HOMOPOLAR PULSE RESISTANCE WELDING—A NEW WELDING PROCESS

Is based on the unique characteristics of pulse homopolar generators and, having been used successfully on pipe, shows promise for tubing, angles and I-beams


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Homopolar Pulse Resistance Welding (HPRW) equipment for 4 in. (101.6 mm) Schedule 80 Type 304 stainless steel pipe

Homopolar generators are high current, low voltage machines that have been known since the 1830's. The present technology of pulsed homopolar generators is, however, a product of government-funded research into the area of controlled thermonuclear fusion. One result is that pulsed homopolar generators may be of immediate benefit to the metal joining industry as a power source for resistance welding.

The University of Texas Center for Electromechanics (UT-CEM) has been involved since 1972 in programs intended to address the need for large pulsed power supplies for use in experiments leading to controlled thermonuclear fusion power generating plants.1 These have included a number of pulsed power machines intended to meet a broad spectrum of performance requirements in terms of quantity of energy stored and energy delivery rates.2,3

One of these machines—the 5 MJ homopolar generator—was designed and built in 1974 to explore further the electrical characteristics of this type machine when used in a pulsed mode. The machine exceeded its design goals by a considerable margin. Moreover, it became apparent that machines of this kind offer promise as pulsed power sources in a variety of industrial, military, and research applications.

One promising application is the welding of large metal sections. Thus two years ago, a program was initiated to develop the homopolar pulse resistance welding (HPRW) process, using the 5 MJ homopolar machine as the power source. Welding activities began as unfunded experiments used to demonstrate the capabilities of the homopolar generator technology. Now under way are several major projects devoted to exploring the characteristics and capabilities of the process for specific metal joining applications.

The objectives of this paper are to describe basic characteristics of the HPRW process; the design, construction and capabilities of pulsed homopolar

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The HPRW Process

The HPRW process is a resistance welding process in which the faying surfaces in solid contact are heated by interface resistance to electric current. In this respect it is similar to upset butt welding. However, several process characteristics and capabilities are sufficiently unique to warrant calling it a new welding process. These are discussed below.

Figure 1 shows a schematic equivalent electrical circuit for the process. The pulsed homopolar generator can be modeled electrically as a large variable capacitor. The mode of operation used in the HPRW process is one in which the generator is "charged" by motoring-up its rotor slowly, either by means of an external motoring system or by closing switch S₁ and applying a voltage across the terminals of the machine, causing it to "self motor."

The 5 MJ homopolar machine is both a motor and a generator. When the generator is charged to slightly over the desired energy level (determined by the rotor speed), switch S₁ is opened, and the generator rotor begins coasting. When the speed has decreased to the appropriate point, the pneumatically actuated brushes are lowered onto the rotor and a fraction of a second later the discharge switch S₂ is closed. At this time, the discharge path is completed and the rotational kinetic energy of the homopolar machine is converted quickly to electrical energy in the form of a very high current, relatively low voltage dc pulse.

Note that at the time the pulse is delivered there is no connection between the homopolar generator and the electric lines. This is an important point of difference from conventional resistance welding processes, which are often subject to high power demand charges because of the sudden loads they impose on the utility power lines.

Capacitance Control

The generator capacitance is controllable by preprogramming a varying field excitation level in the machine during the weld pulse. Generator capacitance can be thought of as a measure of the rate at which energy can be removed from the generator. By varying the generator capacitance, the energy delivery rate of the machine can be controlled. Thus a wide variety of welding current waveforms can be generated into the discharge circuit.

Some of the many waveforms possible are illustrated in Fig. 2. It is possible first to produce the weld and then to provide a degree of heat treatment by controlling the weld metal cooling rate, all during the same current pulse. As in conventional spot welding, welds may cool so fast that quench cracks occur in such materials as ferritic steels. This problem can be eliminated by controlling the cooling rate in the fashion described above.

The process requires the use of a welding fixture. Functions of the fixture are to clamp and hold the workpiece, provide the means (via copper electrodes) to transfer the welding current to the workpiece during weld heating, and then to forge the pieces together after heating. Except for heavier current leads, fixtures are similar to conventional upset butt welding fixtures. A typical welding fixture is shown schematically in Fig. 3.

