			149	300	475	68.9	501	72.6	22.5	76.9
			204	400	436	63.2	524	76.0	27.0	77.6
			260	500	438	63.6	512	74.3	27.5	75.6
			316	600	420	60.9	511	74.1	22.5	74.6
			371	700	437	63.4	514	74.6	22.5	73.2
16	690	1275	24	75	450	65.3	563	81.6	30.0	77.3
			149	300	421	61.1	471	68.3	28.7	74.9
			260	500	408	59.1	492	71.4	26.0	76.4
			371	700	402	58.3	494	76.6	24.6	73.6
16	704	1300	24	75	396	57.4	537	77.9	30.0	75.2
			93.3	200	398	57.8	511	74.1	29.0	75.5
			149	300	394	57.1	498	72.3	29.0	77.8
			204	400	386	56.0	482	69.9	30.0	77.6
			260	500	385	55.8	475	68.9	30.0	75.2
			371	700	378	54.9	478	69.4	24.5	72.9

[a]Preceded by stress relief 2.5 h at 621°C.

[b]All specimens transverse to welding direction.

MATERIAL SA WELD JFK342
SPECIMEN LOCATION: WELD METAL
TEMPER:663C/8H TP=19.57

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
342A1	25	626	721	4.3	23.6	72.9
342A2	25	622	714	4.1	20.9	72.6
342A3	315	470	625	3.8	21.2	71.3
342A4	315	548	630	2.9	20.2	72.0

MATERIAL SA WELD JFK342
SPECIMEN LOCATION: WELD METAL
TEMPER: 677C/16H TP=20.14

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
342B1	25	516	628	6.4	27.0	72.9
342B2	25	527	642	5.4	26.5	72.6
342B3	315	456	553	4.6	21.1	71.3
342B4	315	449	550	5.3	22.7	72.0

MATERIAL SA WELD JFK342
SPECIMEN LOCATION: WELD METAL
TEMPER: SR 621C/2.5H

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
342E1	25	691	779	1.5	6.6	73.6
342E2	25	801	926	4.5	19.5	65.0
342E3	315	742	768	1.1	2.9	72.9
342E4	315	773	854	3.2	17.1	60.7

MATERIAL SA WELD JFK342
SPECIMEN LOCATION: WELD METAL
TEMPER:663C/8H TP=19.57

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
342E1	25	691	779	1.5	6.6	73.6
342E2	25	801	926	4.5	19.5	65.0
342E3	315	742	768	1.1	2.9	72.9
342E4	315	773	854	3.2	17.1	60.7
342A1	25	626	721	4.3	23.6	72.9
342A2	25	622	714	4.1	20.9	72.6
342A3	315	470	625	3.8	21.2	71.3
342A4	315	548	630	2.9	20.2	72.0
342B1	25	516	628	6.4	27.0	72.9
342B2	25	527	642	5.4	26.5	72.6
342B3	315	456	553	4.6	21.1	71.3
342B4	315	449	550	5.3	22.7	72.0
342C1	25	435	568	9.0	27.9	76.2
342C2	25	433	571	8.9	32.3	75.6
342C3	315	383	504	6.5	24.8	74.3
342C4	315	385	506	7.2	24.9	74.0

MATERIAL SA WELD JFK342
SPECIMEN LOCATION: WELD METAL
TEMPER: 704C/16H TP=20.72

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
342C1	25	435	568	9.0	27.9	76.2
342C2	25	433	571	8.9	32.3	75.6
342C3	315	383	504	6.5	24.8	74.3
342C4	315	385	506	7.2	24.9	74.0

MATERIAL SA WELD JFK 344
SPECIMEN LOCATION: WELD METAL
TEMPER: 704C/30H TP=20.98

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
344-10	25	508	634	3.1	29.3	72.1
344-7	25	496	626	8.2	24.6	73.6
344-13	204	440	541	5.8	22.4	73.5
344-1	316	426	533	5.7	19.6	68.5

MATERIAL SA WELD JFK 344
SPECIMEN LOCATION: WELD METAL
TEMPER: 663C/8H TP=19.56

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
344-2	25	647	755	5.9	22.1	69.3
344-8	204	587	669	3.3	19.1	71.9
344-14	316	564	659	3.4	18.2	67.7

MATERIAL SA WELD JFK 344
SPECIMEN LOCATION: WELD METAL
TEMPER: 690C/16H TP=20.42

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
344-15	25	506	632	9.3	29.3	72.2
344-3	25	520	645	7.2	26.6	72.4
344-12	204	468	568	6.0	22.7	74.4
344-5	316	442	547	5.6	19.9	69.7

MATERIAL SMA WELD IN A9349 NT
TRANSVERSE WELD CE
SP KP AS WELDED, SP KO TEMPERED 663C/16H

SPEC NO.	TEMP (C)	YLD (MPA)	UTS (MPA)	UE (%)	EL (%)	RA (%)
KP	25	1023	1098	NA	16.0	48.4
KO	25	611	715	NA	19.0	68.3

Tensile properties of 3 Cr-1.5 Mo-V shielded metal arc weld after postweld heat treatment

Postweld heat treatment	Test temperature °C	Strength, MPa (ksi)[a]		Ductility %	
		Yield[b]	Ultimate	Total elongation	Reduction of area
8 h at 663°C	24	675 (97.9)	774 (112.2)	14.7	65
	149	435 (63.1)	587 (85.2)	17.2	71
	260	405 (58.8)	498 (72.3)	14.9	73
	371	587 (85.2)	667 (96.7)	14.6	75
16 h at 663°C	24	436 (63.3)	736 (106.8)	17.0	74
	149	595 (86.3)	688 (99.8)	15.5	68
	260	566 (82.1)	651 (94.5)	14.5	76
	371	389 (56.4)	501 (72.7)	12.3	75
16 h at 677°C	24	409 (59.3)	585 (84.9)	17.5	73
	149	543 (78.7)	633 (91.8)	15.4	75
	260	528 (75.2)	609 (88.4)	15.0	76
	371	365 (52.9)	485 (70.4)	14.7	65

[a]All specimens transverse to welding direction.

