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Effect of Tempering on the Strength and Toughness of 2 1/4 Cr-1 Mo Steel Weldments

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ABSTRACT

Hardness, tensile, and Charpy V-notch impact tests were performed on samples prepared from submerged-arc weldments of 2 1/4 Cr-1 Mo steel. The intent was to explore the effect of tempering on the strength and ductility of the alloy in order to assess the potential for developing a high-strength alloy for gasifier pressure vessel service to 300°C. The results indicated that good weld metal strength and toughness could be achieved. Limited work on the heat-affected zone of the base metal did not reveal any major problems. We concluded that qualification of a quenched-and-tempered version of 2 1/4 Cr-1 Mo steel with ultimate strength in the range 620 to 758 MPa (90—110 ksi) will be difficult for welded gasifier pressure vessels because of a narrow time-temperature tempering "window." A minimum ultimate strength requirement of 585 MPa (85 ksi), however, would be much easier to achieve because of the larger window.

INTRODUCTION

This report summarizes results of tempering studies of 2 1/4 Cr-1 Mo steel weldments. The purpose was to establish the practicality of producing material with ultimate strengths in the range 620 to 758 MPa (90—110 ksi) while maintaining adequate toughness for gasifier pressure vessel service at temperatures to 316°C (600°F). The justification for performing the studies was provided in a recent assessment report.[1] After the start of our experimental work, similar studies were completed in Japan and begun in the United States to qualify materials equivalent to A 542 class 3 for use in high-temperature, high-pressure hydrogen service.[2,3] Partially for this reason we chose to curtail our work on 2 1/4 Cr-1 Mo steel and emphasize the development of a 3 Cr-1.5 Mo-0.1 V steel that showed promise as a better gasifier pressure vessel steel.[1,4]

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This report describes the heats of 2 1/4 Cr-1 Mo steel selected for the study, the processes and materials used to produce weldments, and the strength and toughness of the steels as a function of a tempering parameter *TP*. Where possible, comparisons are made with information from other investigations.

DESCRIPTION OF MATERIALS

Our studies included three heats of 2 1/4 Cr-1 Mo steel and three combinations of welding consumables for the submerged-arc process (Table 1). The fabrication histories for the three heats have been extensively documented elsewhere,[5-8] so we will keep our description to a minimum.

Table 1. Summary of welds produced by the submerged-arc process in 2 1/4 Cr-1 Mo steel

Weldment	Base metal heat	Weld thickness (cm)	Weld thickness (in.)	Filler metal	Material tested	Type tests
305	646363	18	7	Oerlikon EB-3	Weld	Fracture toughness
306	56447	5	2	Fluxocord 37STC	Weld	Tensile
307	56447	5	2	Oerlikon EB-3	Weld	Tensile
308	646363	18	7	Fluxocord 37STC	Weld	Tensile, Charpy
309	A6660	15	6	Thyssen S1CrMo2	Weld, HAZ,[a] base metal	Tensile, Charpy
310	56447	5	2	Thyssen S1CrMo2	Weld	Tensile
311	56447	5	2	Fluxocord 37STC	HAZ, base metal	Tensile, Charpy
312	56447	5	2	Fluxocord 37STC	HAZ, base metal	Tensile, Charpy

[a]Heat-affected zone.

Heat A6660 is a low-silicon, coarse-grained heat produced by the electric furnace process at Lukens Steel Company. Deoxidation was accomplished by a combination of calcium carbide, calcium–silicon carbide, and aluminum treatments. The ingots were rolled to both 150- and 300-mm (6- and 12-in.) plates, which were extensively studied in connection with other research programs.[5-6] The 150-mm plate was provided to us in the normalized and tempered condition having the composition and tensile properties listed in Tables 2 and 3, respectively. The as-received plate was renormalized at 927°C (1750°F) for 4 h, water quenched, tempered at 677°C (1150°F) for 4 h, then prepared for welding.

The weld joint design was a double-U configuration with a 20° included angle. The weldment is sketched in Fig. 1 and identified as JFK 309. The preheat was 175 to 200°C (350–400°F), and the plate was welded in 79 passes, without restraint, with Thyssen S1CrMo2 filler metal and Thyssen VU420TTR flux. The deposited weld composition was nearly identical with that of Weldment JFK 310 in Table 2. The weldment was stress-relieved at 621°C (1150°F) for 4 h before sectioning for additional tempering.

Heat 56447 was a vacuum-arc-remelted heat produced by Cameron Iron Works to nuclear grade standards and meeting the SA-387 grade 22 class 1 specification for annealed material.[7] Several product forms were available, and from them we selected a 51-mm-thick (2-in.) plate. This was renormalized at 927°C (1750°F) for 1.5 h, fan cooled, and tempered at 621°C (1150°F) for 1.5 h before welding. The plates were machined with a 15° included angle V-groove joint and a 19-mm root opening with a backing strip, as shown in Fig. 2.

Five submerged-arc welds were made in plates from heat 56447. Three, identified as JFK 306, 311, and 312, were produced by using flux-cored wire, Oerlikon Fluxocord 37 STC, with Oerlikon OP-76 flux. Approximately 30 passes were required to weld the 51-mm-thick plates. One weldment, identified as JFK 307, was produced by using a standard Oerlikon EB-3 welding wire and Oerlikon OP-76 flux. This weldment required 41 passes. Another weldment, identified as JFK 310, was produced with Thyssen S1CrMo2 welding wire and Thyssen UV420TTR flux and required 37 passes. All the

Table 2. Chemical composition of materials

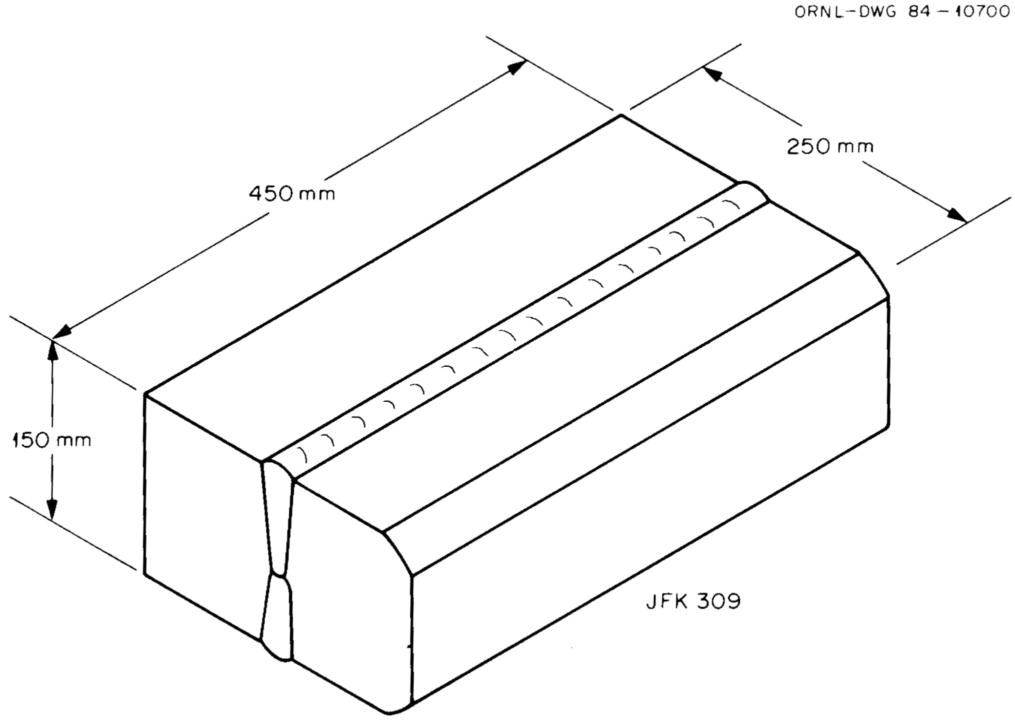
Material	Content (wt %)														
	C	Mn	P	S	Cr	Mo	Si	Ni	Cu	Sn	Al	V	Co	N	As
Lukens heat A6660	0.13	0.33	0.012	0.02	2.34	0.99	0.05	0.12	0.15	0.008	0.004				
Cameron heat 56447	0.10	0.49	0.010	0.007	2.15	1.03	0.23								
Kawasaki heat 646363	0.14	0.53	0.004	0.003	2.45	1.03	0.10	0.16			0.020				
Weld JFK 306															
Wire	0.108	0.71	0.013	0.007	2.44	1.10	0.19								
Weld	0.13	0.69	0.012	0.010	2.51	1.03	0.09	0.03	0.08	0.007	0.014	0.015	0.008	0.009	0.001
Weld JFK 307															
Wire	0.12	0.53	0.010	0.009	2.76	1.00	0.15		0.22						
Weld	0.093	0.54	0.007	0.006	2.76	0.97	0.19	0.19	0.36	0.007	0.010	0.006	0.020	0.010	0.005
Weld JFK 310															
Wire	0.12	0.46	0.005	0.006	2.62	1.01	0.10	0.02	0.01	0.003	0.012	<0.010			0.003
Weld	0.088	0.60	0.005	0.005	2.56	1.01	0.16	0.02	0.06	0.002	0.14	0.002	0.006	0.015	0.003

Table 3. Room-temperature tensile properties of base metals
(Specimens taken from quarter-thickness depth)

Temper (°C)	Temper (h)	Tempering parameter	Strength (MPa) Yield	Strength (MPa) Ultimate	Elongation (%)	Reduction of area (%)
			Lukens heat A6660			
662	6	19.43	545	659	24	71
690	28	20.66	441	558	26	59
			Kawasaki heat 646363			
650	8	19.29	612	722	24.5	76
675	7.5	19.79	556	675	25.5	79
690	15	20.39	488	616	27.5	78
705	25.4	20.94	393	542	31.0	79
690	24.5	20.60	441	587	29.0	80

welds in heat 56447 were sectioned in the as-welded condition. Full-thickness sections were cut for hardness studies. Deposited weld metal chemical analyses for the three flux-wire combinations are provided in Table 2 and designated as welds JFK 306, 307, and 310.

Heat 646363 was melted by the basic oxygen practice and forged from a 200-ton hollow ingot to a ring 4153 mm OD by 3353 mm ID by 3200 mm long.[8] The chemical analysis is provided in Table 2. The specification for the forged shell ring corresponded to ASME SA-336 grade F22, and the heat treatment was the following: normalized at 1070°C for 18 h, water quenched, tempered at 650°C for 16.5 h, air cooled, postweld heat treated (PWHT) at 695°C for 19 h, furnace cooled. As-received properties are provided in Table 3, and a complete evaluation of the base metal is provided elsewhere.[8] Two sections were obtained from the ring, which were 180 mm (7 in.) in the axial direction, 305 mm (12 in.) in the circumferential direction, and 400 mm (16 in.) in the radial direction. One section was sawed radially into two pieces and machined to a double-U-groove, as shown in Fig. 3. This was welded with Oerlikon EB-3 welding wire and Oerlikon OP-76 flux. The weld was identified as JFK 305 and sectioned without any



Heat: Lukens A6660
Condition: 927°C 4 h/water quench
621°C 4 h air cool
Welding wire: Thyssen S1CrMo2
Flux: Thyssen UV420TTR
Weld design: double-U-groove
20° groove angle
175°C preheat
89 passes
Stress relief: 621°C/4 h

Fig. 1. Weldment JFK 309.

stress relief or tempering. The second section was normalized at 927°C (1750°F) for 4 h, water-quenched, and sawed radially into two pieces. A double-U-groove was machined, and a submerged arc weld was produced with Oerlikon Fluxocord 37 STC welding wire and Oerlikon OP-76 flux. The weldment, identified as JFK 308, was PWHT at 621°C for 4 h before sectioning. Weld metal chemical composition is similar to that of Weld JFK 306 provided in Table 2.

