HOMOPOLAR PULSED WELDING FOR OFFSHORE APPLICATIONS

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ABSTRACT

As a low impedance energy storage device, the pulsed homopolar generator (HPG) is capable of delivering a multimegawatt, megampere-current pulse into a resistive or inductive load with high efficiency. Such HPGs have been used for over ten years as power supplies for research in high energy, high-rate processing of metal alloy components and systems. Most of these processes rely on resistive heating during the current pulse to rapidly heat the material as required for a particular process.

One such application is homopolar pulsed welding (HPW), a solid state, forged welding process in which heat generation is concentrated at the interface between workpieces as homopolar current is conducted between them. Because of the very high peak current and power (from 8 to 20 kA/cm^2 and 50 to 100 kW/cm^2), weld time is very short, reducing time-at-temperature exposure and related microstructural changes. Welding is accomplished in air, no flux or filler is used, and the interface disappears completely in a good weld.

This paper reports on recent and ongoing research into the weldability by HPW of various alloys applicable to offshore systems, including stainless steel and titanium alloys, but primarily focusing on various grades of high strength steel pipe. The research includes an investigation of weld parameters, sensitivity of the process to the weld parameters, metallurgical and mechanical evaluation of weld quality, and the development of a real time quality assurance capability that can certify nondestructively an HPW weld before it is removed from the welding fixture.

The research presented here is sponsored by the National Science Foundation (NSF) and various private industry companies.

INTRODUCTION

This paper discusses the ongoing development of HPW as a pipe and structural welding process for offshore industry. As a very fast, high peak power forged joining process, HPW does not require filler materials, flux or cover gases, or multiple passes (1). The process appears to be amenable to a wide variety of alloys and dissimilar materials. Because of the fast welding time (approximately 0.5 to 1.0 s), diffusion-driven effects such as sensitization in stainless steels are minimized or eliminated.

The power supply for this process is an inertial (pulsed) iron-core HPG; a dc generator capable of storing as much as 5 kJ/kg and generating single pulses of current at greater than 1.0 MA and 50 kW/kg average power (2). The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has conducted research in HPW and other high energy, high-rate materials processing since 1976.

Potential applications for HPW in offshore industries have been identified and many alloys, sizes, and shapes have been joined (3,4). Samples of these (solid shapes, pipe and tube, irregular sections, and dissimilar joints) are shown in figure 1. Alloys of interest to offshore industries have been welded by HPW, including 6 in., schedule 80 (16.8 cm diameter, 1.2 cm wall thickness) API X-60 steel linepipe (5).

Under the auspices of the NSF Offshore Technology Research Center (OTRC), The University of Texas at Austin (UT) and Texas A&M University (A&M) are investigating HPW as a process for pipeline and structural welding in deep water. For J-lay seabed linepipe construction in deep water (greater than 1 km) and fabrication of tension legs, HPW has been identified as a potentially cost-effective welding process. This program is focusing on establishing the weld parameters for 3-in. diameter x 0.5 in. wall thickness C1035 steel pipe and 6-in. diameter x 0.325 in. wall thickness X-60 pipe. Metallurgical investigations, full-scale strength and fatigue tests, and corrosion fatigue tests are being conducted to verify weld properties. Diagnostics and controls for a real time quality assurance system are being developed to exploit the solid state (no melting) electrical characteristics of the process.

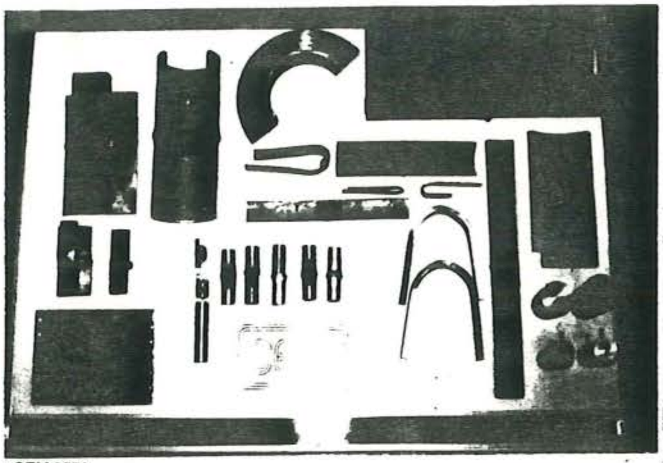

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Fig. 1 Samples of materials, sizes, and shapes welded by HPW

