APPLICATION OF HOMOPOLAR PULSED POWER TO METALS JOINING

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ABSTRACT

Homopolar generators (HPGs) presently being developed at the Center for Electromechanics are capable of delivering megampere pulses of electric current in a controllable manner. One application for these machines is as the power supplies for an industrial welding process. During the past five years, several research projects have been carried out to explore the welding capabilities of HPGs. Among the materials that have been welded are carbon and low alloy steels, several varieties of stainless steels, tool steels, nickel-base and molybdenum-base alloys, aluminum, and several dissimilar-metal couples. Among the shapes that have been welded are bars, sheets, plates, tubes, pipe, angle sections, and rails. The largest cross sections that have been welded to date are 9 in.^{2} (2.9 cm^2), and the smallest have been less than 0.3 in.^{2} (0.58 cm^2). Welding is accomplished in times approximating a second. Unique advantages of the homopolar pulse welding process are that it can be scaled upward to indefinitely large cross sections and that it does not impose a sudden load on the mains.

INTRODUCTION

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is a self-supporting research group in the field of engineering development of pulsed electric power hardware. Its primary goal over the past decade has been the advancement of homopolar generator (HPG) technology, particularly in the areas of bearings, current collection, increased energy storage density, and instrumentation and control. Concurrent with this development, CEM-UT has applied the inherent high current of the HPG discharge pulse to metal joining by the homopolar pulse welding (HPW) process.[1,2] In this process, the interface between two workpieces is preferentially heated as the high current pulse encounters the voltage drop at the interface. High force is applied to forge the workpieces together when the proper temperature has been attained. The advantages of the HPW process include fast welding time (typically about one second), uniform heat generation, a small heat-affected zone, and good strength retention. Also, the amount of flash created is nominal, and relatively little upset is required, reducing material loss. The process has been demonstrated to be especially suitable for pipe welding, where interior profiles must not result in flow constrictions or corrosion-accelerating crevices.

Detailed discussions of both the theory of homopolar generator operation and the HPW process are presented here. The nature and results of several major funded welding research efforts are discussed. Some special considerations that are critical for weld quality are highlighted. Finally, the outlook for the HPW process as an industrial tool is discussed in the light of current and forthcoming developments of interest.

BACKGROUND

In 1972, the Energy Storage Group (ESG) at The University of Texas at Austin was conceived under the joint sponsorship of the Departments of Electrical and Machanical Engineering. The primary objective of the Group was to investigate the feasibility of inertial energy storage machines as power supplies for thermonuclear fusion systems. With funding from the Department of Energy, a 5-megajoule (MJ) HPG was designed, built, and tested by ESG in 1974.[3] The 5-MJ HPG is shown in Fig. 1.

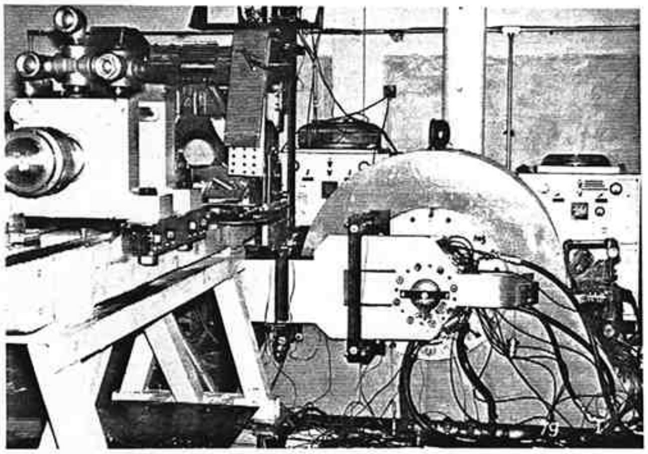

Fig. 1. 5-MJ homopolar generator with hydraulically actuated welding fixture attached

Although the 5-MJ HPG was designed to be merely a proof-of-principle prototype machine having a peak current output of 150 kA, it proved to be much more robust and reliable than expected. In 1979, the hydrostatic bearings and busbars were replaced.[4] During this period, the machine was largely devoted to research on industrial applications such as welding and forging billet heating. In these tests, the machine underwent hundreds of discharges, reaching peak current levels as high as 560 kA.

In 1977, the Energy Storage Group was upgraded to its present status of a full research center (CEM-UT). Since 1978, we have conducted pulse resistance welding research sponsored by the Electric Power Research Institute (EPRI), the National Science Foundation (NSF), Ford Motor Company, General Motors Corporation, and others.

In 1980, NSF funded a major rebuilding and upgrading of the generator.[5] This involved replacement of the shaft, rotor, field coils, brush mechanisms, busbars, and motoring system. The new generator was designed to be motored to 10 MJ of stored energy with reduced brush wear and internal resistance, and to have current capabilities as high as 750 kA. The rebuilt 10-MJ HPG is shown in Fig. 2. This version of the generator has been discharged about 300 times at current levels as high as 800 kA with no loss of performance.

