Vickers Controlarc

Developed 4 years

Dan Martinez 40
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Development and Evaluation of a Modulated Power Control for Fusion Welding

Development of an adaptive type electronic control circuit for magnetic amplifier controlled power supplies leads to a capability for all-position gas metal-arc welding in narrow groove joint configurations and to improved uniformity of penetration and weld bead contour for gas tungsten-arc welding

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203 777 5361

Bob Young Electric Boat

Less than 1 amp

ABSTRACT.—A versatile, adaptive type electronic control circuit employs low-cost solid state components to modulate the output of commercially available, magnetic amplifier controlled power supplies. The system is capable of modulating weld currents at various frequencies and amplitudes as applied to consumable and non-consumable weld processes.

The use of a specially designed optical monitoring system permitted observation of various metal transfer phenomena. The effects of frequency variations, wave shapes and other circuit parameters are discussed.

Very directional metal transfer characteristics were observed when the system was applied to the gas metal-arc process, providing a unique capability of all-position welding in narrow groove joint configurations.

Improved uniformity of penetration and weld bead contour, combined with a reduction of hot cracking tendencies of certain materials resulted when the system was applied to the gas tungsten-arc process.

An increase of parametric tolerances was observed when the system was applied to plasma-arc welding.

Introduction

The subject adaptive type electronic control system was conceived for the purpose of determining the advantages of modulated electrical energy at various frequencies as applied to consumable and non-consumable electrode weld processes. Since at the inception of the project no suitable experimental type power sources were commercially available, development was undertaken on an add-on type modulated power supply control system. To this end, modifications were made to a few conventional magnetic amplifier controlled power sources, both constant potential (essentially) and constant current types.

The paper describes the outcome of this work and reviews the significant effects which the equipment had on weld characteristics.

Equipment Design Approach

Two weld power supplies incorporating fast response and requiring but low control currents such as manufactured by Vickers Electric Products Division of Sperry Rand Corporation were modified for pulsing operation. Since experiments were to be conducted with the pulsed gas metal-arc, pulsed gas tungsten-arc and pulsed plasma arc processes, two basic power supply output characteristics had to be provided to cover these processes; the constant potential and the constant current characteristics.

Due to the inherent slow response of saturable reactors or magnetic amplifiers a special feature has been incorporated* which speeds up this response and permits operation of the pulsed gas metal-arc process at 60 Hz. Without this feature the pulsing frequency would be restricted considerably, while the pulses would tend to be much wider and run into one another. It would also be impossible to obtain pulse peak values up to the rated power supply capacity except at very low frequencies.

Another factor affecting the overall frequency response capability of the power supply is the choke in the power supply output circuit. Therefore, this choke was substituted for one with a lower inductance, thus permitting rapid rise and decay of the current pulses.

Tentative pulse frequency ranges have been established for each process; they are:

1. Pulsed gas tungsten-arc, from less than one to 10 Hz.
2. Pulsed gas metal-arc, from 15 to 60 Hz.
3. Pulsed plasma arc, from 3 to 12 Hz.

In all instances, only one weld power supply is required for pulse operation.

Equipment Description

The weld power supplies used incorporate magnetic amplifiers for controlling the output current levels. The output of the add-on pulse control circuit described separately is inductively coupled into the power supply control circuit, thus permitting use of output controls already present in the control circuit—Fig. 1.

The adaptive type pulse control circuit, itself, used the 60 cycle line frequency as reference source for the pulse frequency selected. A combination of frequency dividing, gating and phase shifting techniques provided the control capabilities for variables such as pulse frequency, amplitude and pulse duration. The overall circuitry shown in Fig. 2 uses solid state type components only and is relatively economical to assemble. Each func-