OFFSHORE APPLICATIONS FOR HPW

Welds for offshore service must have excellent joint efficiency and reliability in order to withstand complex, repeated loading, corrosive environments, galvanic corrosion, and other extremes of ocean petroleum production. An additional requirement, especially for deepwater applications, is that welding must be fast and economical. Enhanced weld quality, system compactness, speed, efficiency, and versatility are potential advantages of HPW as a shop or field welding process for offshore applications.

Materials

Table 1 presents a summary of alloys joined by HPW in research at CEM-UT. Of specific interest in offshore duty are corrosion resistant alloys (stainless steels (SS), nickel-based superalloys) and high-strength steels (high strength, low alloy (HSLA), API 5L pipe). Figure 2 shows typical as-welded microstructures of HPW welds in these materials. These are characterized by defect-free weld zones with diffusive grain growth across the original weld plane, completely eliminating the original interface. The heat affected zone (HAZ) may or may not be visible, depending on the hardenability of the alloy. The 304L SS weld was for a nuclear grade application and displayed no weld zone sensitization--chromium carbide aggregation at grain boundaries--which can occur in small degrees after conventional welding (6). The Inconel™ X-750 weld is indistinguishable in structure and mechanical properties from the parent (3). The HSLA joint, which was a half-lap mash seam (i.e., each workpiece overlaps the other by one half the workpiece thickness), had joint efficiency (weld strength to parent strength ratio) of 150% without a corresponding loss in ductility (4). The X-60 steel pipe met or exceeded API/5L-1104 acceptance criteria (5).

Offshore Structures

Two of the technical challenges that must be met for production of petroleum resources in waters deeper than approximately 1.0 km (such as the Gulf of Mexico) are construction of deepwater tension legs and J-lay seabed linepipe. Platform construction must be rapid to avoid inclement weather. Currently, long sections of pipe are welded on shore (sometimes rolled into large diameter coils) and towed to the platform where they are welded and installed to form tension legs. If high-quality welds could be completed on a five minute turnaround at the platform, this process could be completed faster and more economically, with lower risk.

Table 1 Summary of funded HPW research at CEM-UT

MATERIAL	CONFIGURATION	WELDMENT CROSS SECTIONAL AREA (in.^{2})	DATE/SPONSOR
VARIOUS ALLOYS			
- carbon steels - stainless - tool steels - titanium - aluminum - dissimilar joints	1, 1.5" round	0.79 to 2.5	1979/NSF
STAINLESS STEELS			
- 304 L SS, various tempers	1 in. D, 0.1 in. wall colsure weld	0.3	1983/SNL
- 304 SS	4 in. schedule 80 pipe	4.11	1978/EPRI
- 409 SS	flange-to-flange projected seam	14.5	1985*
CARBON STEELS			
- A-106-B steel	2 in. schedule 40 pipe	0.91	1978*
- high-strength, low alloy steel	12 ga half lap mash seam weld	0.90	1980*
- 1010 steel	6 in. D, 0.25 in. wall tube to 1 in. flange	4.52	1981*
- 1045 steel	1 in. round	0.79	1981*
- 1080 steel	90 lb/yd rail	8.82	1982/NSF, AAR
- API X-60 steel	6 in. schedule 80 ERW pipe	8.5	1984*
high-strength, low alloy steel	6 in. schedule 80 seamless pipe	8.5	1984*

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Offshore Pipelines

Petroleum transport from offshore platform is usually by seabed linepipe. In waters less than 1 km, such lines are constructed by the "S-lay" process, in which pipe is welded horizontally on the deck of a lay barge and gradually strung to the sea floor. Several welding stations operate simultaneously on the barge deck. This process is not feasible for line pipe construction in deep Gulf waters because the bending stresses during lay are high enough to buckle the pipe. Instead, a "J-lay" process must be used, in which pipe is welded vertically and lowered directly. There is no active J-lay barge today because productivity cannot offset expense. Since there is only room for one or two welding stations, traditional multipass arc welding processes are not cost effective. Furthermore, connections between line pipe risers to forged wellhead completion components require a process capable of joining dissimilar materials. A fast, reliable, and inexpensive welding process is required to enable petroleum production in deep waters (7).