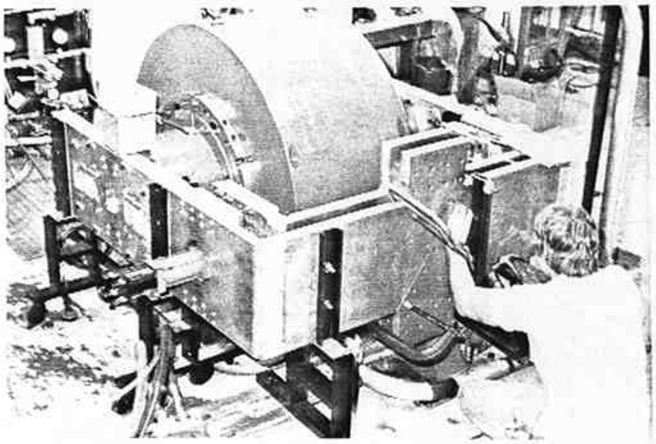

Fig. 2. 10-MJ homopolar generator

PRINCIPLES OF HPG OPERATION

Although the homopolar generator can be constructed using several different geometries,[6] the simplest form for discussion purposes is the disk, shown schematically in Fig. 3. This also happens to be the basic geometry of the 5- and 10-MJ HPGs. Energy is stored kinetically in a cylindrical rotor by motoring it to a high speed. The rotor is surrounded by a ferromagnetic back-iron that contains a field coil coaxial with the rotor. When excited, the coil creates a magnetic flux through the back-iron, air gap, and rotor. Thus the elements of rotor mass constitute an electrical conductor moving orthogonally to a magnetic field, and a potential gradient is developed between the shaft and the outer rotor diameter. Sets of sliding brushes at each end end of the shaft and at the outer circumference of the rotor serve to connect the rotor to the external load circuit, which may include a making switch.

The voltage at the HPG terminals is proportional to the angular velocity of the rotor, ω, and to the magnetic flux, ϕ:

$$V = \frac{\omega\phi}{2\pi} .$$

Compared to conventional generators, this voltage is typically low. The maximum design voltage for the 10-MJ HPG, for example, is 45 V.[5] The low internal resistance of the massive rotor and shaft result in very high current capability, however. Thus, an HPG with energy storage of 10 MJ is capable of discharge pulses having peak power levels of about 30 megawatts (MW).

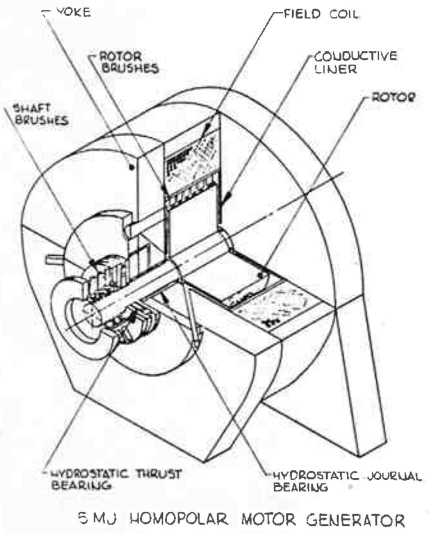

Fig. 3. Schematic drawing of disk-type HPG

Electrically, an HPG models as a very high capacitance. The equivalent capacitance can be calculated by equating the kinetic mechanical energy to the corresponding electrical energy:

$$C = \frac{4\pi^2 J}{\phi^2} ,$$

where J is the rotor polar moment of inertia. Thus, the discharge pulse of the HPG (either current or voltage) into a resistive load such as a weld consists of a rapid current rise to a peak value followed by a first-order decay to zero. This decay has a time constant, τ, given by

$$\tau = \frac{1}{R\ C} .$$

In welding applications, the output circuit resistance is usually dominated by the (time-varying) resistance of the workpieces and the weld interface, while the circuit capacitance is almost entirely concentrated in the HPG. Figure 4 illustrates the output circuit of the 10-MJ HPG.

PRINCIPLES OF HOMOPOLAR PULSE WELDING

Homopolar pulse welding (HPW) is an upset welding process that uses the unidirectional HPG current pulse to heat preferentially the interface between two workpieces which are lightly loaded mechanically