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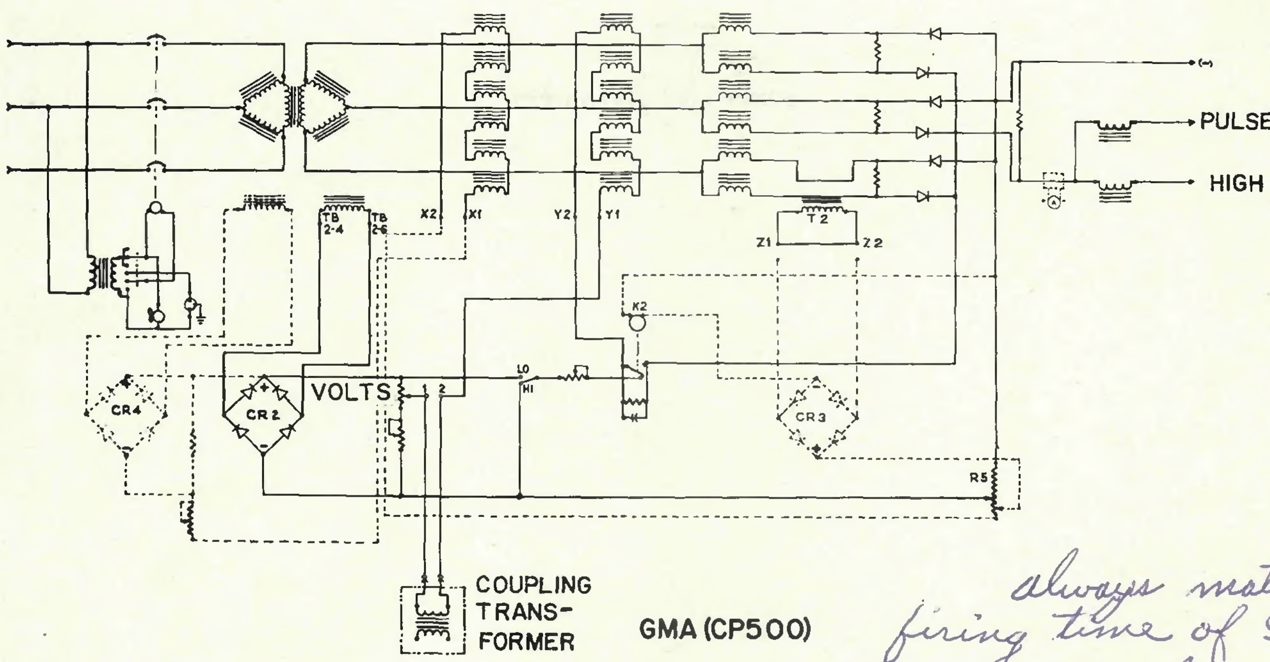
Based on paper presented at the AWS 49th Annual Meeting held in Chicago, Ill., during April 1-5, 1968.

The work described in this paper was performed while both authors were with General Dynamics Corp.