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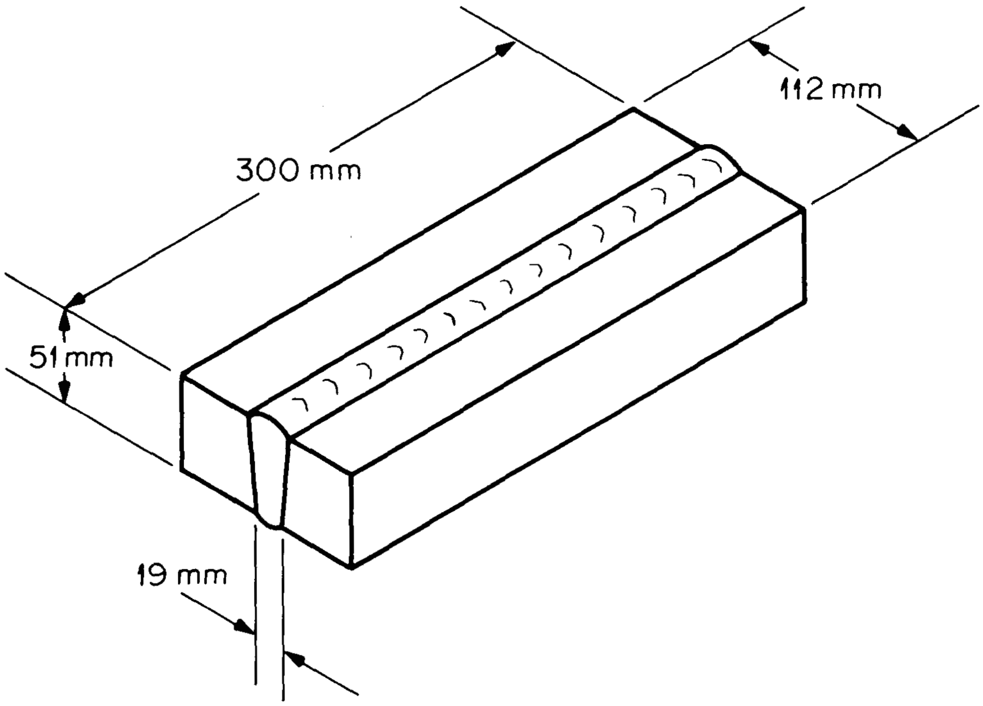

Weldment:	307	310	311, 312, 306
Heat:	56447	56447	56447
Condition:	927°C/1.5 h/AC	927°C/1.5 h/AC	927°C/1.5 h/AC
Welding wire:	Oerlikon EB-3	Thyssen S1CrMo2	Oerlikon Fluxocord 37
Flux:	Oerlikon OP-76	Thyssen UV420TTR	Oerlikon OP-76
Weld design:	V-groove	V-groove	V-groove
	15° included angle	15° included angle	15° included angle
	19-mm root gap	19-mm root gap	19-mm root gap
	175°C preheat	175°C preheat	175°C preheat
	41 passes	37 passes	~30 passes

Fig. 2. Weldments JFK 306, 307, 310, 311 and 312.

The tempering parameter used in this study was calculated from the equation

$$TP = T(20 + \log t) \times 10^{-3} , \qquad (1)$$

where

TP = tempering parameter,

T ≡ temperature, K

t ≡ time, h.

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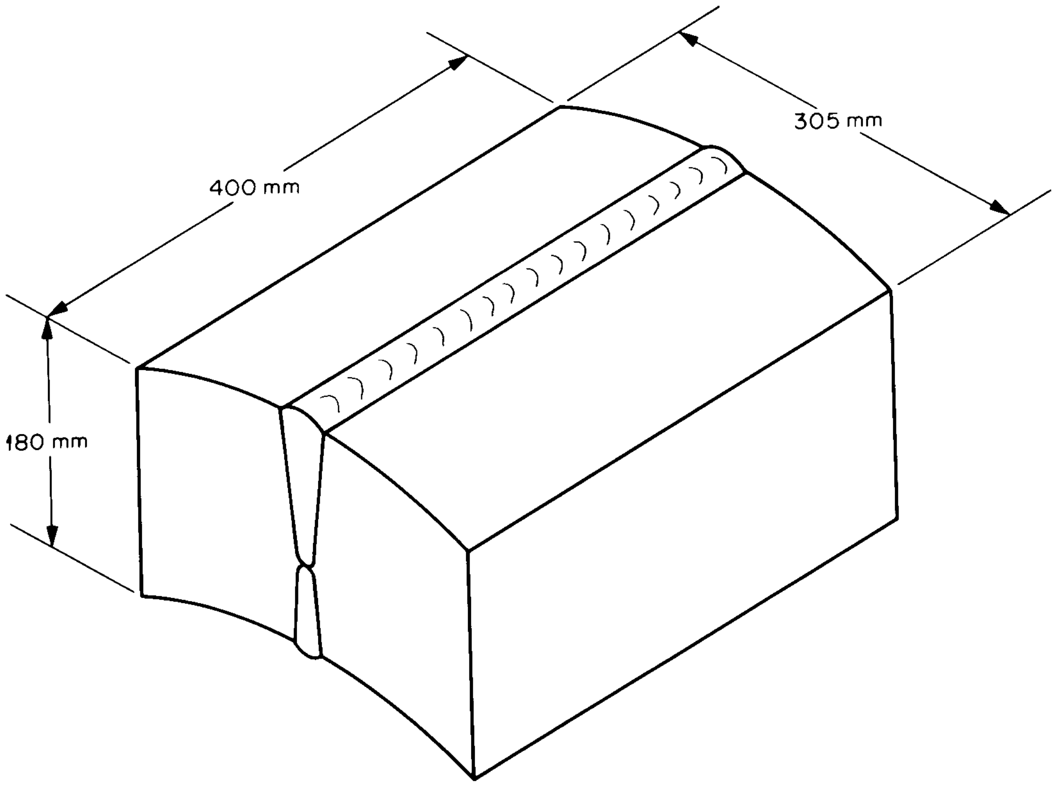

	JFK 305	JFK 308
Heat:	Kawasaki 646363	Kawasaki 646363
Condition:	1070°C/18 h/WQ	927°C/4 h/WQ
	650°C/16.5 h/AC	
	695°C/19 h/FC	
Welding wire:	Oerlikon EB-3	Oerlikon Fluxocord 37STC
Flux:	Oerlikon OP-76	Oerlikon OP-76
Weld design:	double-U-groove	double-U-groove
	20° groove angle	20° groove angle
	175°C preheat	175°C preheat
	116 passes	101 passes
Stress relief:	621°C/4 h	621°C/4 h

Fig. 3. Weldments JFK 305 and JFK 308.

HARDNESS RESULTS

Hardness profiles were obtained for several of the weldments after sectioning. A typical section is shown in Fig. 4, which is a photograph of weldment JFK 308. Diamond pyramid hardness indentations were made at intervals of approximately 1 mm in the region of the heat-affected zone (HAZ) and fusion line. Readings at larger intervals were taken into the weld metal and base metal. A typical hardness profile for weldment JFK 308 is plotted in Fig. 5. These profiles exhibited a consistent trend. The weld metal was always harder than the base metal in the as-welded condition. The PWHT of 621°C reduced the weld hardness to slightly higher than that of the base metal.

Rockwell B hardness data were obtained on the weldments as a function of the tempering conditions. In characterizing the starting materials, only small differences were found in the hardness through the thickness. An example is shown in Fig. 6 for weldment JFK 311. Three regions across the weld were selected: at the center of the weld, at the center of the HAZ, and at a location in the base metal away from the HAZ. Seven or more tempering conditions were examined for five different weldments: JFK 307, 308, 309, 310, and 311/312 (JFK 311 is equivalent to JFK 312). Some of the data are provided in Table 4 and plotted in Fig. 7. Data for the different base metals, HAZs, and weld metals are superimposed in the figure, which allows a comparison of hardness number as a function of tempering parameter. The weld metals were generally harder than the base metal, but the HAZ data scattered widely between the maximum and minimum values for the base and weld metal data. The hardness numbers corresponding by correlation to the range of ultimate tensile strengths from 620 to 758 MPa (90–110 ksi) are indicated in Fig. 7 by the scales on the right. The trend indicates that tempering parameters above 18.5 would produce strengths below 758 MPa (110 ksi), while tempering parameters above 19.5 produce ultimate strengths below 620 MPa (90 ksi) in some regions of the weldment.

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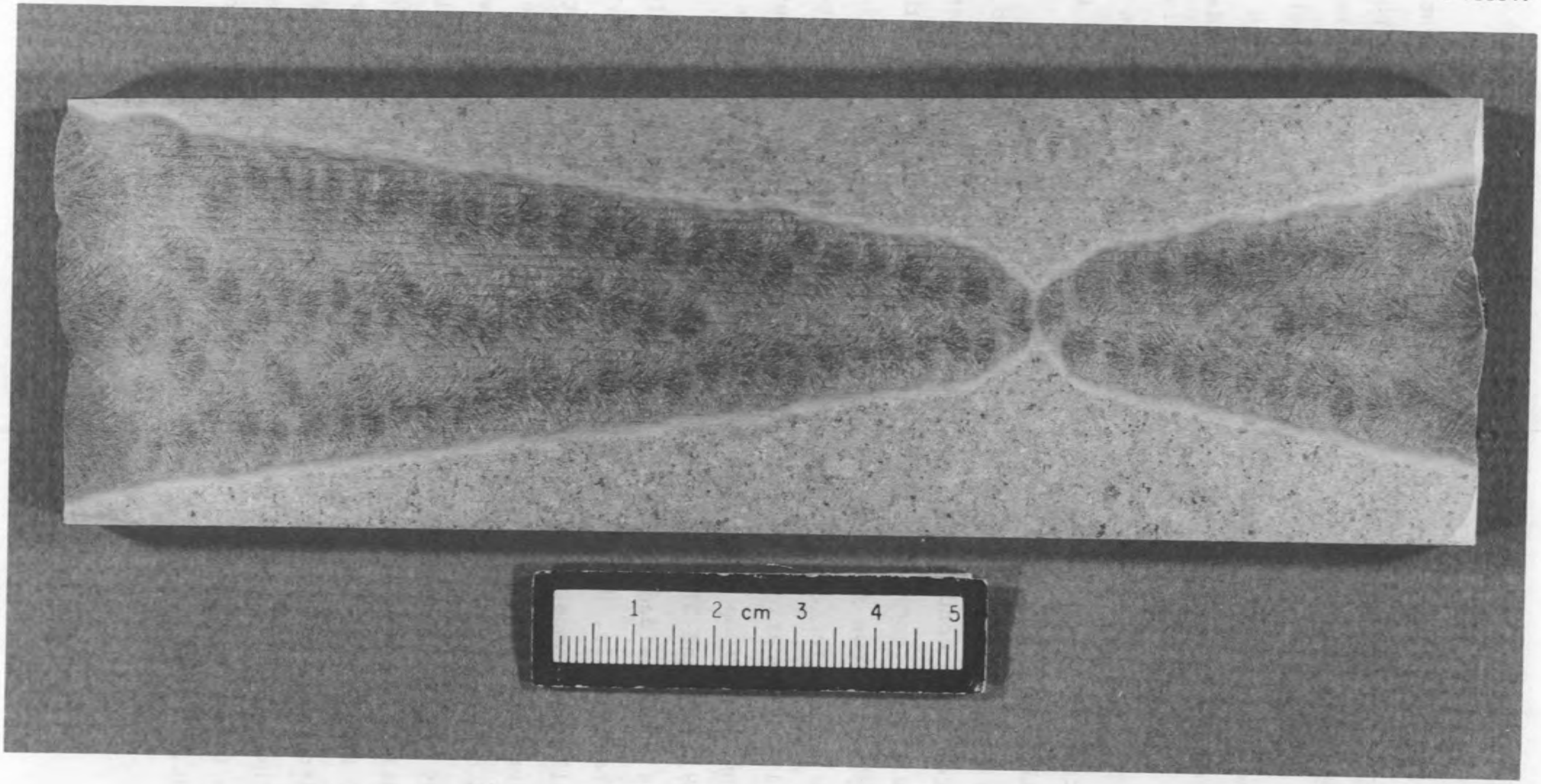

Fig. 4. Cross-sectional view of weldment JFK 308.