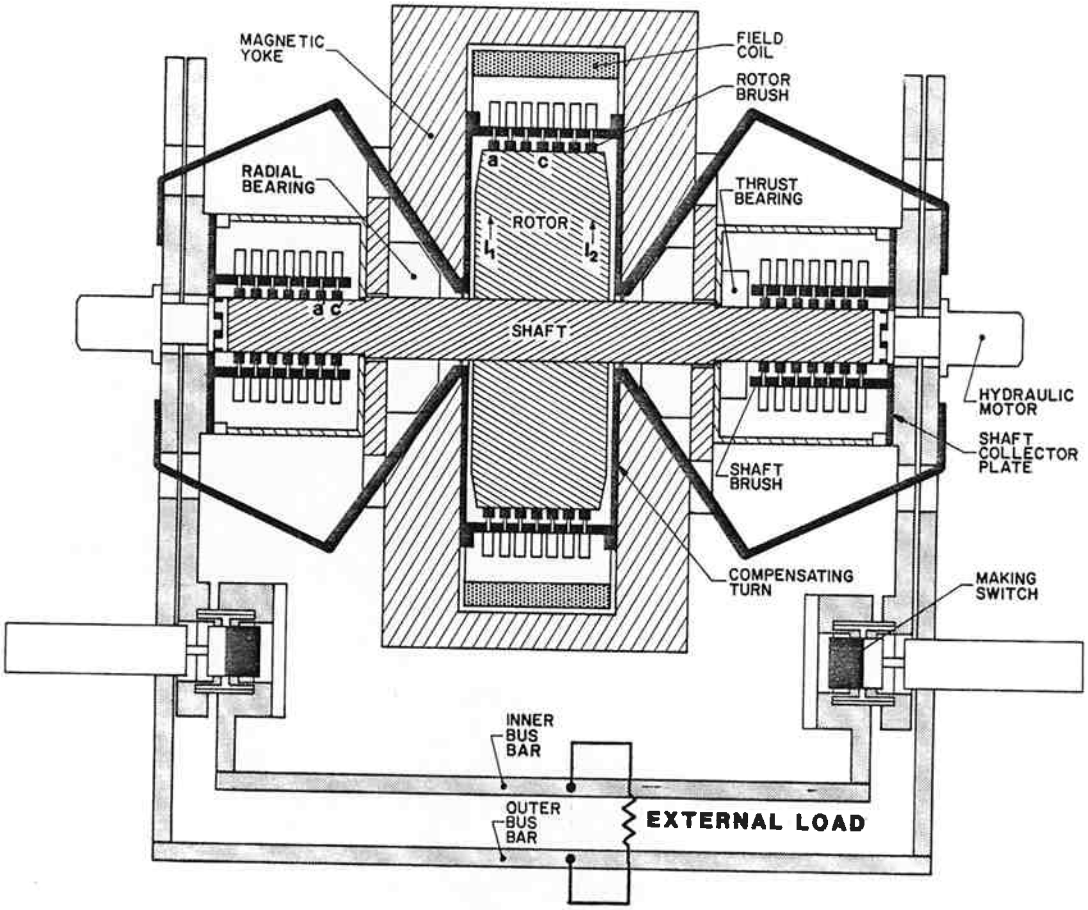

Fig. 4. Schematic drawing of 10-MJ HPG output circuit

but are in solid contact, and then increases the axial force to forge the workpieces together without melting them. The time variation of the various HPW parameters during a weld is shown in Fig. 5.

Heat generation is initially concentrated at the interface due to constriction resistance at the faying surfaces. Interface pressure is kept low early in the pulse to maximize the I^2R heating. Ideally, the interface and the adjacent bulk material will have been heated to forging temperature just as the pressure is increased. The workpieces continue to upset either to refusal or until a mechanical stop in the tooling is reached. The amount of upset is typically between 0.20 and 0.25 in. (0.5 and 0.6 cm), regardless of the weld cross section.

Because of the proximity of the electrode leading edges (located about 0.5 in. on either side of the interface), the heat-affected zone is small compared to that obtained using many other processes. The comparatively high heating and cooling rates and the short time at weld temperature minimize grain growth and undesirable metallurgical reactions. Finally, because of the unidirectional nature of the pulse, current distribution and the resulting temperature distribution are relatively uniform over the cross-section, so that large, irregular sections can be successfully welded.

SUMMARY OF WELDING PROJECTS AND RESULTS

The major welding projects completed to date by CEM-UT are summarized in Table 1. Typical values of process parameters are given in Table 2. The National Science Foundation has funded two major research projects. The first of these was a survey of the weldability of a variety of engineering alloys. The second, co-funded with the Federal Railroad Administration (FRA), the Association of American Railroads (AAR), Ford Motor Company, and General Motors Corporation, was concerned with welding railroad rails and vehicle components.

The EPRI project [2,7,8] involved welding 4-in. (10-cm) schedule 80 type 304 stainless steel pipe. The objective was to determine the feasibility of joining boiling water reactor coolant piping with minimum disruption of the interior contour and minimum sensitization of the weld heat-affected zone. An as-welded pipe, sectioned to show the interior profile, is shown in Fig. 6.

The first NSF project was to investigate the pulse resistance weldability of a number of important engineering alloys, which are listed in Table 3.

