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A STUDY OF POSSIBLE INCREASE
OF INITIAL NDT IN THE SM-1
PRESSURE VESSEL WELD
HEAT AFFECTED ZONE

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SUMMARY

The potential increase in initial nil-ductility transition temperature (NDT) in the weld heat affected zone of the SM-1 reactor vessel was initially studied by applying data on synthetic heat affected zones obtained in a prior investigation and using the SM-1 weldment conditions. The individual effects of heat input rate, base metal temperature, and plate thickness on the heat affected zone (HAZ) cooling rate were established from the available data. Results from application of this data to the SM-1 vessel welding conditions indicated that the heat affected zones in the longitudinal and girth welds may have suffered an NDT increase of up to $100 + ^\circ\text{F}$ with 70% probability that this occurred.

A duplicate SM-1 weld test plate was produced and results analyzed using criteria derived from the prior investigation. One-half of the test plate remained in as-welded condition and one-half was stress relieved at 1150°F to duplicate SM-1 reactor vessel treatment. From microhardness tests and microstructure examination, it was estimated that the small medium-coarse grained areas within the SM-1 weld heat affected zone have increased 20 to 50°F in NDT above the base metal. These regions are less than 5% of the volume of the HAZ and are bounded by (1) weld metal, (2) by initially coarse grained regions which have been refined (normalized) by heat of subsequent adjacent weld beads, and (3) by intermediate to fine grained regions which were never heated to the grain coarsening temperature by the initial weld pass. Thus the net NDT of the heat affected zone is assumed no greater than the base metal and may be significantly less due to the general grain refinement of the heat affected zone as a whole.

INTRODUCTION

In January 1961 reports that large increases in initial nil-ductility transition temperature of the heat affected zone in welded A-212B carbon steel plate were being found in a government sponsored research program came to our attention at a joint WSB/ARM-NRL-Alco meeting.

It was decided that Alco Products should conduct an investigation to determine whether this new data indicated the probability of serious NDT rise in the Army pressure vessel weldments. If results were affirmative, a second phase of the investigation would proceed with duplicate vessel test-weld production and testing. A weld section of the SM-1 reactor vessel was to be selected for analysis because this vessel alone has a continuous longitudinal weld through the maximum fast flux dosage region and research work was being conducted on the same vessel material. Work on this report was accomplished under Item 6.11 of the FY 1961 Program for Engineering Support and Development of Army PWR Power Plants.* Phase I of this report contains the original research data⁽¹⁾ on 1 in., and 4 in. thick plates and the application and translation of this data to the SM-1 reactor vessel problem.

This study indicated a good probability of NDT increase; therefore a duplicate SM-1 weld test plate was manufactured and analyzed metallographically. This work is reported in Phase II of this report.

ACKNOWLEDGEMENTS

The generosity of Mr. P. Patriarca of ORNL, and Professor E.F. Nippes of Rensselaer Polytechnic Institute in making this data available to us is greatly appreciated. The current program from which this data was taken is sponsored by the Oak Ridge Laboratory.

* AP Note 286 Addendum 1, Revision 1, Alco Products, Inc. May 1, 1961.

(1) Nippes, E.F., Savage, W.F., Brown, W.A., "A Study of the Weld Heat Affected Zone, RPI Progress Report # 2, ORNL LAR Program, February 1961.

PHASE I

APPLICATION OF DATA FROM AN ORNL SPONSORED INVESTIGATION ON THE WELD HEAT AFFECTED ZONE OF A-212B CARBON STEEL TO THE SM-1 REACTOR VESSEL WELDMENT

1.0 INTRODUCTION

Data presented in "A Study of the Weld Heat Affected Zone," (1) on 1 in. and 4 in. thick A-212B carbon steel plate indicates that:

1. The weld heat affected zone (HAZ) suffers a transition temperature increase of from 100° to 200°F as welded.
2. This increase in HAZ transition temperature is restored to its initial value or lower after stress relieving, provided that the cooling rate of the HAZ during welding is greater than approximately $40^{\circ}\text{F}/\text{sec}$ at 1000°F .
3. Cooling rates less than approximately $40^{\circ}\text{F}/\text{sec}$ at 1000°F result in a permanent increase in HAZ transition temperature up to $+ 150^{\circ}\text{F}$.
4. The effect of cooling rates on transition temperature is related to the microstructures produced at these rates.