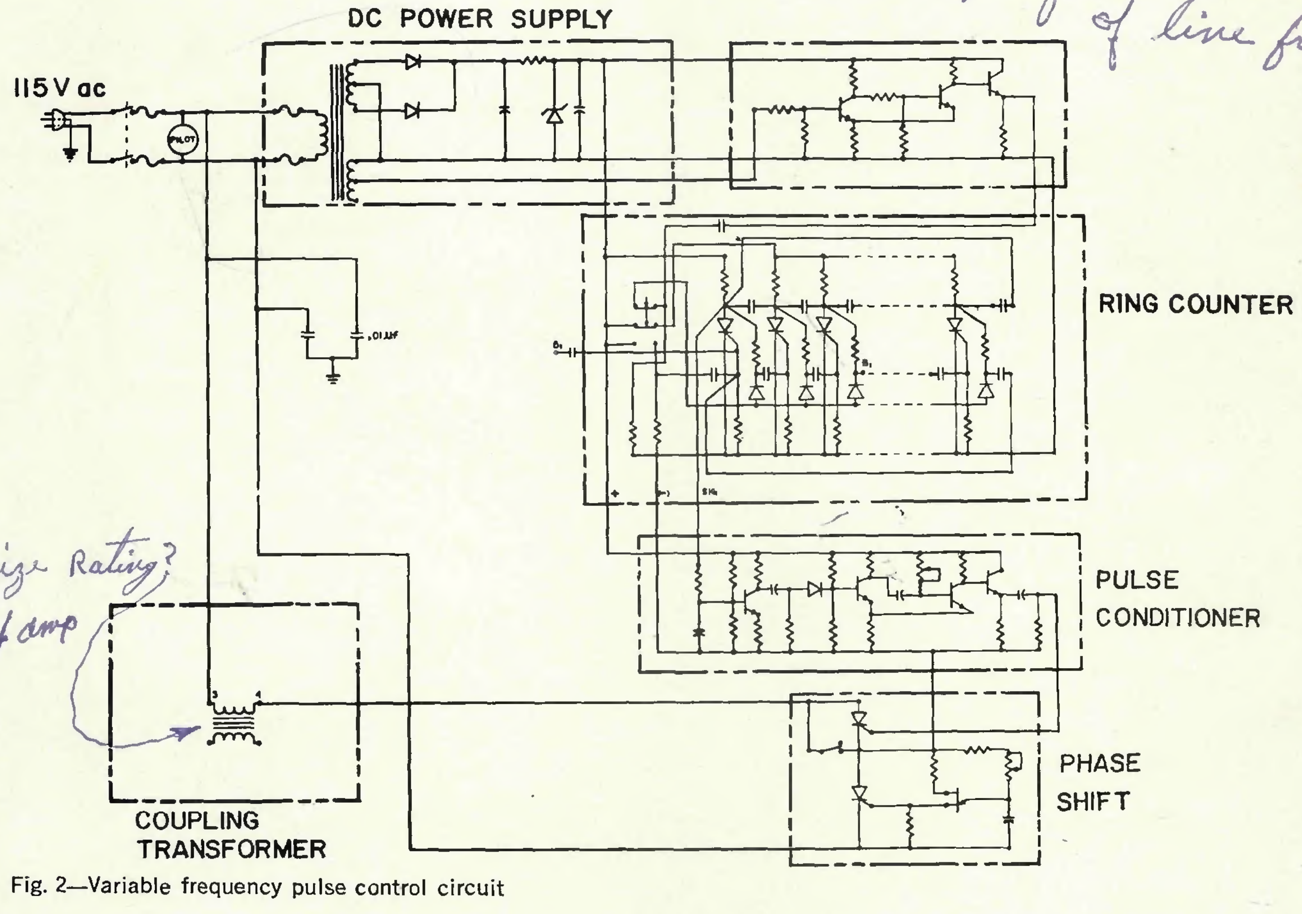
*U.S. Patent 3,522,411.

Rienks —



always match firing time of SCR to specific division of line freq.

Fig. 1—Gas metal-arc (CP500) simplified weld power schematic



size Rating? 4 amp

Fig. 2—Variable frequency pulse control circuit

tional block in the circuit is shown within broken lines to facilitate describing the variable pulse control circuit applicable to the gas metal-arc, gas tungsten-arc and plasma-arc processes.

The 115 VAC 60 cycle line voltage is fed into a small step-down transformer with two secondary windings. The output of one of these windings is rectified and the d-c voltage is regulated with a zener diode. The 60 cycle frequency reference signal is provided by the other secondary winding and fed into the first stage pulse conditioner. The square wave output of this circuit provides the signal input to a ring counter which is equipped with a multi-deck selector switch. This switch permits the selection of different numbers of counting stages and frequencies. If, for instance, ten stages are connected, the 60 cycle line frequency is divided by the number of stages or $60/10 = 6$ Hz.