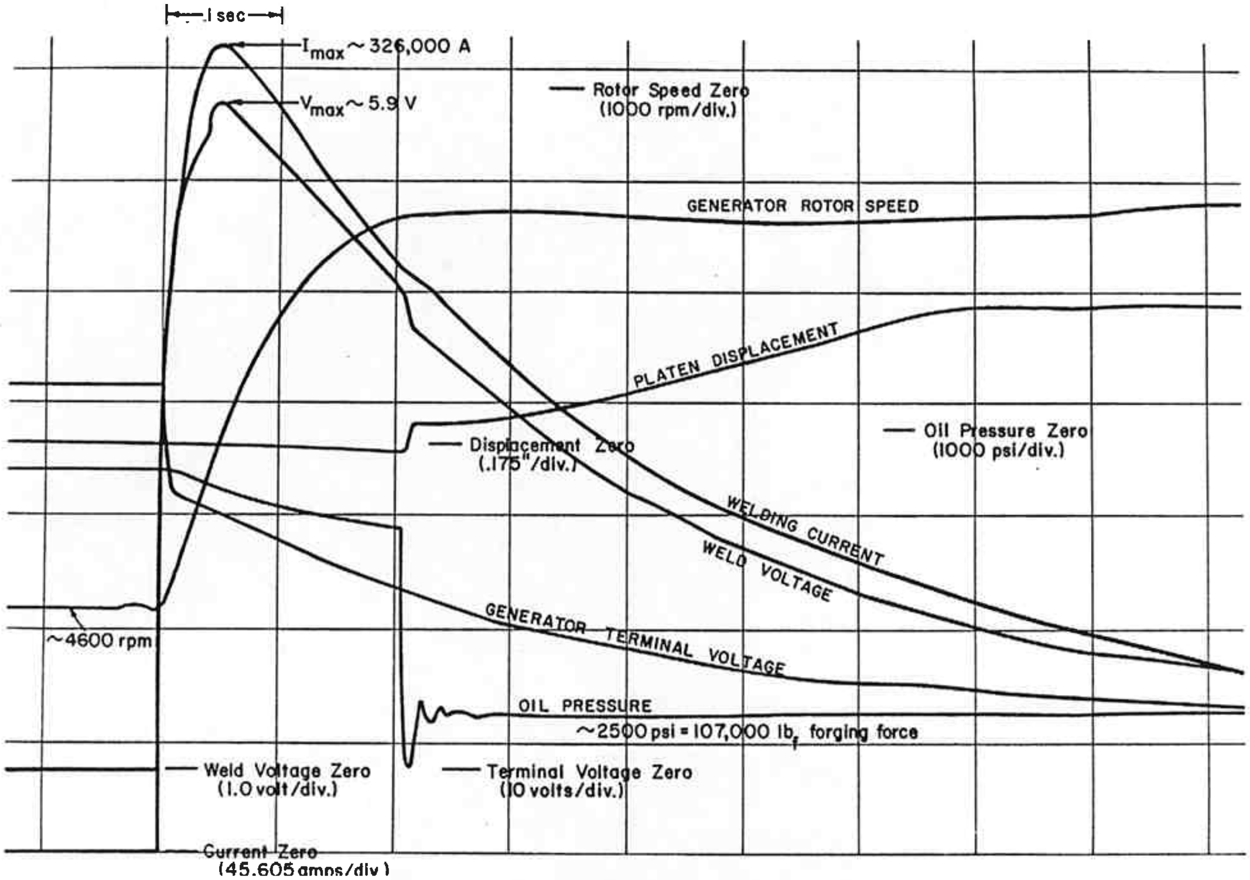

Fig. 5. Parameter variation during a weld

Table 1
SUMMARY OF MAJOR CEM-UT WELDING PROJECTS

Sponsor	Material	Configuration	Area, in.^{2} (cm^2)
EPRI	304 SS	pipe	4.4 (28.4)
NSF	*	round bar	0.8 (5.2)
FRA/AAR †	eutectoid carbon steel	rail	8.8 (56.8)
Ford †	high-strength low-alloy steel	mash-lap seam	0.9 (5.8)
GM †	1010 steel	pipe-to-flange	4.5 (29.0)

* various ferrous and nonferrous alloys and dissimilar metal couples -- see Table 3
† co-funded with NSF

Table 2
TYPICAL HOMOPOLAR PULSE WELDING PARAMETERS

Parameter	Magnitude	Units
Initial pressure	7.5 - 15 (5.2 - 10.3)	ksi (kN/cm^2)
Upset pressure	20 - 30 (13.8 - 20.7)	ksi (kN/cm^2)
Peak current density	60 - 100 (9.3 - 15.5)	kA/in^2 (kA/cm^2)
Time to peak current	0.05	s
Energy density	0.14 - 0.16 (0.02 - 0.025)	MJ/in^2 (MJ/cm^2)
Peak interface voltage	3	V
Pulse duration	3 - 4	s