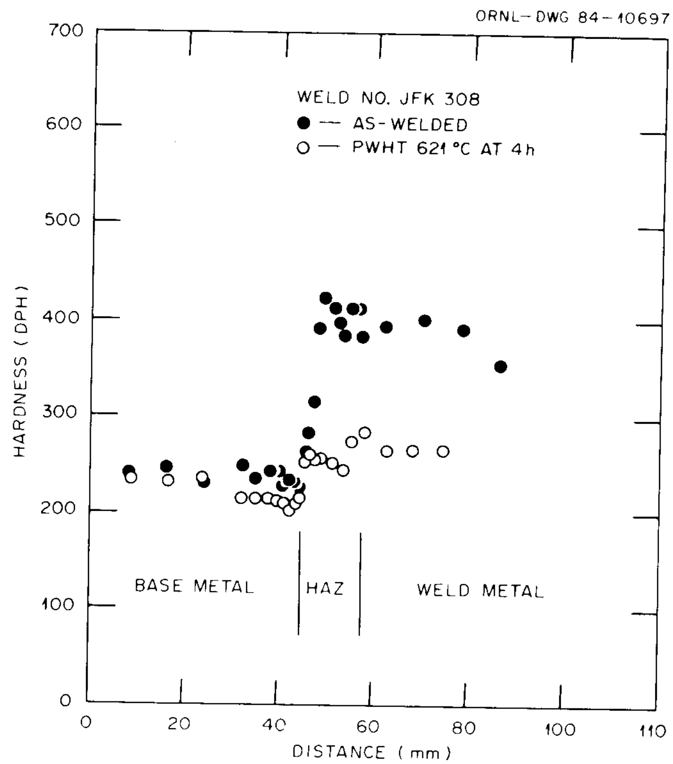

Fig. 5. Diamond pyramid hardness readings across weldment JFK 308.

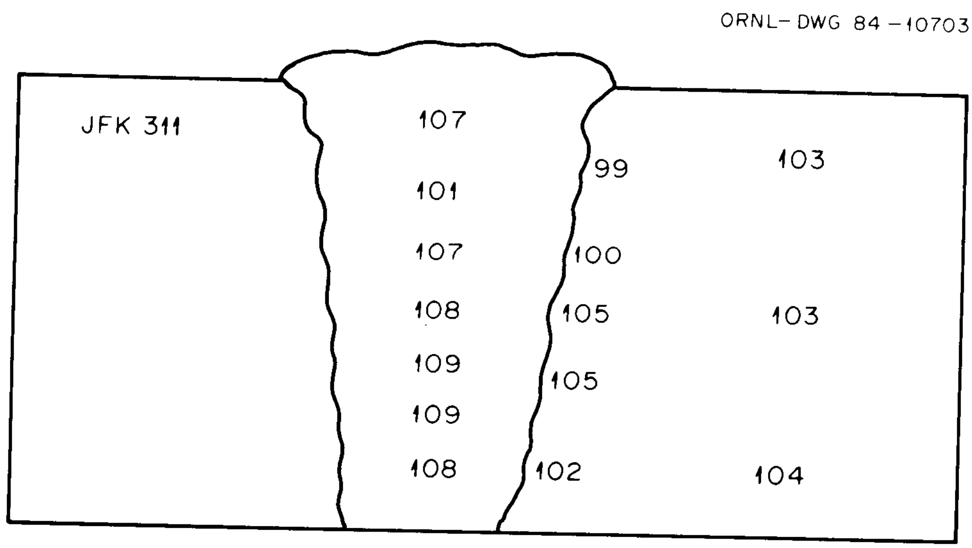

Fig. 6. Rockwell B hardness readings across the section of weldment JFK 311.

Table 4. Room-temperature hardness results for weldments

Weldment	Location	Tempering conditions (°C)	(h)	Tempering parameter	Rockwell B hardness
JFK 307	Weld	649	8	19.27	97.2
JFK 307	Weld	677	16	20.15	93.6
JFK 308	Base	621	4	18.42	97.5
JFK 308	Base	663	8	19.57	94.0
JFK 308	Base	663	16	19.85	91.0
JFK 308	Base	676	8	19.84	94.0
JFK 308	Base	676	16	20.12	89.0
JFK 308	Base	690	8	20.13	90.5
JFK 308	Base	690	16	20.42	88.0
JFK 308	HAZ	621	4	18.42	98.0
JFK 308	HAZ	663	8	19.57	90.5
JFK 308	HAZ	663	16	19.85	95.0
JFK 308	HAZ	676	8	19.84	97.0
JFK 308	HAZ	676	16	20.12	93.0
JFK 308	HAZ	690	8	20.13	91.5
JFK 308	HAZ	690	16	20.42	92.5
JFK 308	Weld	676	8	19.84	97.0
JFK 308	Weld	649	8	19.27	~100.0
JFK 308	Weld	621	4	18.42	~100.0
JFK 308	Weld	621	4	18.42	99.0
JFK 308	Weld	663	8	19.57	94.0
JFK 308	Weld	663	16	19.85	95.5
JFK 308	Weld	676	8	19.84	96.0
JFK 308	Weld	676	16	20.12	93.5
JFK 308	Weld	690	8	20.13	96.0
JFK 308	Weld	690	16	20.42	93.0
JFK 309	Base	621	4	18.42	97.4
JFK 309	Base	663	8	19.57	93.9
JFK 309	Base	663	16	19.85	91.7
JFK 309	Base	676	8	19.84	92.0
JFK 309	Base	676	16	20.12	90.8
JFK 309	Base	690	8	20.13	91.0
JFK 309	Base	690	16	20.42	88.6
JFK 309	HAZ	621	4	18.42	98.4
JFK 309	HAZ	663	8	19.57	95.5
JFK 309	HAZ	663	16	19.85	92.3
JFK 309	HAZ	676	8	19.84	93.6
JFK 309	HAZ	676	16	20.12	89.5
JFK 309	HAZ	690	8	20.13	91.3
JFK 309	HAZ	690	16	20.42	91.0

Table 4. (continued)

Weldment	Location	Tempering conditions		Tempering parameter	Rockwell B hardness
		(°C)	(h)		
JFK 309	Weld	621	4	18.42	98.1
JFK 309	Weld	663	8	19.57	96.1
JFK 309	Weld	663	16	19.85	94.3
JFK 309	Weld	676	8	19.84	94.0
JFK 309	Weld	676	16	20.12	92.6
JFK 309	Weld	690	8	20.13	92.1
JFK 309	Weld	690	16	20.42	92.0
JFK 310	Weld	649	8	19.27	98.0
JFK 310	Weld	677	16	20.14	94.3
311/312	Base	621	4	18.42	98.3
311/312	Base	649	8	19.27	91.3
311/312	Base	649	16	19.55	91.8
311/312	Base	663	8	19.57	90.7
311/312	Base	663	16	19.85	89.6
311/312	Base	676	8	19.84	90.6
311/312	Base	676	16	20.12	89.3
311/312	Base	690	8	20.13	87.2
311/312	Base	690	16	20.42	86.5
311/312	HAZ	621	4	18.42	102.5
311/312	HAZ	649	8	19.27	90.8
311/312	HAZ	649	16	19.55	93.0
311/312	HAZ	663	8	19.57	93.8
311/312	HAZ	663	16	19.85	91.0
311/312	HAZ	676	8	19.84	89.8
311/312	HAZ	676	16	20.12	87.3
311/312	HAZ	690	8	20.13	86.9
311/312	HAZ	690	16	20.42	88.7
311/312	Weld	621	4	18.42	101.2
311/312	Weld	649	8	19.27	95.6
311/312	Weld	649	16	19.55	95.4
311/312	Weld	663	8	19.57	93.5
311/312	Weld	663	16	19.85	92.5
311/312	Weld	676	8	19.84	92.8
311/312	Weld	676	16	20.12	90.3
311/312	Weld	690	8	20.13	90.4
311/312	Weld	690	16	20.42	89.0
312	Weld	649	8	19.27	98.6

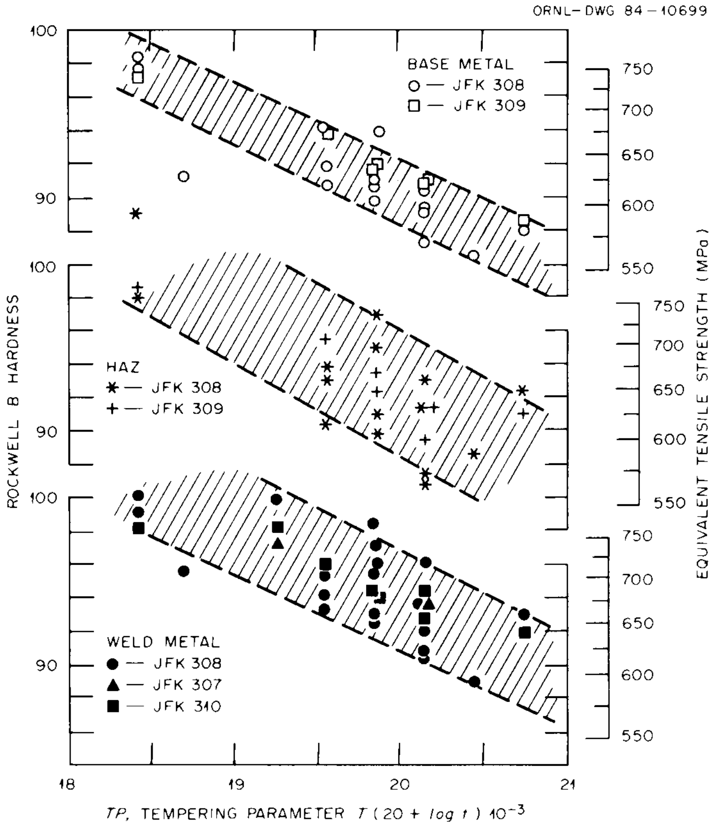

Fig. 7. Rockwell B hardness readings versus tempering parameter for several weld metals, heat-affected zones, and base metals. *T* is temperature in kelvins.