To obtain 10 Hz, 6 counting stages are to be switched into the circuit. A

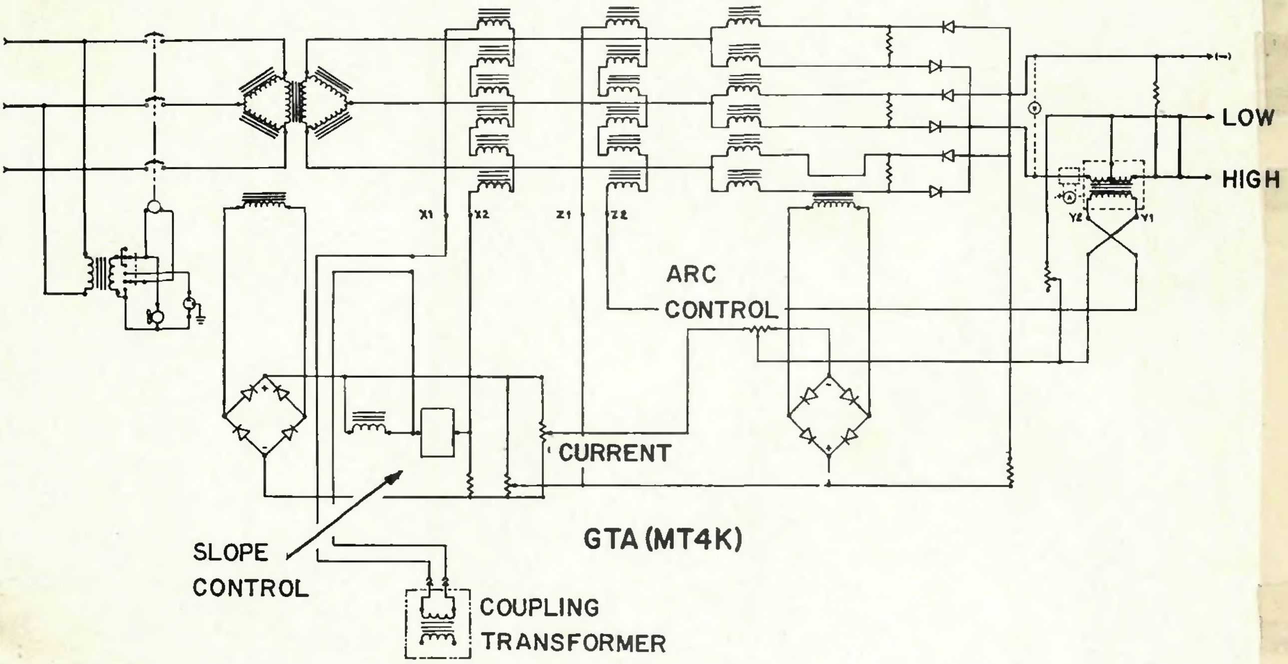
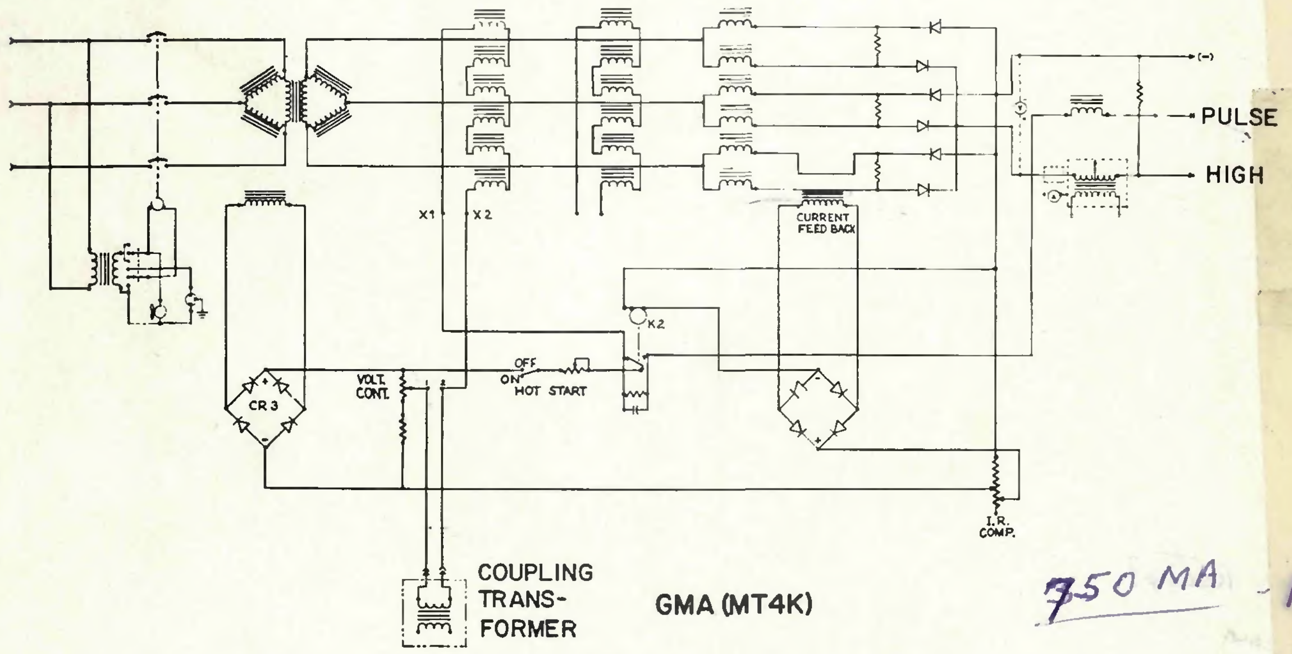