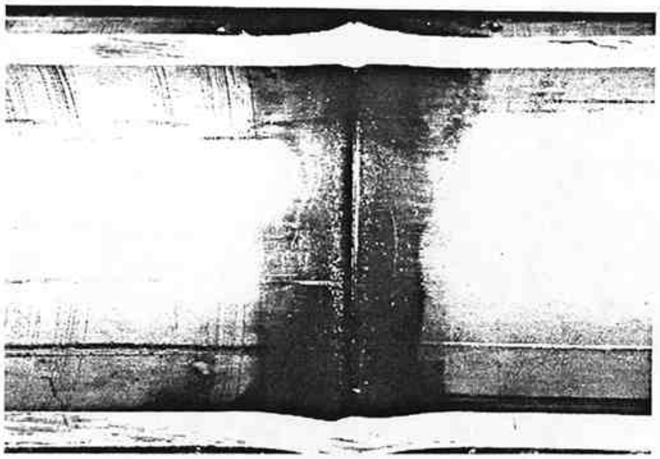

Fig. 6. Longitudinal section through 4-in. diameter type 304 stainless steel pipe

Table 3
MATERIALS STUDIED IN NSF SURVEY PROJECT

Carbon Steels	Alloy Steels	Tool Steels
1018	4140	W1
1020	4340	S7
1045	Mn-Mo-Nb	
1070		
1144		

Stainless Steels	Aluminum Alloys	Titanium
316	2024-T351	Ti-6Aℓ-4V
416	6061-T6	
18Cr-2Mo		
630 (17-4PH)		

Molybdenum Alloy	Ni-base Alloy	Dissimilar Couples
TZM	Inconel X-750	ETP Cu/6061-T6 Aℓ
		316 SS/6061-T6 Aℓ
		316 SS/1020 steel
		Inconel/1045 steel
		316 SS/Ti-6Aℓ-4V

All of the alloys studied in the NSF survey project, including the 1144 resulfurized steel, can be welded with the HPW process. As-welded joint efficiencies varied from 57 to 126 percent and averaged 92.5 percent, as measured in tensile tests, but there were considerable losses in ductility. Metals having high thermal and electrical conductivity, such as aluminum alloys, are difficult to weld because of rapid heat dissipation and low interface voltage drops. On the other hand, titanium, which is highly resistive and is also chemically reactive, could be successfully welded in air. Figure 7 shows the microstructure of a somewhat underheated weld in Ti-6Aℓ-4V alloy.

Dissimilar metals can be welded with varying degrees of success. Whereas stainless steel/carbon steel and stainless steel/aluminum welds were successful and titanium/aluminum welds showed promise, copper/aluminum welds were unsuccessful. The number of welding attempts that could be made on any single material or couple in a broad survey of this kind was limited, however, so these results might be modified as the result of further work.

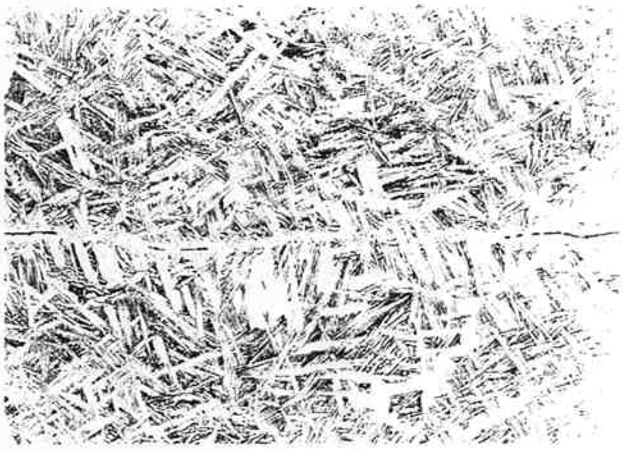

Fig. 7. Microstructure of weld line in Ti-6Aℓ-4V
200 X Etchant: Kroll's reagent

Before the goal of the second NSF welding project, welding railroad rails,[10] could be accomplished, two other tasks had to be performed. These were upgrading the original 5 MJ HPG to 10 MJ as discussed earlier and designing and constructing a fast-acting rail welding fixture capable of applying an upset force of 375 tons. The welds in 90 lb_m/yd rail, with an area of 8.8 $in.^2$ (56.8 cm^2), are the largest homopolar pulse welds attempted to date. The welding fixture is shown attached to the 10-MJ HPG in Fig. 8. A typical rail weldment is shown in Fig. 9.