[b]0.2% offset.

MATERIAL: SMA WELD JFK 341
TRANSVERSE
TEMPERS: AW, 663C/8H, 663C/16H, 690C/5H

SPEC NO	TEMP (C)	YLD (MPA)	UTS (MPA)	EL (%)	RA (%)	TP K
341E1	24	758	1055	15.7	51.7	AW
341E2	149	600	1020	14.3	52	AW
341E3	260	498	1096	12.3	17.0	AW
341E4	371	721	1075	3.9	5.6	AW
341A1	24	645	754	22.5	57.8	19.56
341A2	149	623	720	20.7	69.0	19.56
341A3	260	571	683	17.5	65.0	19.56
341A4	371	543	656	20.4	65.0	19.56
341B1	24	585	639	19.0	69.9	19.85
341B2	149	553	642	18.5	71.8	19.85
341B3	260	496	612	14.7	64.1	19.85
341B4	371	496	601	13.2	63.8	19.85
341C1	24	605	718	23.1	72.4	19.93
341C2	149	602	644	18.7	70.2	19.93
341C3	260	507	640	18.5	67.5	19.93
341C4	371	522	622	14.9	65.9	19.93

Appendix B

CHARPY V-NOTCH IMPACT DATA

The data in this appendix are reported in degrees F, foot-pounds, and mils. They can be converted to degrees C, joules, and millimeters as shown below.

$$°C = 5(°F - 32)/9;$$

$$J = 1.36 \times ft\text{-}lb;$$

$$mm = 0.0254 \times mils.$$

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1300F/30h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-140.	3.	0.	1.
-120.	26.	6.	17.
-100.	9.	3.	5.
-100.	39.	14.	30.
-100.	47.	14.	34.
-80.	65.	21.	53.
-60.	84.	33.	66.
-40.	98.	41.	75.
-30.	93.	40.	76.
-20.	120.	52.	86.
0.	126.	66.	90.
20.	140.	70.	95.
20.	150.	79.	86.
30.	116.	67.	87.
30.	138.	75.	92.
30.	169.	100.	94.
40.	179.	100.	96.
60.	179.	100.	94.
80.	174.	100.	97.
100.	171.	100.	96.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1175F/4h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-120.	9.	0.	2.
-100.	13.	3.	5.
-80.	15.	6.	6.
-60.	25.	8.	12.
-40.	47.	11.	26.
-20.	44.	11.	26.
0.	51.	14.	33.
20.	71.	18.	34.
40.	63.	25.	37.
60.	70.	28.	44.
80.	76.	44.	47.
100.	91.	55.	60.
100.	110.	70.	72.
120.	103.	69.	65.
140.	104.	78.	65.
140.	123.	85.	77.
160.	144.	100.	79.
180.	142.	100.	79.
200.	144.	100.	83.
220.	144.	100.	76.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1200F/4h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-120.	9.	0.	3.
-100.	14.	3.	7.
-80.	24.	6.	13.
-60.	31.	10.	20.
-40.	30.	10.	19.
-20.	45.	14.	30.
0.	49.	15.	32.
20.	54.	29.	44.
40.	72.	32.	47.
60.	94.	47.	62.
60.	111.	61.	70.
80.	102.	67.	67.
100.	106.	69.	68.
120.	103.	69.	66.
120.	125.	78.	76.
140.	136.	87.	84.
160.	152.	89.	82.
180.	168.	100.	91.
200.	163.	100.	91.
220.	166.	100.	84.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1240F/4h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-120.	6.	0.	3.
-100.	24.	3.	14.
-80.	28.	3.	17.
-60.	26.	6.	16.
-40.	33.	6.	20.
-20.	34.	8.	25.
0.	36.	11.	24.
20.	56.	24.	39.
40.	75.	36.	50.
60.	78.	39.	52.
80.	95.	62.	62.
100.	116.	80.	71.
120.	140.	88.	85.
140.	132.	91.	82.
140.	143.	88.	87.
160.	145.	90.	90.
160.	169.	100.	82.
180.	168.	100.	92.
200.	165.	100.	92.
220.	170.	100.	92.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1275F/4h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-140.	7.	0.	3.
-120.	22.	6.	12.
-100.	21.	6.	12.
-80.	6.	0.	4.
-60.	29.	6.	18.
-40.	30.	6.	18.
-20.	32.	11.	19.
0.	44.	14.	30.
20.	37.	19.	26.
30.	65.	28.	47.
40.	104.	60.	69.
60.	106.	64.	73.
80.	74.	47.	54.
100.	136.	85.	84.
120.	155.	95.	85.
140.	137.	88.	84.
160.	147.	39.	89.
180.	173.	100.	95.
200.	172.	100.	93.
220.	169.	100.	92.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1300F/4h
Specimen Location: T/2
Reference: Lukens

TEMPERATURE(F)	ENERGY ABSORBED(FT-LBS)	% FIBROUS FRACTURE	LATERAL EXPANSION,MILS
-140.	9.	0.	5.
-120.	16.	3.	9.
-100.	24.	6.	16.
-80.	33.	11.	21.
-60.	33.	11.	21.
-40.	55.	18.	44.
-40.	71.	27.	55.
-20.	55.	23.	40.
-20.	78.	34.	60.
0.	66.	27.	52.
20.	85.	44.	62.
40.	95.	60.	69.
60.	100.	65.	66.
70.	129.	65.	83.
80.	145.	83.	88.
100.	144.	90.	92.
120.	170.	100.	92.
140.	177.	100.	90.
160.	172.	100.	96.
180.	172.	100.	92.