After the welding current pulse has been delivered, the generator has usually been fully discharged and its rotor is at standstill. In a production environment the generator would again be charged by accelerating its rotor with a clutch-connected prime mover while the completed workpiece is being removed from its welding fixture and a new one installed.

Little or no time is lost waiting for the system to become ready to deliver the next weld pulse, and the electrical load on the utility is essentially constant. The attainable cycle time is dependent only on how fast the
workpiece can be changed and how large a prime mover is used to rotate the machine rotor. It follows that for very large, low production welds, the machine charging (or rotor accelerating) time could be relatively long, requiring only a small power input, while the system could still produce the megawatt-level output power required for the weld. The resulting savings on installed electrical capacity, buswork, and electrical demand costs compared to a large transformer-type flash welding system, for example, could be substantial.

**HPRW Process Features**

Probably the most significant process feature is the speed at which the weld can be created. For example, in using the HPRW process to weld 4 in. (101.6 mm) Schedule 80 Type 304 stainless steel pipe (4.4 in.², 2.84 × 10⁸ mm²), the weld occurs in less than 0.5 second (s), with a total weld pulse time of less than 3 s—lead photograph.

Conventional resistance welding machines—both spot and upset butt—can also produce welds in a few tenths of a second. However, we are not aware of a process with this speed that can weld sections as large with the relatively low (less than 250 kW) input power required. Even more important are the scaling characteristics of the technology which make it appear possible to weld much larger cross sections (up to at least 100 in.², 64.5 × 10⁸ mm²) on the same time scale, with comparable input power requirements.

HPRW shares another feature with conventional resistance welding that is not readily available with arc-welding processes. Since the process can be automated, the power across and energy deposited in the weld zone can be preprogrammed and monitored in real time. This offers the possibility of having an accept/reject criterion based on comparison of the monitored parameter values with waveforms of previous destructively tested welds. Also, feedback control may eventually be possible and this could further assure high weld quality. Thus for large-section welding, the process offers the possibility of weld quality control/monitoring techniques similar to those now available and being used in conventional spot welding.

Finally, the variable capacitance feature of the pulsed homopolar generator offers the possibility of controlling heating and cooling rates to produce the desired properties in the weld zone. It may eventually be possible with improved generator field control systems and weld process models to completely preprogram temperature vs. time waveforms for a given weld. This would allow sophisticated heat treating to be accomplished after the weld is accomplished but during the same welding pulse.

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**Fig. 4—Functional illustration of disk and drum configurations of homopolar generators: A—disk type (left); B—drum type (right)**
HPRW Advantages/Limitations

Comparison to Arc Welding

The HPRW process offers major potential advantages when compared both to conventional arc welding and to resistance/flash welding in some applications. Significant potential advantages that the HPRW process has when compared to the arc welding processes are as follows:

- It is much faster (weld time measured in seconds).
- It is less labor intensive (the process is easily automated).
- It may make welds more easily inspectable (the weld zone is very narrow).
- It uses no filler metal, flux, or protective gas atmosphere (cost of consumables should be less).
- It leaves no cast metal in the weld zone (all molten metal is pushed out of the weld zone during forging).
- It may eliminate metallurgical problems in some applications (weld metallurgy is much simpler; process heating and cooling rates are easily controllable).
- It should result in an improved residual stress pattern, since heating and cooling are peripherally symmetrical.
- Pre- and postweld heat treating are possible at the time of welding.
- It may make possible reliable in-process weld quality control.
- It minimizes noxious or unsafe fumes present when arc welding some alloys.
- It may be possible to join a wider variety of dissimilar metals.
- It offers to the welding of large metal cross sections many of the resistance welding process features available previously only in the production of smaller parts.