PROCESS DESCRIPTION

The HPW Process

An HPG is a dc machine that characteristically produces a low voltage and a very high current. In the pulsed or inertial mode, the machine models electrically as a capacitor. A flywheel is motored to speed in a few minutes. After reaching speed, a magnetic field is applied, current collectors are actuated, and a closing switch is used to initiate the discharge. During the discharge, all or part of the kinetic energy stored in the flywheel is electromagnetically converted into electrical energy.

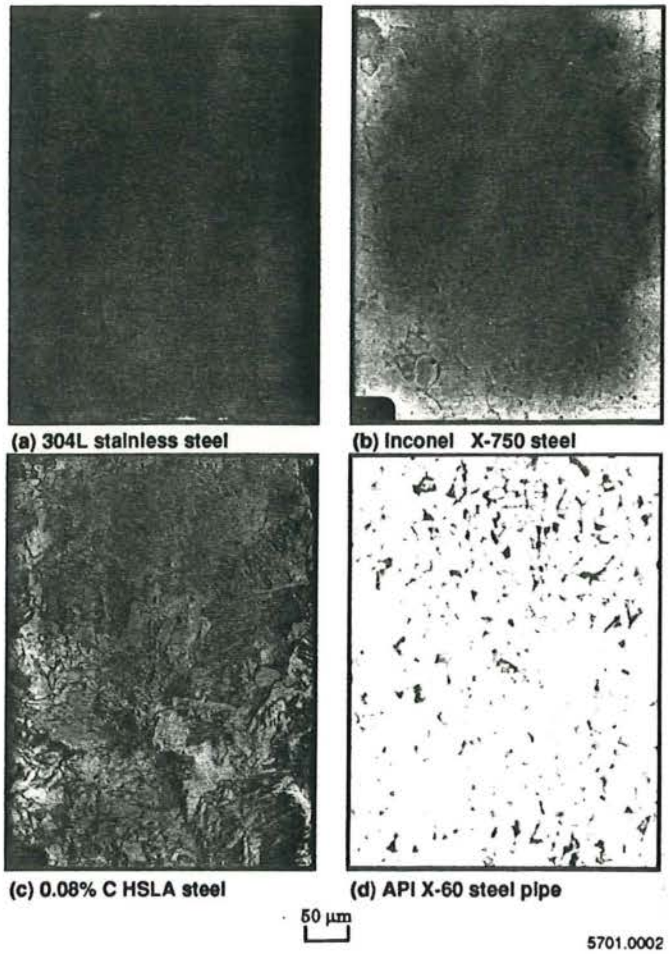

Fig. 2 As-welded microstructure of various alloys joined by HPW. Weld line centered, vertical. Etchant varies.

Because of its low internal impedance, the pulsed HPG is capable of converting stored mechanical energy in the flywheel/armature to a high current, high-power electric pulse with very high efficiency. These machines are capable of storing 5.0 kJ/kg inertially and generating megampere peak current pulses at average powers of 50 kW/kg. These characteristics make inertial iron-core HPGs efficient power supplies for very rapid heating of resistive loads.

Homopolar pulse welding is a solid-state forged joining process (fig. 3), in which two or more contacting workpieces conduct the discharge current pulse from a HPG through their faying (contacting) surfaces or interface(s). Heat generation is concentrated at the interface due to the relatively high-constriction resistance. This resistance is caused by the constriction of current into the small area of real contact between the asperities of each workpiece surface (fig. 4). The magnitude of the resistance is a function of the apparent contact pressure.