TENSILE RESULTS

Tensile testing was largely confined to an examination of the variation of room-temperature properties of weld metal with tempering parameter. Data are provided in Table 5 for weldments JFK 306, 307, and 310. (Table 5 also gives data for the HAZ of weldment JFK 309.) The ultimate strengths for the weld metals are plotted against the tempering parameter in Fig. 8. Trends reveal that the tempering parameter must be at least 19 to assure that the ultimate strength not exceed 760 MPa (110 ksi) but no more than 19.7 to prevent the lower strength material from falling below 620 MPa. This is a narrow tempering window but considerably wider than the window expected from a previous evaluation.[1]

Table 5. Room-temperature tensile properties of weld metal and heat-affected zone

Location[a]	Temper (°C)	Temper (h)	Tempering parameter	Strength (MPa) Yield	Strength (MPa) Ultimate	Elongation (%)	Reduction of area (%)
			JFK 306				
M	621	1.5	18.04	737	839	24.6	69.6
M	621	8	18.69	714	794	20.9	67.6
T	635	8	18.98	675	768	20.3	69.5
T	649	8	19.27	649	736	19.2	75.4
M	663	16	19.85	573	639	21.4	73.4
T	676	8	19.84	632	716	24.2	75.6
T	676	16	20.12	554	653	23.3	73.2
T	676	16	20.12	561	661	21.3	71.2
T	690	4	19.84	595	691	23.3	74.6
M	690	28	20.66	528	633	27.1	75.0
T	690	4	19.84	599	700	21.2	72.2
T	677	8	19.86	584	687	21.4	74.6
B[b]	690	16	20.42	527	638	20.4	74.6
T	621	4	18.42	714	825	14.8	75.0
T	677	24	20.31	572	675	13.1	72.1
			JFK 307				
M	621	1.5	18.04	646	743	23.7	72.6
T	621	8	18.69	595	687	25.9	71.5
T	635	8	18.98	562	665	22.9	72.5
M	649	8	19.27	566	671	22.2	76.5
T	663	16	19.85	488	605	26.6	75.9
T	676	8	19.84	512	623	27.1	75.7
T	676	16	20.12	464	588	26.2	75.1
T	676	16	20.12	498	601	24.6	73.8
T	690	4	19.84	505	623	25.9	76.3
M	690	28	20.66	431	557	29.3	76.1
T	690	4	19.84	515	637	24.5	74.2
B	677	8	19.86	513	622	25.4	77.2
T	621	1.5	18.04	654	759	19.9	71.9
B	690	16	20.42	466	588	28.6	76.1
T	621	4	18.42	645	754	22.6	73.4
T	677	24	20.31	502	620	24.1	73.5
			JFK 309				
HAZ	635	8	18.98	469	714	19.1	72.7
HAZ	635	8	18.98	604	709	21.0	74.1
HAZ	649	8	19.27	618	715	18.0	67.9
HAZ	649	8	19.27	600	705	19.7	72.1
HAZ	663	16	19.85	585	688	19.2	68.9
HAZ	663	16	19.85	567	679	21.7	70.6
HAZ	677	16	20.15	530	642	22.5	73.5
HAZ	677	16	20.15	551	655	22.8	74.2
HAZ	690	26	20.62	492	604	26.0	76.2

Table 5. (continued)

Location[a]	Temper		Tempering parameter	Strength (MPa)		Elongation (%)	Reduction of area (%)
	(°C)	(h)		Yield	Ultimate		
				JFK 310			
T	621	8	18.69	647	740	22.2	74.3
T	635	8	18.98	633	723	21.7	76.5
M	649	8	19.27	591	680	23.8	75.0
T	663	16	19.85	536	629	22.7	73.1
T	676	8	19.84	563	657	24.1	74.3
T	676	16	20.12	518	609	24.5	76.5
T	676	16	20.12	529	619	23.0	74.4
T	690	4	19.84	545	639	24.4	76.9
M	690	28	20.66	487	565	27.6	77.7
T	690	4	19.84	556	660	24.4	75.2
T	677	8	19.86	544	641	21.1	76.0
B	690	16	20.42	501	597	24.0	79.4
T	621	4	18.42	680	779	22.8	74.4
T	677	24	20.31	532	632	22.8	74.3

[a]M = midthickness; T = near top (crown) of weld; B = bottom.

[b]Base-metal failure.

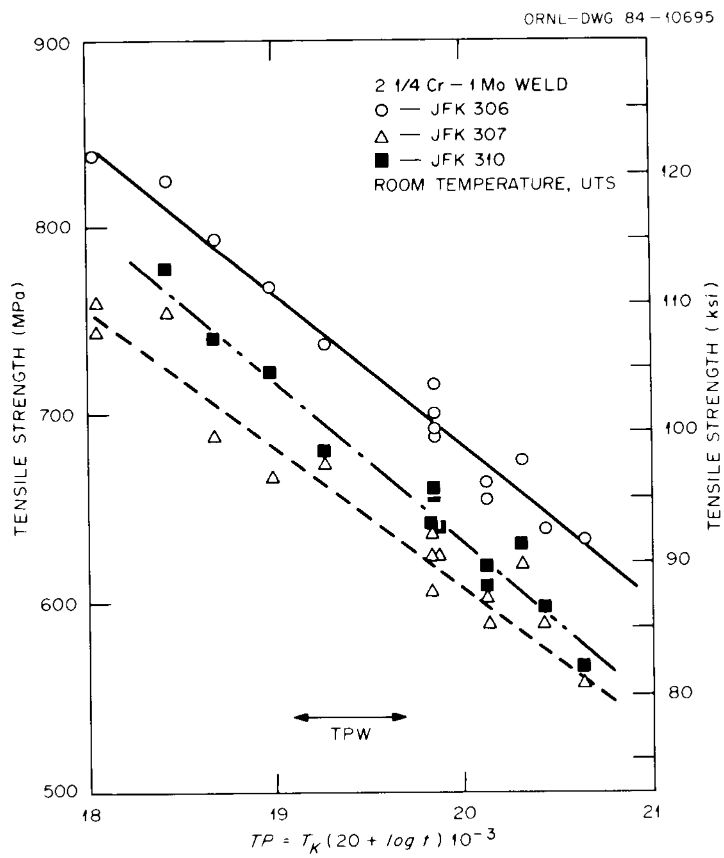

Fig. 8. Ultimate tensile strength versus tempering parameter for three weld metals.

Numerous studies have been performed to examine the tempering response of base metal, and the scatter bands for heat-to-heat variation of the base metal ultimate strength have been developed elsewhere.[1,3,4,9] In Fig. 9, the base metal and weld metal strengths have been compared, and the scatter in weld metal strength is somewhat greater than the scatter band developed by Rawlins et al.[3] (Fig. 9).

Elevated-temperature tensile properties are summarized in Table 6. Only two test temperatures were examined (316 and 482°C) with two tempering parameters (19.86 and 20.66), so a detailed analysis is impossible. However, the data in Table 6 do show that, for a test temperature of 316°C (600°F), increasing the tempering parameter from 19.86 to 20.66 reduced the strengths and increased the measures of ductility of all three welds. The reduction in yield strength ranged from 14 to 21%, while corresponding reductions in tensile strength ranged from 12 to 13%.

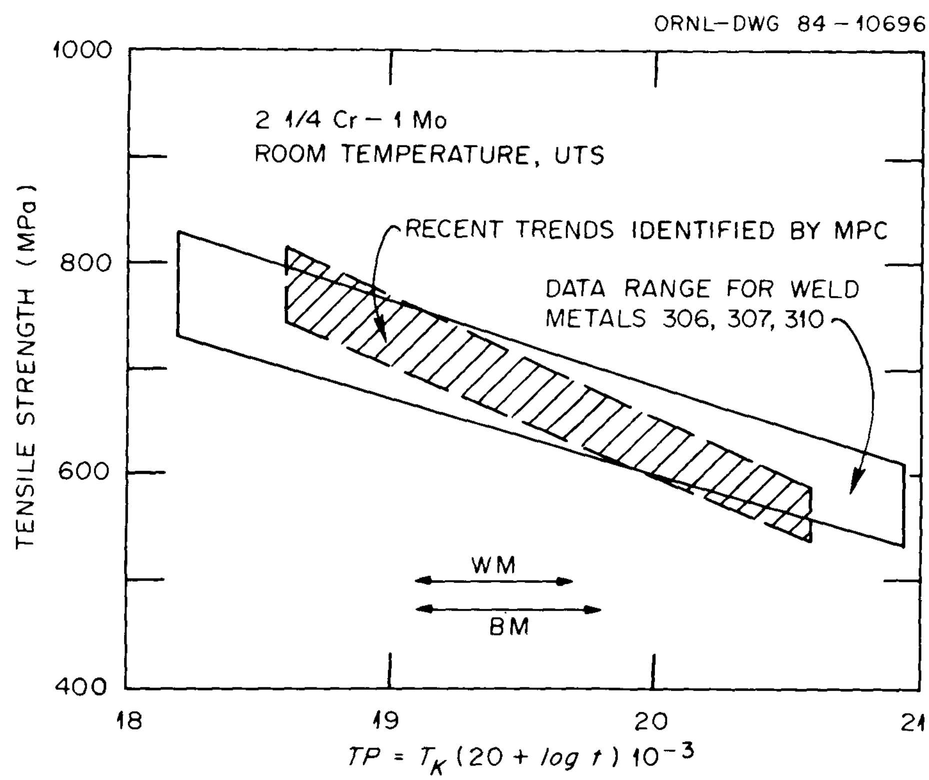

Fig. 9. Comparison of the tempering response of weld metal with base metal on the basis of the ultimate tensile strength.

Table 6. Elevated-temperature tensile properties of weld metal

Temper (°C)	Temper (h)	Tempering parameter	Test temperature (°C)	Strength (MPa) Yield	Strength (MPa) Ultimate	Elongation (%)	Reduction of area (%)
			JFK 306				
677	8	19.86	316	546	634	19.7	66.0
690	28	20.66	316	450	556	23.8	70.6
690	28	20.66	482	419	483	19.2	74.6
			JFK 307				
677	8	19.86	316	462	556	22.0	67.6
690	28	20.66	316	364	483	23.4	69.0
690	28	20.66	482	332	431	26.0	74.3
			JFK 309 heat-affected zone				
690	26	20.62	482	375	444	22.0	77.1
690	28	20.66	482	404	459	22.6	77.8
690	28	20.66	482	363	430	23.0	78.0
690	28	20.66	482	377	441	23.0	75.8
690	28	20.66	482	359	431	24.0	76.7
			JFK 310				
677	8	19.86	316	508	584	20.4	70.5
690	28	20.66	316	436	515	23.0	75.2
690	28	20.66	482	411	458	24.8	77.7

CHARPY IMPACT RESULTS

Charpy impact data were produced from five of the weldments. Included were two base metals (heats A6660 and 56447), two HAZs (one in each base metal heat), and three weld metals (Oerlikon EB-3, Fluxocord 37STC, and Thyssen S1CrMo2). Most of the testing was performed with material tempered at either 649°C for 8 h (TP = 19.27) or 677°C for 16 h (TP = 20.14). All the Charpy impact curves shown were obtained by a hyperbolic tangent (tanh) curve-fitting procedure developed by Oldfield.[10] The equation used is

$$\text{CVN energy} = A + B \tanh[(T - T_0)/C] \ . \qquad (2)$$

Figure 10 graphically defines the parameters used in the equation. For this program, a computer was used to optimize the values of T_0 and C for the best fit to each set of data. Table 7 provides the curve-fitting parameters determined for each material.

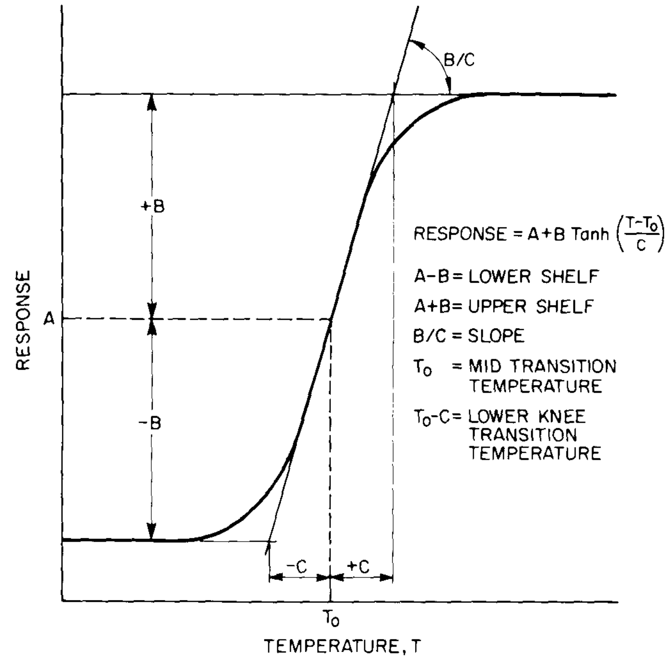

Fig. 10. Interpretation of the coefficients of the hyperbolic tangent regression.

Charpy results for the Oerlikon EB-3 weld metal from JFK 307, designated 307WM1 and 307WM2, are provided in Table 8 and shown graphically in Fig. 11. The temper for 16 h at 677°C substantially increased the upper-shelf energy of the weld metal over that for the temper for 8 h at 649°C: 345 and 166 J, respectively. The 54-J transition temperatures are both about −90°C. Thus, the increased tempering, in this case, decreased both the yield and ultimate strengths by over 10% while doubling the upper-shelf energy.