Fig. 3—Gas tungsten-arc (MT 4K) simplified weld power supply schematic



750 MA - MAX

Fig. 4—Gas metal-arc (MT 4K) simplified weld power supply schematic

pushbutton is incorporated into the counter circuit to initiate its operation since no self-starting capability has been designed into the circuit.

The output of the ring counter is connected to the second stage pulse conditioner which processes the signal through an inverter, amplifier and pulse width control. The latter adjusts pulse widths from approximately 7-45 millisec and provides the trigger signal for the SCR. This SCR is connected in series with another SCR which is part of the phase shift control circuit. A highly efficient means of controlling how much of the half wave a-c is being passed to the coupling transformer is provided in this manner.

In recapitulation, the upper SCR is triggered according to the pulse frequency selected and the lower SCR is used to determine the duration of the control pulse conduction which is always less than approximately 8.3 millisec ($^1/_2$ cycle, 60 Hz).

If the pulse width needs to be increased, the trigger pulse width is increased, whereupon the upper SCR will permit conduction of more than one $^1/_2$ cycle in succession. This, combined with capacitance added to the secondary of the coupling transformer in order to fill the gaps between the "pulse trains", provides overall system capability of producing current pulses with various widths.

If 60 cycle operation is required, the upper SCR is bypassed and only the phase shift circuit is used to provide the amplitude control.

Weld Power Supply Modifications

To permit modulated power supply operations, certain modifications in their control circuits were carried out in such a manner that standard (non-modulated) operation could be maintained. The required modifications are indicated in simplified circuit diagrams shown in Figs. 1–5. The broken lines shown in Fig. 1 indicate