Table 1—Mechanical and Electrical Parameters of 5 MJ Homopolar Generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator weight (without auxiliaries)</td>
<td>~7700 kg (17,000 lb)</td>
</tr>
<tr>
<td>Major dimensions (length x width x height) without auxiliaries</td>
<td>~1.37 x 0.91 x 1.52 m</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>(D_R = 0.61 \text{ m (2 ft)})</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>(I_R = 29.71 \text{ kg-m}^2) (21.9 lb-ft-s²)</td>
</tr>
<tr>
<td>Maximum rated speed</td>
<td>(W_{\text{MAX}} = 504 \text{ kJ} ) (5580 rpm)</td>
</tr>
<tr>
<td>Maximum energy storage</td>
<td>(E_{\text{MAX}} = 5 \times 10^9 \text{ J} ) (3.74 x 10³ ft-lb)</td>
</tr>
<tr>
<td>Maximum terminal voltage (open circuit)</td>
<td>(V_{\text{MAX}} = 42 \text{ V} )</td>
</tr>
<tr>
<td>Maximum discharge current</td>
<td>(I_{\text{MAX}} = 560,000 \text{ A} )</td>
</tr>
<tr>
<td>Equivalent minimum capacitance</td>
<td>(L_{\text{MIN}} = 5670 \text{ F} )</td>
</tr>
<tr>
<td>Peak power output (tested to date)</td>
<td>(P_{\text{MAX}} &gt; 10 \text{ MW} )</td>
</tr>
<tr>
<td>Maximum power consumption (input)</td>
<td>(P_{\text{natur}} &lt; 250 \text{ kW} )</td>
</tr>
</tbody>
</table>

Comparisons to Conventional Resistance/Flash Welding

Significant potential advantages possessed by the HPRW process when compared to conventional resistance and flash welding systems include:

- Its energy storage capability which makes power requirements for very large welds relatively small (mega-watt outputs from kilowatt inputs).
- Process equipment that can be made semi-portable for on-site field welding (a relatively small diesel generator would supply all the power required for megawatt-level welds).

Limitations

- The process does, of course, have limitations; the most important of these (relative to arc welding) are as follows:
  - Process capital equipment requirements are extensive; a relatively large initial investment in equipment would be required for most applications.
  - The equipment is relatively large and heavy compared to an arc welding supply.
  - The process requires special fixturing for clamping and forging the work.
  - The process may prove to be cost-effective only in applications in which there is a relatively high production volume to defray fixturing costs.
  - Periodic maintenance of the sliding electrical contacts (brushes) is required.
  - Process equipment is still in an early stage of commercial development.

Pulsed Homopolar Generators

Homopolar generators have been studied and used for both continuous and pulsed duty ever since Michael Faraday built the first one in 1831. They have not achieved widespread use because they are inherently high current, low voltage machines and are thus not suited for transmitting energy over long distances. For some applications, however, including resistance welding and other forms of resistance heating, the electrical characteristics of these machines are ideal.
Comparison to Conventional Generators

In homopolar machines, a voltage is generated across a conductor that moves through a unidirectional magnetic field. The essential difference from a conventional generator is that the current travels through the rotor, itself, and makes only one transit across the magnetic field. There are no rotor windings, and there is no commutator. There are two basic machine configurations suitable for welding—a disk rotating in an axial magnetic field with radially separated sliding contacts (Fig. 4A), or a drum rotating in a radial magnetic field with axially separated sliding contacts (Fig. 4B). Each configuration has its own advantages. Other machine topologies have been analyzed in detail elsewhere.

There are homopolar machines that have been used as welding power supplies. Westinghouse built a homopolar generator resistance welding supply for pipe seam welding in the mid 1930's and Progressive Welder Company built a small homopolar flash/spot welding unit in the late 1940's. Both machines were used in a continuous duty mode (from the brush heating/wear viewpoint) and had relatively complex rotor geometries. The Progressive Welder machine also used a separate flywheel. Neither machine received widespread acceptance as welding supplies. The homopolar machines developed at UT-CEM differ greatly from both of these machines in design, construction, and mode of operation, particularly with respect to their rotors, and brushes.

In a homopolar machine the brushes must slide on the rotor at a large radius and must carry full power. Because of this, frictional brush losses and heating are significant and contribute to brush wear. Two developments help overcome this basic machine limitation. The first is the use of the generator as a stored energy machine in a pulsed duty mode. Remotely controllable brush actuation mechanisms which lower the brushes when necessary during a discharge but raise them during external motoring, minimize machine frictional losses and brush wear. Second, the development of very high metal-content composite brushes has further increased the wear life of brushes operating at high current densities for pulsed power machines of this kind.

The simple solid disk or drum rotor configurations offer at least two significant and equally important advantages over some of the complex geometries used in the past:

1. With no slots, wedges or laminations, the rotor consists only of a right circular cylinder of steel; as a result, the manufacturing cost is inherently low.

2. When using the homopolar machine in a pulsed duty, stored energy mode, the machine rotor serves also as the energy storage flywheel; consequently, deceleration forces resulting during a discharge are body forces acting directly on all rotor mass elements in which the energy is inertially stored.

