HOMOPOLAR PIPELINE WELDING RESEARCH PROGRAM

18TH QUARTERLY REPORT
SEPT. 6,1997
AUSTIN, TEXAS

Presented to:

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AMOCO Corporation
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RF 170

Presented by:

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INTRODUCTION

This report is the eighteenth quarterly report to the sponsors of the Homopolar Offshore Pipeline Welding Research Program. The Joint Industry Program, which began in February 1993, was initially supported by a team of six oil companies and one welding contractor. The five-year program's ultimate goal is to produce a prototype system suitable for installation on a J-lay barge. This is to be achieved by building and demonstrating operation of a full scale vertical HPW system capable of producing industry acceptable homopolar pulse welds in 12 in. schedule 60 (0.562 in. wall) carbon steel pipe. The research effort is being performed by the Center for Electromechanics at The University of Texas at Austin.

The current list of sponsors are:

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Quarterly review meetings brief sponsor representatives on program status and solicit sponsor input. These meeting locations alternate between Austin and Houston.

The preliminary work necessary to initiate this program was supported by the National Science Foundation through the Offshore Technology and Research Center (OTRC).

1.0 SUMMARY

1.1 Background

Typically, offshore pipelines are constructed using the S-lay method, which permits the pipe to be welded and inspected in the horizontal position. Multiple welding and inspection stations are possible with this method, being limited only by the deck length of the welding barge. Due to increased buckling stresses, deep water pipelines require the steeper angle of entry into the water presented by the J-lay method. The vertical or near-vertical welding position inherent in J-lay necessitates a single welding station, presenting great economic incentive to minimize pipe handling and welding cycle times.

Homopolar pulse welding (HPW) is a one-shot resistance welding process being investigated as a method to join API 5L carbon steel linepipe. Homopolar pulse welding utilizes the high current, low voltage electrical pulse produced by a homopolar generator to rapidly resistance heat the interface between abutting pipe ends, producing a full circumference resistance forge weld in under 3 seconds.

A five year joint industry program is sponsoring HPW research with the goal of developing the process for deep water offshore pipeline construction utilizing the J-lay method. The first two years of the program concentrated on weld parameter optimization by producing, testing and evaluating welds in various grades, wall thicknesses, types and compositions of 3 in. nominal (3.5 in. OD) diameter API 5L carbon steel pipe. Mechanical properties of the welds and parent metal were evaluated by tensile testing, impact testing and hardness traverse testing according to guidelines and criteria established by the industrial sponsors.

Homopolar pulse welding has demonstrated the capability to produce industrially acceptable full circumference welds in 3 inch nominal OD carbon steel linepipe via a rapid, one-shot process. The next stage of the program has concentrated on developing the process for commercial field installation, with the program's goal being the demonstration of a prototype system for producing HPW welds in 12 in. diameter pipe in a J-lay configuration.

During the fourth and final years of the HOPWRP, a 12-Inch welding fixture was designed and built to determine how the homopolar welding process scales up to larger diameter pipes as the process was developed for a commercial field installation. The main tasks in scaling up the process included designing a fixture and buswork capable of delivering 1.5 MA peak currents, applying 400,000 pounds of upset force, and limiting lateral displacement during upset. Designing and building a data acquisition system, establishing the weld parameters, and learning the operation of the new power source complete the main tasks.

The commissioned 12 inch fixture uses three of the Balcones Homopolar Generators and has successfully joined 12 inch diameter material (19.25 in^2). Work continues to refine the weld parameters and fixture performance as homopolar welding technology is incorporated in the design and construction of the first commercial prototype system.

1.2 Quarterly Summary

During the past quarter, two 12 inch welds were produced and mechanically tested. Charpy V-Notch testing and hardness testing were completed on all 12 in welds. Improvements to the 12 inch fixture data acquisition system are underway and ultrasonic testing of 3 inch welds resumed.

The fourth and fifth twelve inch welds (N1.4&5) were produced with parameters selected to reduce the displacement rate of the step collapse. A wider step was used on both and on the fifth weld, the upset load was reduced by 25%. On the N1.5, the radius on the bevel shoulder was replaced with a more easily machined second bevel. Process data for both welds was similar to previous welds and the step displacement rate was slowed. On N1.5, using a lower load resulted in the accumulator exhausting its energy prematurely and supplying an even lower load after the step collapsed than expected.

Hardness test results were consistent with weld and process parameters. No significant HAZ softening was observed with low energy welds, but both HAZ softening and weld line hardening were present in full energy welds. The microstructures corresponded somewhat with weld parameters: lower energy, shorter thermal cycle welds had finer weld line microstructures. NS2, the simulated weld and N1.2 were lower energy welds. N1.1 had only slightly more energy than NS2, but its microstructure was noticeably coarser. N1.3 - N1.5 had coarser microstructures, with N1.5 having the coarsest. Charpy V-Notch results corresponded to the weld line microstructure: welds with finer microstructure had substantially higher impact toughness and the coarser the microstructure, the worse the impact toughness. NS2 had acceptable toughness, while N1.2 had one low reading with two others exceeding the parent metal toughness.

Ultrasonic testing resumed with tests designed to differentiate weld line microstructure form base metal and to scan for base metal flaws that could weaken the forged weld joint if present.

Included in Appendix B is a copy of the paper on the recent advances in homopolar welding technology submitted to the Society of Petroleum Engineers (SPE).

2.0 MATERIALS

The pipe materials investigated to date are presented in Table A-1 in Appendix A. Note the change in the material prefix designation for the NKK X65 material for "O" to "P".

3.0 EXPERIMENTAL PROCEDURE AND RESULTS

Mechanical testing performed on weld series include impact toughness (Charpy V-Notch), hardness (Vickers), and microscopic examination. Routine tensile testing was discontinued because the test results showed little variation among welds of a given material. Complete descriptions of mechanical test procedures are found in the 13th Quarterly Report of the HOPWRP §4.1.

The remainder of this section presents a summary of the D material Charpy V-Notch impact toughness test results and the N1 weld series parameters and results. Closing remarks consider criteria for adjusting weld parameters for the 12 inch homopolar welding tests.

3.1 Summary of D Material Charpy V-Notch Test Results

Nearly 100 welds were produced in the D material, and of those, 86 were impact toughness tested. Seventy of these welds were produced under ideal laboratory conditions, and twenty-seven more were produced under "real world" conditions. The results of the CVN testing are summarized Tables A2 and A3, found in Appendix A. The Hammond Acceptance Criteria for half size X65 specimens, tested at 0° C, are a minimum individual value of 18.6 ft-lb and a minimum average over three tests of 23.6 ft-lb.

Table A2 shows that, under ideal conditions, six welds failed the minimum average requirement and 3 additional welds failed the individual minimum requirement. Of the six failing the minimum average requirement, five had a step aspect ratio of one, and one had a step aspect ratio of zero. The step aspect ratio refers the ratio of the step length to step width. The long narrow step (0.1" x 0.1") and no step at all (bevel only) are cases of limiting step geometry with the other weld parameters used. By avoiding use of extreme step geometry, the occurrence of entire welds with low toughness may be avoided.

Of the three additional welds failing the individual minimum value, each had low displacement as a result of modifications to the upset load. By avoiding weld parameters that do not produce sufficient displacement, the isolated low toughness may be avoided.

Table A3 presents the results for real world condition welds, which consisted of welds with mismatched step geometry, misalignment, coarser contact surface finishes, wavy interfaces, and commercially prepared ends. Of the twenty-nine welds performed, twenty-five were impact toughness tested, with five failing the minimum average requirement. Three of these welds had either a longer step on one pipe and bevel only on the other, or two bevel ended pipes with a "ring" step inserted between them. The other two were either from low total displacement or uneven heating from interface and step conditions. Of the three additional failing the individual minimum requirement, one had low displacement and two had uneven heating.

Overall, these results demonstrate that with careful parameter selection, welds with low impact toughness may be avoidable. Further, even when attempting to produce poor welds, 75% were acceptable.

3.3 N1 Welds Series and Simulated Weld NS2

The N1 series is the first 12 inch pipe weld series produced using the N material, an X65 quenched and tempered material supplied by the Nippon Steel Corporation having similar chemistry and properties as the D material, also supplied by Nippon. The objectives of the first 12 inch weld series include establishing a set of baseline weld parameters to form full section welds and evaluating the effect of changing weld parameters on process data, mechanical properties and weld profile. It was hoped the initial weld series would provide sufficient information for selecting weld parameters to affect the mechanical properties of the welds, in particular impact toughness. The weld data, joint preparation, impact toughness results, and tensile test results are presented in Appendix A, Tables A4-A7, and hardness test results are presented in Appendix A, Figures A1-A3.

3.3.1 Small Geometry Welds

As previously reported, simulated welds and the first 12 inch weld (N1.1) were produced using two homopolar generators and similar weld parameters. With two generators operated at their rated speed, insufficient energy was delivered to the workpiece to form full section welds, so a third generator was brought on-line. The next two welds had similar weld parameters as N1.1, but with modification to the field current level and discharge speed to increase the energy delivered to the workpiece. The second weld, N1.2, was the first three generator weld, but lacked sufficient energy to form a full section weld. The third weld, N1.3, was a full section weld, joined with similar peak current density and interface energy density as successful 3 inch welds. The joint preparation and weld parameters for the first three welds and the simulated welds were based on weld D7.7, a small geometry 3 inch weld.

NS2, N1.1, and N1.2 had uniform heating in the interface region followed by typical displacement of the step, but no significant deformation of the bevel. The displacement rates appear to be several time faster than that of the comparable 3 inch welds, which is partially attributed to the elastic energy stored in the long central tension rod. The actual displacement is approximately equal to the step length. These two welds had peak current densities of 66 and 71 kA/in^2, respectively, but the pulse length was too short to heat the bevel to forging temperatures. The weld zone energy for the two welds is estimated at 70% of the required level. Sufficient energy was delivered to N1.3 to heat the bevel region to forging temperatures and form a full section weld. The average interface energy density for N1.3 is 112.4 kJ/in^3. The average energy density is calculated from the product of the current and interface volts data and the estimated volume of material between the interface voltage probes.

The macrostructure of the partial welds is similar to one of the first 3-inch step end welds performed at insufficient discharge speed, D2.5. The fin is formed but not displaced past the faces of the pipe wall. The microstructure in the weld zone of N1.1 and N1.3 is coarser than the parent metal while NS2 and N1.2 had a fine weld line microstructure. The hardness traverse of the partial welds showed only weld line hardening, with no HAZ softening. N1.3 displayed some HAZ softening.

Impact toughness test results for the initial welds and the simulated weld corresponded somewhat to the microstructure. N1.1 and N1.3 had lower values, under 28 ft-lb on 3/4 size specimens from N1.1 and under 20 ft-lb for full size specimens form N1.3. NS2 had acceptable impact toughness with values of 60, 99 and 246 ft-lb, while N1.2 only failed the individual minimum with values of 7.5, 243 and 246 ft-lb. Parent metal CVN values for 3/4 size specimens is 236 ft-lb. For full size specimen, CVN values exceed the capacity of the test fixture (263 ft-lb.).

The Hammond Acceptance Criteria for 3/4 size X65 specimens, tested at 0° C, are a minimum individual value of 22.1 ft-lb and a minimum average over three tests of 28.1 ft-lb. Similarly for full size specimens a minimum individual value of 28.1 ft-lb and a minimum average over three tests of 33.2 ft-lb are required.

Tensile tests were performed on N1.3 only with yield and tensile strengths and percent elongation of 68.4 ksi, 85 ksi, and 31.4%, respectively. More tensile testing is scheduled.

3.3.2 Modified Large Geometry Welds

Welds N1.4 and 5 used a modified large end geometry for the joint preparation to decrease the forging rate and possibly lower peak temperature. To further lower the forging rate, N1.5 was welded at 75% of the typical load. N1.5 was prepared with a second bevel instead of the radius between the bevel and the pipe OD and ID to investigate a more practical joint preparation. Both were full section welds with slightly higher peak current density, but lower average interface energy density. This slight reduction in average interface energy density may be from the increased interface volume.

The process data was similar to previous 12 inch welds. The displacement data on N1.4 was lost. Comparing step collapse rates between N1.3 and N1.5, show the rate dropping from better than 3 in/s to less than 1.5 in/s. The load trace on N1.4 was similar to N1.3, but the load trace on N1.5 indicates a reduction of upset pressure shortly after collapsing the step. The degree of deformation following the step collapse was reduced due to the reduction in upset pressure. This drop in forging pressure probably resulted from lowering the hydraulic pressure in the upset cylinders without adjusting the charge pressure in the accumulator.

Both welds had a coarser weld line microstructure than the base metal with N1.5 being the coarser of the two. Hardness test showed slight ID HAZ softening and more pronounced OD HAZ softening. OD and ID weld centerline hardening was similar. Both had low CVN values for weld line notches. For tests with the notches place 1 and 2 mm off the weld line, the impact toughness increased to parent metal values.

3.3.3 Discussion

These initial welds have demonstrated the ability of homopolar welding to scale up to larger pipe diameters and cross-sectional areas. Full strength welds were easily achieved, but acceptable impact toughness was not. On lower energy welds, impact toughness values increased. Some features of the new fixture may contribute to the coarse weld line microstructure and the low toughness, including forging rates and cooling rates. The higher than expected forging rates may be limiting the heat input and producing a narrower weld zone with more sharply turned flow lines. The slower cooling rates are likely due to the lack of massive copper heat sinks present in the three inch fixture. The cross-sectional area of the electrodes, fixture buswork, and hexapolar cables is approximately the same and designed for a maximum temperature rise. The reduced thermal conductivity of the flex braid inserts on the electrodes may also be contributing to slower cooling. In the next section, a criteria for parameter selection is presented.

