HOMOPOLAR PULSE WELDING FOR OFFSHORE DEEP WATER PIPELINES

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ABSTRACT

Homopolar pulse welding (HPW) is a one-shot resistance welding process being investigated as a method to join API 5L carbon steel line pipe. 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 requiring no filler metal in under three 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 have concentrated on weld parameter optimization by producing, testing, and evaluating welds in various grades, wall thicknesses, types and compositions of 3 inch nominal (3.5 inch 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 carbon steel line pipe via a rapid, one-shot process. Future work will concentrate 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 inch diameter pipe in a J-lay configuration.

References and figures at end of paper.

J-LAY FOR DEEP WATER PIPELINES

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 permits a single welding station, presenting great economic incentive to minimize pipe handling and welding cycle times.

Springmann and Hebert¹ described a J-Lay Pipelay System used by McDermott Marine Construction to install deep water portions of Auger 12 inch oil and gas pipelines. This system virtually removed pipe joint handling operations from the weld cycle critical path. Development of a rapid, one-shot welding process would decrease weld cycle times and further increase lay rates. Homopolar Pulse Welding (HPW) has been proposed as a viable one-shot welding process for this application.

HOMOPOLAR PULSE WELDING

Homopolar pulse welding is properly classified as a resistance-forge welding process. The primary components of a HPW system are the homopolar generator and the hydraulic welding fixture. The homopolar generator is a device that stores energy kinetically in a rotating flywheel and converts it to electrical energy in a discharge circuit via electromechanical energy conversion.

Homopolar generators are not in common use because they are inherently high current, low voltage devices unsuitable for power transmission over long distances. Homopolar generators have been previously used as welding power supplies; Westinghouse² constructed a homopolar generator resistance welding power supply in the 1930's for pipe seam welding and Progressive Welder Company³ built a homopolar generator flash/spot welder in the 1940's. The novel aspect of homopolar pulse welding is that it uses the homopolar generator as a huge capacitor, delivering the electrical energy in a single, large current pulse.

Fig. 1 presents a schematic of the Homopolar Pulse Welding cycle. The HPW process begins by accelerating the homopolar generators rotor to a predetermined discharge speed. Then the generator is energized by exciting the field and engaging the sliding electric contacts, or brushes, onto the slip ring of the spinning rotor. Discharge is initiated by closing switches in the circuit at the generator terminals. The resultant current pulse is directed through the pipes where weld joint electrical resistance produces extensive localized heating. After a preset time delay, upset pressure is applied to the pipes, displacing some metal at the former interface and creating a full circumferential butt weld.

Postweld cooling rate is via thermal conduction, and is determined by the pipe and electrode physical dimensions, with the copper electrodes acting as a heat sink during cooling. Increasing the distance between the electrodes heats a larger bulk of the pipe on either side of the weld joint and increases the conduction path from the weld zone, slowing the cooling rate. In combination with electrode location, generator discharge speed and field current, pipe end preparation, upset pressure, time between generator discharge and application of upset pressure, and duration of the upset pressure are all controllable process parameters affecting weld quality.

The method is similar to other resistance welding methods, with the exception that the energy is delivered in the form of a single high-current DC pulse. The process is, therefore, fast and does not produce the localized skin heating effects present in AC resistance welding methods. Flash Butt Welding can be used on the same pipe diameters that are being targeted for J-lay, but flash butt welding takes from one to two minutes per joint, and produces extensive melting and a large heat affected zone (HAZ). Homopolar pulse welding requires only a few seconds and is considered a solid state welding process.

The same generator and fixturing used to produce a homopolar pulse weld may be utilized to heat treat the weld and HAZ. After the weld zone has cooled below the transformation temperature, an additional HPG pulse may be used to reheat the weld zone. Electrode location and generator parameters can be preselected to control the amount of heating, width of heated zone, and the subsequent cooling rate.

JOINT INDUSTRY PROGRAM

This Joint Industry Program, which began in February 1993, was initially funded by a consortium 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 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 inch schedule 60 (0.562 inch wall) carbon steel pipe.

WELD PROPERTIES

Weld process parameter optimization is being performed by producing and evaluating welds in 3 inch nominal diameter API 5L carbon steel pipe of various grades, wall thicknesses, and production methods. To date in the Joint Industry Program, welds have been produced using the materials listed in Table 1. The materials have been assigned the designations A, B, C, and D for later reference.

Steel A

The parent metal microstructure consists of a typical banded ferrite-pearlite, as shown in Fig. 2. The weld line microstructure of a weld produced with the electrodes located close to the weld interface (short electrode gap) is presented in Fig. 3. The rapid cooling rate produced by a short electrode gap resulted in a coarse bainitic structure. Increasing the electrode gap substantially to drastically reduce the cooling rate produced the microstructure shown in Fig. 4. Grain boundary ferrite clearly indicates the large prior austenite grain size. Re-austenitizing the weld zone by application of a single postweld homopolar generator current pulse resulted in the fine grained ferrite-pearlite microstructure of Fig. 5.