Torques and stresses are thus distributed and are relatively low. This means that the energy can be safely transferred very quickly at very high power levels. This is not the case when using an external flywheel. The reason is that the entire deceleration torque must be transmitted through a connecting shaft; this limits the energy transfer rate due to allowable shaft stress levels.

Fundamental Equations

As mentioned earlier, a pulsed homopolar generator electrically behaves as a large variable capacitor. The governing equation for its capacitance is:

\[ C = \frac{2E}{V^2} \]  

where \( C \) = machine capacitance (F); \( E \) = energy stored (J); \( V \) = voltage generated (V).

For homopolar machines of the configurations shown in Fig. 4, the voltage generated between the sets of sliding contacts on the rotor rotating in the cylindrically symmetric magnetic field is:

\[ V = \frac{w^2\Phi}{2\pi} \]

where \( \Phi \) = total flux cut by the rotor between the sliding contacts (Wb); \( w \) = rotor rotational speed (rad/s); and the energy stored in the rotor is:

\[ E = \frac{Jw^2}{2} \]

where \( J \) is the rotor mass moment of inertia (kg·m²).

The final fundamental design equation gives the electromagnetic torque acting on the rotor during a discharge, and is:

\[ T = \frac{\Phi}{2\pi} \]

<table>
<thead>
<tr>
<th>Table 2—Homopolar Generator Scaling Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy stored, MJ</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>5 Disk</td>
</tr>
<tr>
<td>5 Drum</td>
</tr>
<tr>
<td>10 Drum</td>
</tr>
<tr>
<td>20 Drum</td>
</tr>
<tr>
<td>30 Drum</td>
</tr>
<tr>
<td>40 Drum</td>
</tr>
<tr>
<td>50 Drum</td>
</tr>
</tbody>
</table>

**Tested to date.

**Projected from 4.4 in.² welds; all other values calculated.
Table 3—Welds Made to Date With the HPRW Process

<table>
<thead>
<tr>
<th>Shape configuration**a</th>
<th>Description (material)</th>
<th>Metal area</th>
<th>Weld current peak, A</th>
<th>Peak forging force</th>
<th>Weld tensile strength</th>
<th>Number of welds to date</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 in. dia. bar--1018 steel</td>
<td>0.79 (5.1)</td>
<td>36,000</td>
<td>15,300(4) (68,100)(4)</td>
<td>85,000 (586)</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>2 in. Sch. 40 Pipe--A 106B steel</td>
<td>3.79 (25.1)</td>
<td>25,000</td>
<td>15,300(4) (68,100)(4)</td>
<td>85,000 (586)</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>4 in. Sch. 80--304 stainless pipe</td>
<td>3.79 (25.1)</td>
<td>25,000</td>
<td>15,300(4) (68,100)(4)</td>
<td>85,000 (586)</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>15 in. dia, track--shoe pin--1045 Mn mod, steel</td>
<td>3.17 (20.4)</td>
<td>215,000</td>
<td>14,000(4) (62,300)(4)</td>
<td>83,000 (573)</td>
<td>55</td>
</tr>
<tr>
<td>E</td>
<td>Track-shoe grouser bar; high carbon steel</td>
<td>3.17 (20.4)</td>
<td>215,000</td>
<td>14,000(4) (62,300)(4)</td>
<td>83,000 (573)</td>
<td>10</td>
</tr>
<tr>
<td>F</td>
<td>Railroad rail</td>
<td>5.4 (34.8)</td>
<td>162,000</td>
<td>14,000(4) (62,300)(4)</td>
<td>83,000 (573)</td>
<td>14</td>
</tr>
<tr>
<td>G</td>
<td>Spot weld--1 in. steel</td>
<td>10.0 (6.6)</td>
<td>130,000</td>
<td>20,000 (89,000)</td>
<td>83,000 (573)</td>
<td>2</td>
</tr>
</tbody>
</table>

**b**Shape configurations corresponding to A through G are as follows:

- **A**: 1 in. dia. bar--1018 steel
- **B**: 2 in. Sch. 40 Pipe--A 106B steel
- **C**: 4 in. Sch. 80--304 stainless pipe
- **D**: 15 in. dia, track--shoe pin--1045 Mn mod, steel
- **E**: Track-shoe grouser bar; high carbon steel
- **F**: Railroad rail
- **G**: Spot weld--1 in. steel

**b**Calculated force (from Belleville washers)

where $T =$ electromagnetic torque (N-m); $i =$ rotor current (A).