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1174F/4h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft.Lbs)	Fibrous (%)	Lat.Exp. (Mils)
10	13	6	5
50	50	20	31
73	47	23	30
90	73	44	48
100	79	45	50
120	79	57	53
140	85	62	54
160	100	76	62
180	128	86	77
200	136	100	82

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1200F/4h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft.Lbs)	Fibrous (%)	Lat.Exp. (Mils)
73	11	2	8
120	24	8	15
160	26	15	18
200	31	22	23
240	39	34	30
280	63	45	46
300	61	52	47
320	88	62	62
360	128	88	81
400	152	100	89

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1240F/4h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft·lbs)	Fibrous (%)	Lat. Exp. (Mils)
75	14	5	10
120	24	6	16
140	10	3	5
160	27	10	22
180	24	12	16
200	25	17	18
220	33	20	26
240	53	31	39
260	81	60	55
280	65	48	46
300	85	69	59
310	78	52	52
320	134	88	74
340	150	90	88
360	133	92	85
380	131	92	80
400	137	92	82
420	157	100	82
440	158	100	87
460	155	100	81

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1275F/4h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft·lbs)	Fibrous (%)	Lat. Exp. (Mils)
75	10	2	5
120	29	9	21
140	35	12	25
160	31	12	24
180	22	14	17
200	33	17	25
220	46	38	39
240	45	36	36
260	79	59	58
280	93	65	63
300	88	66	67
310	138	85	77
320	130	77	73
340	117	85	84
360	128	80	85
380	143	94	87
400	152	99	87
420	156	100	90
440	162	100	88
460	157	100	90

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1300F/4h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft·lbs)	Fibrous (%)	Lat. Exp. (Mils)
-30	4	0	2
-10	13	0	10
10	20	3	16
30	19	3	13
50	26	6	19
75	30	11	23
100	40	15	35
120	34	15	28
140	30	17	25
160	75	44	60
180	50	34	41
200	87	55	70
220	69	52	60
240	112	78	76
260	124	74	85
280	151	82	94
300	152	97	99
320	179	100	83
340	181	100	83
360	217	100	71

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1300F/8h +TE*
Specimen Location: T/2
Reference: Lukens

* 1100°F, 1 hour, F.C. to
1000°F, 16 hours, F.C. to
975°F, 24 hours, F.C. to
925°F, 48 hours, F.C. to
875°F, 72 hours, A.C.

Temp. (°F)	Energy (Ft·lbs)	Fibrous (%)	Lat. Exp. (Mils)
-50	10	2	9
-30	7	0	7
-10	22	3	19
10	26	6	24
30	25	6	22
50	55	24	46
75	43	17	37
90	21	19	20
100	70	21	66
120	70	49	57
130	73	35	67
140	122	68	85
160	118	66	94
180	149	94	92
200	128	80	90
200	130	80	96
210	138	84	84
220	217	100	76
240	202	100	82
260	200	100	76

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1050F/2h
Specimen Location: .18T (229–233); .32T (234–238); .68T (239–243); .82T (244–247)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-229	67	10.0	1.5	0
AN-230	- 50	3.5	.3	0
AN-231	200	16.5	5.5	0
AN-232	300	16.7	39.0	40
AN-233	400	111.5	54.0	≈90
AN-234	550	118.0	67.0	100
AN-235	175	26.0	15.5	0
AN-236	275	48.5	18.5	0
AN-237	300	75.0	38.6	40
AN-238	200	40.2	16.0	0
AN-239	450	122.0	58.3	100
AN-240	350	94.0	52.0	70
AN-241	500	122.0	62.9	100
AN-242	250	59.7	28.2	5
AN-244	330	84.0	39.9	55
AN-245	100	7.5	4.3	0
AN-246	225	55.0	23.6	0
AN-247	125	26.8	14.7	0

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1225F/8h
Specimen Location: .66T (139–145); .80T (146–152)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-139	74	100.0	58.0	64
AN-140	250	159.5	82.0	100
AN-141	450	157.5	73.0	100
AN-142	0	84.0	52.0	31
AN-143	125	158.5	83.0	100
AN-144	25	62.0	39.0	20
AN-145	-75	31.0	19.0	0
AN-146	150	160.0	78.0	100
AN-147	350	162.0	79.0	100
AN-148	550	150.5	75.0	100
AN-149	-50	33.5	23.0	10
AN-150	100	120.5	71.0	72
AN-151	50	109.0	66.0	50
AN-152	-25	41.7	26.0	10

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1225F/8h
Specimen Location: .66T (139–145); .80T (146–152)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-79	74	121.0	75.0	73
AN-80	250	169.5	86.0	100
AN-81	450	149.5	72.0	100
AN-82	0	42.5	24.0	16
AN-83	- 25	41.5	25.0	16
AN-84	200	167.5	87.0	100
AN-85	50	83.0	50.0	43
AN-86	- 75	25.0	13.0	7
AN-87	500	156.8	78.0	100
AN-88	-125	14.5	6.0	0
AN-89	150	160.0	77.0	100
AN-90	350	178.0	80.0	100
AN-91	550	153.5	80.0	100
AN-92	- 50	40.0	24.0	13
AN-93	25	98.5	61.0	36
AN-94	400	169.7	83.0	100
AN-95	100	163.5	87.0	100
AN-96	0	77.0	49.0	26
AN-97	-100	21.2	11.0	5
AN-98	65	106.3	63.0	68