The heat affected zone (HAZ) cooling rate is affected by several variables during welding. The individual effects of heat input rate, base metal temperature, and plate thickness have been estimated by graphical means from available data. Therefore, curves Fig. 3 through Fig. 7 represent our best judgment, based on interpolation, extrapolation and cross-plotting of all data, including Professor Nippes' earlier work on 3/8 in. to 1 in. thick plates.

(1) Nippes, E.F., Savage, W.F., Brown, W.A., A Study of the Weld Heat Affected Zone, RPI Progress Report # 2, ORNL LAR Program, February 1961.

Further actual data on 4 in. plate and on plate with some thickness intermediate between 1 in. and 4 in. will be required to establish these relationships firmly; however, we do not expect any major changes either qualitatively or quantitatively.

2.0 DISCUSSION OF ORIGINAL TEST DATA

The original data developed by Nippes, et al at RPI ⁽¹⁾ is tabulated on Fig. 1. This data, showing hardness, microstructure and transition temperature increase as a function of cooling rate, is plotted in Fig. 2.

2.1 Hardness-Vickers Pyramid Number (VPN or DPN)

Hardness is shown to increase from a value of 240 VPN ($\approx$ 20 Rockwell C) in the as-welded condition with a cooling rate of 2°F/sec at 1000°F to 375 VPN ($\approx$ 25 Rockwell C) at 44°F/sec. The major increase in hardness occurs at cooling rates greater than 15°F/sec at 1000°F.

Hardness of the same specimens after stress relieving exhibits the same trend, but at lower hardness values; and the reduction in hardness due to stress relieving is, of course, greater for the greater as-welded hardness values.

The theoretical maximum attainable hardness in the as-welded condition is approximately 49 Rockwell C (500 VPN), with a cooling rate fast enough to result in 99.9 percent martensite. We estimate, in terms of the original data, that this rate would be in excess of 1000°F/sec at 1000°F.

The as-welded hardness attained at 44°F/sec is equivalent to that produced by the formation of a 65 percent martensitic structure in a 0.27 carbon steel.

(1) Nippes, E.H., Savage, W.F., Brown, W.A., "A Study of the Weld Heat Affected Zone," RPI Progress Report #2, ORNL LAR Program, February 1961.

2.2 Microstructure

Grain size depends primarily on the peak temperature attained and because this temperature was greater than the grain coarsening temperature for this steel, all microstructures regardless of cooling rate, are very coarsened grained. This will be the case in any single pass weld HAZ, because the temperature gradient adjacent to the molten weld varies from the base metal melting point down to the base metal ambient temperature. Multi-pass welding can result in refining of the prior coarse structure provided that the heat from the next pass raises all of this coarse grained zone to some temperature greater than the α - γ transformation temperature and less than the grain coarsening temperature. Stress relieving alone cannot have any effect on grain size because these temperatures are lower than the transformation temperature.

All microstructures exhibited a grain boundary network of proeutectoid ferrite. This ferrite envelope became thinner and less continuous with increasing cooling rates.

With increasing cooling rates, γ - α transformation temperature is lowered. This lowering results in the formation of finer pearlite, high temperature to low temperature bainite, and low-carbon martensite. This trend is also indicated by the increasing recovery of initial, transition temperature after stress relieving, because the notch toughness properties of these transformation products after tempering increase in the same order.