3.4 Parameter Selection Criteria and Optimum Forging Rates

For the 12 inch welding fixture, modifications to the design to improve the operation or conform to a constraint affect how weld parameters are selected. The load application system was changed from an actively controlled system with an accumulator to a passive system with an accumulator providing the entire displacement response. Presently, the modified system upsets the workpiece several times more rapidly than that of the 3 inch fixture. Similarly the electrode design provided hydraulically actuated electrodes capable of being pulled off the workpiece to slow the cool rate. However, the relatively uniform cross sectional area of the circuit elements connecting the fixture to the generator eliminates the short path to a massive heat sink present in the 3 inch fixture. The result is a slower cooling rate which produces a coarser microstructure.

With homopolar welding in its current state, as many as eight parameters can be varied, including homopolar generator discharge speed (rpm) and field current magnitude, hydraulic fixture upset load, loading rate and electrode gap, and workpiece joint geometry: step length, width, and bevel angle. With the exception of the bevel angle and electrode gap, these parameters interact as they affect the heating and forging rates.

With the present welding system, the high constant load, the shaped end and the generator output interact in such a way that the process has a self-regulating forging action. As the current from the generator heats the shaped end differentially according to its cross-sectional area, the high load initiates the forging action as each cross-section reaches its forging temperature. The step reaches a forging temperature over its entire length nearly simultaneously and collapses in response to the high load. Besides heating more rapidly, the stresses in the step are higher by the ratio of wall to step area. Similarly for the bevel, its heating rate and stress vary over its length decreasing to that of the wall. Forging continues as long as energy is supplied to the workpiece. When the generator stops, typically after 2.5 to 3 s, the deformation slows then stops. Factors that influence the forging rate include step width, load system response rate, upset load setting, and generator field current and discharge speed.

Increasing the field current alone increases the heating rate as the energy from the generator is delivered more rapidly to the workpiece and reaches a higher peak current value in less time. If the rate of heat input exceeds the loading rate of the hydraulic fixture, the temperature in the smallest cross-sections may heat to melting, expel the melt then arc. This occurred during early 3 in. welds using a reduced cross-section and the light initial load. The local heating rate depends on the square of the local current density, so reducing the contact area to 33% of the wall, triples the current density and increases the heating rate nine times.

Increasing the generator discharge speed increases the peak current value but has little effect on the time to peak. The rate of heat input increases, but more importantly, the amount of energy supplied increases roughly with the square of the ratio of the discharge speeds.

Increasing the step width affects the time required for the step to reach a forging temperature and the flow stress level in the step. Changing the step width from 33% to 50% of the wall decreases the heating rate by $\left(\frac{33}{50}\right)^2 = 43\%$ and the stress by 66%. For the same current pulse, the following are predicted: delayed onset of step collapse, reduced rate of step collapse, and lower peak temperatures are expected across the step. The bevel should develop similar heating and stress profiles. Increasing step length functions more like generator discharge speed: increase in the volume of high temperature material and increase in amount of upset.

The last parameters that affect the forging rate are the upset load magnitude and the load system response rate. The upset load controls the stress level in the step and how much elastic energy will be stored in the weld stackup. The load system response rate determines how rapidly the load can collapse the workpiece. For high field current levels, too slow of a load response results in a melt and arcing. The accumulator on the 12 inch fixture is charged to level to deliver a relatively constant upset force for a given displacement. Changing the hydraulic pressure alters the response of the accumulator.

By selecting weld parameters that match the heating rate to the forging rate, the self-regulating forging action of this process can be used to limit the heating rate and control the efficiency of energy transfer from the generator to the workpiece. With electrical resistive heating generating heat according to the product of the current squared (I^2) and the resistance $\left(R = \rho(T)\frac{l}{A}\right)$, the self-regulating forging action limits the heating rates and the peak temperature by three events that may occur:

- reshaping the primary resistive heating element to a shorter, wider shape, which lowers the heating rate geometry (decrease $\frac{length}{Area}$)
- expelling hot material whose temperature dependence contributes to the electrical resistive heating rate ($\rho(T)$) as current continues to pass through the workpiece.
- expelling hot material that might otherwise conduct its heat axially down the workpiece.

With excessive forging rates, these events may occur prematurely, shorten the heating cycle, and deposit insufficient energy for a complete weld. Weld series D6 demonstrated these results. In that weld series, the load and field current were varied independently. Better welds were produced when both load and field were set high or low.

For optimum properties in the forged material, the forging rate may require adjusting for different materials. Identifying the optimum forging rate for each material could be determined using Gleeble simulations. Once identified, welds could be performed to verify forging rate and optimize the weld parameters.

3.5 Status of 12 inch Homopolar Welding Machine

During this quarter, work on the 12 inch fixture has been limited to improving the data acquisition system (DAS). Slow isolation modules have been replaced for the load cell, the thermocouples and the voltage readings. Also, an additional displacement sensor is being installed to measure the relative movement between the pipe ends. Such a measurement should provide a more accurate measure of the weld displacement. These improvements should greatly improve our perception and understanding of the welding process.

4.0 NDE

4.1 Status of Nondestructive Testing Program

During the past quarter, ultrasonic testing homopolar weld resumed. The test fixture was modified to improve the repeatability of the test, in particular the coupling uniformity between the probe and the workpiece. Additional probes have been designed and fabricated to permit scanning of the 12 inch welds and to further investigate the performance of the tandem probe when optimized for OD and ID reflectors.

Current tests are designed to evaluate the contributions of the weld bulge geometry to the total reflected signal. Scans are performed by moving the probe axially towards and away from the weld line for welds produced with substantially different welding conditions. Removal of OD, ID and both OD an ID weld bulge permits isolating weld plane reflections from the surface irregularities.

Another test is designed to examine the base metal in the joint geometry for laminations and other reflectors prior to welding. The initial tests will be performed using a dual probe with a roof angle set to produce only transverse waves in the pipe wall. A second test will use a normal incidence pulse echo probe which will produce only longitudinal waves.

4.2 Microstructural Characterization and Process Monitoring

From earlier research, two possible flaws occurring in homopolar welds were the "kissing bond" and the array of microinclusions, both planar, zero volume flaws. These findings were based on welds produced with pulsed loading and the flat end geometry. With the constant high pressure and the shaped end, these flaws become less likely, since both occur only at the interface. The "kissing bond" resulted from forging insufficiently heated material, while the array of microinclusions resulted from unexpelled interface artifacts. Examination of the weldline microstructure from recent welds reveals no interface artifacts.

What is observed near the weldline are flow lines resulting from reorienting the banding in the microstructure along the weld plane. Also, some pores were detected in some specimens located at the brittle fracture initiation site on CVN specimens. Theories offered for the occurrence of such pores and the occasional low impact toughness pertain to incipient melting of low melting temperature microconstituents, differential metal flow rates between ferrite and the carbide colonies, and base metal contamination.

These findings suggests developing nondestructive tests to investigate these phenomena and use the results to monitor the process and assist in developing weld parameters for new material and new fixtures. These latter flaws might be referred to as process induced flaws, where proper process monitoring and control will eliminate them.

To assure success with this microstructural characterization of HPW, researchers from Iowa State University propose to supply assistance with assessing test sensitivity using a ray tracing model. They may also provide some hands on assistance with the testing. In addition, fracture mechanics modeling is proposed to determine critical flaw size and model and evaluate flow line characteristics.

5.0 PLANNED ACTIVITIES

During the next quarter, work on ultrasonic testing of the welds and base metal will continue. More 3 inch welds may be produced with intentionally placed defects and mechanical testing performed on them after nondestructive testing. 12-Inch welds will be performed as needed. During the month of October, papers an posters will be presented at four conferences. A poster on HPW will be presented at the SPE annual conference in San Antonio, Texas. A paper on the same material will be presented at the AWS resistance welding conference in Chicago and at a conference in London. A paper on the nondestructive testing program for HPW will be presented at the ASNT Fall Conference in Pittsburgh. These presentations will be prepared during September.

6.0 ADMINISTRATIVE

6.1 Financial Statement

FINANCIAL BALANCE SHEET
JIP
THRU JULY 1997

CONTRACT: JIP A/C 26-6010-02XX	BUDGET INC./TRANS.	YEAR 1 2/93-1/94	YEAR 2 2/94-1/95	YEAR 3 2/95-1/96	YEAR 4 2/96-1/97	FEBRUARY 1997	MARCH 1997	APRIL 1997	MAY 1997	JUNE 1997	JULY 1997	FREE BALANCE Y-T-D
SALARIES & WAGES	$498,119.26	$80,646.82	$118,862.46	$122,534.57	$135,714.82	($9,267.99)	$14,130.02	$8,625.97	$7,146.13	$11,221.98	$7,861.44	$643.04
FRINGE BENEFITS	$120,293.13	$20,989.31	$31,803.88	$31,316.31	$27,334.71	($1,764.95)	$2,744.41	$1,681.66	$1,484.30	$2,295.46	$1,527.52	$880.52
OTHER EXPENSE	$58,233.00	$7,396.38	$8,889.75	$14,364.38	$19,396.39	$355.25	$810.49	$2,322.48	$0.00	$1,727.39	$1,405.60	$1,564.89
COMPUTATION (67)	$499.00	$0.00	$0.00	$0.00	$29.73	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$469.27
TRAVEL	$22,253.00	$1,890.14	$5,386.35	$6,643.61	$3,044.87	$0.00	$0.00	$1,158.79	$2,306.62	$1,773.56	$0.00	$49.06
MTDC	$699,397.39	$110,922.65	$164,942.44	$174,858.87	$185,520.52	($10,677.69)	$17,684.92	$13,788.90	$10,937.05	$17,018.39	$10,794.56	$3,606.78
OVERHEAD	$349,326.83	$54,350.62	$82,340.62	$87,429.43	$92,760.26	($5,338.85)	$8,842.46	$6,894.45	$5,468.53	$8,509.20	$5,397.28	$2,672.83
TUITION	$4,200.00	$1,066.40	$924.89	$1,198.97	$879.80	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$129.94
EQUIP /FAB (83&80)	$67,075.78	$34,016.43	$6,020.91	$24,145.47	($2,817.73)	$1,269.59	$0.00	($148.53)	$1,546.07	$254.97	$0.00	$2,788.60
TOTAL	$1,120,000.00	$200,356.10	$254,228.86	$287,632.74	$276,342.85	($14,746.95)	$26,527.38	$20,534.82	$17,951.65	$25,782.56	$16,191.84	$9,198.16

REMARKS:

FUNDED Y-T-D: $1,080,000 EXPIRATION: 1/31/98

3:33 PM

8/29/97

APPENDIX A

WELD DATA

Table A-1. Mill test report data

API 5L Carbon Steel Linepipe WELD PREFIX CODE	**A**	**B**	**C**	**D**	**M**	**N**	**P**
SUPPLIER	Dixie Pipe	Prudential	Lone Star	Nippon	NKK	Nippon	NKK
API 5L GRADE	X52	X60	X52	X65	X52	X65	X65
SCHEDULE	160	80	160	80	60		60
OUTSIDE DIAMETER	3.5	3.5	3.5	3.5	12.75	12.75	12.75
WALL THICKNESS	0.438	0.300	0.438	0.315	0.562	0.50	0.562
TYPE	seamless	ERW	ERW	seamless	seamless	seamless	seamless
HEAT TREATMENT (not on mill test report)	Hot rolled	controlled rolled	normalized	quenched & tempered	Hot Finished	quenched & tempered	Hot Finished
LADLE CHEMISTRY							
C	0.23	0.13	0.11	0.08	0.08-0.12	0.08	0.11
Mn	1.04	0.65	1.13	1.29	1.07-1.13	1.29	1.34
P	0.010	0.005	0.014	0.011	0.006-0.014	0.011	0.015
S	0.009	0.004	0.005	0.002	0.001	0.0017	0.002
Si		0.22	0.28	0.19	0.21-0.29	0.189	0.23
Al		0.042	0.037		0.026-0.046		
Cr		0.03	0.073		0.04-0.07		
Mo		0.01	0.028	0.22	Tr	0.215	
Ni		0.01	0.07		0.02-0.03		
Cu		0.02	0.13		0.01-0.02		
Cb		0.18	0.034	0.032	Tr	0.032	
Ca		0.0048		0.0026	0.0020-0.0028	0.0026	
Ti			0.008		0.002-0.005		
V	0.08		0.040		0.003-0.04		0.065
B			0.0003		Tr -0.0003		
				0.035 Ti-Al		0.035 Ti-Al	
IIW C_{eq}	0.42	0.23	0.34	0.34	0.28-0.33	0.34	
Yield Strength (ksi)	66.0	79.5	59.5	71.6 *	62.75*		65
Tensile Strength (ksi)	94.4	86.1	79.5	80.7 *	78.4*		83
% elong in 2"	30	22	37	26.6 *	31.37*		42.7
Vickers Hardness (kg.mm^2)	193.2	181.9	171.0	185 *	186-204	219*	

* In-house test results, not included with mill test report.