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1245F/16h
Specimen Location: .66T (153-159); .80T (160-166)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-153	76	172.5	84.0	100
AN-154	250	165.0	82.0	100
AN-155	450	158.5	88.0	100
AN-156	0	85.0	57.0	37
AN-157	-100	19.5	11.0	5
AN-158	60	167.5	88.0	100
AN-159	- 25	84.0	60.0	36
AN-160	150	168.5	86.0	100
AN-161	350	163.0	75.0	100
AN-162	550	174.5	76.0	100
AN-163	- 50	51.5	34.0	15
AN-164	40	91.0	57.0	48
AN-165	- 75	48.3	32.0	10
AN-166	-125	9.0	4.0	3

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1270F/8h
Specimen Location: .66T (99–108); .80T (109–118)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-99	77	129.5	72.0	73
AN-100	200	177.7	88.0	100
AN-101	350	175.0	83.0	100
AN-102	0	76.0	50.0	34
AN-103	-100	9.5	11.0	0
AN-104	- 75	30.5	-	12
AN-105	125	167.5	81.0	100
AN-106	500	177.3	73.0	100
AN-107	- 25	88.0	60.0	30
AN-108	90	178.5	88.0	100
AN-109	550	159.3	77.0	100
AN-110	150	176.8	90.0	100
AN-111	250	184.0	81.0	100
AN-112	450	174.5	79.0	100
AN-113	50	126.5	80.0	72
AN-114	- 50	75.0	48.0	31
AN-115	100	175.5	81.0	100
AN-116	25	118.2	73.0	60
AN-117	550	192.5	70.0	100
AN-118	- 60	70.0	51.0	20

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1280F/16h
Specimen Location: .66T (167—173); .80T (174—180)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-167	74	155.5	84.0	100
AN-168	250	182.5	85.0	100
AN-169	450	199.5	72.0	100
AN-170	0	94.0	64.0	45
AN-171	- 25	95.5	66.0	41
AN-172	- 75	59.5	41.0	14
AN-173	-125	8.0	5.0	0
AN-174	150	183.0	80.0	100
AN-175	350	178.5	78.0	100
AN-176	550	226.2	76.0	100
AN-177	- 50	26.0	14.0	10
AN-178	100	174.0	91.0	100
AN-179	25	139.5	79.0	73
AN-180	-100	25.0	16.0	8

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 5
Heat Treatment: 1293F/16h
Specimen Location: .66T (119–128); .80T (129–138)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-119	76	162.5	90.0	100
AN-120	250	177.0	78.0	100
AN-121	0	104.0	69.0	49
AN-122	-100	60.5	44.0	23
AN-123	-150	10.0	6.0	0
AN-124	300	178.0	74.0	100
AN-125	200	174.0	85.0	100
AN-126	20	129.0	78.0	68
AN-127	- 25	107.0	76.0	47
AN-128	- 90	12.8	3.5	0
AN-129	150	174.7	72.0	100
AN-130	350	~239.0*	82.0	100
AN-131	550	~239.7*	72.0	100
AN-132	- 50	88.5	67.0	35
AN-133	- 75	2.5	0	0
AN-134	40	165.5	87.0	100
AN-135	100	185.5	86.0	100
AN-136	-125	20.0	14.0	6
AN-137	- 65	88.0	63.0	30
AN-138	- 70	85.0	60.0	25

Material: 3Cr-1.5 Mo-V
Heat: A9349 NT
ASTM Grain Size: 8
Heat Treatment: 1275F/8h
Specimen Location:
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-360	68	140.0	81.0	100
AN-361	150	156.5	83.0	100
AN-362	300	151.5	82.0	100
AN-363	0	60.0	41.0	12
AN-364	- 50	50.5	37.0	10
AN-365	-100	20.0	15.0	6
AN-366	-150	7.5	5.0	0
AN-367	35	110.5	72.0	65
AN-368	- 35	93.5	64.0	38
AN-369	500	144.5	79.0	100

Material: 3Cr-1.5 Mo-V
Heat: A9349 QT
ASTM Grain Size: 8
Heat Treatment: 1275F/16h
Specimen Location: .18T (289–292); .32T (293–296); .68T (297–300); .82T (301–304)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-289	72.5	162.0	82.0	100
AN-290	- 50	81.7	56.0	93
AN-291	100	169.0	86.0	100
AN-292	0	109.3	70.0	56
AN-293	0	102.3	68.0	58
AN-294	-100	25.0	10.0	10
AN-295	50	160.0	46.0	100
AN-296	- 75	58.0	38.0	28
AN-297	- 25	98.0	71.0	52
AN-298	-150	9.0	8.0	0
AN-299	200	169.0	84.0	100
AN-300	500	163.5	90.0	100
AN-301	- 75	77.5	55.0	33
AN-302	25	153.5	89.0	100
AN-303	-100	29.5	23.0	
AN-304	300	172.5	94.0	100

Material: 3Cr-1.5 Mo-V
Heat: A9349
ASTM Grain Size: 8
Heat Treatment: 1300F/30h
Specimen Location: .18T (273–276); .32T (277–280); .68T (281–284); .82T (285–288)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-273	71.1	166.3	88.0	100
AN-274	- 50	95.8	67.0	42
AN-275	200	177.5	91.0	100
AN-276	500	231.0	68.0	100
AN-277	-100	29.5	21.0	10
AN-278	-150	5.0	3.0	0
AN-279	50	153.5	87.0	85
AN-280	350	185.0	83.0	100
AN-281	0	108.0	72.0	58
AN-282	- 25	92.0	62.0	52
AN-283	- 50	86.5	61.0	42
AN-284	100	174.0	86.0	100
AN-285	- 50	93.5	68.0	43
AN-286	- 75	50.0	35.0	27
AN-287	150	171.0	92.0	100
AN-288	25	132.0	78.0	74