2.3 Transient Temperature

The transient temperature criteria selected by the authors were 10 ft-lb V-notch charpy, 15 mil expansion and 50 percent shear fracture appearance. The 10 ft-lb criteria was replaced by a 20 ft-lb V-notch charpy criteria by Alco Products for two primary reasons: (a) NRL experience has shown that 20 ft-lb charpy is a much closer correlation value to NDT (drop weight tests) and (b), a trial plotting of the 10 ft-lb criteria indicated anomalies we were certain did not in fact exist. The increase

in 20 ft-lb V-notch transition temperature (ΔT) is shown graphically on Fig. 2 as a function of cooling rate. The increase for both the as-welded and the welded and stress relieved conditions is essentially constant at $+150^{\circ}\text{F}$ for cooling rates from 2 to 10 or 15°F/sec at 1000°F . Above this critical cooling rate the as-welded condition exhibits an increasing ΔT with increasing cooling rate. After stress relieving, ΔT decreases with increasing cooling rate and approaches zero at approximately 40°F/sec at 1000°F . Both the as-welded increase and the welded and stress relieved decrease are caused by the increasing percentages of the lower transformation products which are more brittle in the untempered and more notch tough in the tempered condition.

It was of interest to note by different TT criteria (10 ft-lb, 20 ft-lb, and 15 mil expansion) the value of ΔT approached zero at $40\text{--}48^{\circ}\text{F/sec}$ cooling rate in the stress relieved condition. TT's for the as-welded condition increased with increasing temperatures, but the quantitative values varied widely at the faster cooling rates.

3.0 APPLICATION OF DATA TO SM-1 VESSEL (2 1/2 in. A-212B PLATE)

3.1 Safe Welding Limits (Fig. 3)

The combination of preheat or interpass temperature and heat input rate which will result in a minimum cooling rate of 40°F/sec at 1000°F in welding a 2 1/2 in. thick plate are shown in (Fig. 3).

Conditions whose coordinates lie to the left of this curve will result in a complete restoration of initial base metal NDT in the heat affected zone after stress relieving.

Higher values of plate temperature and/or heat input which fall to the right of this curve will result in a permanent increase in HAZ NDT, the magnitude of which is indicated by the family of dashed lines.

3.2 Actual Welding Data (Fig. 4)

The welding data for SM-1 vessel longitudinal and girth seams is tabulated on Fig. 4. The values of heat input ϕ expressed in kilojoules/in. are calculated by $\phi = \frac{V \times A \times 60}{IPM \times 1000}$ where "V" is volts, "A" is amperes, and "IPM" is travel speed in inches per minute. The value for base metal temperature θ was a minimum of 150°F (specified min. preheat temperature) and an estimated maximum of 350°F interpass temperature for the submerged arc longitudinal weld and 400°F for the submerged arc girth welds. The tabulated values for ϕ and θ are considered to be the minimum and maximum credible values for this process, vessel diameter, wall thickness, etc.

Superimposing these submerged arc values for ϕ and θ , on Fig. 3 results in a rectangle whose boundaries enclose all possible credible combinations of ϕ , and θ , for these welds, less than 1/3 the area of this rectangle lies on the safe side of this curve.

4.0 EFFECT OF INDIVIDUAL VARIABLES ON COOLING RATE

4.1 Heat Input (Fig. 5)

The effect of heat input when plate thickness and initial temperature is kept constant, is shown on Fig. 5. Increasing heat input results in decreasing cooling rate.

4.2 Preheat or Interpass Temperature (Fig. 6)

The effect of ambient plate temperature when heat input and plate thickness is kept constant, is shown on Fig. 6. Increasing the plate temperature results in decreasing the cooling rate.

4.3 Plate Thickness (Fig. 7)

The effect of plate thickness when plate temperature and heat input is kept constant is shown on Fig. 7. The cooling rate increases with increasing thickness. At low values of thickness, the cooling rate is nearly proportional to the square of the thickness; however, at greater

thicknesses, as pointed out verbally by Professor Nippes, for a given plate temperature and heat input, there is an effective infinite thickness that results in a maximum cooling rate regardless of future thickness increase. This is also indicated by the leveling off of the Fig. 7 curves.