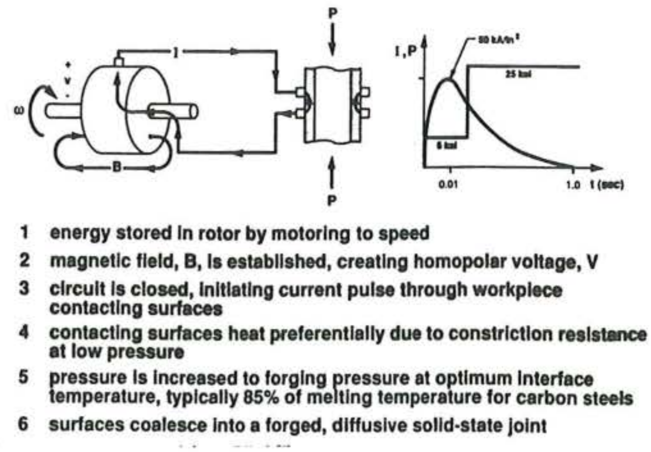

Fig. 3 HPW process summary

This pressure is maintained at a relatively low value for the first part of the pulse in order to maximize heat generation at the interface. At peak weld plane temperature, pressure is increased to greater than yield pressure and the workpieces upset or plastically deform, until the bulk strength of the surrounding parent material limits further displacement. The faying surfaces coalesce, original interfacing surfaces disappear due to diffusion between workpieces, and a strong, forged joint results.

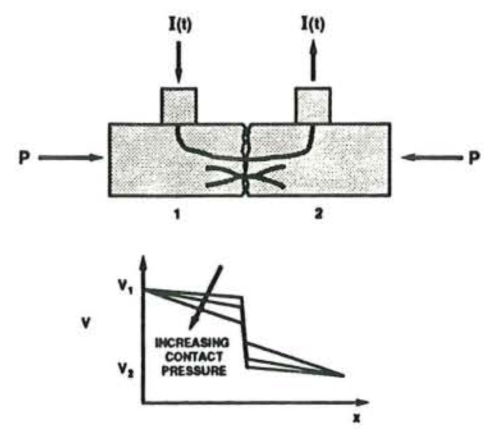

Fig. 4 Current constriction at HPW workpiece interface

Weld current, voltage, pressure, and pressure profile are the main control parameters in HPW. Current is a function of the HPG's speed and excitation, and the workpieces varying resistance. Voltage at the weld is a function of bulk resistance of the workpieces and the varying constriction resistance at the interface which is, in turn, strongly affected by contact pressure, joint design, and joint surface finishes. Pressure is increased at some point during the pulse to the forging pressure--this event is controlled by a simple timer or feedback control based on peak interface temperature. At this point, welding is accomplished, which is indicated in the voltage waveform by the sudden decrease in weld voltage as the constriction resistance is removed. Heating and cooling rates can potentially be controlled by varying the excitation current to the HPG; preweld and postweld pulses could therefore be achieved, allowing desirable heat treatment effects in the same fixture.

Numerous advantages of HPW have been identified: no flux or filler material is required, no bulk melting occurs, no cast structure remains in the weld zone. The heat-affected zone is relatively small and time dependent effects such as grain coarsening, sensitization, and segregation are practically eliminated. Because of the high-pressure forging of the joint, impurities and foreign particles in the interface can be extruded out of the weld. Dissimilar metals can be joined. Cycle time is limited only by the motoring period of the HPG (typically 2 to 5 min).

Process Parameter Selection

Table 2 summarizes the controlled parameters and properties of an HPW joint and the method of control. In determining the proper HPW parameters for a particular material, shape, and size, the stored energy is first set according to weld size. Next, the open circuit voltage is set (approximately 15 V for steel). The initial contact force is selected to achieve an apparent contact pressure at the weld interface of approximately 34.5 MPa. Upset force is based on parent metal yield strength at welding temperature. The force profile--the timing of application of upset force--is set or controlled to occur at peak interface temperature.