Table A-2. Summary of CVN test results for ideal condition welds

Series No.	# Welds in Series	# Welds CVN tested	# Welds Fail mean CVN Criteria	# Welds Fail min CVN Criteria and not fail mean.	Explanation for low toughness
D3	8	8	3	0	3 failed mean CVN had Aspect Ratio =1
D5	6	6	0	0	
D6	8	8	0	1	1 failed individual CVN had low displacement Weld parameters 45 kip/300 field
D7	9	6	0	0	
D8	11	9	2	0	2 failed mean CVN had Aspect Ratio = 1
D10	4	2	0	0	
D11	8	0	0	0	
D12	4	0	0	1	1 failed individual CVN had low displacement Weld parameters 45 kip
D13	6	0	1	0	1 failed mean CVN had Aspect Ratio = 0
D14	6	0	0	1	1 failed individual CVN had low displacement Weld parameters pulsed high load
Total	70	63	6	3	

Note: For Ideal Condition D weld CVN tests:

Average of mean: 80.5 ft-lb	Standard Deviation of mean: 27.8 ft-lb
Average of min: 63.0 ft-lb	Standard Deviation of min: 29.3 ft-lb

Table A-3. Summary of CVN Test Results for Real World Condition Welds

Series	# Welds	# Welds CVN tested	# Welds Fail mean CVN Criteria	# Welds Fail min CVN Criteria and not fail mean.	Explanation
D9	8	8	1	1	Low displacement on both that failed CVN min Criteria
D10	12	8	1	2	Uneven heating: segmented step and non-parallel interface
D11	1	1	0	0	
D12	4	4	0	0	CRC end prep
D13	4	4	3	0	uneven step length or ring insert
Total	29	25	5	3	

Note: For Real World Condition D weld CVN tests:

Average of mean: 66.9 ft-lb Standard Deviation of mean: 32.5 ft-lb

Average of min: 49.1 ft-lb Standard Deviation of min: 34.27 ft-lb

Table A-4. N1 summaries

a. Weld Parameters

Weld No.	# Gen	RPM	Field	Load	Gap	Step width	Step Len.	Bevel Angle	Sh'der Rad.
			[A]	[kip]	[inch]	[inch]	[inch]	[°]	[inch]
N.S2	2	5850	280	385	2.5	0.166	0.083	30	0.150
N1.1	2	6050	280	385	2.5	0.166	0.083	30	0.150
N1.2	3	4500	350	385	2.5	0.166	0.083	30	0.150
N1.3	3	5700	265	385	2.5	0.166	0.083	30	0.150
N1.4	3	5700	270	400	2.5	0.250	0.125	45	0.15
N1.5	3	5700	270	315	2	0.250	0.125	45	2nd bevel

b. Output Data

Weld No.	TOTC	@ Time	INTV	@ time	Disp1[a]	@ time	Disp2[a]	@ time	Load actual	Actual Disp
	[kA]	[sec]	[v]	[sec]	[inch]	[sec]	[inch]	[sec]	kip	[inch]
N.S2	1302.5	0.0982	1.72	.142	.087	.066	.166	2.187	380	0.176
N1.1	1272.3	0.0982	1.678	.108	.082	.055	.173	2.188	393	0.183
N1.2	1370.	0.085	1.4[1]	0.1748[1]	.104	.063	.171	2.25	379	0.186
N1.3	1415.	.0948	1.806	0.0925	.142	.058	.285	2.081	400	0.2950
N1.4	1428	0.104	1.908[2]	0.1736	NA[3]	NA[3]	NA[3]	NA[3]	393	0.346
N1.5	1479[4]	0.104	2.02[2]	0.1690	.1314	.108	.3059	20.5	315	0.322

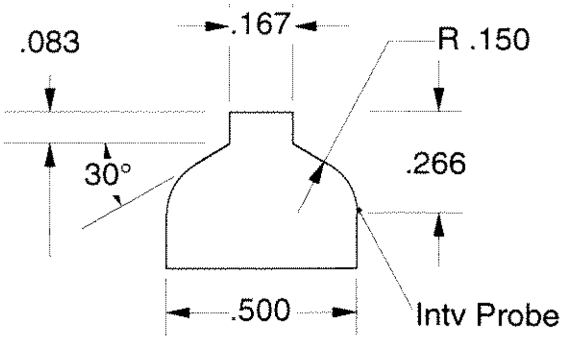
c. Calculated Results

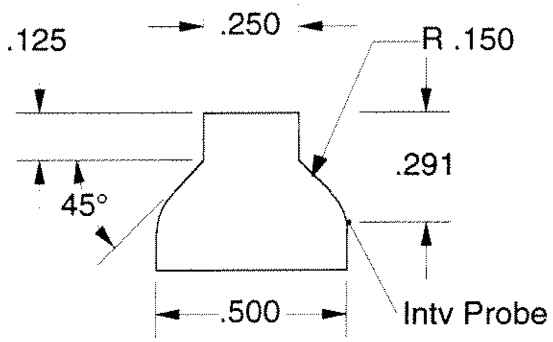
Weld No.	Peak Current Density	Energy	Interface Volume	Average Interface Energy Density	Total Action	Final Interface Resistance
	[kA/in^2]	[kJ]	[in^3]	[kJ/in^3]	[E12 A^2-s]	[μΩ]
N.S2	67.7	501	6.604	75.9	0.545	0.92
N1.1	66.1	502	6.604	76.0	0.55	0.91
N1.2	71.2	477[1]	6.604	72..2	0.522	0.91
N1.3	73.5	742	6.604	112.4	0.881	0.84
N1.4	74.2	913[2]	8.297	110.0	0.860	1.1
N1.5	76.86[4]	901[5]	8.197	109.9	0.881	1.0

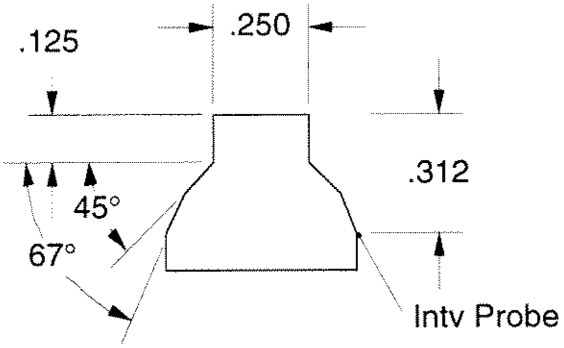
1. Interface volts data and calculated energy inaccurate: slow isolation module.
2. Interface volts probes separation increased to 0.66" from 0.54" due to geometry.
3. Displacement data lost.
4. Total current from BHPG intregrated rogowski output, duration under 2 seconds. HPW fixture TOTC lost.
5. Energy calculation is low since based on 1.6 second interval from BHPG rogowski output.

a. Process Displacement (Disp1, Disp2) for all experiments are estimates, based on assumption that final process displacement is 95% of actual displacement.

Table A-5. N1 series joint preparation

<table>
<tr><th>Description</th><th>Joint Geometry</th></tr>
<tr><td>Small End Geometry
NS.2, N1.1-3</td><td>


</td></tr>
<tr><td>Modified Large End Geometry
Intermediate Step length
N1.4</td><td>


</td></tr>
<tr><td>Modified Large End Geometry
Intermediate Step length
Second Bevel-no Radius
N1.5</td><td>


</td></tr>
</table>

Table A-6. N1 series CVN results

0°C Temperature Tests

WELD #	CVN	ft-lb	%shear
3/4 Size			
NS2.	1	246	100 (ST)
	2	99	25
	3	60	15
	min	60	
	mean	135	
	max	246	
3/4 Size			
N1.1	1	28	5
	2	9	0
	3	16	0
	min	9	5
	mean	17.7	0
	max	28	5
3/4 Size			
N1.2	1	243	100 (ST)
	2	7.5	0
	3	246	100 (ST)
	min	7.5	
	mean	165	
	max	243	
3/4 Size			
NPM	1	232	100
	2	226	100
	3	250	100
	min	232	
	mean	236	
	max	250	

Specimen size noted above Weld No.

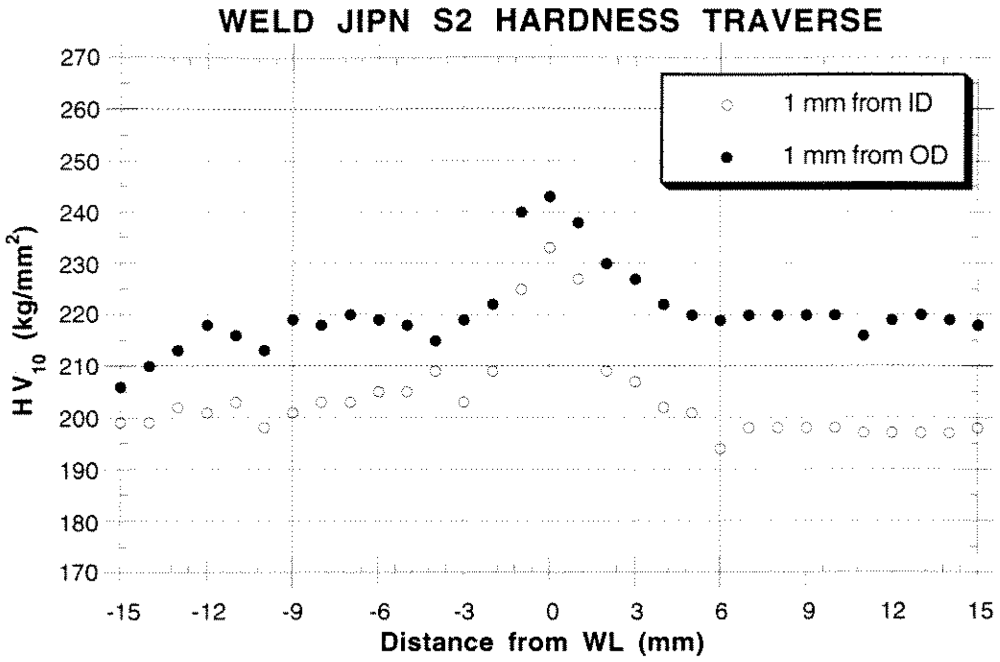
WELD #	CVN	ft-lb	%shear
Full size			
N1.3	4	10	0
	6	20	0
	8	2	0
	min	2	
	mean	10.67	
	max	20	
Full size			
N1.4	2	7.5	0
	4	14.5	0
	9	8	0
-1 mm	*10*	*59*	*0*
-2 mm	*6*	*264*	*100*
	min	2	
	mean	10	
	max	20	
Full size			
N1.5	4	1.5	0
	8	1.5	0
	10	1	0
-1 mm	*6*	*100*	*15*
-2 mm	*2*	*264*	*100 (ST)*
	min	1	
	mean	1.33	
	max	1.5	
Full size			
NPM	1	263*	100
	2	263*	100
	3	263*	100
	min	263	
	mean	263	
	max	263	

Notes

1. Parent Metal Specimens toughness exceeded Charpy V-Notch Impact Tester Maximum 263 ft-lb toughness.
2. -1 mm and -2 mm refer to specimens with off-weld line notches. Off-weld line tests not used in determination of mean, min, or max.
3. 3/4 size specimens from partial section welds.

Table A-7. Weld N1.3 tensile test results

Number	Yield (ksi)	Tensile (ksi)	% El	Notes
N1.3.3	66.9	85.5	32.3	PM fracture
N1.3.5	66.9	84.4	30.5	PM fracture
Average	68.4	85	31.4	



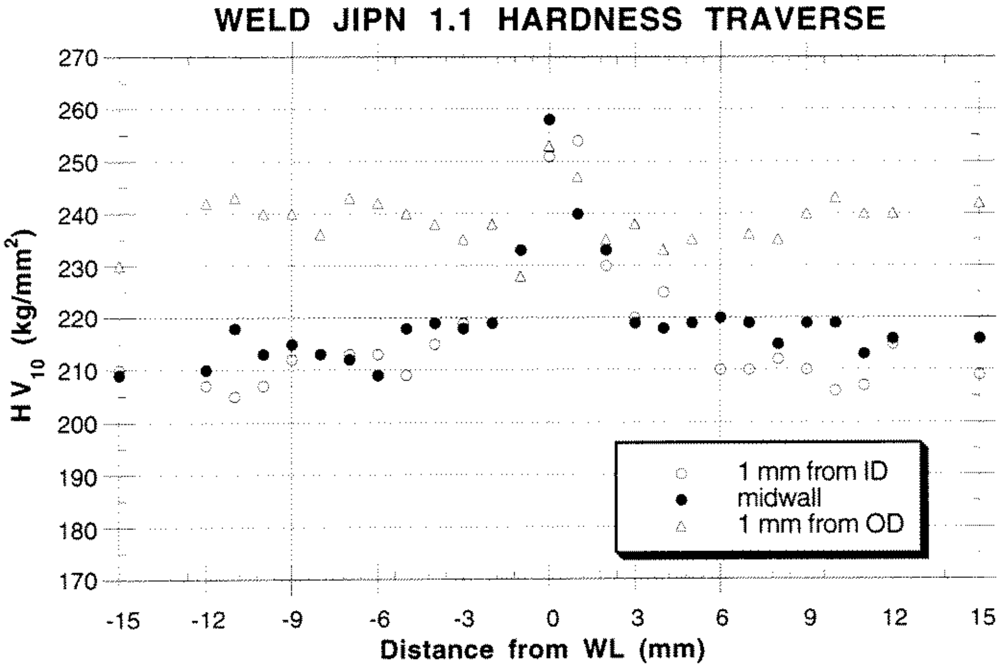
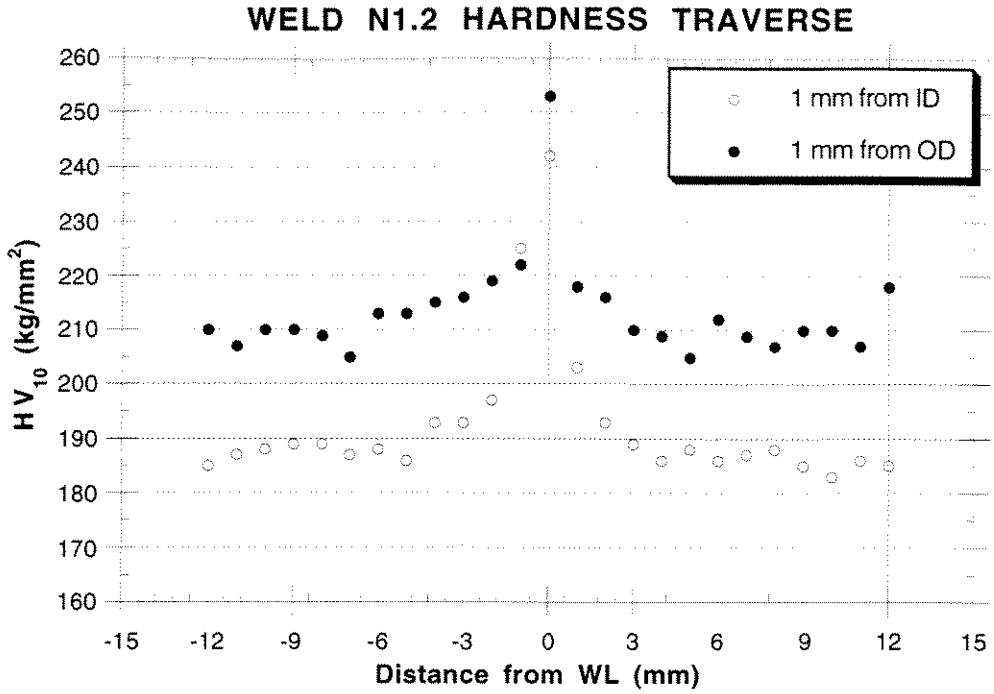