For the Oerlikon Fluxocord 37STC weld metal, four tempers were examined. These included 4 h at 621°C (*TP* = 18.42), 8 h at 649°C (*TP* = 19.27), 8 h at 677°C (*TP* = 19.85), and 16 h at 677°C (*TP* = 20.14). From the lowest to the highest tempering parameter, the four welds are designated 308WM2, 308WM1, 308WM3, and 308WM4. Charpy results are provided in Table 9 and shown in Fig. 12. For the three lowest tempering parameters, the 54-J transition temperatures vary from −17 to −25°C, while that for 308WM4 (tempered 16 h at 677°C) is −50°C. Relative to the upper shelf, the increasing tempering parameter results in obvious increases in

Table 7. Charpy impact curve fitting parameters

Group	Temper (°C)	Temper (h)	Tempering parameter[b]	tanh Parameters[a]: A	B	T_0 (°C)	C (°C)	54-J temperature (°C)
			Lukens heat A-6660					
309BP1	649	8	19.27	51	84	−51	29	−50
309BP2	677	16	20.15	84	70	−54	25	−65
			Cameron heat 56447					
312BP1	621	1.5	18.04	87	98	−50	67	−74
312BP3	677	16	20.15	179	178	−37	5	−44
312BP4	621	8	18.69	118	240	−51	55	−67
312BP5	649	8	19.27	193	157	−54	15	−75
312BP6	677	8	19.86	180	177	−50	13	−61
			JFK 307					
307WM1	649	8	19.27	82	84	−73	37	−86
307WM2	677	16	20.15	87	258	−73	139	−91
			JFK 308					
308WM1	649	8	19.27	72	76	−19	23	−25
308WM2	621	4	18.42	66	59	−12	25	−17
308WM3	621 677	4 8	19.86	97	88	−14	17	−23
308WM4	621 677	4 16	20.15	107	98	−47	5	−50
			JFK 310					
310WM1	649	8	19.27	107	109	−15	20	−26
310WM2	677	16	20.15	70	283	−46	115	−52

[a]Energy = $A + B \tanh[(T - T_0)/C]$; energy in joules, T = test temperature, °C.

[b]Tempering parameter = $T(20 + \log t) \times 10^{-3}$; T = temperature, K; t = time, h.

upper-shelf energy. Over that range of tempering parameters (18.42 to 20.14), the upper-shelf energy increases from 125 to 205 J, an increase of nearly a factor of 2. The transition temperatures are higher and the upper-shelf energies are lower for this weld metal than for the Oerlikon EB-3 weld metal.

Table 8. Charpy impact results for weld JFK 307

Specimen[a]	d/t Locations[b]	Test temperature (°C)	Test temperature (°F)	Dial energy[c] (J)	Dial energy[c] (ft-lb)	Lateral expansion (mm)	Lateral expansion (in.)	Fracture appearance (% shear)
			Group 307WM1, 8 h at 649°C (*TP* = 19.27)					
RS-60	0.79	−115	−175	11.0	8.1	0.142	0.0056	0
RS-56	0.52	−73.3	−100	87.6	64.6	1.074	0.0423	42
RS-59	0.52	−31.7	−25	146.7	108.2	1.740	0.0685	81
RS-55	0.24	21.1	70	163.0	120.2	2.017	0.0794	100
RS-57	0.79	148.9	300	175.7	129.6	1.918	0.0755	100
RS-58	0.24	287.8	550	158.0	116.5	1.699	0.0669	100
			Group 307WM2, 16 h at 677°C (*TP* = 20.15)					
RS-54	0.79	−115	−175	6.8	5.0	0.127	0.0050	0
RS-50	0.52	−73.3	−100	90.4	66.7	1.219	0.0480	34
RS-53	0.52	−31.7	−25	174.0	128.3	2.164	0.0852	77
RS-49	0.24	21.1	70	226.4	167.0	2.243	0.0883	100
RS-51	0.79	148.7	300	331.8	244.7	1.118	0.0440	100
RS-52	0.24	287.8	550	339.5	250.4	1.923	0.0757	100

[a]All specimens had the WL orientation, in which the specimen axis was perpendicular (W = width) to welding direction and the crack propagation was in the welding direction (L = longitudinal).

[b]*d/t* = Ratio of depth (*d*) from weld crown surface to weld thickness (*t*).

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. The impact machine has a potential energy of 358 J (264 ft-lb).

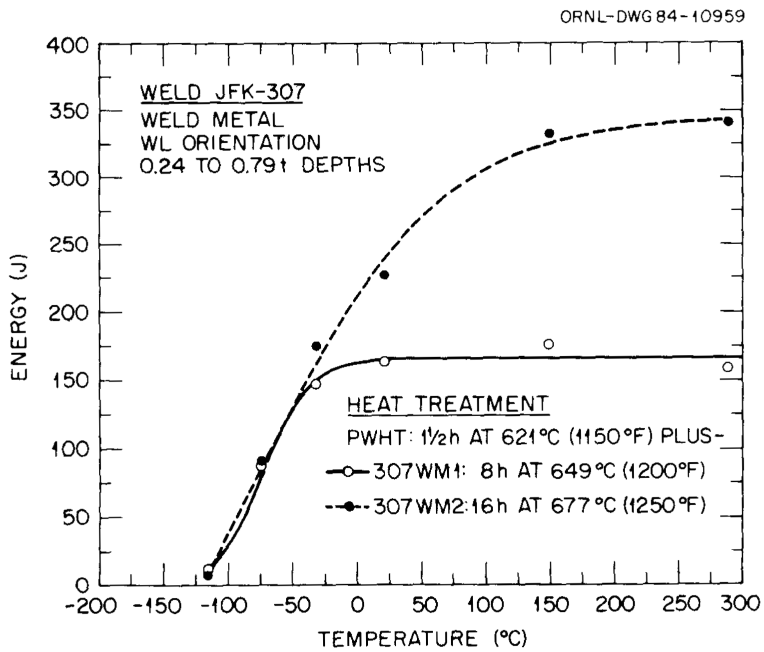

Fig. 11. Effect of tempering on the Charpy impact energy of weld metal from a 51-mm-thick submerged-arc weld made with Oerlikon EB3 filler wire and OP76 flux.

Table 9. Charpy impact results for weld JFK 308

Specimen[a]	d/t Locations[b]	Test temperature (°C)	Test temperature (°F)	Dial energy[c] (J)	Dial energy[c] (ft-lb)	Lateral expansion (mm)	Lateral expansion (in.)	Fracture appearance (% shear)
			Group 308WM2, 4 h at 621°C (*TP* = 18.42)					
RS-18	0.22	−45.6	−50	15.3	11.3	0.097	0.0038	17
RS-10	0.22	−17.8	0	50.8	37.5	0.551	0.0217	42
RS-34	0.22	4.4	40	106	78.0	1.265	0.0498	78
RS-2	0.22	19.4	67	106	78.0	1.250	0.0492	86
RS-26	0.22	37.8	100	127	93.5	1.499	0.0590	97
RS-42	0.22	176.7	350	126	92.7	1.684	0.0663	100
			Group 308WM1, 8 h at 649°C (*TP* = 19.27)					
RS-9	0.13	−45.6	−50	14.9	11.0	0.130	0.0051	27
RS-33	0.13	−31.7	−25	32.5	24.0	0.338	0.0133	33
RS-17	0.13	−17.8	0	71.9	53.0	0.848	0.0334	53
RS-25	0.13	−3.9	25	121	89.0	1.336	0.0526	80
RS-1	0.13	19.4	67	139	102.3	1.676	0.0660	90
RS-41	0.13	176.7	350	153	112.5	1.923	0.0757	100
			Group 308WM3, 4 h at 621°C; 8 h at 677°C (*TP* = 19.86)					
RS-19	0.30	−73.3	−100	6.8	5.0	0.015	0.0006	5
RS-27	0.30	−31.7	−25	30.8	22.7	0.325	0.0128	30
RS-43	0.30	−3.9	25	145	110.5	1.717	0.0676	80
RS-11	0.30	20.0	68	172	126.5	1.953	0.0769	93
RS-35	0.30	176.7	350	192	141.5	2.032	0.080	100
			Group 308WM4, 4 h at 621°C; 16 h at 677°C (*TP* = 20.15)					
RS-21	0.47	−128.9	−200	4.1	3.0	0.028	0.0011	0
RS-37	0.47	−87.2	−125	9.5	7.0	0.112	0.0044	5
RS-45	0.47	−67.8	−90	13.8	10.2	0.130	0.0051	10
RS-13	0.47	−45.6	−50	127	93.7	1.311	0.0516	70
RS-5	0.47	20.0	68	206	152.0	2.080	0.0819	94
RS-29	0.47	176.7	350	204	150.7	1.979	0.0779	100

[a]All specimens had the WL orientation, in which the specimen axis was perpendicular (W = width) to welding direction and the crack propagation was in the welding direction (L = longitudinal).

[b]d/t = Ratio of depth (d) from weld crown surface to weld thickness (t).

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. The impact machine has a potential energy of 358 J (264 ft-lb).

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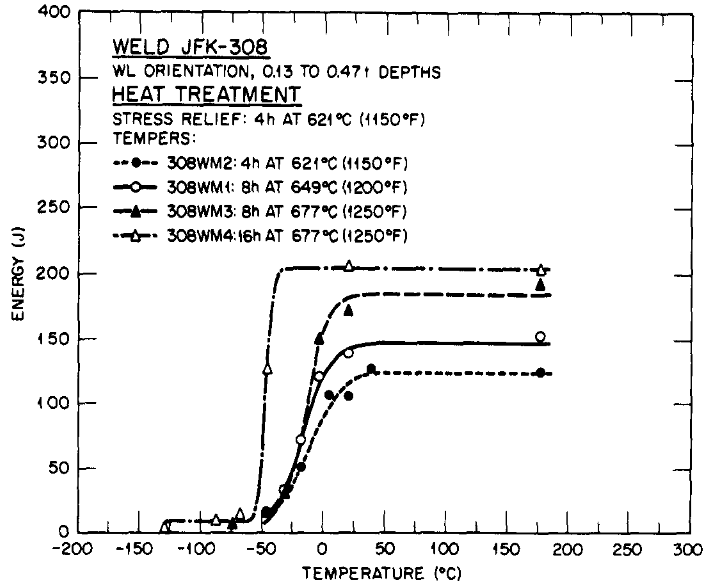

Fig. 12. Effect of tempering on the Charpy impact energy of weld metal from a submerged-arc weld in 178-mm-thick 2 1/4 Cr-1 Mo steel plate using Oerlikon Fluxocord 37STC filler wire and OP76 flux.

The Thyssen S1CrMo2 weld metal was examined in both weldments JFK 309 and 310. Only sparse data are available for JFK 309, and they are not presented in this report. Table 10 provides the test results for JFK 310, and Fig. 13 graphically compares the two tempering conditions. Increasing the tempering parameter from 19.27 to 20.14 resulted in a decrease in the 54-J transition temperature from −26 to −52°C and an increase in upper-shelf energy from 216 to 358 J. The test at 288°C resulted in an absorbed energy at the limit of the impact machine capacity.

Figures 14 and 15 graphically compare the three weld metals for tempering conditions of 8 h at 649°C (*TP* = 19.27) and 16 h at 677°C (*TP* = 20.14), respectively. As shown in Fig. 14, the two Oerlikon weld metals have substantially different 54-J transition temperatures but similar upper-shelf energies at the lower tempering parameter. At the higher tempering parameter, Fig. 15 shows that the EB-3 weld metal experienced little change in the transition temperature, but the upper-shelf energy was twice that for the lower tempering condition. In comparison, the Thyssen S1CrMo2 weld metal experienced a similarly substantial increase in upper-shelf energy but also experienced a decrease in transition temperature of 26°C.