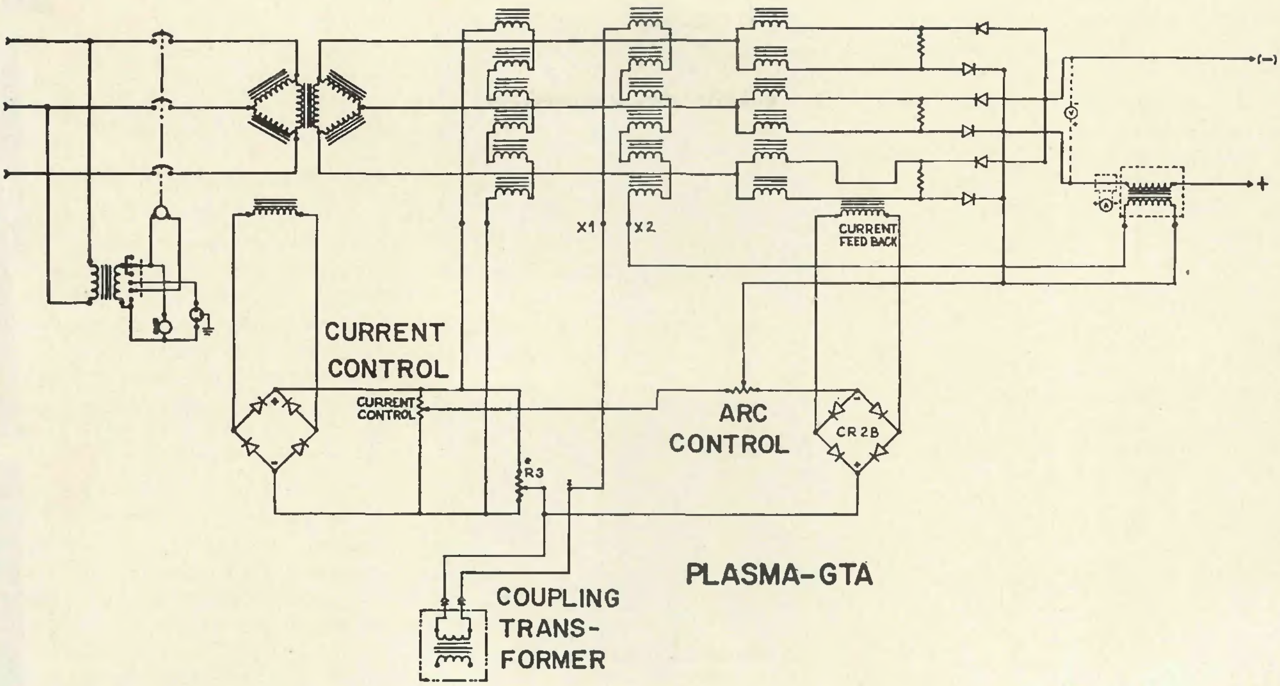


Fig. 5—Plasma/gas tungsten-arc simplified weld power supply schematic

the components disconnected in the gas metal-arc power supply. A low inductance choke was added to the output circuit. The original power supply choke was left in place and its output brought out to a separate tab in front of the power supply. In this manner its inductance can be added to the output circuit for non-pulsed gas metal-arc welding applications if so desired.

Figure 3 shows the simplified circuit of a combination gas metal-arc/gas tungsten-arc power supply after modification for modulated gas tungsten-arc operation. The slope control located on the left side of the power supply can be substituted with a 25 Henry choke to permit modulated operation.

Figure 4 shows the simplified circuit of the same power supply as in Fig. 3 after modification for modulated gas metal-arc operation. Again, the original power supply choke was left in place except that its "low" output was disconnected and a separate low inductance choke added to the circuit and its output connected to the "low" tab in front of the equipment.

Figure 5 shows the simplified circuit diagram after modification for modulated plasma arc operation. In all aforementioned modification procedures the bridge rectifiers in the control circuits were substituted for units with a higher voltage rating.

Basic Principle of Operation

The pulsing action of the weld power supply is obtained by inductively introducing pulses into the d-c magnetic amplifier circuit of the weld power supply. With pulse control off, a d-c auxiliary power supply provides a bias current to the magnetic amplifier coils. The higher a current is supplied the more saturated the magnetic amplifiers become and the less a-c current they will permit to pass to the rectifiers which in turn provide the d-c weld current. In other words, the weld current level is inversely proportional to the d-c magnetic amplifier control current.

In order to rapidly increase the weld current, a sudden decrease of d-c control current is required. This is accomplished by inductively coupling a current pulse of an opposite polarity into the control current circuit, thus momentarily counteracting this d-c current and desaturating the magnetic amplifiers. This desaturated condition permits the flow of an increased a-c current through the magnetic amplifiers into the rectifiers and the welding arc. As soon as the energy of the control pulse has been spent into the inductive coupling circuit, a residual pulse. resulting from magnetic energy, stored in the coupling transformer and having an opposite polarity as the main pulse, will rapidly restore the current control function of the magnetic amplifier. This residual pulse has thus the same polarity as that of the d-c control current to the magnetic amplifier.

Optical Arc Monitoring Device

In order to permit observation of the molten droplets that are being tansferred in the pulsed gas metal-arc welding process, the use of high speed motion pictures provides a reliable method. However, practical considerations such as the shortness of actual welding time covered per 100 ft of film combined with the time lag imposed for shipping and processing of the film makes photography a poor tool for continuous monitoring purposes.

In view of these considerations, an optical arc monitoring device* was assembled which projects enlarged arc images on a screen. The presence of a synchronized rotating reticle in the optical path provides a controlled image chopping capability, thus permitting the selection of only the desired parts of the repetitive phenomena in the welding arc area. The use of this device permitted a closer study of the metal transfer characteristics the instant it takes place in a very economical manner.