Figure A-1. Hardness test results NS2 and N1.1



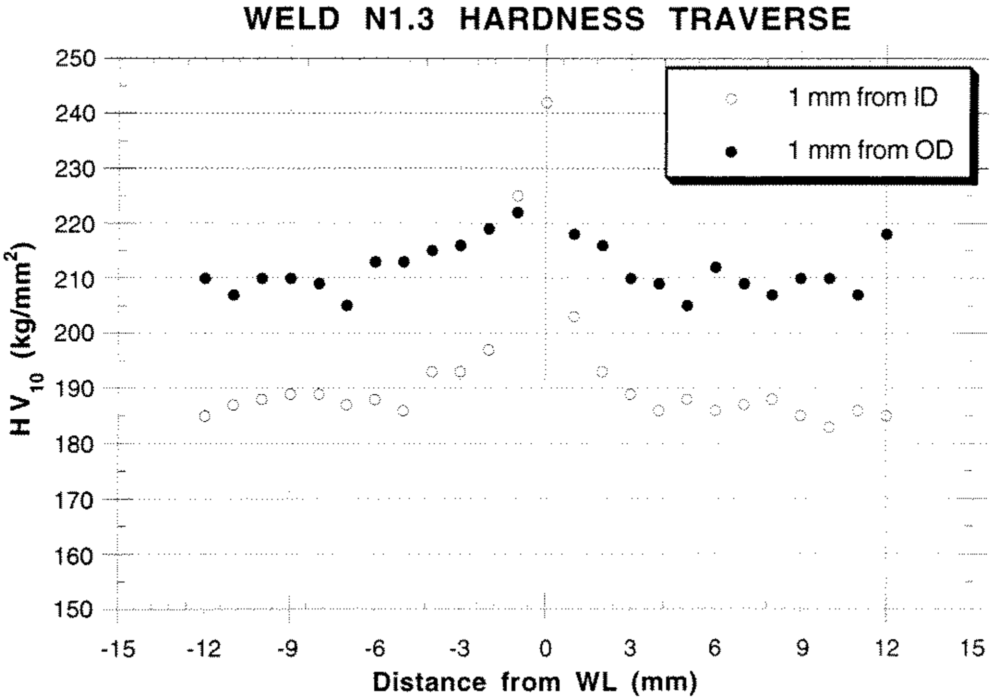
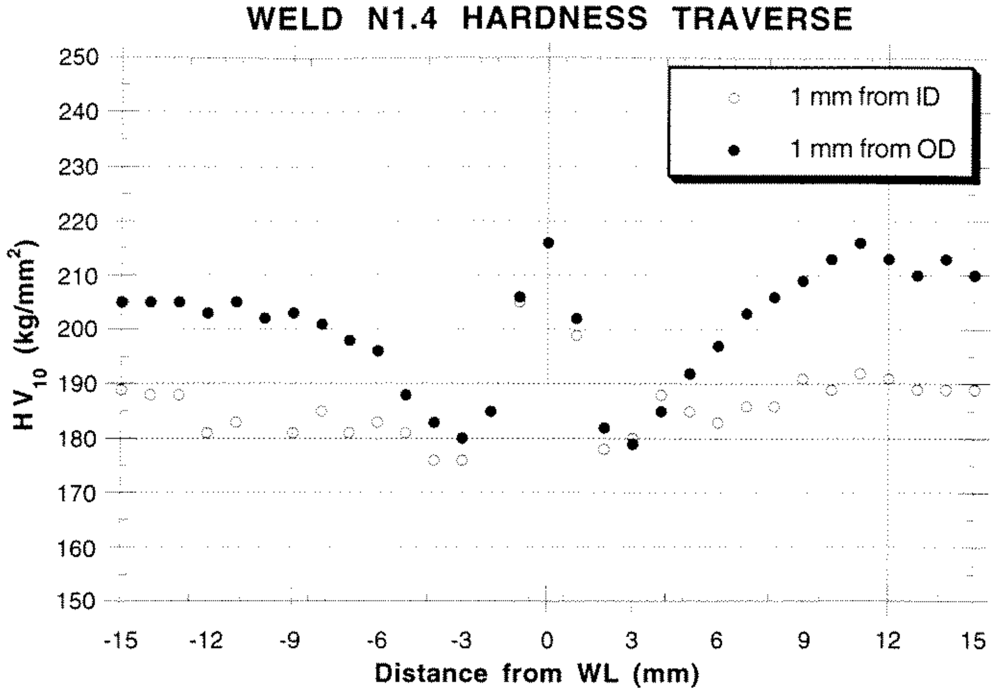


Figure A-2. Hardness test results N1.2-3



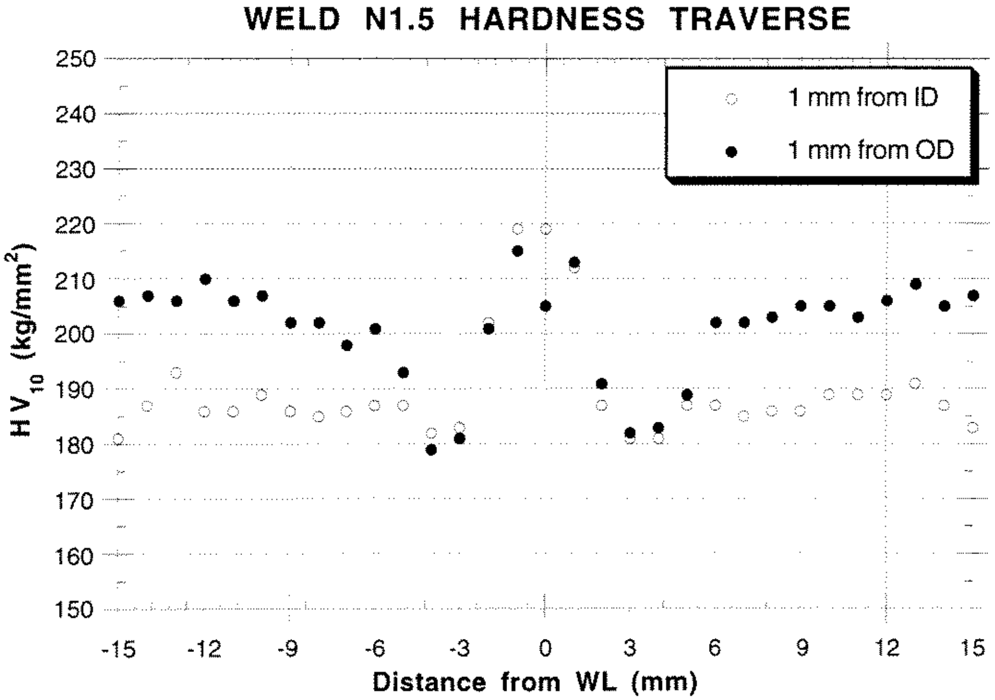


Figure A-3. Hardness test results N1.4-5

APPENDIX B

ADVANCES IN HOMOPOLAR WELDING OF API LINEPIPE FOR DEEPWATER APPLICATIONS

Society of Petroleum Engineers

SPE 38840

Advances in Homopolar Welding of API Linepipe for Deepwater Applications

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Abstract

The University of Texas at Austin Center for Electromechanics is conducting a research program, funded by six oil companies, two industrial contractors, and two government agencies, to study homopolar welding of line pipe for J-Lay applications. In 1995, the third year of the five year research program, the set of weld parameters, those input variables used to control weld performance and quality, was expanded to include joint geometry, with dramatic improvement in the mechanical properties of two HSLA nominal 3-inch line pipe materials, X60 and X65. These improvements increased the Charpy V-Notch impact toughness properties to near parent metal values, while maintaining acceptable strength. After demonstrating repeatable performance with the new parameters, new research focused on real world effects including tolerancing the parameters and evaluating the effect of poor fit up resulting from misalignment and rough and wavy interfaces. During the final year of the research program, the pipe welding program has scaled up to 12-inch nominal line pipe, a sevenfold increase in cross-sectional area. The paper will cover basics of homopolar welding, weld parameters and modifications, effects of these changes on real time process data, mechanical properties, weld upset profile, HPW metallurgy, and the studies of real world effects. Results from homopolar welding of 12-inch pipe will also be presented.

Introduction

Homopolar Welding (HPW) is a resistance forge welding process that uses the high amperage direct current discharge from a Homopolar Generator (HPG) to produce full circumferential pipe welds in under five seconds without using filler metal. HPW is being developed as a candidate single station, or "one shot", welding method for J-lay pipe laying. With the continued discovery of deep water oil fields, the J-Lay method was developed to overcome the problem of buckling, occurring when the pipe enters the water from conventional S-lay barges. J-lay requires single station welding process because the pipe is welded vertically then lowered directly into the water[1]. Besides enabling pipe laying in deep water fields, the reduced cycle time per weld should lower the cost[2,3].

Homopolar Offshore Pipeline Welding Research Program. A consortium of six oil companies (Amoco, BP, Exxon, Mobil, Shell, and Texaco) and a welding contractor (CRC-Evans) funded this joint industry program (JIP) at The University of Texas at Austin Center for Electromechanics, beginning in February 1993, to develop homopolar welding for J-Lay applications. Since that time, an additional equipment contractor (Parker Kinetic Design) and two federal agencies (the Office of Pipeline Safety of the DOT and the Mineral Management Services of the DOI) have joined the program. The major objectives of the research program have been achieved. They include:

- optimize weld parameters for homopolar welding 3-inch HSLA API 5L line pipe
- investigate a range of materials with varying strength, wall thickness, composition, heat treatment and manufacturing method
- produce 3-inch welds with acceptable mechanical properties
- improve the finished weld profile
- design and build a laboratory welding fixture for joining 12-inch Schedule 80 line pipe
- demonstrate homopolar weldability of 12-inch pipe
- transfer technology in preparation for commercialization of HPW
- develop an NDE program

One of the first requirements of the research program was developing an acceptance criteria for the welding program that was compatible with existing welding codes. John Hammond, with BP Exploration of London, developed this document, known as the "Hammond Criteria", which has served to guide the research through the development of a new welding process[4].

Recent Advances. During the second and third year of the program, the weld parameters, those inputs used to control the welding process and weld quality, were significantly expanded on 3-inch pipe welds as a new approach to welding, using HPGs, was investigated. The results were dramatic: besides producing higher, more uniform impact toughness in two high strength materials, process robustness increased substantially. During the fourth and current years, preparation and production of 12-inch pipe welds are underway.

Homopolar Welding

A homopolar welding system consists of a homopolar generator and a hydraulic welding fixture. The homopolar generator is an inertial energy storage device that provides the mega-ampere direct current electrical pulse to resistively heat the joint for welding. The hydraulic welding fixture delivers the current to the workpiece, provides the forging force to upset the heated interface material, and maintains alignment during upset.

Homopolar Generators. Homopolar generators are simple industrial machines that convert the stored rotational kinetic energy of its spinning rotor to direct current electric energy by electromagnetic induction. The low voltage, high current discharge, characteristic of these machines, makes them well suited for electrical resistive heating. A magnetic field imposed across the electrically conductive rotor produces a voltage and supplies a characteristic current pulse when connected to a discharge circuit. The principle of electromagnetic induction is demonstrated in the Faraday disc, or more fundamentally by moving a straight conductor though a magnetic field[5].

HPG Parameters. The parameters governing the HPG output current are the discharge speed and the field current magnitude. The discharge speed determines the magnitude of the stored inertial energy and the field current magnitude, which induces the magnetic field across the rotor, controls the shape of the current pulse. Higher field current settings shorten the pulse length and increase the magnitude of the peak discharge current[6].

The Hydraulic Welding Fixture. This fixture consists of a hydraulic press capable of delivering the forging load and the portion of the discharge circuit that delivers the current pulse to the workpiece. The copper electrodes deliver the current for welding through the outer pipe wall and are uniformly spaced around the circumference of the pipe and clamped to its outer surface. In the laboratory fixture, short pipe sections are joined with the upset load applied through the ends. The load is controlled via a servo valve and a control system.

Fixture Parameters. The fixture parameters used to control the homopolar welding cycle include four load related parameters and one electrode parameter. The load control system permits stepping an initial load to an upset load after a preset delay and holding the upset load for a duration. Traditionally, the initial load setting controls the degree of heating at and near the interface and the delay setting controls the extent of diffusion of interface heat to the adjacent material. The upset load and duration control the extent of joint forging. The last primary fixture parameter is the electrode gap, which refers to the axial distance between the weld interface and the leading edge of the electrode. The electrodes act as a heat sinks and affect post weld cooling rates.

HPW Welding Cycle. A typical HPW cycle begins by accelerating the HPG to a preset speed, then energizing the field coils to produce a uniform magnetic field across rotor. Lowering the brushes produces a potential across them. At the discharge speed set point, a switch is closed and the stored energy of the HPG rotor converts to a direct current pulse as electromagnetic torque rapidly stops the rotor. The current is directed through the discharge circuit containing the workpiece. Due to its substantially higher resistance, the interface and adjacent material rapidly heat and soften permitting forging to form the finished weld. Homopolar welds have a narrow heat affected zone (HAZ) due to the short thermal cycle with resistance heating concentrated at and near the interface. Figure 1 shows a schematic of the homopolar welding process.