Table 10. Charpy impact results for weld JFK 310

Specimen[a]	d/t Locations[b]	Test temperature (°C)	Test temperature (°F)	Dial energy[c] (J)	Dial energy[c] (ft-lb)	Lateral expansion (mm)	Lateral expansion (in.)	Fracture appearance (% shear)
			Group 310WM1, 8 h at 649°C (*TP* = 19.27)					
RS-64	0.24	−73.3	−100	7.5	5.5	0.038	0.0015	0
RS-66	0.79	−31.7	−25	18	13.6	0.292	0.0115	22
RS-65	0.52	−3.9	25	178	131.2	2.070	0.0815	82
RS-61	0.24	23.3	74	186	136.9	2.248	0.0885	100
RS-63	0.79	148.9	300	221	163.3	1.793	0.0706	100
RS-62	0.52	287.8	550	225	165.6	1.880	0.0740	100
			Group 310WM2, 16 h at 677°C (*TP* = 20.15)					
RS-70	0.24	−73.3	−100	10	7.6	0.132	0.0052	5
RS-72	0.79	−45.6	−50	14.8	10.9	0.137	0.0054	20
RS-71	0.52	−31.7	−25	163	120.1	2.035	0.0801	75
RS-67	0.24	23.3	74	214	157.5	2.286	0.0900	100
RS-69	0.79	148.9	300	328	241.7	1.826	0.0719	100
RS-68	0.52	287.8	550	358	264	1.943	0.0765	100

[a]All specimens had the WL orientation, in which the specimen axis was perpendicular (W = width) to welding direction and the crack propagation was in the welding direction (L = longitudinal).

[b]*d*/*t* = Ratio of depth (*d*) from weld crown surface to weld thickness (*t*).

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. The impact machine has a potential energy of 358 J (264 ft-lb).

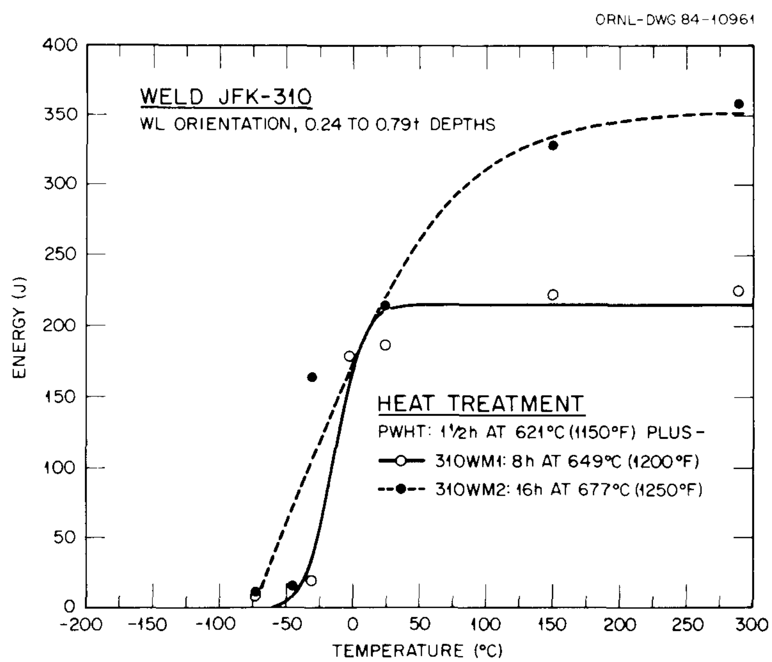

Fig. 13. Effect of tempering on the Charpy impact energy of weld metal from a 51-mm-thick submerged-arc weld made with Thyssen S1CrMo2 filler wire and UV420TTR flux.

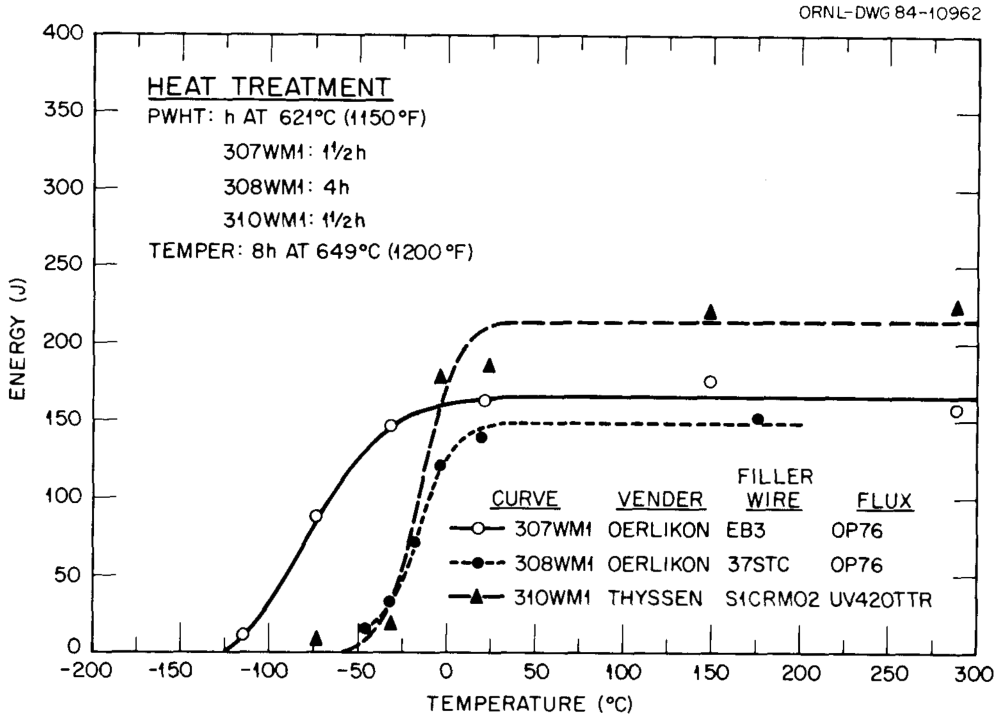

Fig. 14. Effect of filler wire and flux on the Charpy impact energy of weld metal from submerged-arc welds in 2 1/4 Cr-1 Mo steel plate after a postweld heat treatment and a temper of 8 h at 649°C.

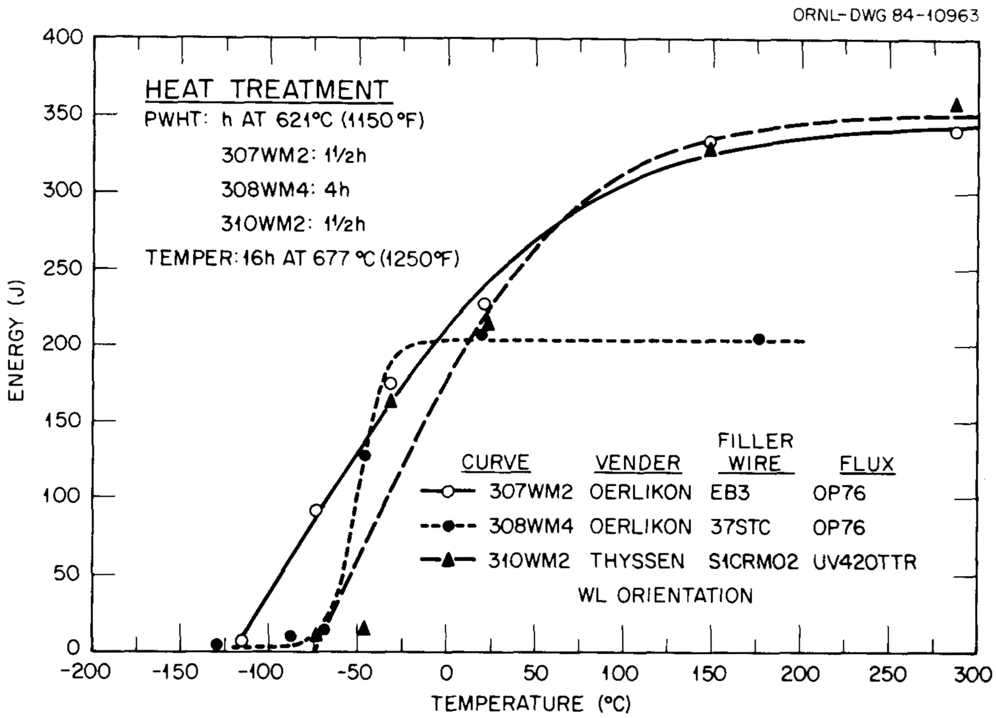

Fig. 15. Effect of filler wire and flux on the Charpy impact energy of weld metal from submerged-arc welds in 2 1/4 Cr-1 Mo steel plate after a postweld heat treatment and a temper of 16 h at 677°C.

Charpy impact results were also obtained for the two base metals, Lukens heat A6660 and Cameron heat 56447. Table 11 and Fig. 16 provide the results for the Lukens base plate tempered to parameters of 19.27 and 20.15. As shown in Fig. 16, the increase in tempering decreased the 54-J transition temperature from −50 to −65°C and increased the upper-shelf energy from 135 to 154 J, relatively modest changes compared with those in some of the weld metals. The Cameron heat 56447 results are provided in Table 12 and Fig. 17 and show substantially higher upper-shelf energies for the tempered materials than those for the Lukens heat, although the transition temperatures are similar.

Table 11. Charpy impact results for Lukens heat A-6660

Specimen[a]	d/t Locations[b]	Test temperature		Dial energy[c]		Lateral expansion		Fracture appearance (% shear)
		(°C)	(°F)	(J)	(ft-lb)	(mm)	(in.)	
		Group 309BP1, 8 h at 649°C (*TP* = 19.27)						
RS-123	0.70	−73.3	−100	5.3	3.9	0.053	0.0021	0
RS-133	0.80	−59.4	−75	6.9	5.1	0.051	0.0002	0
RS-122	0.30	−45.6	−50	90	66.1	1.184	0.0466	34
RS-141	0.70	−31.7	−25	93	68.2	1.323	0.0521	36
RS-139	0.20	−17.8	0	103	75.7	1.389	0.0547	52
RS-140	0.30	−3.9	25	148	109.2	1.941	0.0764	100
RS-121	0.20	21.1	70	145	107.1	1.656	0.0652	100
RS-124	0.80	93.3	200	146	107.5	2.009	0.0791	100
RS-130	0.20	148.9	300	138	101.7	1.720	0.0677	100
RS-131	0.30	204.4	400	116	85.4	1.549	0.061	100
RS-142	0.80	246.1	475	128	94.7	1.618	0.0637	100
RS-132	0.70	287.8	550	139	102.4	1.519	0.0598	100
		Group 309BP2, 16 h at 677°C (*TP* = 20.15)						
RS-167	0.30	−73.3	−100	3.5	2.6	0.0965	0.0038	0
RS-168	0.70	−67.8	−90	70	51.8	1.102	0.0434	16
RS-166	0.20	−59.4	−75	95	70.0	1.326	0.0522	26
RS-149	0.30	−45.6	−50	97	71.2	1.303	0.0513	47
RS-160	0.80	−31.7	−25	127	94.0	1.758	0.0692	54
RS-148	0.20	−17.8	0	159	117.6	2.068	0.0814	100
RS-169	0.80	37.8	100	161	118.5	2.080	0.0819	100
RS-150	0.70	93.3	200	164	120.9	2.101	0.0827	100
RS-151	0.80	148.9	300	158	116.6	1.806	0.0711	100
RS-157	0.20	204.4	400	139	102.2	1.905	0.075	100
RS-158	0.30	246.1	475	149	109.6	1.674	0.0659	100
RS-159	0.70	287.8	550	146	107.5	1.486	0.0585	100

[a]All specimens had the WR orientation, in which the specimen axis was perpendicular (W = width) to rolling direction and the crack propagation was in the rolling direction (R = rolling).

[b]*d*/*t* = Ratio of depth (*d*) from weld crown surface to weld thickness (*t*).

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. Impact machine has a potential energy of 358 J (264 ft-lb).