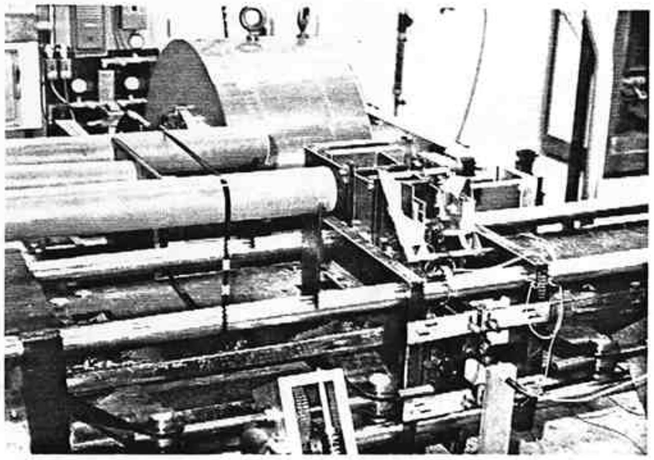

Fig. 8. Rail welding fixture attached to 10-MJ HPG

Eight rail welds were made during the project. Figure 10 shows a typical rail weld microstructure. Grain growth across the original interface is characteristic of properly made homopolar pulse welds, and, as in this case, it is often difficult to perceive the weld line. Maximum hardness observed in the rail welds was 293 BHN or 31 HRC, which is consistent with the metallographic observation that there were no martensitic regions anywhere in the welds.

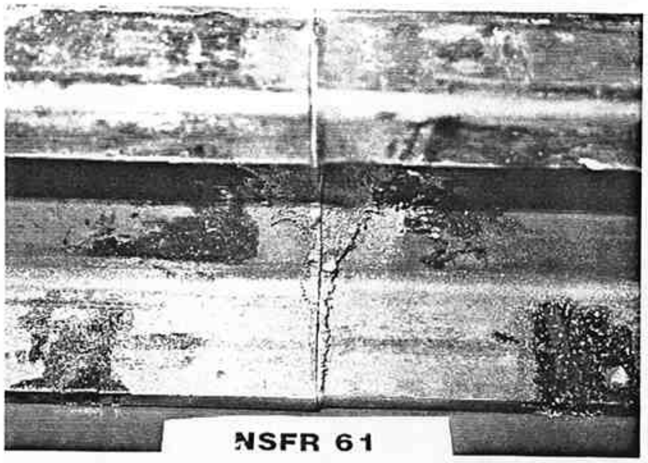

Fig. 9. As-welded 90 lb_m/yd railroad rail

Two weldments in the as-welded condition, with the welds at their midpoints, were subjected to three-point bending. After yielding, both weldments broke outside the weld zone.

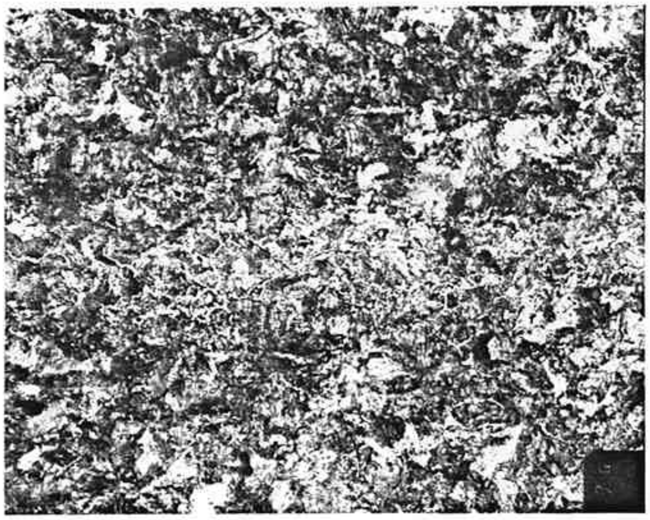

Fig. 10. Microstructure of weld line in 90 lb_m/yd rail
200 X Etchant: Picral

The portion of this project sponsored by the Ford Motor Company involved the mash-lap seam welding of 0.110 in. thick high-strength, low-alloy steel wheel rim stock. Figure 11 shows the contour of a typical weld. The 8-in. (20.3-cm) seam welds were made using the bar welding fixture that was designed and built during the NSF survey project, which was equipped with electrodes provided by Ford. Although good bonding was achieved, subsequent forming tests at Ford resulted in tearing of the welds originating at the ends of the seams.

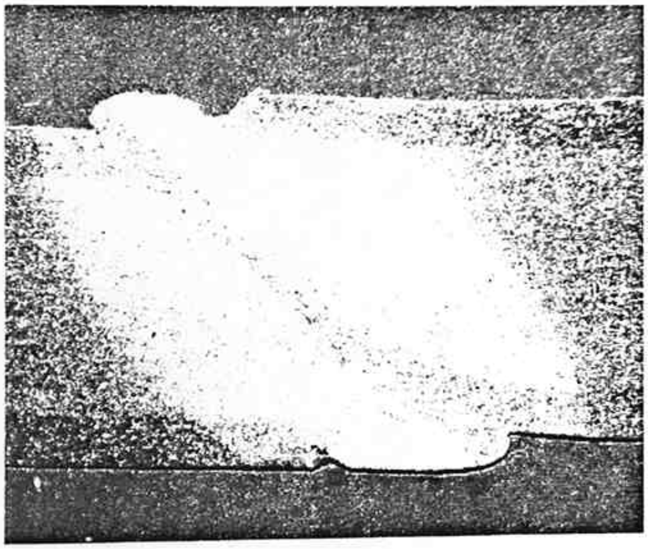

Fig. 11. Contour of mash-lap seam weld in high-strength, low-alloy steel sheet
20 X Etchant: 2% Nital