Traditional Homopolar Welding Methods. Traditionally, or prior to the latter part of the second year of the JIP, welds were performed using pipes prepared with smooth, flat ends and light initial loads followed by increased upset loads. With this method intense heat was generated at the interface of the lightly loaded, flat-ended pipes by carefully controlled contact resistance heating, and relied on axial thermal diffusion to heat and soften adjacent material for forging. This method was extremely sensitive to the uniformity of the contact over the interface, and experienced melting or near melting temperatures at the interface surface.

Modified Homopolar Welding Methods. The modified welding method uses shaped pipe ends and constant, high interface pressures to control resistive heating as the current pulse discharges through the weld circuit. Increasing the initial load to the upset load value combined with the reduced contact area of the shaped end increases the interface pressure as much as eighteen fold and results in a sharp reduction of interface resistance[7,8]. Increased current flow from the reduced interface resistance supplies more Joule heating in the shaped ends, thereby offsetting the reduction in interface heating.

The shaped pipe end, a modified double bevel preparation, was prepared by machining the pipe wall from both inside diameter (ID) and outside diameter (OD) surfaces, resulting in a reduction in cross-sectional area near the interface. The reduced cross-section increased the local current density and Joule heating rates, allowing improved control of temporal and spatial temperature profiles, without relying on thermal diffusion to heat adjacent material.

Modified Weld Parameters. The modified welding method added end geometry parameters and reduced load parameters. The new set of weld parameters consists of generator discharge speed and field current, hydraulic fixture constant load and electrode gap, and end geometry parameters consisting of contact width, bevel angle, and shape factor.

Primary Process Parameters. The primary process parameters used to monitor and analyze the workpiece response include total current, interface volts, and displacement as shown in figure 2. The total current is the HPG discharge current that flows through the workpiece. Interface voltage is the voltage drop across the workpiece measured with voltage probes attached to the OD surfaces nominally 6.35 mm on either side of the interface. The displacement measurement reflects the change in length of the workpiece as it upsets. Reliable temperature measurements near the interface have been unsuccessful due to the extreme temporal and spatial temperature gradients present with such high heating rates.

Characteristic Workpiece Response. With the modified parameters, the workpiece thermal and mechanical response is clearly reflected in the interface voltage trace (fig. 2). The total current trace represents the primary energy input, driving the thermal response. The time of peak interface voltage coincides with the onset of rapid displacement after the shaped ends heat to their forging temperature. As the shaped end widens and shortens in response to the applied upset load, the workpiece resistance decreases causing a decrease in the interface voltage. Current from the HPG continues to pass through the interface region, differentially heating regions according to cross-section and previous thermal history[9]. Continued heating and slower deformation is inferred from the interface voltage and displacement traces, as the joint upsets to refusal.

3-inch Welding Program

As previously reported[10,11], four different API 5L materials were under investigation in the JIP, two X52 Schedule 160, two Schedule 80, an X60 and an X65. The materials, designated A, C, B, and D, are listed in table 1. Mechanical testing consisted of tensile testing, Charpy V-Notch impact toughness testing, hardness testing and metallurgical examination. Impact tests were performed at 0°C on full size specimens (10×10×55 mm) in materials A and C and on half size specimens (5×10×55 mm) in materials B and D.

The Hammond Criteria for Charpy V-notch impact toughness values for half size specimens of X65 grade at 0°C are a minimum individual value of 25 J (18.6 ft-lb) and a minimum average over three tests of 32 J (23.6 ft-lb). The more rigorous X65 criteria was applied to the X60 specimens since an X60 criteria was not available. For full size X65 grade specimens at 0°C, the minimum individual value is 38 J (28 ft-lb) and the minimum average value is 45 J (33 ft-lb). For the full size X52 grade specimens at 0°C, the minimum individual value is 30 J (22 ft-lb) and the minimum average for three is 36 J (26.6 ft-lb).

Traditional Method Results. Using the traditional weld parameters, full strength was achieved in material A, but acceptable impact toughness was only achieved with post weld heat treatment. For material B , homopolar welding with the traditional parameters produced welds with slight reduction in yield and tensile strengths, while meeting impact toughness requirements. Traditional weld parameters were not used on materials C and D.

Modified Weld Method Results. These new weld parameters were used on all materials, achieving full strength in all but the B material, which continued to display a slight loss of both yield and tensile strength. As with the traditional methods, materials A and C failed to meet the impact toughness criteria. Further attempts to join these two materials were postponed as both were judged to have compositions unsuitable for homopolar welding. In contrast, materials B and D consistently achieved better than 75% of parent metal impact toughness values, far surpassing the sponsor criteria. Tensile testing was discontinued after testing demonstrated consistent yield and tensile properties in these welds. Hardness testing was continued, and Charpy V-Notch impact toughness testing became the primary criteria for judging weld quality.

Material D- 3-inch X65 Quenched and Tempered. Over 70 welds have been produced in material D, investigating the effect of varying six of the seven modified weld parameters. The short electrode gap, which rapidly cools the weld, was held constant for all modified parameter welds. Twenty-four of these welds constituted three fully saturated, three parameter, two level test matrices, designed to investigate weld parameter primary effects and interactions. The results for 70 welds, produced under ideal conditions with identical interface preparation on both pipe ends, are summarized in table 2, which lists the number of welds performed and, of those, the number that were tested. The minimum CVN average is based on the single low value for each weld tested. The range of weld parameters used for these welds in presented in table 3.

From these welds, 5 welds failed to meet the average impact toughness requirement, and two additional welds had a single low test result, less than the minimum individual value. All that failed the average value criteria were performed with the shape factor set at an extreme values, while all that failed the individual value criteria were from welds performed with parameters that minimized displacement.

Material D Metallurgy. The base metal is a quenched and tempered, low carbon, Niobium micro-alloyed material, having a fine grained microstructure(fig. 3). The weld line microstructure displays a similar grain size and morphology with slight coarsening through the HAZ (fig. 4 and 5).

Weld Profile. The macrograph in figure 6 shows the material flow during the forging process and the finished weld profile, which has a small weld bulge with a thin "fin" extending from its center. The extruded "fin" contains the interface and adjacent material that experienced the highest temperature (fig. 7) and much of the original interface material, as evidenced by the coarse bainitic structure in the larger austenite grains[12].

Adjustments made to the joint profile improved the shape of the weld bulge and produced the fin, which can be easily removed following the weld. After skiving the fin, the final profile will have a slight weld bulge, smoothly transitioning from the wall with no weld line crack or other stress riser.

Material D Typical Hardness and Strength. A hardness traverse for a typical material D weld is presented in fig. 8. All welds in material D have a similar hardness profile: HAZ softening 5 to 7 mm on either side of the weld line and hardening at the weld line. The degree of HAZ softening and weld line hardening is primarily controlled by the discharge speed and field current parameter selection. Tensile specimens fail in the base metal at parent metal values.

Material B- 3-inch X60 ERW. A limited number of welds have been performed in material B using the modified parameters due to limited availability of material B. Weld parameters selected for material B welds were repetitions of those used on good quality material D welds. In all such welds, the thermal and mechanical response was similar to those of D material welds, and the mechanical properties of the welds met the acceptance criteria with the exception of the tensile strength, as reported earlier.

Material B Metallurgy. The base metal is a controlled rolled low carbon, Niobium micro-alloyed material, having a very fine grain, and the weld line microstructure has a similar fine grained microstructure (fig. 9 and 10). Moving through the HAZ, the carbide colonies become more pronounced due to the light banding in the base metal.

Material B Typical Hardness and Strength A hardness traverse for a typical material B weld is presented in figure 11. Compared to material D, the HAZ has a similar width but with more softening in material B, and lacks any weld line hardening. Tensile test specimens consistently fail at the weld line at 85-90% of parent metal strengths and display ductile fracture surfaces. These results are consistent with the thermal cycles in controlled rolled materials, and PWHT of these welds was observed to further soften the HAZ[13].

Real World Condition Welds. Twenty-five additional material D welds were performed using the modified weld parameters to determine tolerances on joint geometry, interface alignment and surface conditions. These results are summarized in table 2. In the tolerancing series, the joint geometry between the pipe pair differed in contact width, shape factor, and radial prep centerline position. All welds in the tolerancing series had circumferentially uniform contact area and pressure.

In the misalignment series, pipes with standard end preparations were misaligned by displacing the pipe centerlines radially and by tilting one of the pipes. The expected response to radial misalignment is circumferentially non-uniform heating from the variation in contact width and contact pressure around the interface surface. For angular misalignment, the expected response is increased contact pressure at the initial contact point. As previously mentioned, increasing the local contact pressure reduces the contact resistance and allows more current flow along that path.

In the surface condition weld studies, the interface surfaces of typical joints were single point lathe turned to produce substantially coarser finishes, cut with a full width shearing cutter, or machined to produce a wavy surface. Coarsest surface finishes exceeded 17.8 μm rms (700 μin.), and the wavy surface had a total wave amplitude of 127 μm (0.005 in.).

On the last four real world welds, the joint machining was performed using a commercial pipe-facing machine leaving a coarse, wavy finish on the interface surfaces. Typically, the joints are lathe-turned producing a smooth (<1.62 μm [64 μin]), flat surface. These welds displayed typical thermal and mechanical response and had exceptional impact toughness.

Despite parameter selection designed to produce unacceptable welds, overall, these welds achieved circumferentially uniform heating, and displayed typical displacement response. The effect of these weld parameters generally lowered the impact toughness, but only two failed to achieve the minimum average impact toughness. Three additional welds had an individual value below the acceptance limit.

Discussion and Summary 3-inch welds. The new welding method had several distinct benefits besides improving the mechanical properties and weld profile. Using a constant load simplified the control requirements for the upset load. Using a shaped end reduced the energy requirement for welding, permitting 14% lower discharge speed settings. The high constant load combined with the shaped end limited the peak temperature by forging material as it softened to its forging stress. These combined parameters prevent overheating because the opportunity for overheating, melting and melt expulsion/arcing, occurs early in the thermal cycle when the current is rapidly rising to its peak value. By permitting an "on-demand" forging action, hot material is extruded as it heats, rather than continuing to heat. With this type of process, the load system must be able to respond sufficiently fast to maintain a gapless interface. The continuous deformation during upset resulted in dynamic recrystallization, refining the grain and promoting grain growth across the interface.

In the 3-inch homopolar welding program, four materials were successfully joined achieving full strength or near full strength joints. While all met hardness requirements, the limit on achieving acceptance for offshore pipelines remained acceptable impact toughness. The modified weld parameters achieved acceptable results in the two high strength materials, but not the lower strength materials. The weldability of materials B and D was attributed to their clean chemistry and possibly the use of calcium as a manganese cleaner. Extensive studies to determine bounds of the process revealed that for a given material, acceptable welds were achievable over a broad range of parameters, permitting optimization of a single parameter.

Conclusions of modified parameter 3-inch welds. The results of the 3-inch welding program permit these conclusions:

- Material chemistry strongly influences the homopolar weldability of a material.
- High strength materials are easily joined.
- Modified weld parameters produce acceptable finished profile .
- Modified parameters make HPW more robust and more tolerant to real world conditions.
- Careful selection for weld parameters assures good welds in weldable materials.

12-inch Homopolar Welding Program

Success in homopolar welding of 3-inch schedule 60 line pipe led the way in the design of a fixture for joining 12-inch schedule 80 line pipe. The modified weld parameters demonstrated the robustness and simplicity of the process, while reducing some of the fixture requirements. The next section reviews the critical issues associated with scaling the process to a larger pipe, a larger cross-section, and prototype issues for a commercial fixture.

Design Requirements for Scaling Up. Designing a fixture to join nominal 12-inch schedule 80 line pipe based on 3-inch schedule 60 line pipe weld parameters constituted a sevenfold increase in cross-sectional area. Historically, the homopolar welding thermo-mechanical cycle was assumed to be independent of cross-sectional area joined. The process was treated as an adiabatic process, since the thermal cycle was so fast, and the peak current was reached in less than 4% of the pulse length. To achieve comparable thermal and mechanical responses in the workpiece, the local heating rates and stress distribution were maintained, and the joint profile was scaled using the wall thickness as the characteristic dimension.

To meet the thermal requirements, local current densities were maintained since the square of current density determines electrical resistance heating rates. For a comparable response throughout the heating cycle, the current density, based on the pipe cross-section, as a function of time was reproduced. In short, the total current profiles should have the same shape, including time to peak current (100 ms) and the pulse length (2.5 s) and they should scale with the cross-sectional area.

To maintain the stress distribution, the upset load requirements should scale with pipe wall area. Further, during upset, when the workpiece deforms, the rate of deformation was to be maintained.

Some of the general requirements for successful homopolar pipe welding are mentioned here for completeness:

- circumferentially uniform current distribution
- minimal circuit losses
- maintain axial alignment during upset
- limit electrode leading edge peak current density.

Prototype 12-inch HPW Machine. The first prototype HPW machine for joining 12-inch line pipe was implemented as a laboratory fixture primarily to demonstrate the scalability of HPW. Of interest was whether the required current pulse could be introduced into a pipe and whether the pipe would heat and forge similar to the 3-inch welds. To address scalability and minimize costs, the design requirement of applying the upset force through the pipe wall was deferred to the next fixture proposed as a prototype field HPW system.

The new welding machine consisted of a two piece welding fixture and three 10 MJ HPGs. The hydraulic load module of the welding fixture provides an upset load of 1.91 MN (430,000 lb) and an accumulator passively maintains a relatively constant force to the workpiece during deformation. An internal 101.6 mm (4 in.) diameter tension rod transmits the force from a pair of hydraulic cylinders configured in parallel and applies the upset load to the ends the pair 152 mm (6 in.) long pipes.

The other component, an upset frame, contains the electrodes and busswork to transfer the current through the workpiece and maintain the axial alignment during upset. Twelve pairs of hydraulic cylinders extend and retract the electrodes and limit transverse motion of the workpiece. The three 10 MJ HPGs are connected in parallel and capable of storing 30 MJ of rotational kinetic energy for welding. The system is designed for a peak current of 1.5 MA.