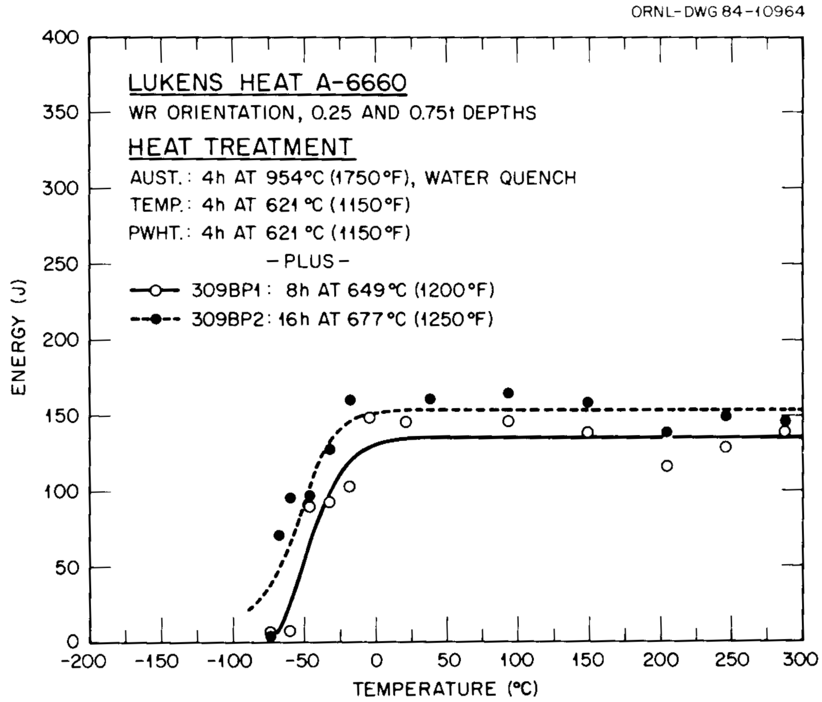

Fig. 16. Effect of tempering on the Charpy impact energy of a 152-mm-thick 2 1/4 Cr-1 Mo steel plate.

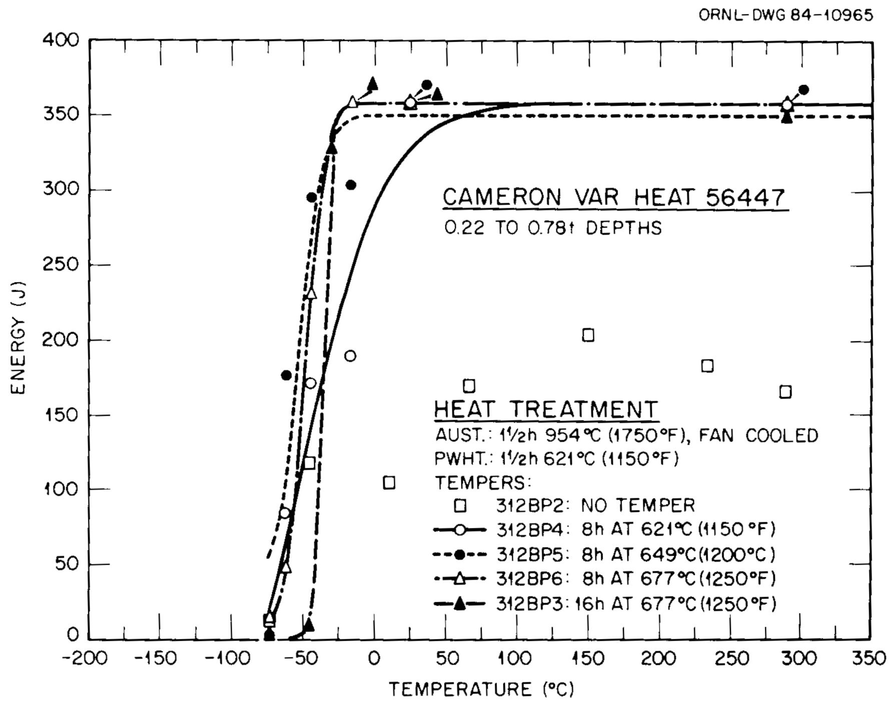

Fig. 17. Effect of tempering on the Charpy impact energy of a 51-mm-thick vacuum-arc-remelted, forged and hot-rolled 2 1/4 Cr-1 Mo steeel plate after a postweld heat treatment of 1.5 h at 621°C.

Table 12. Charpy impact results for Cameron heat 56447

Specimen	Orientation[a]	d/t Locations[b]	Test temperature		Dial energy[c]		Lateral expansion		Fracture appearance (% shear)
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(in.)	
Group 312BP1, no temper									
RS-183	RW	0.78	−101.1	−150	17.6	13.0	0.117	0.0046	0
RS-182	RW	0.50	−45.6	−50	115	84.6	1.486	0.0585	10
RS-176	RW	0.50	−17.8	0	118	87.3	1.582	0.0623	23
RS-177	RW	0.78	10.0	50	146	107.7	2.027	0.0798	38
RS-178	RW	0.22	65.6	150	207	152.4	2.146	0.0845	100
RS-179	RW	0.50	148.9	300	189	139.7	2.037	0.0802	100
RS-180	RW	0.78	232.2	450	187	137.6	1.725	0.0679	100
RS-181	RW	0.22	287.8	550	161	118.5	1.760	0.0693	100
Group 312BP2, no temper									
RS-186	WR	0.78	−45.6	−50	117	86.3	1.580	0.0622	17
RS-184	WR	0.22	10.0	50	104	76.8	1.367	0.0538	17
RS-185	WR	0.50	65.6	150	169	124.5	1.887	0.0743	64
RS-187	WR	0.22	148.9	300	203	150.0	1.679	0.0661	100
RS-188	WR	0.50	232.2	450	183	134.8	2.075	0.0817	100
RS-189	WR	0.78	287.8	550	166	122.1	1.941	0.0764	100
Group 312BP3, 16 h at 677°C (*TP* = 20.15)									
RS-117	WR	0.78	−73.3	−100	3.5	2.6	0.107	0.0042	0
RS-118	WR	0.22	−45.6	−50	9.0	6.6	0.152	0.0060	0
RS-120	WR	0.78	−31.7	−25	328	241.9	2.149	0.0846	100
RS-119	WR	0.50	−17.8	0	358	264	2.367	0.0932	100
RS-115	WR	0.22	23.3	74	358	264	2.507	0.0987	100
RS-116	WR	0.50	287.8	550	349	257.2	2.301	0.0906	100
Group 312BP4, 8 h at 621°C (TP = 18.69)									
RS-99	WR	0.78	−73.3	−100	11.5	8.5	0.145	0.0057	0
RS-102	WR	0.78	−62.2	−80	84	61.6	1.186	0.0467	11
RS-100	WR	0.22	−45.6	−50	171	125.8	2.207	0.0869	31
RS-101	WR	0.50	−17.8	0	179	139.3	2.342	0.0922	42
RS-97	WR	0.22	23.3	74	358	264	2.172	0.0855	100
RS-98	WR	0.50	287.8	550	358	264	1.996	0.0786	100
Group 312BP5, 8 h at 649°C (*TP* = 19.27)									
RS-105	WR	0.78	−73.3	−100	3.1	2.3	0.190	0.0075	0
RS-108	WR	0.78	−62.2	−80	176	129.7	2.352	0.0926	31
RS-106	WR	0.22	−45.6	−50	295	217.5	2.629	0.1035	100
RS-107	WR	0.50	−17.8	0	303	223.5	2.207	0.0869	100
RS-103	WR	0.22	23.3	74	358	264	2.240	0.0882	100
RS-104	WR	0.50	287.8	550	358	264	2.276	0.0896	100
Group 312BP6, 8 h at 677°C (*TP* = 19.86)									
RS-111	WR	0.78	−73.3	−100	15.3	11.3	0.119	0.0047	0
RS-114	WR	0.78	−62.2	−80	47.9	35.3	0.658	0.0259	5
RS-112	WR	0.22	−45.6	−50	232	171.0	2.649	0.1043	53
RS-113	WR	0.50	−17.8	0	358	264	2.375	0.0935	100
RS-109	WR	0.22	23.3	74	358	264	2.240	0.0882	100
RS-110	WR	0.50	287.8	550	358	264	2.304	0.0907	100

[a]WR, specimen axis oriented perpendicular (W = width) to rolling direction; crack propagation in rolling direction (R = rolling). RW, specimen axis oriented in rolling direction; crack propagation perpendicular to rolling direction.

[b]d/t = Ratio of depth (d) from weld crown surface to weld thickness (t).

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. Impact machine has a potential energy of 358 J (264 ft-lb).

Comparing Figs. 16 and 17 shows that, in addition to the higher upper shelf, the slopes of the toughness curves after tempering are much steeper for the Cameron heat than for the Lukens heat. The lower carbon and sulfur contents of the Cameron VAR heat likely contributed to those effects.

The HAZ was examined in weldment JFK 309 by fixing the Charpy V-notch testing temperature and testing samples with notches located at various distances from the fusion line. Typical results are given in Table 13 and plotted in Figs. 18 and 19 for two testing temperatures (—18 and 38°C) after two different tempers (8 h at 649°C and 16 h at 677°C). Trends indicate that the HAZ had about the same fracture energy as the base metal and perhaps less than the weld metal had. One HAZ specimen, given a 16-h temper at 677°C (Fig. 19), with the notch located 2.5 mm from the fusion line, had about half the energy of the other specimens. This is the same region where low hardness readings were sometimes found. The specimen tested at the same distance from the fusion line at the lower temper (Fig. 18) also showed substantially lower toughness than did the other specimens, but the effect was not as pronounced.

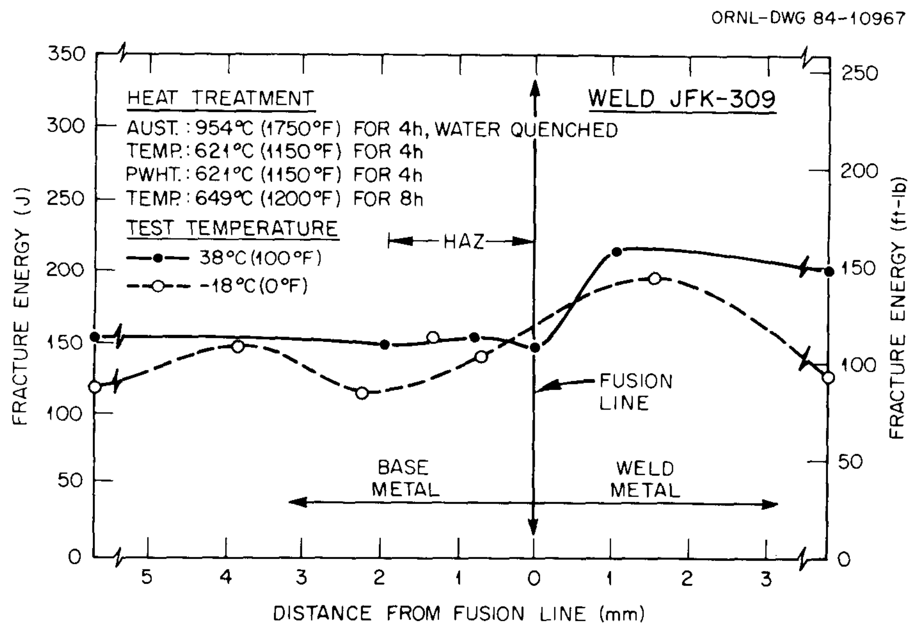

Fig. 18. Variation of Charpy-V impact energy across the heat-affected zone of a submerged-arc weld in a 154-mm-thick 2 1/4 Cr-1 Mo steel plate after a postweld heat treatment of 4 h at 621°C and tempering for 8 h at 649°C.