Material: 3Cr-1.5 Mo-V
Heat: A9349 QT
ASTM Grain Size: 8
Heat Treatment: 1050F/2h
Specimen Location: .18T (251–255); .32T (256–260); .68T (261–265); .82T (266–270)
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-251	72	23.0		
AN-252	72	20.8	9.3	0
AN-253	- 50	8.8	4.0	0
AN-254	200	37.2	14.2	10
AN-255	400	100.0	51.8	100
AN-256	550	97.0	46.0	100
AN-257	50	13.3	4.2	0
AN-258	150	33.0	10.0	10
AN-259	175	54.2	20.0	0
AN-260	125	28.0	8.7	10
AN-261	450	98.0	38.2	100
AN-262	350	90.7	43.0	100
AN-263	500	96.0	47.5	100
AN-264	250	67.0	28.8	48
AN-265	200	65.3	26.5	40
AN-266	0	2.5	0.5	0
AN-267	300	83.0	35.0	82
AN-268	150	48.0	17.5	20
AN-269	100	27.5	9.0	0
AN-270	200	78.5	34.5	58

Material: 3Cr-1.5 Mo-V
Heat: A9349 QT
ASTM Grain Size: 8
Heat Treatment: 1225F/8h
Specimen Location:
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-374	68	131.5	78.0	88
AN-375	0	32.0		
AN-376	35	110.5	64.0	70
AN-377	500	147.5	82.0	100
AN-378	300	175.5	74.0	100
AN-379	- 50	36.0	22.0	12
AN-380	-100	23.0	16.0	7
AN-381	150	147.0	74.0	100

Material: WAMAX Weld
Heat: A9349
ASTM Grain Size:
Heat Treatment: 704C/16h
Specimen Location:
Reference: AMAX

Specimen No.	Notch Location	Test Temperature C (F)	Impact Energy J (ft-lb)	Percent Shear Fracture
L13A	HAZ	23 (74)	214 (158)	100
L13B	HAZ	-20 (-4)	125 (92)	56
L13C	HAZ	-40 (-40)	138 (102)	60
L13D	HAZ	-60 (-76)	137 (101)	49
L14A	HAZ	-80 (-112)	56 (41)	21
L14B	HAZ	-100 (-148)	4 (3)	0
L14C	HAZ	-70 (-94)	102 (75)	35
L14D	HAZ	-5 (23)	255 (188)	100
L15C	HAZ	-10 (14)	197 (145)	80
L15D	HAZ	40 (104)	254 (188)	100
L15A	Weld Metal	23 (74)	171 (126)	87
L15B	Weld Metal	23 (74)	156 (115)	85
L16A	Weld Metal	-20 (-4)	84 (63)	35
L16B	Weld Metal	-40 (-40)	11 (8)	10
L16C	Weld Metal	-10 (14)	141 (104)	65
L16D	Weld Metal	0 (32)	125 (92)	59
L17A	Weld Metal	-15 (5)	137 (101)	63
L17B	Weld Metal	40 (104)	239 (176)	100
L17C	Weld Metal	-30 (-22)	75 (55)	30
L17D	Weld Metal	-35 (-31)	62 (46)	26

Material: WAMAX Weld
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1250F/16h
Specimen Location:
Reference: AMAX

Specimen No.	Notch Location	Test Temperature C (F)	Impact Energy J (ft-lb)	Percent Shear Fracture
L23A	HAZ	23 (74)	193 (143)	92
L23B	HAZ	-20 (-4)	99 (73)	50
L23C	HAZ	-40 (-40)	125 (92)	63
L23D	HAZ	-60 (-76)	99 (73)	36
L24A	HAZ	-80 (-112)	69 (51)	21
L24B	HAZ	-100 (-148)	9 (7)	0
L24C	HAZ	-70 (-94)	39 (29)	10
L24D	HAZ	-5 (23)	168 (124)	76
L25C	HAZ	-10 (14)	168 (124)	80
L25D	HAZ	40 (104)	237 (175)	100
L25A	Weld Metal	23 (74)	133 (98)	70
L25B	Weld Metal	23 (74)	182 (134)	95
L26A	Weld Metal	-20 (-4)	27 (20)	15
L26B	Weld Metal	-40 (-40)	18 (13)	5
L26C	Weld Metal	-10 (14)	122 (90)	57
L26D	Weld Metal	0 (32)	114 (84)	55
L27A	Weld Metal	-15 (5)	41 (30)	26
L27B	Weld Metal	40 (104)	149 (110)	80
L27C	Weld Metal	70 (158)	210 (155)	100
L27D	Weld Metal	-15 (5)	49 (36)	30

Material: WAMAX Weld
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1200F/8h
Specimen Location:
Reference: AMAX

Specimen No.	Notch Location	Test Temperature C (F)	Impact Energy J (ft-lb)	Percent Shear Fracture
L33A	HAZ	23 (74)	178 (131)	95
L33B	HAZ	-20 (-4)	92 (68)	40
L33C	HAZ	-40 (-40)	88 (65)	40
L33D	HAZ	-60 (-76)	64 (47)	30
L34A	HAZ	-10 (14)	111 (82)	55
L34B	HAZ	-100 (-148)	12 (9)	0
L34C	HAZ	-70 (-94)	22 (16)	10
L34D	HAZ	-80 (-112)	24 (18)	10
L35C	HAZ	-10 (14)	62 (46)	35
L35D	HAZ	40 (104)	198 (146)	100
L35A	Weld Metal	23 (74)	155 (114)	85
L35B	Weld Metal	23 (74)	84 (62)	50
L36A	Weld Metal	-20 (-4)	15 (11)	10
L36B	Weld Metal	-40 (-40)	9 (7)	5
L36C	Weld Metal	-10 (14)	28 (21)	21
L36D	Weld Metal	0 (32)	45 (33)	30
L37A	Weld Metal	10 (50)	56 (41)	35
L37B	Weld Metal	40 (104)	133 (98)	74
L37C	Weld Metal	70 (158)	210 (155)	100
L37D	Weld Metal	23 (74)	107 (79)	65