The First 12-inch Welding Series. After commissioning this new system, the first weld series began with the objective of establishing a set of baseline weld parameters that would produce complete welds comparable to 3-inch welds. The material selected for this first series, designated with the prefix "N", was substantially identical to material D, as both were provided by the same supplier. This material has a wall thickness of 0.50 in. and wall area of 12,419 mm^2 (19.25 in^2). Material composition is listed in table 1.

As of this writing, four 12-inch welds have been completed, with the third and fourth welds having sufficient energy to join the full wall and produce a finished weld profile similar to 3-inch welds (fig. 12). The process parameters, total current, interface voltage and displacement (fig. 13), indicate the similarity of the process to the 3-inch. (Compare to fig. 2) The peak current (1.43 MA), time to peak (0.094 ms) and pulse length (3 s) are similar to the 3-inch, indicating that comparable energy was delivered to the workpiece. The displacement and interface voltage responses display the same response as for 3-inch welds, with the exception of the more rapid initial displacement rate. The average energy density between the interface voltage probes was also comparable to material D welds.

Mechanical Properties. The mechanical properties and metallurgy of the initial material N welds were similar to material D welds, with the exception of the impact toughness. The parent metal is fine-grained similar to that of material D (fig. 14). Weld metal is slightly coarser, but still fine grained and the HAZ metal is coarser still (figs. 15 and 16). The hardness traverse shows similar weld line hardening surrounded by a narrow zone of HAZ softening (fig. 17). In the tensile test, the specimens broke in the base metal at parent material properties. These welds had unacceptably low impact toughness, displaying only limited shear fracture.

Discussion of First 12-inch welds. The first 12-inch weld series successfully demonstrated the scalability of HPW to larger pipe sizes and comparability of the process parameters used to monitor the process. This effort was unique in several ways. It was the largest cross-sectional area joined using HPW. It was the largest scale to date. It demonstrated the modified weld parameters scaled with cross-section. It demonstrated acceptable design considerations were appropriate for scaling up.

The failure to achieve acceptable impact toughness by the fourth weld is not unexpected. In previous welding programs, it has typically taken dozens of welds to identify weld parameters capable of increasing impact toughness, often never achieving acceptable toughness. For the first few welds, possible causes of low toughness may be related to the faster displacement rate or the slower cooling rate, both characteristics of the new welding fixture. The features of the fixture producing these effects were not in the primary design considerations. Presently, modification to the weld parameters are under consideration to adapt them to the new fixture.

NDE Program for HPW

The nondestructive evaluation (NDE) effort for the homopolar welding program consisted of two key components: process monitoring and nondestructive testing of the welds. As an automatic welding process, monitoring specific weld parameters was proposed as a method to control weld quality[6,14]. This research, based on traditional HPW method, suggests that monitoring the weld displacement may be one the best measures of weld quality. This approach appears applicable to the modified HPW process.

The other key component in NDE of HPW is developing appropriate nondestructive tests for HPW. Based on its similarity to friction welding, where the faying surfaces are held under constant pressure during the heating phase of the process, HPW was assumed to be susceptible to planar, no volume flaws, oriented along the weld interface. Problematic flaws included the cold weld and the array of microinclusions. The cold weld, or kissing bond, occurs when the softened weld metal makes intimate contact at the interface without forming a metallurgical bond[15]. The array of microinclusions occurs when the interface contamination is not fully expelled from the joint. Laminations and manganese sulfide stringers may also occur in HPW.

Based on its ability to detect these planar reflectors, automatic ultrasonic inspection (AUT) was selected as the best method for inspecting HPW. Additional features of AUT include high rate of inspection, immediate display and analysis of test results, provides a permanent record of each test, and allows post-inspection review and analysis of the test data.

Presently, work is underway to characterize the possible flaws and identify optimum probe configurations. The tandem probe is being investigated as a single probe capable of providing a go-no-go test for the presence of a flaw. This probe is designed to detect planar reflectors oriented perpendicular to the inspection surface, and as such might detect an array of microinclusions located on the interface.

Future Work

Work for the remainder of the present JIP includes continuing welding both three and twelve inch pipe and characterizing HPW flaws. The emphasis of the 12-inch welding program will be identifying weld parameters that increase impact toughness properties. The 3-inch welding program will continue to investigate fundamental relationships between weld parameters as they affect the process parameters and mechanical properties.

After this JIP, a follow-on program is proposed to accomplish the following:

- Optimize weld parameters for large diameter pipe
- Complete HPW flaw characterization and develop prototype and commercial nondestructive test procedures
- Investigate homopolar weldability of other important material, like duplex, Cr-A, and titanium.

Commercialization Efforts

A joint effort by the industrial contractors of this JIP is placing a prototype HPW system in a land based operation as a low risk, first commercial operation. Parker Kinetic Designs has designed an industrial homopolar generator for joining 4, 6, and 8 in. diameter schedule 80 line pipe, with maximum pipe wall area of 8,387 mm^2 (13 in.^{2}). This machine produces 15 MJ at 3,440 rpm, uses rolling element bearings, requires an eight hour brush maintenance after 10,000 discharges, and is skid mountable. Its dimensions are 1.40 m (55 in.) long and 1.52 m (60 in.) diameter, and weigh 133 kN (30,000 lb).

Adapting the features of the laboratory fixture for field welding requires developing a method for gripping the pipe to apply the upset force. Field fixture design and testing is underway at CRC-Evans. Knowledge acquired from the 12-inch fixture at CEM will be incorporated in the design of the next HPW fixture.

Acknowledgments

We gratefully acknowledge the support of the Joint Industry Program Sponsors, Amoco, BP, Exxon, Mobil, Shell, Texaco, CRC-EVans, PKD, and the MMS/DOT. The preliminary work necessary to initiate this program was supported by NSF through the Offshore Technology and Research Center.

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Table 1. Material Data

Weld Prefix Code	A	C	B	D	N
API 5l Grade	X52	X52	X60	X65	X65
Outside Diameter	3.5	3.5	3.5	3.5	12.75
Wall Thickness	0.438	0.438	0.300	0.315	0.50
Type	seamless	ERW	ERW	seamless	seamless
Heat Treatment (Not On Mill Test Report)	Hot rolled	normalized	controlled rolled	quenched and tempered	quenched and tempered
Ladle Chemistry					
C	0.23	0.11	0.13	0.08	0.08
Mn	1.04	1.13	0.65	1.29	1.29
P	0.010	0.014	0.005	0.011	0.011
S	0.009	0.005	0.004	0.002	0.0017
Si		0.28	0.22	0.19	0.19
Al		0.037	0.042		
Cr		0.073	0.03		
Mo		0.028	0.01	0.22	0.215
Ni		0.07	0.01		
Cu		0.13	0.02		
Cb		0.034	0.18	0.032	0.032
Ca			0.0048	0.0026	0.0026
Ti		0.008			
V	0.08	0.040			
B		0.0003			
Ti-Al				0.035	0.035
Iiw C_{eq}	0.42	0.34	0.23	0.34	0.34
Yield Strength (Ksi)	66.0	59.5	79.5	71.6	71.6
Tensile Strength (Ksi)	94.4	79.5	86.1	80.7	80.7
% Elong in 2"	30	37	22	26.6	26.6
Impact Toughness (J [ft-lbs])	85 (63) full size	214(158) full size	81(60) half size	168(124) half size	<358 full size
Vickers Hardness	193	171	182	185	219

Table 2. Summary of Mechanical Test Results for Material D Welds

	Units	Ideal Conditions	Real World Conditions
# Welds Performed		70	25
# Weld CVN Tests		63	21
CVN Ave.	J	109.1	101
CVN Ave. St.Dev	J	37.7	34.6
# Fail Ave. Criteria		5	2
Min CVN Ave.	J	85.6	75.9
CVN Min St.DEV	J	39.9	44.5
# Fail Min Criteria		4	3
# Weld Tensile Tests		29	
Yield Ave	MPa	500	
Yield St.Dev	MPa	9.5	
Tensile Ave	MPa	567	
Tensile St.Dev	MPa	9.5	
% EL Ave		26	
% EL St.Dev		1.85	

Table 3. Range of Weld Parameters for Ideal Condition Welds

	Unit	Minimum Value	Maximum Value	% Variation
Discharge Speed	rpm	2000	2200	10
Field Current	A	300	390	30
Load	kPa	200	267	25
Joint Angle	Deg	30	45	33
Contact Width	mm	1.905	3.81	50
Shape Factor		0	1	100

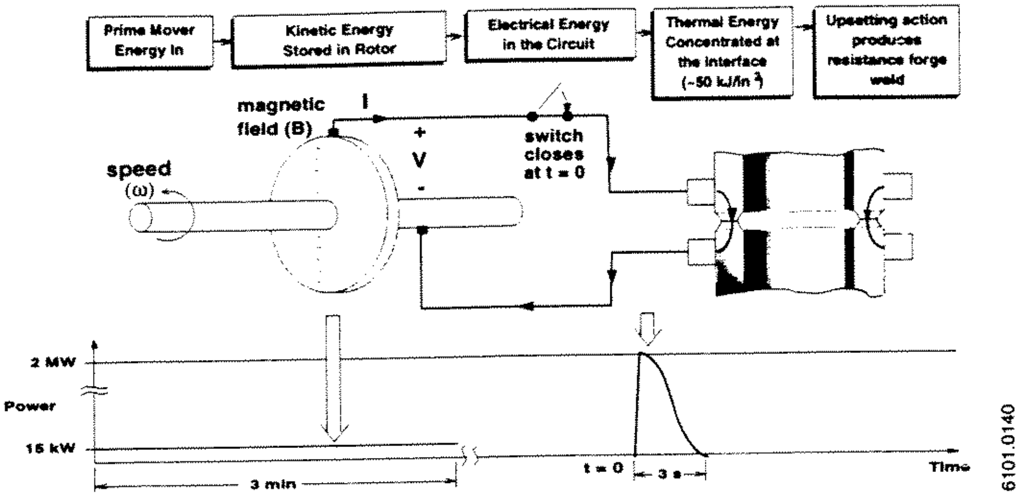

Fig. 1 - HPW process schematic.

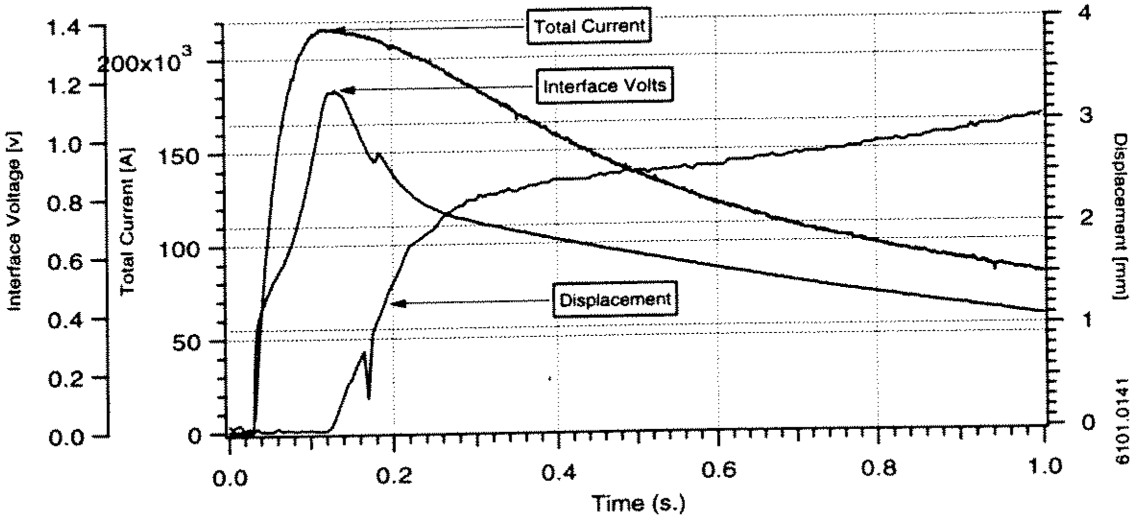

Fig. 2 - Typical Material D Process Data.