The welding task sponsored by General Motors was the attachment of a 1-in. (2.54-cm) thick AISI-SAE 1010 steel flange to a 6 x 0.25-in. (15.2 x 0.64-cm) 1010 steel tube. Similar flanges are presently being arc welded to tubes to form locomotive drive shafts. To accomplish this weld, the pipe welding fixture designed and built during the EPRI project was modified with electrodes provided by GM. The cross section of a typical weldment is shown in Fig. 12. Because of the differing masses of the tube and the flange, a joint design had to be developed that would result in adequate heating of the faying surface of the flange without overheating the tube.

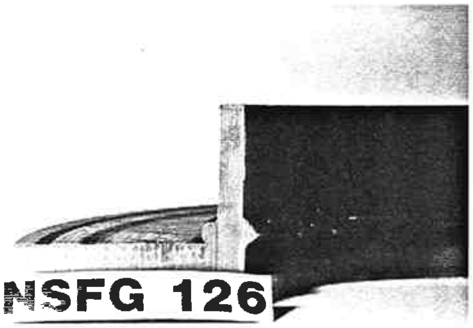

Fig. 12. Cross section of a typical tube-to-flange weld

PROBLEM AREAS, PROCESS VARIABLES, AND CONTROL TECHNIQUES

As in all welding processes, the HPW process has a number of electrical and mechanical variables, most of which are highly interdependent. It is therefore difficult to arrive at an optimum weld schedule without some experimental trial and error.

Experience at CEM-UT with the HPW process has shown that at least three potential problem areas must be addressed during the engineering of each welding application. The problem areas are

- uneven heating at the weld interface;
- overheating of the workpiece material under the electrodes; and
- misalignment of the workpieces.

These problems are not unique to the HPW process, but are frequently encountered in electrical resistance welding processes of the upset type.

Introduction and balancing of the comparatively high currents used in the HPW process into shapes as complex as rails has been successfully accomplished at CEM-UT by the use of flexibly-mounted copper-base alloy shoes clamped to the workpieces with a pressure of at least 4,000 psi (27.6 MPa) to prevent excessive voltage drop at the electrode-workpiece interface. Current partitioning among electode shoes can be accomplished by varying the numbers of copper strips in the flexible mounting structure.

Overheating of the workpieces under the electrodes causes rapid electrode wear, pickup of electrode material by the workpiece, and, in some cases, such adverse metallurgical effects as local melting or martensite formation. The overheating problem is aggravated when welding complex shapes that limit the number and placement of electrodes. For instance, the linear electrode leading edge current density was 58 kA/in. (22.8 kA/cm) for rail, but was only 19 kA/in. (7.5 kA/cm) for the EPRI pipe. One possible remedy for overheating beneath the electrodes is to lower the magnetic flux in the HPG, thus decreasing the current and extending the pulse length. Another remedy may be to use an electrode construction consisting of a series of alloys having decreasing conductivities in the direction approaching the weld interface. This should force some current partitioning into the workpiece at each alloy interface, creating in effect an electrode having several leading edges, each with its own linear current density.

Misalignment of the workpieces during upsetting becomes a serious problem with high-aspect-ratio workpieces. It results from column instability of the hot plastic weld region under the influence of the upset force, and can be expected to be more severe if there is any molten metal film at the interface. Future HPW fixtures will combine the mechanical grips with the electrodes to shorten the column length of the workpieces, and this plus adequate rigidity of the fixtures should prevent misalignment.

The HPG is subject to control of the welding current and the voltage by controlling the rotor speed at discharge and the field excitation current. In addition, the shape of the current pulse can be controlled by varying the field current during discharge. By ramping the field current upward early in the pulse, for example, the magnetic flux seen by the rotor can be at least doubled during the pulse. This has the effect of decreasing the time constant of the output circuit, thus shortening the decay portion of the pulse, raising the effective power, and resulting in more efficient energy transfer into the weld. The peak output voltage and welding current occur within the first 50 ms, however, while the field current is still low.