Table 2 Parameters and properties for HPW welds

ITEM	CONTROL METHOD
Stored energy	Flywheel speed at discharge
Open circuit voltage	HPG excitation
Interface resistance	Initial force End preparation
Weld contour	End preparation Weld displacement
Upset force	(Based on parent strength)
Heat affected zone	Electrode spacing
Mechanical properties	Pulse shaping

With these basic control parameters set to rough values based on previous data, initial test welds are evaluated in order to make fine adjustments. It will be shown that the control variables are highly coupled; however, some simplifying assumptions can be employed to give a fairly simple decision theory for these adjustments. Table 3 summarizes this process. By observing this model and other more complex algorithms (8), the number of experiments required to obtain an optimum parameter set can be minimized.

CURRENT RESEARCH

Within the OTRC, researchers at CEM-UT, the Phil M. Ferguson Structural Engineering Laboratory (FSEL-UT), and A&M are developing HPW for offshore structural and pipe welding. This two - to three-year program began in early 1989 and is composed of several tasks. First, HPW joints in several grades of high-strength steel pipe with cross-sectional areas from 27 to 50 cm^2 (4.5 to 8.0 $in.^2$), will be produced for testing and evaluation. Pipe sizes to be welded are 3-in. schedule 160 and 6-in. schedule 80. These are being welded using the 10 MJ, disk-type HPG research system at CEM-UT (fig. 5) (9). Mechanical property testing of these welds at FSEL-UT and Vetco Gray, Inc., includes tensile, fracture toughness, cyclic fatigue, bend, and other subscale and full-scale tests. Researchers at A&M are evaluating these welds for their resistance to galvanic and general corrosion. After the welds are fully characterized, a series of tests will be conducted to determine the sensitivity of weld performance to weld parameters and to fit tolerances (angular and axial alignment, diametral variation).

Table 4 shows process parameters, variables, and subscale tensile test data for a typical 3-in. Schedule 160 C1035 pipe welded in this program. Figure 6 shows a microhardness traverse taken from parent metal to weld plane in this same weldment. The general hardness

Table 3 HPW parameter refinement decisions

OBSERVED PHENOMENA	POSSIBLE CAUSE	RESPONSE
Cold weld	Energy too low Current too low	Increase rpm Increase V_{oc}
Bulk heating	Initial resistance too low Upset too early	Decrease initial contact force Delay upset
Blowout	Initial resistance too high Upset too late	Increase initial contact force Advance upset timing
Hot weld	Energy too high Current too high	Decrease rpm Decrease V_{oc}

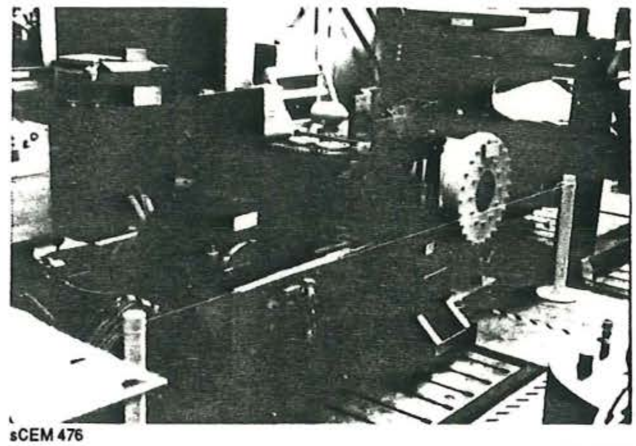

Fig. 5 10 MJ disk-type HPG research system at CEM-UT increase is due to the high, natural cooldown rate of the current-carrying zone due to conduction, while the high-hardness peaks probably indicate carbide islands. In spite of the high hardness, side bend tests from this weld passed satisfactorily.

Table 4 Control parameters, variables, and mechanical test results for a 3-in. schedule 60 C1035 steel pipe weldment (HPW)

CONTROL PARAMETER	NUMBER	UNITS
HPG discharge speed	314	s^{-1}
HPG energy stored	3.6	MJ
HPG excitation current	450	A
HPG excitation density	1.2	T
Initial contact pressure (apparent)	27.4	MPa
Upset pressure (apparent)	205.4	MPa
Upset time	0.47	s
PROCESS VARIABLES	**NUMBER**	**UNITS**
Peak current	309.9	kA
Peak weld voltage	2.35	V
Weld displacement	0.26	cm
Weld energy	0.80	MJ
MECHANICAL TEST RESULTS	**NUMBER**	**UNITS**
Type		QW-462.1B
Size	1.91 x .785 (1.501)	cm (cm^2)
Ultimate load	90.41	kN
Tensile strength	601.25	MPa
Parent UTS	546.8	MPa
Fracture location		Outside HAZ