Material: SA Weld JFK 329
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1290F/16h
Specimen Location:
Reference: ORNL

Number	Location (t)	Temperature	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-217	.13	67	148.0	94.3	83
AN-218	.27	0	153.5	87.0	83
AN-219	.39	-100	8.0	4.3	0
AN-220	.56	- 75	11.6	8.0	0
AN-221	.70	- 50	85.3	61.5	33
AN-222	.84	- 25	90.5	62.0	42
AN-223	.13	550	235.0	76.0	100
AN-224	.27	150	185.0	94.0	100
AN-225	.39	250	210.3	77.0	100
AN-226	.56	400	239.3	85.0	100
AN-227	.70	100	191.0	95.0	100
AN-228	.84	- 62	23.0	15.0	10

Material: SA Weld JFK 328
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1300F/16h
Specimen Location:
Reference: ORNL

Number	Location (t)	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-205	.09	74	217.3	82.0	100
AN-206	.23	- 50	115.3	76.8	44
AN-207	.37	550	239.0	82.4	100
AN-208	.50	200	217.2	70.4	100
AN-209	.64	- 60	8.0	4.4	5
AN-210	.78	90	205.5	80.1	100
AN-211	.09	0	159.5	82.3	71
AN-212	.23	-100	6.0	1.3	0
AN-213	.37	150	215.2	80.0	100
AN-214	.50	- 75	9.0	4.5	5
AN-215	.64	300	239.7	85.8	100
AN-216	.78	50	113.0	84.2	100

WT direction

Material: SA Weld JFK 328
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1225F/16h
Specimen Location:
Reference: ORNL

Number	Location	Temperature	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-181	.09t	74	186.0	96.1	100
AN-182	.23	25	116.0	73.0	76
AN-183	.37	550	173.0	83.9	100
AN-184	.50	250	179.5	84.4	100
AN-185	.64	- 75	12.2	6.5	0
AN-186	.78	- 50	22.0	12.9	5
AN-187	.09	0	23.7	18.5	22
AN-188	.23	125	175.5	87.0	100
AN-189	.37	400	179.8	81.1	100
AN-190	.50	- 25	58.5	39.1	28
AN-191	.64	50	141.0	85.3	83
AN-192	.78	10	109.0	70.6	67

Material: SA Weld JFK 328
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1275F/8h
Specimen Location:
Reference: ORNL

Number	Location (t)	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-193	.09	74	200.1	79.8	100
AN-194	.23	- 50	56.6	37.5	28
AN-195	.37	550	239.2	82.0	100
AN-196	.50	350	206.7	73.3	100
AN-197	.64	40	196.2	96.2	100
AN-198	.78	25	132.0	85.8	78
AN-199	.09	0	129.3	82.0	62
AN-200	.23	-100	9.5	5.0	0
AN-201	.37	150	208.0	86.3	100
AN-202	.50	250	210.0	76.9	100
AN-203	.64	- 25	130.7	80.1	50
AN-204	.78	- 75	11.3	4.1	0

Material: HAZ of SA Weld JFK 329
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1150F/2.5h
Specimen Location:
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)
AN-321	50	64.0
AN-322	-100	26.3
AN-323	-200	15.0
AN-324	-50	46.5
AN-325	100	134.0
AN-327	-150	19.0
AN-328	0	70.5
AN-329	72	108.0
AN-330	300	131.3

Material: SA Weld JFK 329
Heat: A9349
ASTM Grain Size:
Heat Treatment:
Specimen Location:
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Fibrous (%)
AN-331	75	6.5	0
AN-332	0	6.0	4
AN-333	50	6.5	0
AN-335	100	15.5	10
AN-336	200	59.5	68
AN-337	400	68.5	100
AN-338	300	80.5	100
AN-339	250	79.0	95
AN-340	150	42.5	42
AN-341	400	68.0	100
AN-342	500	77.0	100

Material: Base Metal of SA Weld JFK 329
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1150F/2h
Specimen Location:
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Fibrous (%)
AN-343	75	129.0	55
AN-344	0	80.5	27
AN-345	- 50	29.0	0
AN-346	500	170.5	100
AN-347	150	158.0	100
AN-348	-100	15.0	0
AN-349	25	92.0	33
AN-351	200	160.5	100
AN-352	-150	7.7	0
AN-353	400	165.0	100
AN-354	300	183.5	100

Material: 3Cr-1.5 Mo-V
Heat: A9349
ASTM Grain Size: 2
Heat Treatment: 1225F/9.7h
Specimen Location: .25T; .75T
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
A-11	71	71.0	44.2	42
A-12	150	139.0	92.0	80
A-13	250	174.5	84.8	100
A-14	450	162.5	85.8	100
A-15	300	180.5	86.8	100
A-21	0	42.5	35.0	20
A-22	- 50	16.0	21.9	8
A-23	-100	16.0	15.2	8
A-24	-150	4.5	1.2	4
A-25	35	50.5	37.8	28

Material: SMA Weld BH
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1300F/8h
Specimen Location:
Reference: CE

Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
-100	5	1	0
- 80	7	2	0
- 60	61	39	30
- 40	62	41	30
- 20	57	33	25
0	116	63	70
20	121	66	70
50	150	81	100
100	148	82	100
200	160	80	100
300	164	77	100
400	207	62	100
500	204	77	100

Material: SMA Weld BF
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1300F/8h
Specimen Location: T/2
Reference: CE

Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
-100	46	26	15
- 80	53	31	20
- 60	70	42	40
- 40	97	54	60
- 20	110	61	70
0	123	69	80
20	134	71	100
50	153	80	100
100	145	79	100
200	154	78	100
300	169	76	100
400	173	69	100
500	226	58	100

Material: SMA Weld BG
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1300F/8h
Specimen Location: T/2
Reference: CE

Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
-100	18	9	5
- 80	44	26	15
- 60	95	59	50
- 40	102	62	70
- 20	110	66	70
0	130	76	80
20	129	74	80
50	158	80	100
100	160	77	100
200	156	77	100
300	232	59	100
400	201	70	100
500	212	57	100

Material: SMA Weld BF
Heat: A9349
ASTM Grain Size:
Heat Treatment: As welded
Specimen Location: T/2
Reference: CE

Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
500	40	22	100
400	44	22	40
200	39	19	20
25	18	10	10
20	12	2	0

Material: SMA Weld BF
Heat: A9349
ASTM Grain Size:
Heat Treatment: 1225F/16h
Specimen Location: T/2
Reference: CE

Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
400	117	78	100
200	171	83	100
25	99	63	100
20	96	60	90
0	83	53	70
- 20	84	36	40
- 40	52	28	30
- 60	41	20	20
- 80	12	2	0
-100	3	0	0

Material: 3Cr-1.5 Mo-Ni
Heat: A9749
ASTM Grain Size: 6
Heat Treatment: 1300F/30h
Specimen Location: T/4
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-14	72	155.0	84	100
AN-15	150	160.0	85	100
AN-23	300	167.8	94	100
AN-24	500	168.0	84	100
AN-25	0	95.7	61	59
AN-32	- 50	65.5	42	21
AN-35	-100	23.0	19	8
AN-41	-150	6.8	6	0
AN-42	- 75	43.5	28	12
AN-43	25	109.5	67	77

Material: 3Cr-1.5 Mo-Ni
Heat: A9749
ASTM Grain Size: 6
Heat Treatment: 1225F/3h
Specimen Location: T/4
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
AN-11	72	106.0	59	62
AN-12	150	114.5	48	66
AN-13	300	152.5	88	100
AN-21	500	147.0	83	100
AN-22	0	85.5	42	31
AN-31	- 50	24.0	16	6
AN-33	-100	10.5	8	0
AN-34	-150	5.5	1	0
AN-44	25	87.5	49	52
AN-45	- 25	34.8	31	10

Material: 3Cr-1.5 Mo-Ni
Heat: A9749
ASTM Grain Size: 6
Heat Treatment: 1275F/16h
Specimen Location: T/4
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
B-11	72	161.0	91	100
B-12	150	159.5	92	100
B-15	300	157.5	90	100
B-21	500	158.7	86	100
B-22	0	91.3	56	50
B-24	- 50	61.5	41	42
B-25	-100	15.0	9	4
B-35	-150	13.0	6	4
B-41	- 75	40.7	29	13
B-44	25	123.0	82	81

Material: 3Cr-1.5 Mo-Ni
Heat: A9749
ASTM Grain Size: 6
Heat Treatment: 1125F/4h
Specimen Location: T/4
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
B-13	72	5.0	1.5	0
B-14	100	17.5	10.5	3
B-23	125	5.0	0	0
B-31	200	49.0	23.0	12
B-32	300	68.5	46.5	71
B-33	400	94.0	50.0	100
B-34	550	92.5	47.0	100
B-42	350	93.0	47.0	100
B-43	150	41.0	16.0	9
B-45	250	50.0	22.5	37

Material: 3Cr-1.5 Mo-Ni
Heat: A9349
ASTM Grain Size: 2
Heat Treatment: 1275F/8h
Specimen Location: .25T; .75T
Reference: ORNL

Number	Temperature (°F)	Energy (Ft-lb)	Lat. Exp. (mils)	Fibrous (%)
A-31	71	102.5	66.7	52
A-32	150	147.0	75.9	84
A-33	250	175.5	80.3	100
A-34	450	171.5	84.6	100
A-35	300	172.5	87.4	100
A-41	0	36.0	26.3	14
A-42	- 50	31.5	27.5	15
A-43	-100	9.0	9.0	8
A-44	-150	7.5	4.5	5
A-45	35	94.5	58.8	42

Appendix C

CHARPY DATA SUMMARY

Summary of Charpy impact results

Material identification	TP[a] (K)	UTS[b] (MPa)	TT_{54}[c] (°C)	FATT[d] (°C)	USE[e] (J)	CVE_{RT}[f] (J)
			Base Metal			
A9349 NT	18.71	932	−37	32	195	50
A9349 NT	19.02	842	−29	16	225	50
A9349 NT	19.43	789	−18	19	228	40
A9349 NT	19.84	749	−21	16	232	60
A9349 NT	20.44	656	−57	4	234	90
A9349 NT	21.01	586	−76	−32	237	155
A9349 NT[g]	17.03	1310	98	160	169	10
A9349 NT[g]	19.57	774	−39	−12	218	155
A9349 NT[g]	19.85	731	−37	6	225	170
A9349 NT[g]	20.08	687	−55	−12	230	220
A9349 NT[g]	20.09	678	−60	−13	243	220
A9349 NT[g]	20.48	621	−58	−20	266	220
A9349 NT[g]	20.65	590	−72	−28	273	230
A9349 NT[h]	20.09	707	−57	−7	207	180
A9349 QT[h]	17.03	1262	67	118	136	25
A9349 QT[h]	19.56	770	−73	−29	225	220
A9349 QT[h]	20.44	626	−70	−35	233	220
A9349 QT[h]	21.0	582	−78	−34	266	220
A9349 QT[g]	19.56	792	−47	−13	216	180
A9349 NT[i]	19.64	763	−11	29	239	96
A9349 NT[i]	20.13	720	−29	18	236	139
A9749	17.03	1170	90	130	130	10
A9749	19.56	771	−38	10	190	150
A9749	20.42	633	−60	−25	225	220
A9749	21.0	593	−57	−25	225	220
NKK	20.5	672	−60	−44	210	NA
NKK	19.54	745	−68	−30	205	169
NKK	20.44	666	−60	−18	210	209
NKK	20.98	555	−54	−30	280	250
			Submerged-Arc Welds			
WAMAX	19.27	750	10	15	210	100
WAMAX	20.14	622	−15	−5	210	160
WAMAX	21.69	572	−35	−15	240	200
WAMAX/HAZ	19.27	741	−45	−15	200	741
WAMAX/HAZ	20.14	610	−70	−40	235	210
WAMAX/HAZ	21.69	572	−80	−50	250	240
JFK328	19.85	581	−27	−18	240	215
JFK328	20.13	589	−52	−29	280	270
JFK328	20.72	537	−56	−29	300	285
JFK329	AW		65	74	100	8
JFK329	20.61		−50	−20	320	230
JFK329/HAZ	18.15		−47		180	150
JFK329/BASE	19.31		−42	10	230	175