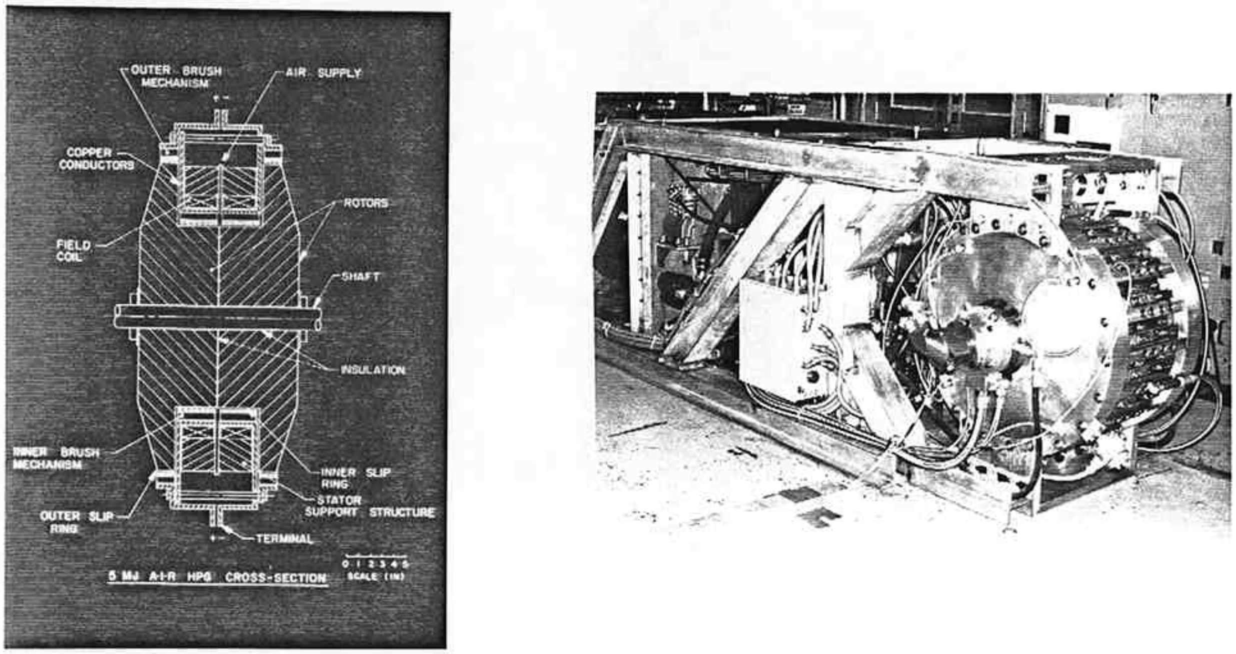

Fig. 13. Compact homopolar generator prototype

Thus, large-area welds are now possible at high power levels, but with tolerable peak current densities and current rise rates.

Studies are underway that are expected to lead to simple closed-loop control of weld behavior during the pulse using limit switches actuated by the hydraulic cylinder motion to sense the beginning of plastic flow and trip a "crowbar" switch placed across the HPG terminals. Closing of this switch shunts the HPG out of the output circuit, stopping the current flow and consequently the heating.

The temperature rise of the weld zone can also be observed directly using a rapid-response 2-color fiber optic pyrometer, which is presently being fitted to a temperature controller, after which upset force can be applied to the weld at a predetermined forging temperature and the HPG can then be crowbarred out of the circuit at a maximum allowable temperature.

OUTLOOK FOR HOMOPOLAR PULSE WELDING

The HPW process was developed largely with public-sector funding from NSF. The next logical step would involve private-sector investment in further process development and specialized applications. With this in mind, three forthcoming events of interest to industry are presented here.

First, at this writing, CEM-UT is about to begin a major welding project for OIME, Inc. This project will involve welding 6-5/8 x 1/2-in. (16.8 x 1.27-cm) API X52 steel line pipe and several API grades of well casing. Both of these applications are attractive, since oil well casing installation and pipeline construction are both expensive, time-consuming, labor-intensive operations.

Second, CEM-UT has recently designed, built, and tested the first compact homopolar generator.[11] This machine, the prototype of which is shown in Fig. 13, can store 6.2 MJ, has four times the energy storage density of the 10-MJ HPG, and has delivered output current pulses of over 1 MA peak. The compact HPG was designed for field portability. Commercial manufacture of compact HPGs under license from The University of Texas by OIME, Inc., Odessa, TX, is under way, and the first machines will become available during 1983.

Finally, construction of a new laboratory facility for CEM-UT is expected to begin by mid-1983. To be located at the Balcones Research Center, this laboratory will include a 60-MJ homopolar generator power supply system. This system will consist of six 10-MJ drum-type machines, each rated at 110 V (open circuit) and 830 kA (pulsed). The generators will be operable independently, in series, or in parallel combinations, depending upon load requirements. At full power, the system will operate at a peak power level of about 400 MW. The system should be capable of welding cross sections as large as 100 in.^{2} (645 cm^2) of steel. The new facility will also include a fully-equipped materials laboratory, and is expected to be in full operation by early 1985.

ACKNOWLEDGEMENTS

The following present or former CEM-UT staff members have made significant contributions to the development of homopolar pulse welding: J. D. Becker, T. M. Bullion, S. J. Dean, W. M. Featherston, G. B. Grant, J. L. Kepner, K. R. McFerren, and R. C. Zowarka.

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