Full tensile strength in this material was easily achieved, requiring only the combination of sufficient energy input and a nominal forging action applied before excessive weld zone cooling. Tensile failure of welds meeting these criteria was ductile fracture outside of the weld and heat affected zones. This was demonstrated in both tensile specimens with the inner diameter (ID) and outer diameter (OD) weld bulge reinforcement left intact, and in tensile specimens machined flat.

Hardness traverse testing confirms strengthening of the weld and heat affected zones, with peak hardness values at the weld line. Varying the distance between the electrodes, and hence the post-weld cooling rate, has produced peak hardness values between 300 HV₁₀ (rapid cooling) and 230 HV₁₀ (slow cooling).

The sponsors' criteria for Charpy V-notch impact toughness values on full size specimens of X52 grade at 0°C are a minimum individual value of 30 J (22 ft-lbs) and a minimum average over

three tests of 36 J (26.6 ft-lbs). The parent metal exhibited an average impact toughness of 81.3 J (60 ft-lbs), but displayed only a 20 to 30% shear fracture surface appearance. These criteria were difficult to meet in the as-welded condition. Individual welds were produced that met the criteria, but the as-welded impact toughness of this material has, in general, been low.

Postweld pulse heat treatment of a weld in material A improved impact toughness greatly, with the resultant impact properties easily satisfying the criteria.

Steel B

The material B parent metal microstructure is very fine grained, as shown in Fig. 6. The microstructure of a homopolar pulse weld produced in this material with a rapid cooling rate (short electrode gap) is presented in Fig. 7. The microstructure is bainitic but possesses a fine structure. Increasing the electrode gap (reducing the cooling rate) results in a coarser structure for this material, as evidenced in Fig. 8. Postweld pulse heat treating produced a polygonal structure, presented in Fig. 9.

Tensile tests on strip specimens, with the ID and OD weld reinforcement bulges left intact, indicated full strength welds with failure occurring outside the weld zone. Tensile testing flat machined weld and parent metal specimens revealed a slight decrease (5 to 10%) in the ultimate strength of the welds tested compared with the parent metal. Failure occurred in the HAZ, not at the weld line. The yield strength of the parent metal was very close to the ultimate strength, whereas, the welds exhibited an apparent localized yield point phenomena at 56 to 60 ksi, with a yield/ultimate strength ratio of about 0.8.

Hardness traverses performed on these welds indicated softening in the HAZ about 3 to 5 mm on either side of the weld line. The parent metal has a typical Vicker's hardness value of 200 HV₁₀. The welds tensile tested as flat specimens showed softening in the HAZ down to a minimum value of 150 HV₁₀. This softening can be attributed to time-at-temperature effects and although residual softening of this steel may not be eliminated, it is expected that weld heat input and cooling rate can be adjusted to reduce this effect.

The sponsors did not specify an impact toughness for welds in API 5L grade X60 pipe, therefore, the more stringent criteria for grade X65 was used to determine acceptability. For half size specimens (5 mm x 10 mm) this criteria is 25 J (18.4 ft-lbs) minimum individual test value and 32 J (23.6 ft-lbs) minimum average of three tests, all at 0°C testing temperature. The parent metal average Charpy V-notch impact toughness at 0°C for half size specimens is 80.8 J (59.6 ft-lbs). Half size specimens are required due to the 0.300 inch wall thickness of this schedule 80 pipe.

The minimum average impact toughness requirement is easily met in the as-welded condition. There are occasional individual specimens with low impact toughness. A recent series of six welds was subjected to extensive Charpy V-notch testing, with twelve specimens machined from each weld and notched at the weld line. Of the seventy-two impact specimens tested in this series, two specimens did not meet the minimum individual toughness requirement of 25 J (18.4 ft-lb). The average impact toughnesses of the twelve specimens from each weld ranged from 67 to 100 J (50 to 74 ft-lbs) among the six welds.

Postweld pulse heat treating welds in steel B produced greater uniformity in impact toughness, with an average CVN value of 95 J (70 ft-lbs) and a minimum impact toughness of 47 J (35 ft-lbs) among the twelve specimens tested.

Steel C

The parent metal microstructure of steel C is shown in Fig. 10, and the microstructure of a HPW joint in this material is presented in Fig. 11. Welds in this material have been few to date, but the results have been comparable with steel A.

Tensile tests on welds have revealed strengthening throughout the weld and heat affected zones, with tensile specimens failing at parent metal strengths outside of the weld and heat affected zones. Hardness traverse testing revealed a typical peak hardness of 220 HV₁₀ at the weld line, with hardness dropping off to parent metal values 10 mm on either side of the weld line, for welds produced with 2 inch electrode gap.

Impact test results on welds in this material have been unacceptably low. Postweld pulse heat treating has not yet been performed on welds in this material, but is expected to produce improvements in impact toughness.