Safe limit curves for welding 1 in., 2 1/2 in. and 4 in. thick plate are shown on Fig. 8.

5.0 SUMMARY OF RESULTS (A-212B CARBON STEEL)

1. That portion of the heat affected zone heated above the grain coarsening temperature incurs a transition temperature increase of approximately 150 to 200°F.
2. This transition temperature increase is permanent, provided that:
 - (a) subsequent welding pass or thermal treatment temperatures do not exceed the lower critical temperature (A_{c1}) and,
 - (b) the cooling rate from welding is less than 10-15°F/sec at 1000°F (25-35°F/sec at 1300°F).
3. If the cooling rate from welding is greater than 40°F/sec at 1000°F then stress relieving at 1150°F restores the transition temperature to its initial value or lower.
4. For cooling rates intermediate between 15°F/sec and 40°F/sec, stress relieving restores some fraction of the transition temperature increase which occurred during welding.
5. Behavior of the transition temperature has been correlated with the microstructures resulting from the cooling rates investigated.
6. For a given cooling rate from 2400°F, the resultant transition temperature, microstructure, and hardness is the same for both 1 in. and 1/4 in. thick plates.
- 5) 7. Application of this data to the SM-1 vessel indicates the probable existence of initial NDT increase in the weld heat affected zone.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Application of this data to the SM-1 vessel manufacturing procedure indicates that the heat affected zones in the longitudinal and girth welds may have suffered an initial NDT increase of up to $100 \pm ^\circ\text{F}$. The indicated probability for this occurrence is approximately 70 percent.

A duplicate vessel weld test section representing SM-1 vessel material and manufacturing practice should be produced and examined metallographically for evidence of unfavorable cooling rates.

Test Series No.	Energy Input Joules/Inch	Peak (HAZ) Temp. °F	Initial Plate Temp. °F	Plate Thickness Inches	Test Condition	Cooling Rate		Hardness (Vickers) VPN	Transition Temp. °F		
						°F/sec at 1000°F	°F/sec at 1300°F		20 ft-lb* V-notch	15 mil expans.	Fracture 50% Shear
IA	---	---	---	1	As Rec'd	---	---	164	+4	-7	70
IIA	50,000	2400	80	1	As Welded	43.8	83.4	378	200	460	--
IIB	50,000	"	"	1	S.R.1150°F	"	"	280	+5	+4	25
IIIA	100,000	"	"	1	As Welded	13.6	31.9	271	166	177	230
IIIB	100,000	"	"	1	S.R.1150°F	"	"	229	151	125	210
IVA	150,000	"	"	1	As Welded	5.5	15.4	260	152	125	220
IVB	150,000	"	"	1	S.R.1150°F	"	"	236	152	135	213
VA	200,000	"	"	1	As Welded	2.0	7.2	235	176	125	233
VB	200,000	"	"	1	S.R.1150°F	"	"	227	132	110	203
XXA	100,000	"	"	4	As Welded	37.7	70.6	371	200	300	---
XXB	100,000	"	"	4	S.R.1150°F	"	"	266	+19	+25	63
XXIB	100,000	"	350	4	S.R.1150°F	15.8	38.0	251	119	90	185

* 20 ft-lb TT read from transition curves

Original Test Data from "A Study of the Weld Heat Affected Zone," by Nippes, Savage and Brown, Tables I & II

Figure 1. WELD HEAT AFFECTED ZONE TEST DATA A-212B CARBON STEEL

Figure 2. Effect of Cooling Rate on Hardness, Microstructure, and Transition Temperature

(1) Data Interpolated from "A Study of the Weld Heat Affected Zone" by Nippes, Savage & Brown Feb. 1961.