Summary of Charpy impact results (continued)

Material identification	TP[a] (K)	UTS[b] (MPa)	TT_{54}[c] (°C)	FATT[d] (°C)	USE[e] (J)	CVE_{RT}[f] (J)
Submerged-Arc Welds (Continued)						
JFK/342	19.57	721	−53		220	220
JFK344	19.56	755	−53	−45	170	147
JFK344	20.42	637	−57	−45	195	182
JFK344	21.0	630	−57	−50	210	190
Electron-Beam Welds						
EBW	19.9		−60		250	220
EB/HAZ	19.9		−60		175	175
EB/BASE	20.5		−60		260	220
Shielded Metal-Arc Welds						
BF	20.33		−70	−45	210	200
KO	19.85	715	−50	−20	160	150
KP	AW	1023	100	230	55	25
BG	20.33		−60	−50	220	220
BH	20.33		−50	−25	220	200

[a]TP ≡ tempering parameter = $T(20 + \log t) \times 10^{-3}$.

[b]UTS ≡ ultimate tensile strength.

[c]TT_{54} ≡ 54-J transition temperature.

[d]FATT ≡ 50% shear fracture appearance transition temperature.

[e]USE ≡ upper-shelf energy.

[f]CVE_{RT} ≡ Charpy energy at room temperature.

[g]ASTM No. 5 grain size.

[h]ASTM No. 8 grain size.

[i]ASTM No. 2 grain size.

Appendix D

FATIGUE DATA

FATIGUE DATA FOR 3CR-1.5MO-V STEEL HEAT A9349

SP NO	TEMP C	%ER	CYCLES	SNF/2 MPA	SNF/20 MPA	SN1 MPA	TP	TEMPER	TYPE SPECIMEN
3CR20	25	1.09	4030	910	986	1110	20.42	690C/16H	HG
3CR3	25	0.76	7580	848	917	1055	20.42	690C/16H	HG
3CR4	25	0.3	310000	683	NA	NA	20.42	690C/16H	HG
3CR6	316	>0.42[a]	5690	648	690	752	20.98	704C/30H	HG
3CR9	316	0.60	7480	607	662	731	20.98	704C/30H	UG
3CR10	25	0.60	10370	703	758	848	20.98	704C/30H	UG
3CR12	25	0.78	1930	1069	1262	1379	19.56	663C/8H	UG
3CR13	316	1.2	1550	807	896	1000	20.42	690C/16H	UG
3CR14	482	0.60	4920	648	731	827	20.42	690C/16H	UG
3CR15	316	0.60	8135	655	710	814	20.42	690C/16H	UG
3CR16	25	0.91	2480	841	931	986	20.42	690C/16H	UG
3CR17	316	0.68	10840	752	807	931	20.42	690C/16H	HG
3CR18	316	0.45	32250	641	690	814	20.42	690C/16H	HG
3CR19	25	0.40	49330	765	814	952	20.42	690C/16H	HG
3CR21	482	0.62	14800	572	655	793	20.42	690C/16H	HG
3CR22	316	0.64	10150	641	696	786	20.98	704C/30H	HG
3CR23	316	0.35	93000	627	634	717	20.42	690C/16H	HG
3CR25	316	0.33	83410	648	672	683	20.42	690C/16H	UG
3CR26	25	0.60	16190	1062	1110	1214	19.56	663C/8H	UG
3CR27	316	0.85	3120	952	1041	1186	19.56	663C/8H	UG
3CR28	25	0.60	15420	848	917	1069	20.42	690C/16H	UG
3CR29	316	0.60	18810	896	972	972	19.56	663C/8H	UG
3CR30	482	0.60	5590	517	593	676	20.98	704C/30H	UG
3CR31	316	0.60	3330	641	703	765	20.98	704C/30H	UG
3CR32	482	0.60	9620	807	883	958	19.56	663C/8H	UG
3CR33	482	0.97	3140	662	738	893	20.42	690C/16H	HG
3CR35	482	0.40	51710	NA	NA	NA	20.42	690C/16H	HG
3CR36	316	>0.7[a]	2370	NA	NA	NA	19.56	663C/8H	HG
3CR37	316	0.85	2910	765	848	972	20.42	690C/16H	UG
3CR38	316	0.35	51840	552	586	641	20.98	704C/30H	UG
3CR39	316	0.43	36370	682	724	786	20.42	690C/16H	UG
3CR40	25	0.91	2740	724	821	938	20.98	704C/30H	UG
3CRW6	482	0.59[b]	4060	552	614	696	20.42	690C/16H	UG
3CRW8	316	0.60[b]	4660	696	690	772	20.42	690C/16H	UG

Notes: %ER = % total strain range; SNF/2 = Stress range at half life; SNF/20 = Stress range at 5% of life; SN1 = Stress range at first cycle; TP = tempering parameter in K; HG = hourglass; UG = uniform gage; Strain rate 0.001/second.

[a]Extensometer off center

[b]Weld metal.

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