Steel D

This pipe has recently been obtained and weld test results are not yet available. As an X-65, quenched and tempered grade, this pipe is a higher strength material than any of the previous steels investigated. Key concerns will be as-welded impact toughness and thermal cycle effects on base material properties in the HAZ.

CONCLUSIONS

The following conclusions can be made regarding the 3 inch nominal (3.5 in. OD) API 5L carbon steel pipe homopolar pulse welding investigation.

1. Homopolar pulse welding is capable of rapidly producing full strength, full circumference welds in API line pipe.

2. Full weld line tensile strength is easily achieved.
3. Heat affected zone softening is a factor that must be addressed in welding controlled rolled pipe.
4. Peak hardness of homopolar pulse welds can be kept below 250 HV₁₀ for sour service applications.
5. Acceptable Charpy V-notch impact toughness was achieved in an API 5L X-60 pipe in the as-welded condition.
6. As-welded impact properties of HPW welds are strongly material dependent. Consideration must be given to selecting steels capable of meeting impact toughness requirements in the as-welded condition, or the weld thermal cycle must be modified to match the material.
7. Postweld pulse heat treatment has demonstrated effectiveness in improving impact toughness of HPW welds.

REFERENCES

1. S. P. Springmann and C. L. Hebert, "Deepwater Pipelaying Operations and Techniques Utilizing J-Lay Methods", paper OTC 7559, Proceedings of the 26th Annual Offshore Technology Conference in Houston, TX, May 2-5, 1994, pp 439-448.
2. E. H. Meyer, "The Unipolar Generator for Resistance Welding", Westinghouse Engr. Mar. 1956, pp 59-61.
3. T. J. Crawford, "The Homopolar Generator for Resistance Welding", Welding Journal, no. 29, vol. 3, March 1950, pp 211-215.

Table 1. Mill test report data

3 in. nominal (3.5 in. OD) API 5L Carbon Steel Linepipe

WELD PREFIX CODE	A	B	C	D
API 5L GRADE	X52	X60	X52	X65
WALL THICKNESS	0.438	0.300	0.438	0.315
TYPE	seamless	ERW	ERW	seamless
HEAT TREATMENT (not on mill test report)	Hot rolled	controlled rolled	normalized	quenched and tempered
LADLE CHEMISTRY				
C	0.23	0.13	0.11	0.08
Mn	1.04	0.65	1.13	1.29
P	0.010	0.005	0.014	0.011
S	0.009	0.004	0.005	0.002
Si		0.22	0.28	0.19
Al		0.042	0.037	
Cr		0.03	0.073	
Mo		0.01	0.028	0.22
Ni		0.01	0.07	
Cu		0.02	0.13	
Cb		0.18	0.034	0.032
Ca		0.0048		0.0026
Ti			0.008	
V	0.08		0.040	
B			0.0003	
				0.035 Ti-Al
HW Ceq	0.42	0.23	0.34	0.34
Yield Strength (ksi)	66.0	79.5	59.5	
Tensile Strength (ksi)	94.4	86.1	79.5	
% elong in 2 in.	30	22	37	

FUTURE WORK

The program goal is to demonstrate applicability of the HPW process to commercial J-Lay methods. This is to be performed by building and operating a full-scale vertical HPW system capable of producing industrially acceptable welds in 12 inch (12.75 in. OD) schedule 60 (0.562 in. wall) carbon steel pipe. Design efforts are concentrating on achieving this task.

Weld parameter optimization will continue by welding 3 inch (3.5 in. OD) carbon steel pipe. This will indicate compatibility of additional pipe grades and compositions with homopolar pulse welding, as well as define process parameters for the full-scale system.

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Fig. 1. The homopolar pulse weld process

Fig. 2. Material A parent metal microstructure magnification 200X (reduced in printing) scale marker = 50 microns nital etch

Fig. 3. Homopolar pulse weld microstructure in Material A with Rapid Postweld Cooling Rate magnification 200X (reduced in printing) scale marker = 50 microns nital etch

Fig. 4. Homopolar pulse weld microstructure in Material A with slow postweld cooling rate

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 5. Homopolar pulse weld microstructure in Material A after postweld pulse heat treatment

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 6. Material B parent metal microstructure

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 7. Homopolar pulse weld microstructure in Material B with rapid postweld cooling rate

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 8. Homopolar pulse weld microstructure in Material B with slow postweld cooling rate

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 9. Homopolar pulse weld microstructure in Material B after postweld pulse heat treatment

magnification 200X (reduced in printing)
scale marker = 50 microns nital etch

Fig. 10. Parent metal microstructure in Material B

magnification 200X (reduced in printing)
scale marker = 50 microns picral etch

Fig. 11. Homopolar pulse weld microstructure in Material B

magnification 200X (reduced in printing)
scale marker = 50 microns picral etch