Once a particular machine has been designed, it is possible to reduce the above equations to a more useful form. For a given field coil when operating below saturation in the yoke, the magnetic flux $\Phi$ can be shown to be directly proportional to the applied field current $i_i$. For a given machine, the above equations (1), (2), and (3) can be reduced to:

$$C = \frac{K_2}{i_i^2}$$

(5)

$$V = K_1 w_i$$

(6)

$$E = K_3 w_i^4$$

(7)

where $i_i$ is the applied field current (A) and $K_1$, $K_2$, $K_3$ are machine constants.

These simple relationships show that:

1. Terminal voltage varies directly with rotor speed and field current.
2. Stored energy varies as the square of rotor speed.
3. Capacitance varies inversely as the square of field current.

The 5 MJ Homopolar Generator

A schematic of the 5 MJ disk-type homopolar generator developed at UT-CEM is shown in Fig. 5; its mechanical and electrical parameters are given in Table 1. The machine constants for the 5 MJ generator are:

$$K_1 = 429 \times 10^8$$

(F-A²)

$$K_2 = 2.62 \times 10^{-5}$$

(V-A)

$$K_3 = 14.66$$

(J-s²)

For the 5 MJ machine, capacitance, voltage, and energy storage characteristics can be easily determined from the independently controlled machine parameters of field current and rotor speed. There is an essential concept to remember regarding machine capacitance—namely, by controlling the field current during a weld, the capacitance and thus the energy delivery rate from the machine, can be controlled. Figure 6 shows the open circuit voltage and energy stored vs. rotor speed and field current for the 5 MJ generator. Using Fig. 6 the desired values of voltage and stored energy for a particular experiment can be quickly found.

Future Homopolar Machines

For resistance welding and other low voltage, high current, high energy applications, it appears that the drum-type configuration shown in Fig. 4B will be superior from performance and economic viewpoints. The scaling relations for these machines are also reason-

Table 4—Tentative List of Materials to be Welded

| Steels: | 1018, 1040, 1080, 4140, 4340 |
| Aluminums: | 6061, 2024 |
| Stainless steels: | 316, 416, 430, 17-4PH |
| Titanium: | 6Al-4V |
| Other alloys: | Inconel X, 57 tool steel |
ably straightforward, and, to date, welding experiment results indicate that we are presently operating on the low end of the cross-sectional area welding capabilities of the technology.

Table 2 gives an indication of the machine scaling characteristics and potential welding capabilities. The welding time will remain short and the required input power small even for the larger machines.

**Welding Experiments**

Table 3 summarizes welds made to date using the HPRW process equipment. For many early welding experiments, only very simple and inexpensive fixtures were built to provide the clamping and forging forces. Also, the current-feeding electrodes were very simple. In fact, the initial experiments in the welding of 1 in. (25.4 mm) bars, 4 in. (101.6 mm) pipe, track-shoe grouser bars, and railroad rail utilized compressed Belleville washers clamped between platens to provide the forging force and displacement.

Control over initial contact force and forging force for these welds was obviously very limited. As a result, considerable flashing occurred at the weld interface. Although flashing resulted in welds with an unappealing appearance (but no worse than conventional flashwelded pieces), it did demonstrate that the 5 MJ machine had more than sufficient energy storage and output power to accomplish the welds in fractions of a second.

The first funded project was to investigate the technical feasibility of making girth welds in 2 in. (50.8 mm) Schedule 40 ASTM A 106B boiler pipe. The second funded project was directed at demonstrating the technical feasibility of welding 4 in. (101.6 mm) Schedule 80 Type 304 stainless steel boiling water reactor (BWR) pipe and investigating the metallurgical characteristics of the welds, particularly regarding heat-affected zone sensitization. BWR piping is one of the most critical of welding applications in terms of required weld metallurgy, mechanical properties, inspection and regulatory requirements.

A third funded welding project is now in its early stages. This project is concerned with establishment of welding requirements and quality criteria for various shapes in a variety of materials. Table 4 lists the materials that will be welded and studied during Phase I of this project.