Table 13. Charpy impact results for heat-affected zone of weld JFK 309

Specimen	Orientation[a]	d/t Locations[b]		Test temperature		Dial energy[c]		Lateral expansion		Fracture appearance (% shear)
				(°C)	(°F)	(J)	(ft-lb)	(mm)	(in.)	
				Group 309HZ1, 8 h at 649°C (*TP* = 19.27)						
RS-125	WT	FZ	0.10	−17.8	0	166	122.4	1.829	0.072	100
RS-126	WT	WM	0.20	−17.8	0	214	157.5	2.225	0.0876	100
RS-127	WT	HAZ	0.29	−17.8	0	139	102.6	1.880	0.074	100
RS-128	WT	WM	0.38	37.8	100	237	174.7	2.344	0.0923	100
RS-129	WT	FZ	0.47	37.8	100	158	116.4	1.885	0.0742	100
RS-134	WT	HAZ	0.10	37.8	100	194	143.0	2.162	0.0851	100
RS-135	WL	WM(1.04)	0.20	37.8	100	216	158.9	2.151	0.0847	100
RS-136	WL	BM(1.96)	0.29	37.8	100	149	109.8	1.941	0.0764	100
RS-137	WL	HAZ(0.78)	0.38	37.8	100	154	113.5	2.116	0.0833	100
RS-138	WL	FL(0)	0.47	37.8	100	146	107.9	1.864	0.0734	100
RS-143	WL	BM(2.26)	0.10	−17.8	0	115	85.1	1.506	0.0593	67
RS-144	WL	WM(1.55)	0.20	−17.8	0	197	145.3	1.808	0.0712	85
RS-145	WL	HAZ(1.32)	0.29	−17.8	0	155	114.4	1.971	0.0776	100
RS-146	WL	BM(3.86)	0.38	−17.8	0	148	109.1	2.047	0.0806	100
RS-147	WL	HAZ(0.71)	0.47	−17.8	0	141	103.9	1.844	0.0726	100
				Group 309HZ2, 16 h at 677°C (*TP* = 20.15)						
RS-152	WL	HAZ(0.41)	0.10	−17.8	0	159	116.9	2.060	0.0811	94
RS-153	WL	BM(3.6)	0.20	−17.8	0	166	122.3	2.101	0.0827	100
RS-154	WL	WM(1.47)	0.29	−17.8	0	182	134.0	1.991	0.0784	80
RS-155	WL	HAZ(0.90)	0.38	−17.8	0	162	120.2	2.156	0.0849	100
RS-156	WL	BM(2.54)	0.47	−17.8	0	73	53.9	1.092	0.043	29
RS-161	WL	BM(4.06)	0.10	37.8	100	183	135.2	1.884	0.0742	100
RS-162	WL	WM(0.46)	0.20	37.8	100	225	166.0	2.017	0.0794	100
RS-163	WL	WM(1.45)	0.29	37.8	100	272	200.7	2.146	0.0845	100
RS-164	WL	BM(2.11)	0.38	37.8	100	168	124.0	1.745	0.0687	100
RS-165	WL	HAZ(1.07)	0.47	37.8	100	176	129.6	2.024	0.0797	100

[a]WL, specimen axis oriented perpendicular (W = width) to welding direction; crack propagation in welding direction (L = longitudinal).

WT, specimen axis oriented perpendicular (W = width) to welding direction; crack propagation in direction of plate thickness (T = thickness).

[b]d/t = Ratio of depth (d) from weld crown surface to weld thickness (t), FZ = fusion zone, WM = weld metal, HAZ = heat-affected zone, FL = fusion line, number in parentheses = distance from fusion line in mm.

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. The impact machine has a potential energy of 358 J (264 ft-lb).

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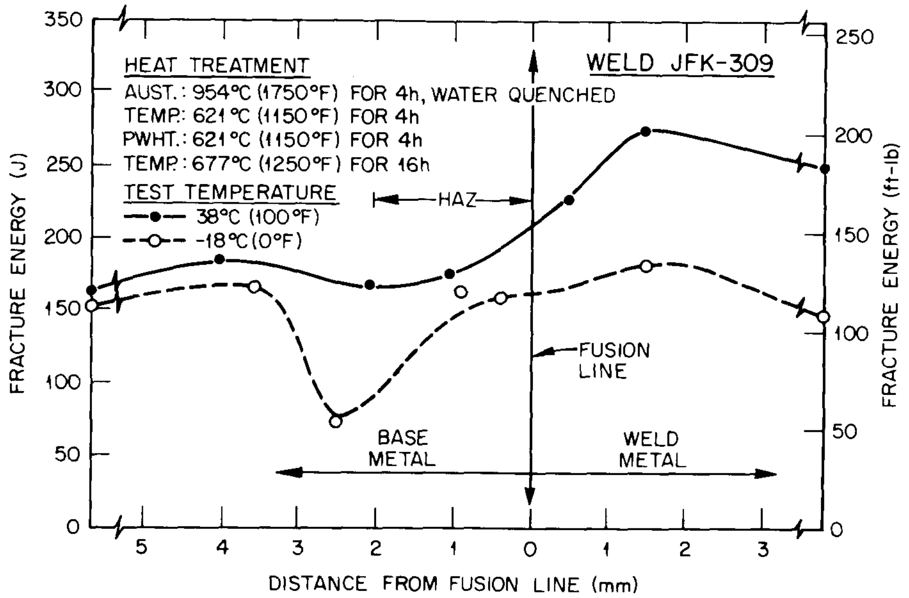

Fig. 19. Variation of Charpy-V impact energy across the heat-affected zone of a submerged-arc weld in a 154-mm-thick 2 1/4 Cr-1 Mo steel plate after a postweld heat treatment of 4 h at 621°C and tempering for 16 h at 166°C.

In weldment JFK 312, the region of the HAZ about 0.8 mm from the fusion line was examined at several temperatures. The fracture energies were high and the trends were more or less consistent with the good toughness properties of the base metal. Results of HAZ testing are provided in Table 14.

DISCUSSION

As stated in the introduction, the purpose for the work described herein was to establish the practicality of producing material with ultimate strengths in the range 620 to 758 MPa (90–110 ksi) while maintaining adequate toughness for gasifier pressure vessel service at temperatures to 316°C (600°F). For the weld metals examined, the trends in tensile data indicate that the tempering parameter must be at least 19.0 to assure that the ultimate strength not exceed 758 MPa (110 ksi), but no more than 19.7 to prevent the ultimate strength from falling below 620 (90 ksi).

Table 14. Charpy impact results for heat-affected zone of weld JFK 312

Specimen	Orientation[a]	Locations[b]	*d/t*	Test temperature (°C)	Test temperature (°F)	Dial energy[c] (J)	Dial energy[c] (ft-lb)	Lateral expansion (mm)	Lateral expansion (in.)	Fracture appearance (% shear)
				Group 312HZ1, 16 h at 677°C (*TP* = 20.15)						
RS-87	WT	HAZ(0.84)	0.75	−101.1	−150	22	15.9	0.229	0.009	
RS-88	WT	HAZ(0.86)	0.25	−73.3	−100	187	138.2	2.256	0.0888	55
RS-86	WT	HAZ(0.64)	0.50	−45.6	−50	248	183.0	2.586	0.1018	100
RS-89	WT	HAZ(0.79)	0.50	−17.8	0	295	217.3	2.261	0.0890	100
				Group 312HZ2, 16 h at 677°C (*TP* = 20.15)						
RS-92	WL	WM(0.77)	0.50	−45.6	−50	194	143.1	2.047	0.0806	55
RS-91	WL	WM(0.48)	0.25	10.6	50	358	264	1.930	0.0760	100
RS-93	WL	WM(0.80)	0.75	−73.3	−100	26	19.3	0.361	0.0142	15
				Group 312HZ3, 8 h at 649°C (*TP* = 19.27)						
RS-75	WT		0.75	−73.3	−100	16	11.9	0.188	0.0074	14
RS-81	WT	WM(1.05)	0.75	−67.8	−90	177	130.7	2.075	0.0817	41
RS-79	WT		0.25	−59.4	−75	212	156.6	2.578	0.1015	62
RS-74	WT		0.50	−45.6	−50	327	240.9	2.047	0.0806	100
RS-80	WT		0.50	10.0	50	358	264	1.831	0.0721	100
RS-73	WT		0.25	37.8	100	345	254.1	1.684	0.0663	100
				Group 312HZ4, 8 h at 649°C (*TP* = 19.27)						
RS-78	WL	HAZ(0.46)	0.75	−101.1	−150	9	6.6	0.0483	0.0019	0
RS-83	WL	HAZ(0.14)	0.50	−101.1	−150	27	20.1	0.381	0.0150	5
RS-77	WL	HAZ(0.79)	0.50	−73.3	−100	192	141.4	2.159	0.0850	51
RS-82	WL	HAZ(0.15)	0.25	−73.3	−100	270	199.3	2.352	0.0926	100
RS-76	WL	HAZ(0.64)	0.25	−45.6	−50	292	215.7	2.471	0.0973	100
RS-84	WL	HAZ(0.24)	0.75	10.0	50	346	255.1	1.731	0.0682	100

[a]WL, specimen axis oriented perpendicular (W = width) to welding direction; crack propagation in welding direction (L = longitudinal).

WT, specimen axis oriented perpendicular (W = width) to welding direction; crack propagation in direction of plate thickness (T = thickness).

[b]*d/t* = Ratio of depth (*d*) from weld crown surface to weld thickness (*t*), WM = weld metal, HAZ = heat-affected zone, number in parentheses = distance from fusion line in mm.

[c]Dial energies are read from a digital display of dial energy obtained from an optical encoder connected to the machine dial. The impact machine has a potential energy of 358 J (264 ft-lb).

Table 15 shows the time required at various tempering temperatures to achieve those tempering parameters. If one assumes a ±14°C (±25°F) variation in the heat treating furnace and a tempering temperature of 635°C (1175°F), the table shows the required time at temperature to be in the range 18 to 23 h to ensure a tempering parameter from 19.0 to 19.7 [ultimate strength from 690 to 620 MPa (100–90 ksi), respectively]. Thus, the tempering "window" is fairly narrow, and, as the tempering temperature increases, the window decreases (e.g., for a temperature of 677 ± 14°C, the time window is from 2 to 2.7 h). The table also shows results of similar calculations for a minimum tensile strength of 586 MPa (85 ksi). This substantially increases the time at temperature allowed to achieve an acceptable tensile strength as a result, of course, of the higher tempering parameter allowed, 20.2. For the same 635 ± 14°C tempering temperature, the time window extends from 18 to 81 h, resulting in a large tempering window, which provides much more flexibility in heat treatment procedures for thick welded vessels. The weld metal strengths varied more than did those of the base metal, and the toughness of weld metal as measured with the Charpy V-notch impact test was equal to or better than that of the base metal.

Table 15. Time and temperature requirements for various weld metal strength levels

Tempering parameter	Tensile strength		Time (h) at selected tempering temperatures						
	(MPa)	(ksi)	607°C (1125°F)	621°C (1150°F)	635°C (1175°F)	649°C (1200°F)	663°C (1225°F)	677°C (1250°F)	691°C (1275°F)
19.0	758	110	39	18	8.4	4	2	1	0.5
19.7	620	90	243	106	50	23	11	5.5	2.7
20.2	585	85	900	394	176	81	38	18	9

CONCLUSIONS

From the above results, the qualification of a quenched-and-tempered version of 2 1/4 Cr-1 Mo steel with ultimate strength in the range 620 to 758 MPa (90—110 ksi) for welded gasifier pressure vessels appears difficult because of a narrow time-temperature tempering window. A minimum ultimate strength requirement of 585 MPa (85 ksi), however, would be much easier to achieve because of the larger window.

A great number of questions are unanswered, but we expect that the work currently in progress under industrial sponsorship will meet these information needs.[3] Specifically, more data are needed for different base metal product forms. Welding processes other than submerged-arc welding should be examined. Fracture toughness testing should be performed for several strength levels and in hydrogen and H_2S atmospheres.

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