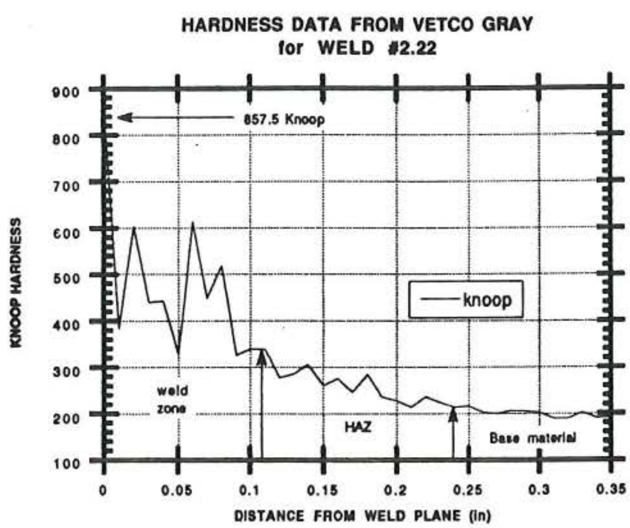

Fig. 6 Microhardness traverse of 3-in. Schedule 160 C1035 pipe weld (HPW)

Although these results are positive, full-scale tensile tests have failed at less than the base material ultimate strength. In addition, repeatability, using identical weld parameters in full-scale testing, has not yet been shown. Modifications to the laboratory hydraulic press are being made to actively control the pressure profile during the weld and investigate the lack of repeatability and full-strength welds. These modifications will include a load cell and servo-controlled hydraulic regulator.

Once HPW of simple steel pipe has been developed, more advanced materials will be investigated. These will include duplex stainless steels, clad pipe (in which an aluminum liner protects the pipe from corrosive attack by sour fluids), and extra high-strength grades such as X-80 and HY-100 series.

A continuing area of research throughout this program is the development of a fast, reliable, nondestructive quality assurance system for HPW. Described in the following section, this system will use sophisticated diagnostics to store and analyze weld data and will ascertain weld quality by such means as acoustic emission, or *in situ* proof loading, before removing the weld from the fixture.

A new HPG power supply is available for HPW research that will enable welds with up to 775 cm^2 cross-sectional area. The Balcones HPG (BHPG) power supply (fig. 7) is a modular system consisting of six 10 MJ drum-type HPGs, each capable of generating 1.5 MA with 100 V open circuit voltage. These can be connected in various series/parallel combinations for a total output current peak of up to 9.0 MA. Several multiyear research programs in HPW are in the proposal stage that will use the BHPG system as the power supply. One such program will develop HPW of 56-cm diameter, 3.8 cm wall thickness steel pipe (typical of tethers for tension leg platforms). Several designs are being considered for the 20 GPa mechanical fixture required for this weld. As illustrated in figure 8, one concept is an externally deadheaded fixture. This and other large-scale welding programs will demonstrate scalability of HPW with weld cross-sectional area.

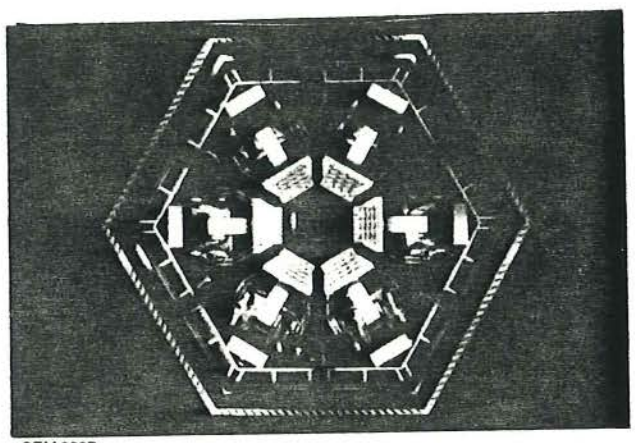

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Fig. 7 60 MJ, 9 MA BHPG system (modular drum type)