During Phases II and III, tubes, angles, I-beams, rails, and possibly other structural shapes will be welded in order to study the effect of work piece shape on current distribution and weld quality. Some dissimilar metal combinations will also be included in the experimental program. A welding fixture of advanced design is being built for this project. When completed, it will handle all of these shapes in cross sections of up to 7 in. (4.5 x 10^2 mm^2) if they will fit inside a 3 in. (76.2 mm) diameter circle.

Following the completion of this project, information will be available which will allow the HPRW process to be more easily applied to a large number of metal joining applications.

**2 in. Schedule 40 Steel Pipe**

A special welding fixture was built to hold and forge the 2 in. (50.8 mm) pipe samples during the welding cycle. This fixture can be switched between two preset upset force levels by means of a hydraulic actuation system. The lower force is used during the initial heating of the weld. The higher forging force is usually applied about 0.15 s after the start of the weld cycle. This fixture also controls the field level of the 5 MJ generator in order to obtain the desired welding current waveform.

Over 60 specimens of the 2 in. (50.8 mm) pipe were welded and studied. It was established early in the project that the HPRW process could produce satisfactory welds as determined by ASME QW-160 bend tests, tensile tests and microstructure analysis.

Once weld quality had been verified, the remainder of the project was devoted to improving the appearance, alignment, and inner diameter weld contour, and to analyzing the various welding parameter records in order to establish a possible in-process weld quality criterion. SMA welded pipe and a HPR welded pipe are compared in Fig. 7. Also, Fig. 8 shows an HPR weld cross section in 2 in. (50.8 mm) ASTM A 106B steel pipe; this weld was made under conditions that resulted in some melting and inward expulsion of metal.

It became evident early in the experimental program that some shaping of the weld current pulse was neces-
sary for this weld configuration. Weld 11011 was made using a programmed reduction in the generator field current 0.35 s after initiation of the weld current pulse. This had the effect of decreasing the total energy, slowing the energy delivery rate during the latter portion of the weld cycle, and decreasing the cooling rate in the heat-affected zone (HAZ).

Figure 9 shows the weld line and base metal microstructures of Weld 11011. Although there was considerable coarsening of the structure in the vicinity of the bond line in this particular heat of steel, repeated 180 deg root bend tests on this and other similarly programmed welds were uniformly successful. The weld line itself, which runs horizontally across the approximate center of Fig. 9A, is not clearly distinguishable.

A microhardness traverse of weld 11011 is shown in Fig. 10. The traverse confirms the metallographic observation that there is no martensitic region in the HAZ. There appears to be a very narrow softened region about 0.175 in. (4.4 mm) from the weld line. A similar region appeared on the traverse of at least one other weld. For this reason, there is reason to believe that the highly localized softening is real, possibly being the stress-relieved region having its peak temperature between about 800 and 1300°F (427 and 704°C).

The significant HPRW parameters for a typical 2 in. pipe weld are given in Table 5. Detailed study of the recorder traces of these parameters for the 14 final welds made during the project led to certain tentative conclusions regarding in-process weld quality monitoring:

1. There appear to be distinct correlations between peak power level, energy deposited in the weld zone, and the mechanical integrity and strength of the weld, all other independent parameters being unchanged.
2. A similar correlation exists between the recorded shapes of voltage, current, and power signals and the weld quality.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak welding current</td>
<td>$I_w \sim 64.0$ (kA)</td>
</tr>
<tr>
<td>Time to end of “weld and forge” cycle</td>
<td>$\sim 0.50$ (s)</td>
</tr>
<tr>
<td>Time to end of postweld heat treat</td>
<td>$\sim 23.0$ (s)</td>
</tr>
<tr>
<td>Peak voltage across weld</td>
<td>$(V_e)_{\text{MAX}} \sim 480 \times 0.15$ (V @ s)</td>
</tr>
<tr>
<td>Peak generator power</td>
<td>$(P_e)_{\text{MAX}} \sim 760.0 \times 0.06$ (kW@s)</td>
</tr>
<tr>
<td>Peak power into weld zone</td>
<td>$(P_w)_{\text{MAX}} \sim 270.0 \times 0.15$ (kW@s)</td>
</tr>
<tr>
<td>Open circuit terminal voltage</td>
<td>$V_{oc} \sim 15.0$ (V)</td>
</tr>
<tr>
<td>Terminal voltage at $t_1$ (0.001 s)</td>
<td>$V_1 \sim 11.6$ (V)</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>$w_0 \sim 3.0 \times 10^4$ (rpm)</td>
</tr>
<tr>
<td>Total energy stored in generator</td>
<td>$K \sim 1.5 \times 10^5$ (l)</td>
</tr>
<tr>
<td>Total energy delivered to weld zone</td>
<td>$E_w \sim 0.2 \times 10^6$ (l)</td>
</tr>
<tr>
<td>Motoring time</td>
<td>$\sim 180$ (s)</td>
</tr>
<tr>
<td>Motoring power</td>
<td>$\sim 250$ (kW)</td>
</tr>
</tbody>
</table>
Traces for two typical pipe welds, one of good quality and one of poor quality, are shown in Fig. 11.