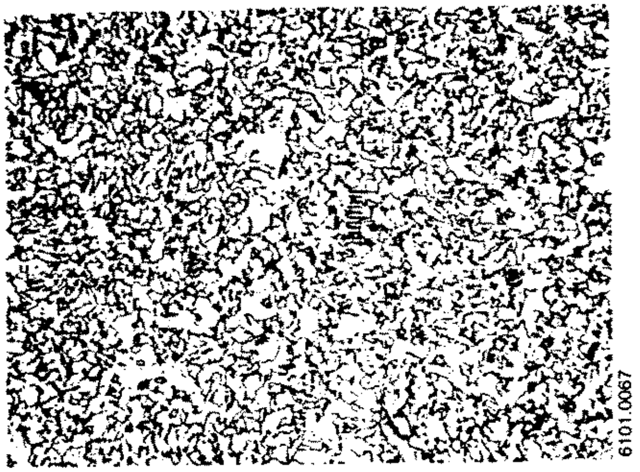

Fig. 3 - Material D parent metal microstructure. (scale maker =20 µm)

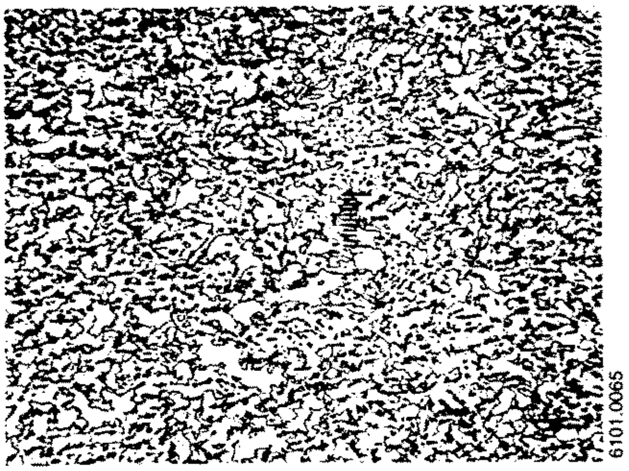

Fig. 4 - Material D weld line microstructure. (scale maker =20 µm)

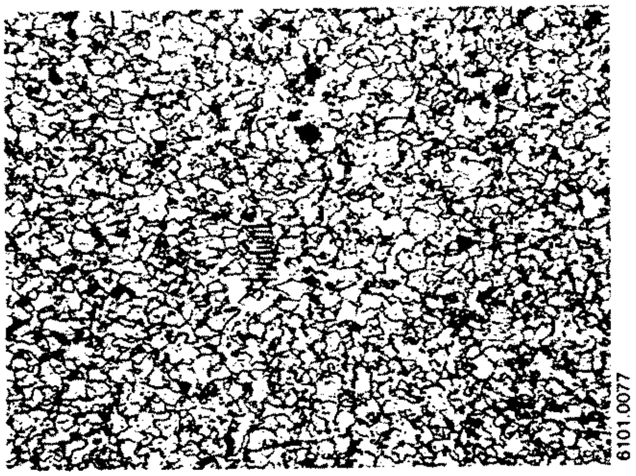

Fig. 5 - Material D HAZ microstructure. (scale maker =20 µm)

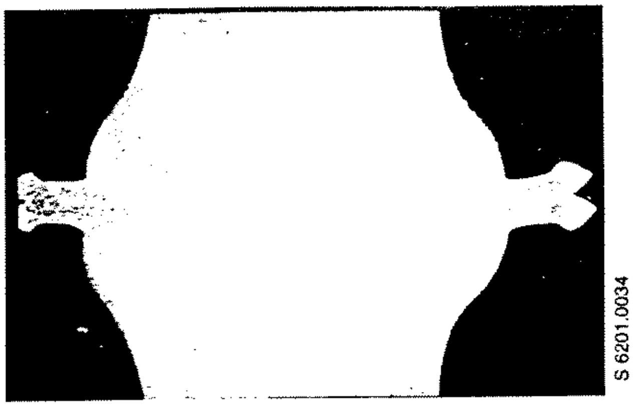

Fig. 6 - Material D weld macrostructure. (magnafication 5×)

Fig. 7 - Material D fin microstructure. (scale maker =20 µm)

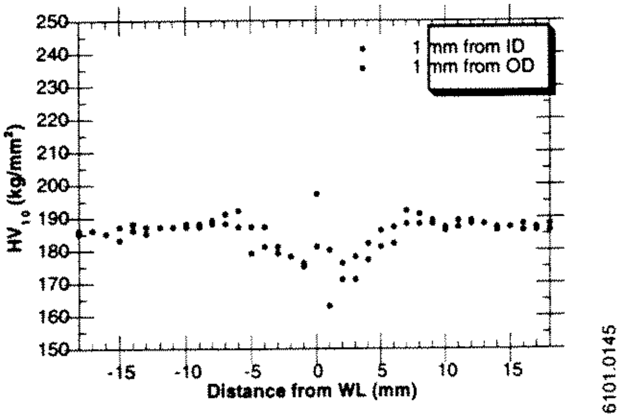

Fig. 8 - Typical material D macrohardness traverse.

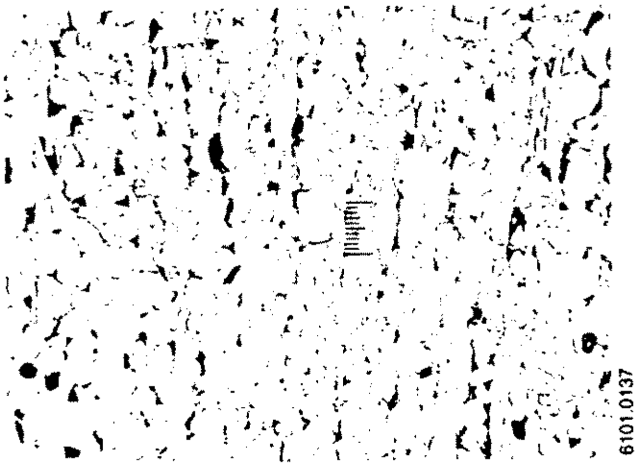

Fig. 9 - Material B parent metal microstructure. (scale maker =20 μm)

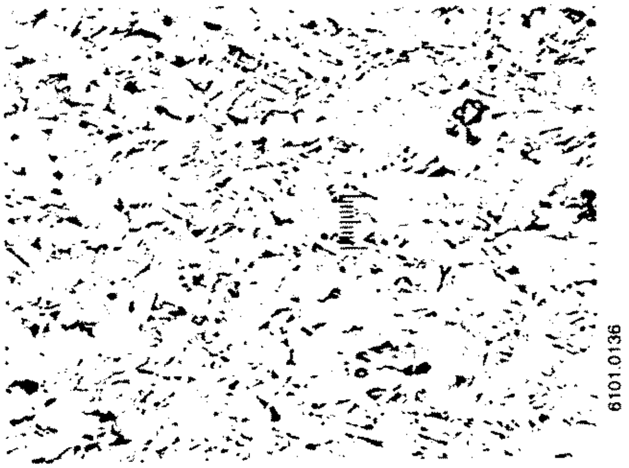

Fig. 10 - Material B weld line microstructure. (scale maker =20 μm)

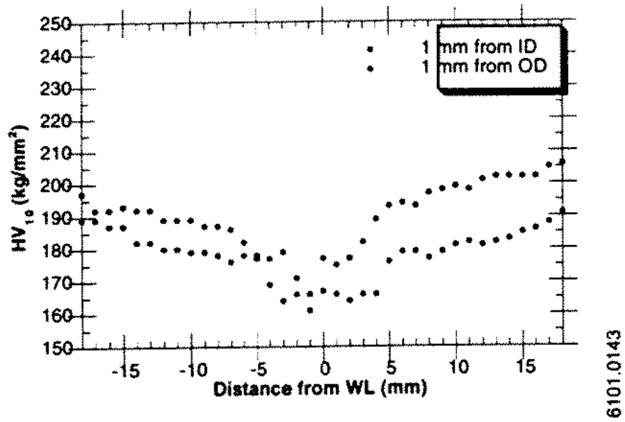

Fig. 11 - Typical material B macrohardness traverse.

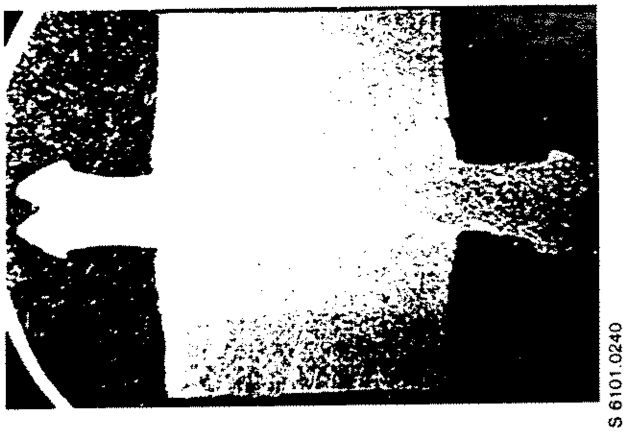

Fig. 12 - Material N weld macrostructure. (magnafication 3×)

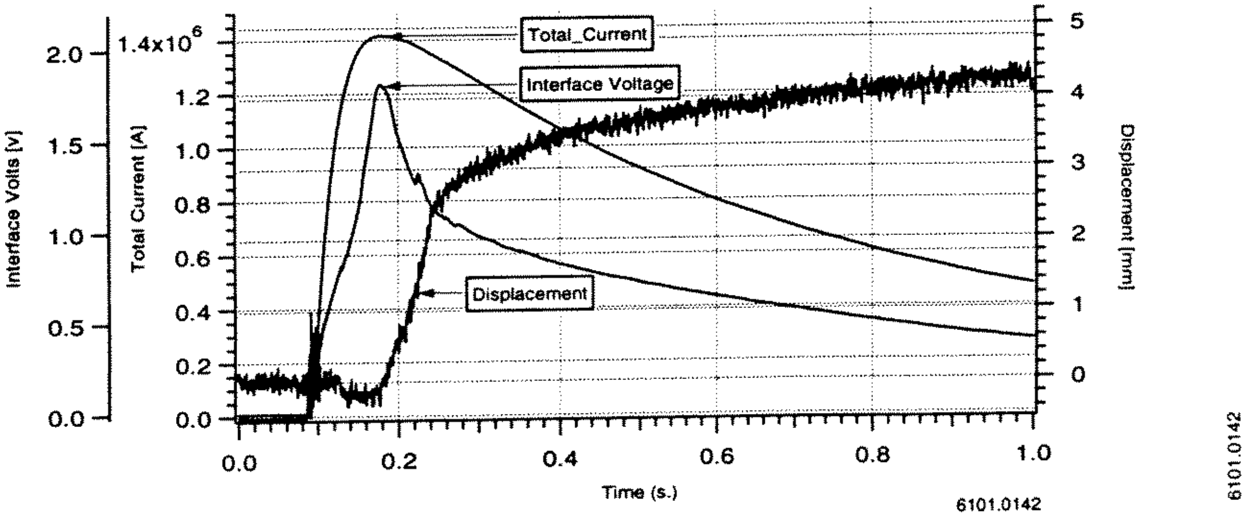

Fig. 13 -Typical 12-inch material process data.

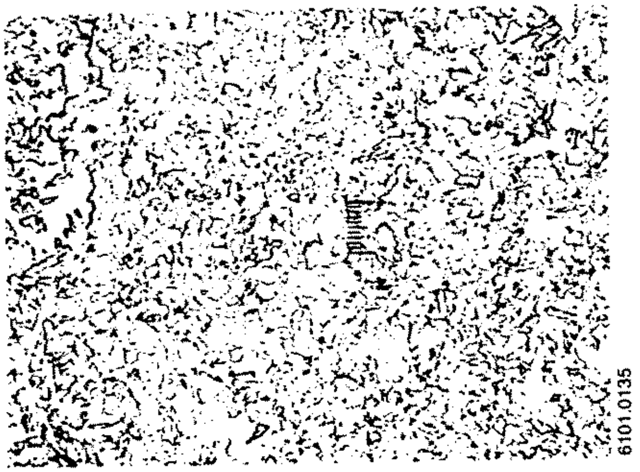

Fig. 14 - Material N parent metal microstructure. (scale marker =20 µm)

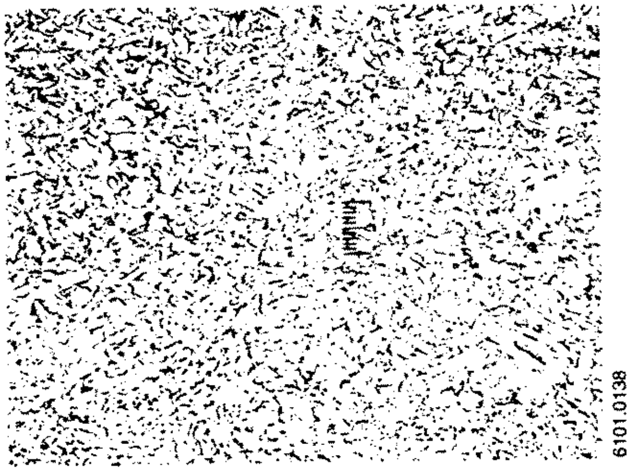

Fig. 15 - Material N weld line microstructure. (scale marker =20 µm)

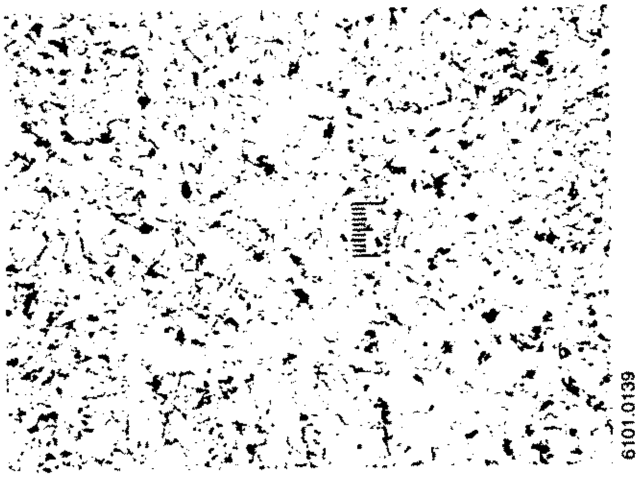

Fig. 16 - Material N HAZ microstructure. (scale marker =20 µm)

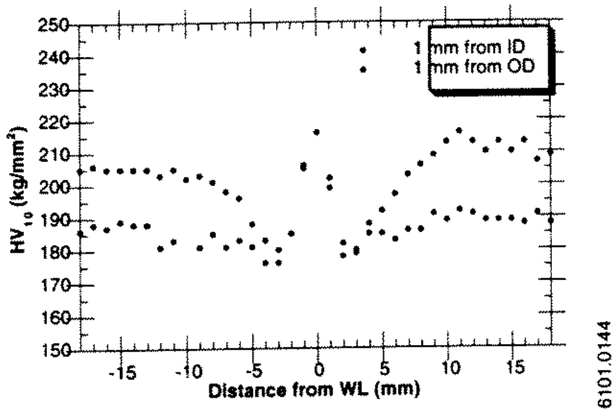

Fig. 17 - Typical material N macrohardness traverse.