Figure 3. Safe Welding Limits for 2-1/2 In. A-212B Plate⁽¹⁾

Welding Data
(from Dunkirk Dwg. B-150552 Mar. 1956)

Zone	Process	Electrode			Current		Travel Speed IPM	Preheat Temp. °F Min.
		Size Inches	Type	Bead No.	Volts	Amps		
A	Sub.Arc	1/8	Oxwell 40A	1-46	34-38	450-600	16-20	150
B	Man.Arc	1/8	E-7016	1	22-24	110-130	5-10 est.	150
	Man.Arc	3/16	E-7020	2-4	24-26	175-240	5-10 est.	150
C	Man.Arc	5/32	Type 310	5-7	22-24	110-135	5-10 est.	150
	Man.Arc	3/16	Type 308 L	8-16	22-24	125-160	5-10 est.	150

Figure 4. SM-1 Reactor Vessel Welding Data

Weld Heat-Affected
Zone A-212B 2-1/2 In.
Plate*

* Interpolated from data
on 1" and 4" Plate.

(1) "A Study of the Weld
Heat Affected Zone",
by Nippes, Savage &
Brown, Progress
Report #2 Feb. 1961.

Figure 5, Effect of Heat Input on Cooling Rate⁽¹⁾

Weld Heat Affected Zone A-212B
2-1/2 In. Plate

(Interpolated from data⁽¹⁾ on 1 In.
and 4 In. Plate

(1) "A Study of the Weld Heat Affected
Zone," by Nippes, Savage & Brown
Feb. 1961.

Figure 6. Effect of Preheat Temperature on Cooling Rate

Weld Heat Affected Zone
A-212B Plate. 80°F Preheat

- (1) Data from "A Study of the Weld Heat Affected Zone," by Nippes, Savage & Brown, Feb. 1961.

Figure 7. Effect of Plate Thickness on Cooling Rate⁽¹⁾

(1) Data Derived from "A Study of the Weld Heat Affected Zone" by Nippes, Savage & Brown Feb. 1961.

Figure 8. Safe Welding Limits for Zero Increase in Transition Temperature after Stress Relief Treatment for 1 In., 2-1/2 In., and 4 In. Plates (1)

PHASE II. METALLOGRAPHIC INVESTIGATION OF A DUPLICATE

SM-1 REACTOR VESSEL WELD

1.0 TEST PLATE PREPARATION

A section of A-212B carbon steel plate 3 ft x 3 ft x 2 1/2 in. thick was cut in half and machined to duplicate the SM-1 reactor vessel weld joint design. The joint was welded by the submerged arc process, duplicating as nearly as possible the original SM-1 vessel weld. The welding data are:

Volts	34/35
Amps	450-525
Travel Speed	20-16 in./min
Heat Output	67-47 kilojoules/in.
Preheat	150°F
Max Interpass Temp	- 400°F
Electrode	1/8" Linda 40A
Union Melt No.	80 flux

After welding, the test plate was cut in half at the weld mid-length. One-half was kept in the as-welded condition. The other half was stress relieved at 1150°F to duplicate the reactor vessel treatment.

2.0 METALLOGRAPHIC EXAMINATION OF THE AS-WELDED HEAT AFFECTED ZONE

A transverse section of the as-welded portion was cut at the original weld mid-length and micro-etched to show the weld joint and heat affected zone (Fig. 9).

The heat affected zone microstructure could not receive as straightforward an analysis as that discussed in Phase I of this report, because the portion induced by each weld bead was, in turn, re-heated by the succeeding adjacent weld bead which complicated the as-welded hardness and microstructure criteria. A simple correlation of these factors with the work previously done on a simulated heat affected zone that was in effect produced by a single pass weld, was not possible. Therefore, the actual cooling rate in the heat affected zone could not be accurately determined for a positive estimate of initial NDT change.

There was, however, one definite factor common to microstructures having significant NDT increase in the prior single pass heat affected zone study, which could not be altered by stress-relieving. The factor was the heavy, continuous, or nearly continuous grain boundary network of proeutectoid ferrite surrounding each large pearlite grain in the brittle structures. This factor was completely absent from the as-welded duplicate vessel microstructure.