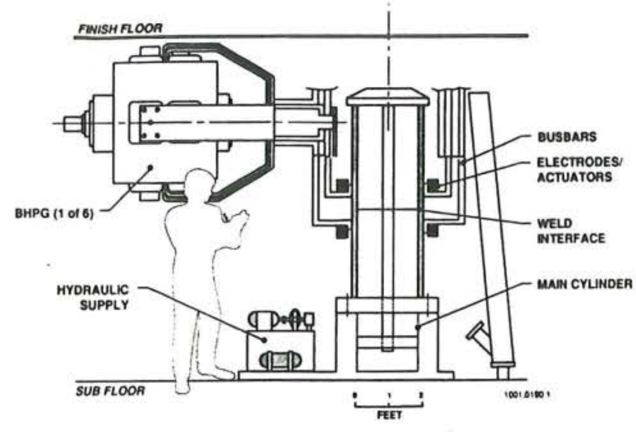

Fig. 8 Proposed 0.56 m pipe welding system powered by the BHPG power supply

PLAN FOR INVESTIGATION OF QUALITY ASSURANCE METHODS

Though possessing many potential advantages, HPW needs further research and development before it becomes an industrial-quality manufacturing process. The fundamental drawback to commercial acceptance of the process is that producing a consistent quality weld is still largely empirical. Primarily, this is due to HPW being a highly coupled electromechanical-thermal process: good welds are produced by an experienced operator searching an acceptable weld parameter window. A topic of current research is quantifying the relationships between process variables, with the goal of developing a real time quality assurance technique. This research seeks to measure key weld quality indicators and correlate these with nondestructive testing (NDT) methods while the weld is occurring.

One advantage of HPW is that fundamental process variables (such as current and energy in the weld zone) can be monitored and controlled during the weld. Controlling the current pulse shape can significantly alter the heating and cooling rates of the interface. The possibility exists of producing a good weld where an unacceptable one might have existed without feedback. At the very least, by identifying and monitoring key process variables, a measure of weld quality can be achieved in real time so that the weld can either be reworked or deemed acceptable. To achieve real time quality assurance, research will be performed in three phases.

Phase I - Data Correlation

Presently, controllable (independent) process variables include: rotor speed, field current, initial interface pressure, upset pressure, and time of upset. Process variables that are dependent on the above include: current through the interface, voltage across interface, interface electrical resistance, magnetic field inside the pipe, and upset displacement. Phase I seeks to quantify important process variables and assemble them into a single, time-synchronized format. Since it is not fully known which variables will be weld quality indicators (investigated in Phase II), visual and thermal imaging will be an important diagnostic. Visual images will, in a global sense, aid in the understanding of process variable significance. Basic to this will be a format in which the process variables can be plotted in real time and synchronized with the visual and thermal images. This will allow fundamental investigation into the correlation between visually observable phenomena and quantifiable data. Through this correlation, functional relationships between process variables will be confirmed and an understanding of how to quantify visual phenomena will be gained.

Phase II - Parametric Relationships

With Phase I diagnostics in place, functional and quantifiable relationships between independent and dependent variables can be identified. Parametric studies can then be performed to isolate one variable at a time and determine its relative significance as a weld quality indicator.

Other parameters to be studied include electrode-interface distance and circumferential uniformity of the above variables. Electrode distance affects the efficiency of the process directly by changing the amount of bulk material (thus, the circuit resistance) in the electrical circuit. Also, recent destructive testing has shown that both good and unacceptable welding can occur in the same pipe. This suggests significant problems with current and heat uniformity. The study of parametric relationships will lead to a functional set of identifiable weld quality indicators and the avoidance, or at least recognition of unacceptable welds.