AGENDA- HOPWRP JIP

18th Quarterly Meeting
Sept. 5, 1997

8:30 Coffee

9:00 Introduction of Guests- Carnes

9:15 Financial- Carnes

9:30 Demonstration Weld

10:15 Technical Update - Hudson
- JIPN1 Series Status
- NDE

11:45 Follow-on Program - Carnes

12:15 In-Kind Updates - PKD and CRC-Evans

12:45 Commercialization Status - Weldon - PKD

12:30 Planned Activities
- Ultrasonic Testing
- Mechanical Testing of N1.6
- Posters, Papers
- Conference Presentations

1:00 Adjourn

Attendee List for 18th JIP Quarterly Meeting, Friday, September 5, 1997, Austin

	Name	Affiliation	Phone	Fax or Email
1	Bobby Hudson	CEM	512-232-1678	b.hudson@mail.utexas.edu
2	Mike Fahrion	Texaco	713-432-6084	FAHRIME@TEXAXO.COM
3	Fred Levert	Texaco	713-296-7707	LEVERFS@TEXACO.COM
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8	Mike Vandenbossche	BP	281-560-3847	vandenmp@bp.com
9	Robert W. Gatlin	Global Ind.	504-876-7592	504-873-6200
10	Jim Hickey	Amoco	281-463-2860	jth446@worldnet.att.net
11	Milton Randall	CRC-Evans Consultant	281-469-1454	
12	Jerry Rubli	RMI Titanium	281-591-4765	
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16	LLoyd W. Ulrich	DOT-Off. of Pipeline Safety	202-366-4556	Lloyd.Ulrich@rspa.dot.gov
17	Richard Huriaux	DOT-Off. of Pipeline Safety	202-366-4565	Richard.Huriaux@rspa.dot.gov 202-366-4566
18	Charles Blankenhorn	Dresser Engineering Company	918-621-5845	918-621-6717
19	Mike Patton	Dresser Engineering Company	918-621-6711	mpatton@ionet.net 918-621-6717
20	Bob Carnes	CEM-UT	512-232-1655	bcarnes@mail.utexas.edu
21	Steve Nichols	CEM-UT	512-471-4496	

Summary of Material D Toughness

Conclusions

- Performed welds over wide range of parameters (rpm, field, load, step width & length, bevel angle)
- Achieved consistently acceptable impact toughness within range by correct parameter selection and specifically by
  - select weld parameters for sufficient displacement
  - avoid extreme aspect ratio
- Acceptable toughness achieved for welds performed under real world conditions (misalignment, commercial end prep)

N1 Weld Series

Initial 12 inch Weld Series

Objective: Identify set of baseline parameters and evaluate effect of parameters on process and properties.

Weld Parameters

Weld No.	No. of HPGs	Discharge RPM	Load	Field Current	Geometry
N.S2	2	5850	385	280	Small-30
N1.1	2	6050	385	280	Small-30
N1.2	3	4500	385	350	Small-30
N1.3	3	5700	385	265	Small-30
N1.4	3	5700	400	265	50% Large-45
N1.5	3	5700	315	270	50% Large-45

All had 2.5 in Electrode gap except N1.5 had 2 in.

N1.5 used second bevel, no radius.

N1 Weld Series

Process Parameters

Weld Parameters

Weld No.	Peak Current [kA]	Peak Current Density [kA/in^2]	Time @ Peak [ms]	Peak Voltage [v]	Actual Disp [10^{-3} in.]	% Weld
N.S2	1302.5	(67.7)	98	1.72	176	Partial
N1.1	1272.3	(66.1)	98	1.68	183	Partial
N1.2	1370.0	(71.2)	85		186	Partial
N1.3	1415.0	(73.5)	95	1.806	295	Complete
N1.4	1428	(74.2)	104	1.91	346	Complete
N1.5	1479	(76.9)	104	2.03	322	Complete

N1 Weld Series

Impact Toughness Test Results

0°C Temperature Test

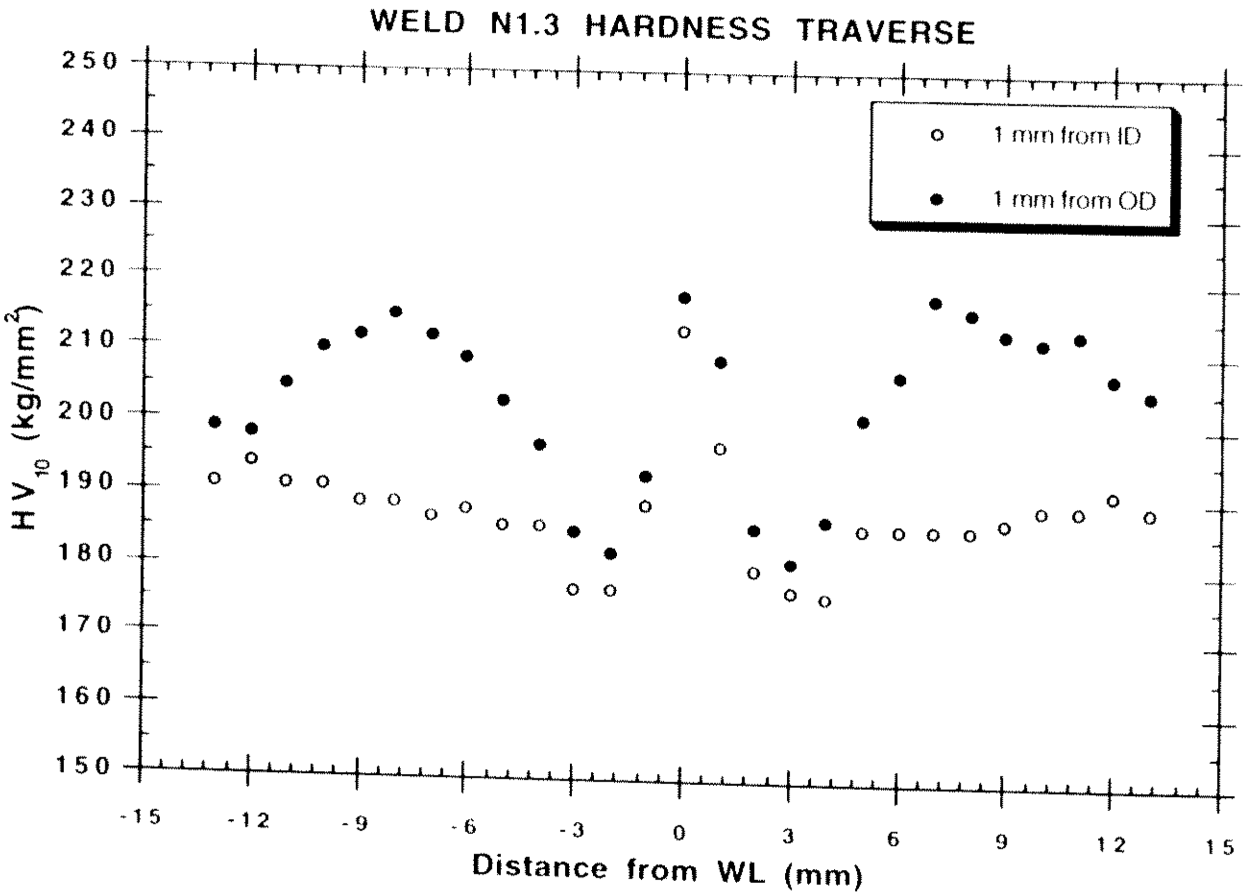
Test Fixture Limit = 264 ft-lb

Number	Impact Toughness Tests [ft-lb]	Mean CVN [ft-lb]	Specimen Size
N.S2	246-99-60	135	3/4
N1.1	28-9-16	17.7	3/4
N1.2	243-7.5-246	165	3/4
N PM	232-226-250	236	3/4
N1.3	10-20-2	10.7	fullsize
N1.4	7.5-14.5-8	10	fullsize
N1.5	1.5-1.5-1	1.33	fullsize
N PM	263-263-263*	263	full size

1 & 2 mm off weld line tests	N1.4	59 & 264 ft-lb
	N1.5	100 & 264 ft-lb

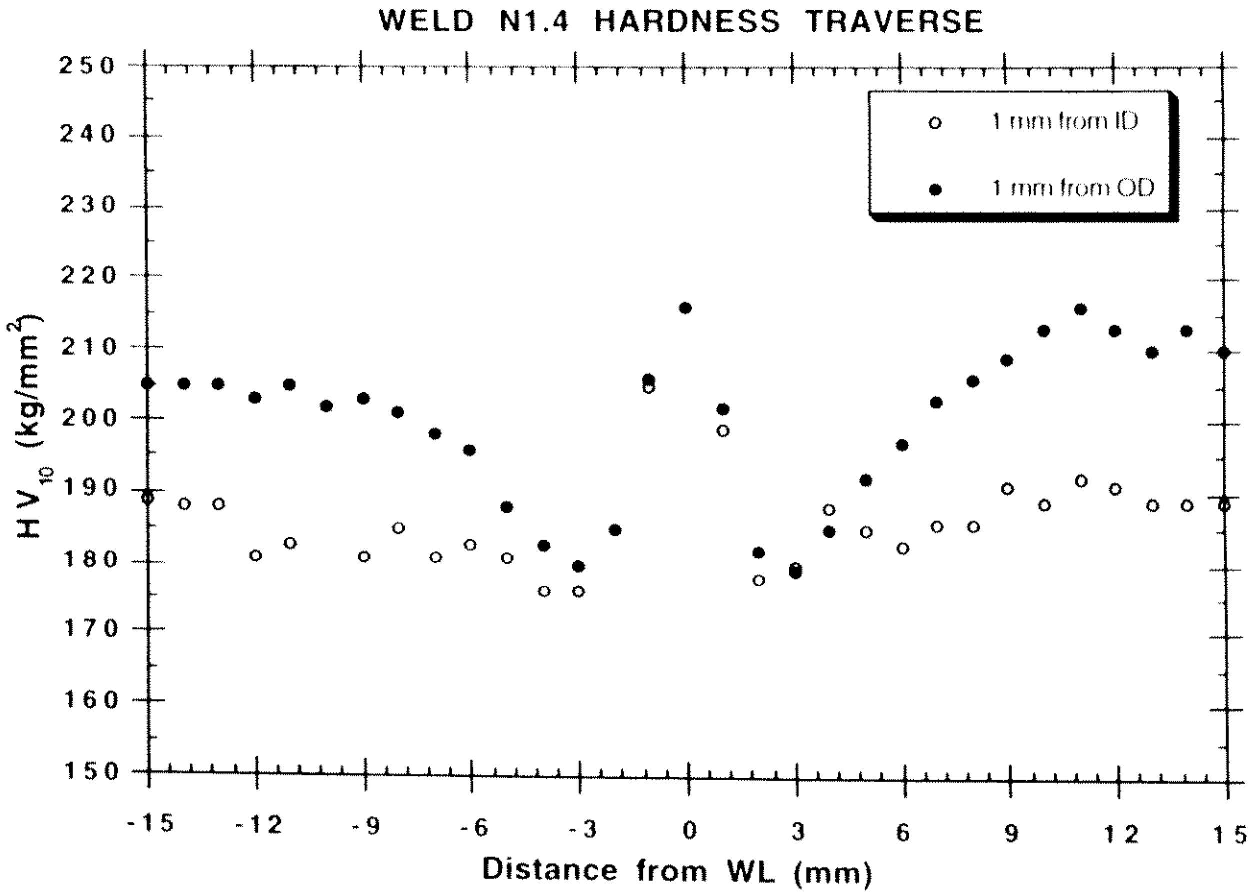
N1.3 Weld Series

Hardness Test Results



N1.4 Weld Series

Hardness Test Results



NDE
Status

Ultrasonic testing resumed on 3 inch welds.

New probes designed and manufactured for 12 inch welds.

Test fixture modified to improve repeatability.

Axial scans performed to compare characteristic ultrasonic reflections of good and bad welds: isolate reflections from weld metal by grinding off weld bulge.

Parent metal scanned for inclusions contributing to occasional low toughness.

Studies initiated to detect HPW microstructural characteristics affecting mechanical properties

Planned Activities for Next Quarter

- Continue ultrasonic testing.
- Present papers/poster at conferences.
- Perform transition temperature studies on past welds.
- Perform 3 and 12 inch welds as needed.

JIP FOLLOW-ON PROGRAM

NONDESTRUCTIVE EVALUATION OF NONTRADITIONAL PIPE WELDS

PARTICIPANTS

CEM- UT Austin
NDE Center, Iowa State U.
Assn. for Fracture Analysis, U Tennessee, Knoxville

OVERALL OBJECTIVES

- To identify and define the kinds and sizes of defects inherent in resistance forge welds which are potential initiators of failure.

- To apply the most advanced techniques of UTS inspection to the UTS of oilfield line pipe welds.

- To learn how to locate the first with the second to a degree inspiring confidence in end users and regulatory bodies.

FRACTURE STUDY

CONDUCTED BY:
DR. JOHN LANDES, UT-KNOXVILLE
BOB CARNES, CEM, UT-AUSTIN

INVESTIGATION RATIONALE

- What is the cause of the occasional low toughness reading in Homopolar Welds?

- What differentiates it from the surrounding matrix?

- Is it a trigger for cleavage (size, configuration and orientation)?

- How does it affect bulk or structural fracture properties?

UULTRASONIC NDE STUDY

CONDUCTED BY:
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SEQUENCE OF INVESTIGATION

- Define possible HPW flaws amenable to ISU modeling capabilities.
- Model UT sensitivity for those flaws.
- Run validation measurements on intentionally flawed HPW specimens.
- Predict detectability of flaws in HPW welds and predict modified UT system characteristics that improve flaw detedtability.

- Measure backscattered noise in virgin pipe and HPW welds.
- Define UT measurement configuration (wave mode, frequency, refracted angle, scan area) for backscattered noise characteristics.
- Perform UT measurements of backscattered noise.
- Correlate noise characteristics to results of destructive tests.

- Investigate feasibility of measuring nonlinear effects from zero volume defects in HP welds.

PROGRAM COSTS

John Landes (18mos at 12%)	
Post Doc (18 mos at 12%)	$60,000
Bob Carnes (18 mos at 25%)	$60,000
Tim Gray and Grad Students (18 mos)	$130,000
Bobby Hudson (18 mos at 50%)	$100,000
Equipment and Material	$50,000
Travel	$20,000
Total (18 mos)	$420,000

Program scheduled to begin at the end of the present JIP