The heat affected zone microstructure consisted primarily of very fine pearlite or high temperature bainite. In regions where the succeeding pass temperatures did not exceed the critical transformation temperature, the area immediately adjacent to the fusion zone had relatively large grains with some high temperature Widmanstätten ferrite "feathers" present. These areas were from 0.001 in. to 0.020 in. wide. The grains were free from proeutectoid ferrite boundaries. Such a region is shown in Fig. 10 at 500 diameters magnification and in Fig. 11 at 100 diameters. The maximum hardness of this structure is 26 Rockwell C or 275 VPN.

A more typical intermediate and fine grain region is shown in Fig. 12 at 100 diameters.

The transition and unaffected base metal structures are shown in Fig. 13 at 100X

3.0 METALLOGRAPHY OF THE STRESS RELIEVED HEAT AFFECTED ZONE

The microstructures, shown in Fig. 14 and 15, were essentially identical to those in the as-welded portion, because the stress relieving temperature was less than the critical transformation temperature and did not visibly affect the as-welded structures previously tempered or transformed by subsequent weld pass heat.

Micro-hardness tests were made on both as-welded and stress relieved portions. These were performed with a Tukon tester, using a Knoop indenter and a 100 gm load.

The results are tabulated below. Hardness values have been converted to Vicker VPN numbers.

<u>Zone</u>	<u>As-Welded</u>	<u>Stress Relieved Range</u>
Weld Metal	235-258	230-235
Large grain	258-276	235-258
Intermediate grain	248-276	230-235
Fine grain	232-258	226-235
Transition zone	200-230	200-225
Base Metal	190-210	190-210

4.0 DISCUSSION

Using the hardness criteria, the large grain region after stress relieving indicates an initial cooling rate after welding of approximately 15 to 30°F/sec at 1000°F. In terms of the single pass weld study this would indicate an uncovered NDT increase of 50 to 100 +°F. The as-welded hardness in this same region, however, indicates a cooling rate of approximately 7 to 15°F/sec. Lack of correlation between the as-welded and stress relieved portions is due to the reheating of the as-welded HAZ by the subsequent weld pass.

Furthermore, both the as-welded, and stress relieved microstructures more closely resemble the single pass stress relieved structures resulting from a cooling rate of 38°F/sec and having an increase of 19°F in NDT. These microstructures do not remotely resemble these structures cooled at a rate of 6 to 16°F/sec having a high NDT increase. These slowly cooled brittle structures were essentially very coarse grains of spheroidized pearlite with proeutectoid ferrite grain boundary envelopes.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Taking the above factors into account, it is estimated that these small local medium-coarse grained areas within the SM-1 weld heat affected zone have increased from 20 to 50°F in NDT above the base metal. However, these regions represent less than 5 percent of the total volume of heat affected zone.

All of these were bounded on all sides by weld metal, by fine grained re-normalized coarse grain area, and by fine grained heat affected zone - all of which were tempered by subsequent pass heat and by the stress relief.

It is, therefore, reasonable to assume that the net NDT of the heat affected zone, which is not more than .100 in. wide, is no greater than that of the base metal. This could possibly be demonstrated by carefully machining impact specimens with the notch and fracture path precisely oriented, but such an activity is outside the scope of this report; and in our opinion, not required.

It is recommended that future ferritic vessels, particularly of unalloyed carbon steel, be welded within the safe limit area shown on Fig. 3.

Figure 9. Macro-Etching of Duplicate SM-1 Weld

Figure 10. As-welded Heat Affected Zone, Coarse Arca-500X

Figure 11. Weld Metal and Adjacent Heat Affected Zone-100X

Figure 12. Intermediate and Fine Grain Heat Affected Zone-100X

Figure 13. Transition Zone and A-212-B Base Metal-100X

Figure 14. Stress Relieved Heat Affected Zone Coarse Area-500X

Figure 15. Weld Metal and Adjacent Heat Affected Zone-100X