Further analysis and testing are required. However, the results thus far suggest the possibility of developing an in-process weld quality criterion which could supplement, or in some cases eliminate, the need for conventional postweld nondestructive testing.

Table 6—Typical HPRW Process Parameter for 4 in. Schedule 80 Type 304 Stainless Steel Pipe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Peak welding current</td>
<td>315 (kA)</td>
</tr>
<tr>
<td>Total weld cycle time</td>
<td>3.0 (s)</td>
</tr>
<tr>
<td>Peak power into weld zone</td>
<td>2000 (kW)</td>
</tr>
<tr>
<td>Peak generator power output</td>
<td>6300 (kW)</td>
</tr>
<tr>
<td>Peak voltage across weld</td>
<td>6.4 (V)</td>
</tr>
<tr>
<td>Terminal voltage @ t1</td>
<td>21.0 (V)</td>
</tr>
<tr>
<td>Open circuit terminal voltage</td>
<td>33.0 (V)</td>
</tr>
<tr>
<td>Rotor speed @ discharge</td>
<td>4400 (rpm)</td>
</tr>
<tr>
<td>Total energy stored (in generator)</td>
<td>$3.2 \times 10^9$ (J)</td>
</tr>
<tr>
<td>Total energy delivered to weld</td>
<td>$0.6 \times 10^9$ (J)</td>
</tr>
<tr>
<td>Motoring time</td>
<td>240 (s)</td>
</tr>
<tr>
<td>Motoring power</td>
<td>250 (kW)</td>
</tr>
</tbody>
</table>

4 in. Schedule 80 Stainless Steel Pipe

With present welding techniques, there are problems of intergranular stress corrosion cracking (IGSCC) in the welds of some stainless steel BWR piping carrying high-purity O₂ saturated water. The IGSCC problems are attributed primarily to sensitization of the weld heat-affected zone during arc welding and to the residual stress pattern in the vicinity of the weld.

HPRW process characteristics offer the possibility of eliminating or reducing significantly the sensitization and residual stress problems in these welds. Sensitization due to carbide precipitation is a time-dependent process, and the HPR welds occur in less than 1 s. Also, because the faying surfaces of HPR welds are heated uniformly and simultaneously, the residual stress pattern in the weld zone is expected to be improved compared to the pattern resulting from a concentrated, moving heat source, such as an arc. This stress pattern is to be the subject of further investigation.

Over 55 welds have been produced to date. The significant process parameter values are given in Table 6.

Figure 12 shows the outside and inside appearance and wall contour of welds in 4 in. (101.6 mm) stainless steel pipe. The exterior view is of weld 25, while the interior view is of weld 14B. A small portion of the exterior of weld 14B is visible at the bottom of Fig. 12B, however, and can be seen to be similar in appearance to
weld 25. The inner contour consists of a small, smooth bead having a slight crevice. Although the contour would probably not present an objectionable obstacle to flow, there is concern about possible corrosion in the crevice, and there are attempts to improve the inner contour. There is also a small crevice in the outer contour; however, this is of less concern than the inside crevice, since it will normally be accessible for removal.

The results of transverse tensile tests of welds in 4 in. (101.6 mm) stainless steel pipe are presented in Table 7, and the specimens themselves after testing are shown in Fig. 13.

Figure 14 shows the contours of weld 14B perhaps more clearly than Fig. 12. This weld contains a narrow fusion zone, which clearly defines the weld line. The shallowness of the outside crevice is apparent.