Phase III - Interface Phenomena

With Phase I diagnostics and Phase II understanding of the global process, a fundamental effort can be made at understanding the weld interface dynamics. Since the two pipe surfaces to be welded will never be perfectly smooth and the initial pressure holding the pipes together is low compared to the yield strength of the metal, the actual contact area is significantly less than the cross-sectional area of the pipe (fig. 4). This reduced area, composed of many contact points (or "a-spots" (10)), produces the initial constriction resistance and initial interface heating. As a-spots heat, the positive valued coefficient of resistivity of steel should increase the resistance and force the current to travel through an area with lower resistance, thereby distributing the current evenly. Although uniform current distribution is plausible theoretically, fundamental questions exist regarding the a-spot dynamics. It is unknown whether the original a-spots grow to eventually occupy the entire surface area, or new ones appear to accommodate the current seeking new routes, or both. This is one question Phase III will address. Also, the effectiveness of the coefficient of resistivity to redirect the current is not fully understood. It is believed that the current does not change paths quickly enough (due to its self-inductance) and can produce a-spot melting and even a plasma. Several methods of NDT have been proposed to observe the interface dynamics, a few of which will be briefly discussed here.

Since the actual initial contact area is significantly less than the total pipe area, the interface can initially be modeled as a two-dimensional network of resistors and capacitors. As such, a phase shift should be detectable with a high-frequency signal imposed on this resistive/capacitive network and the phase shift should disappear as the contact area approaches the total area. Further, it has been shown (11) that this phase shift is only noticeable for frequencies greater than 100 MHz.

Ultrasonic and acoustic emission techniques appear to be possible candidates for observing the weld plane in real time. Ultrasonic is an active method relying on sound waves to bounce off material interfaces/defects; acoustic emission is a passive method, detecting the actual noise emitted by changing material properties. Both methods are candidates for interface investigation and real time quality assurance, although both have their drawbacks and would require special application to work in this particular process.

Ultimately, however, the goal of this research is to produce a real time quality assurance technique. It is possible that the fundamental understanding of the process variables will provide a reliable indicator of the weld quality window without relying on traditional NDT methods.

CONCLUDING REMARKS

Given that pulsed welding by HPGs has high potential as a joining process for high strength steel linepipe and numerous other materials, interest in commercialization of the process remains strong. This is especially true for large diameter pipe and for fabrication of deepwater linepipe by J-barge. Joining large section workpieces by HPW appears to be a relatively straightforward matter of design, since the process parameters and power supply/fixture requirements all scale linearly with weld surface area.

To date, the process has not been industrialized because of several prevailing factors. Commercial HPW systems have not been available until recently, the capital cost of developing such systems has been high, and the process has not been certified by codes and standards committees. These factors have been addressed in part by recent developments in HPG technology, process control, transfer of technology to industry, and efforts to gain codification.

Advanced HPG

Industrially rated pulsed HPGs are now commercially available. Unlike similar laboratory power supplies, these generators are actively cooled to enable full-energy discharges approximately every five minutes. Industrial HPG supplies are designed for ease of maintenance, long life between overhauls, and are available as complete delivered systems.

In addition, design efforts are concentrating on greatly reducing the cost per joule of manufactured generators. Although they deliver very high peak powers at multimegampere current levels, HPGs are simple rotating electric devices. Also, the cost per joule of iron-core HPGs decreases with increased energy storage.

Quality Assurance and Process Control

The reliability of HPW joints is closely linked to process control. While one of the main advantages of homopolar welding is the fast (<1 s) pulse duration, precise control of the pulse in real time is difficult. Laboratory demonstration projects typically have relied on preset speed-at-discharge setpoints, ladder logic controllers, and digital timers to set generator voltage, energy, peak current, and interface pressure in a nonoptimum, open-loop manner.

Recent advances in sensors and control algorithms have been incorporated into HPG controls. Extremely accurate rotor tachometry devices now allow generator speed control to within 1% (12). Actively controlled field excitation power supplies afford similar resolution in voltage control. Fast response hydraulic logic elements and infrared pyrometers have been used to control weld upset and temperature. An integrated HPW control system incorporating these advances and advanced diagnostics will lead to a reliable, nondestructive, real time quality assurance system. Such a system will enable codification and standardization of HPW for specific welding applications.

ACKNOWLEDGMENTS

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