Figure 15 shows the microstructure of the weld line region in a weld that is typical of welds presently being produced. Because the joint design for this weld did not favor transverse flow of metal, oxide films present on the faying surfaces were not swet out of the weld interface; instead, they remained in place and merely spheroidized. This is similar to the way the surface films would have behaved in a diffusion weld.

There was no metallographic evidence of melting in weld 25. In fact, Fig. 15B, which is typical of the microstructure all along the weld line, clearly shows diffusional grain growth across the weld interface. Presence of the oxide particles had no adverse effect on the tensile properties of the weldment (Table 7 and Fig. 13). Welds can also be produced having a variety of microstructures with partial or complete melting at the interface.

A microhardness traverse of weld 25 is shown in Fig. 16. As would be expected in Type 304 stainless steel, there was no hardening in the heat-affected zone—merely a slight softening associated with relief of fabrication stresses.

Figure 17 shows the microstructure of the weld line and one heat-affected zone of weld 25 electrolytically etched with oxalic acid according to ASTM A 262 Procedure A, the screening method for revealing grain boundary sensitization. If sensitization has occurred in any portion of the heat-affected zone during welding,
the carbide-containing grain boundaries are severely attacked by the etch, clearly revealing the sensitized region.

There was no visible sensitization in weld 25, nor did we expect to find any in this or any other HPR weld. Sensitization is a diffusion-controlled process that takes place at intermediate temperatures during heating and cooling. A typical 4 in. (101.6 mm) Schedule 80 BWR pipe weld, if made using arc welding, will require about seven passes, and the HAZ will be within the sensitization temperature range for at least several minutes. An HPR weld, on the other hand, is accomplished within seconds during a single temperature excursion, and the HAZ is within the sensitization region for a significantly shorter time than in an arc weld. There is good reason to believe that sensitization, and therefore susceptibility to intergranular stress corrosion cracking, if it occurs at all, will not be a serious problem in HPR welds made in Type 304 stainless steel.

Other Welds

Presently funded projects will explore the welding characteristics for various materials and metal shapes of up to 7 in.² (4.5 x 10⁴ mm²) cross section. Since the existing 5 MJ disk-type machine appears to be capable of welding only 7 to 10 in.² (4.5 x 10⁴ to 6.5 x 10⁴ mm²) of steel, plans are presently under way to design and build a 50 MJ drum-type generator in the near future.

The 50 MJ machine is expected to give the capability to weld metal sections approaching 100 in.² (6.45 x 10⁵ mm²). It is hoped this will be a major contribution to the welding research capability of the free world.

Conclusion

A new welding process based on the unique electrical characteristics of pulsed homopolar generators is being developed. Homopolar pulse resistance welding (HPRW) is a stored energy resistance welding process having the capability of welding very large metal sections (up to 100 in.², 6.45 x 10⁵ mm²) in very short times (≤ 1 s).

It appears that this process will greatly expand the economically feasible range of weldment size for resistance welding. We believe that HPR welding will become a serious competitor for flash, electron beam, diffusion, and arc welding in some applications. Representatives from several industries, including automotive, pipeline, pipe fabrication, construction, and heavy equipment manufacturing, are already beginning to consider the HPRW process as a supplement or possible alternative to the presently available welding methods. Among HPRW applications visualized but not yet being actively pursued are welding in space and under water.

Several process features make HPRW attractive. The process can be adapted to both shop and field welding. The weld current pulse can be shaped to control weld heating and cooling rates and to accomplish postweld heat treatment. Electrical power requirements are inherently modest. The process also offers the potential for in-process weld quality control.

Welds made to date using the present 5 MJ machine include bars, pipes and other shapes up to 4.4 in.² (2.8 x 10⁴ mm²) in cross section with actual welding times of from 0.5 to 1.0 s at generated power levels in excess of 6000 kW. The power required by the welding equipment during these welds was only about 250 kW. Projects presently under way will explore process characteristics on welds in various metals in sections up to 7 in.² (4.5 x 10⁴ mm²). Future projects include the possible construction of a 50 MJ machine for welding experiments on metal sections approaching 100 in.² (6.45 x 10⁵ mm²).

We believe continued development of the HPRW process will occur and will parallel the commercial development of the pulsed homopolar generator and other equipment which serve as the basis for the process. In addition, development of this equipment will lead to its use in other industrial processes such as billet heating, localized heating and forming, resistance brazing, and other applications requiring or capable of using a large resistance heating power source.

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References