General Discussion on Current Related Phenomena

Modulated Gas Metal-Arc

In order to affect droplet transfer, the pulse current has to be sufficiently large to pinch off the molten droplet that has been formed at the end of the advancing electrode. One of the counteracting forces is surface tension. Overcoming this surface tension requires a certain amount of current; its level is governed by factors such as

*U.S. Patent 3,526,748.

gas mixture, filler metal characteristics and current wave shape. The presence of residual current ripple—effectively a multiple pulse—aids in keeping the molten metal at the end of the advancing electrode in motion. This contributes to overcoming the surface tension and thus affects droplet detachment during the initial part of the current pulse.

A typical current trace is shown in Fig. 6; the applied frequency in this instance was 30 Hz and the peak current approximately 550 amp. It was observed that the surface tension effect was more pronounced in steel than in aluminum. It was also concluded that I^2R effects play an important part when welding electrically resistive filler metals. As the necking action starts to take place between the molten wire tip and the still solid advancing electrode the transition area is reduced. The weld current passing through this reduced area causes a considerable amount of resistive heating. If the current level is low enough to prevent pinching off by overcoming the surface tension of the molten droplet, the latter will keep growing until forces of gravity finally cause it to detach.

When a current pulse occurs, the pinching effect is greatly increased. The drop is detached and transferred to the weld puddle. The transfer speed is mainly governed by the drop size (mass), the level and duration of the arc current after detachment has taken place. For example, if the formed droplet is relatively large, the required current level and duration to accelerate it into the puddle would have to be proportionally large. Conversely, if the formed droplet is small, the required acceleration current and duration can be much lower.

It has been found that the droplet detachment and acceleration into the weld puddle should preferably take place *before* the current pulse has reached its peak. In actual practice, a combination of parameters was found whereby droplet detachment could be affected on or shortly after the first

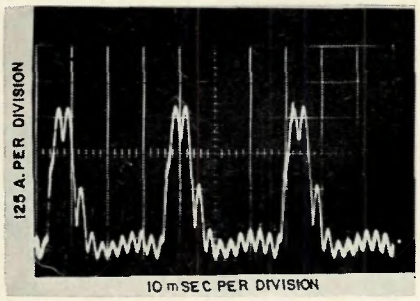


Fig. 6—Gas metal-arc current trace 30 Hz, 185 amp/23v, 550 amp pulse peak

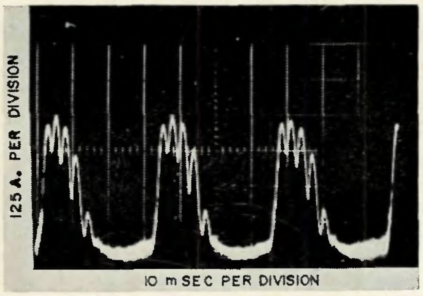


Fig. 7—Gas metal-arc current trace 30 Hz, 185 amp/23v, 475 amp pulse peak and 30 micro Farad added capacitance

current peak occurred—Fig. 6. The second current peak provided the acceleration force and associated directional deposit capability.

The I^2R effects play a much smaller part when welding metals with a low electrical resistivity such as aluminum. This, combined with the very narrow liquid phase temperature range characteristic of aluminum, precludes any appreciable accumulation of molten metal on the end of the electrode. The transferred droplets tend to be small and only very brief necking is in evidence. Additional inductance must be introduced to soften the arc while the pulse amplitude must also be reduced as compared to the amplitudes used for welding steels.

The addition of capacitance across the secondary of the coupling transformer (Fig. 1) resulted in the suppression of both the current level and the residual ripple as indicated in the 30 Hz applied pulse frequency current trace shown in Fig. 7. Premature droplet detachment, which occurs more readily when welding aluminum than steel was successfully prevented in the manner described.

Modulated Gas Tungsten-Arc

It was considered of prime importance to be able to create narrow, high amplitude current phase. In this manner, advantage can be taken of favorable arc characteristics associated with high weld currents *without appreciably increasing* the average current level and without causing pulse frequency restrictions in the 3 Hz region of the frequency spectrum.

Figures 8 and 9 show current traces when a pulse frequency of 3 Hz was applied. The gated pulses derived from half wave 60 cycle (line) pulses are used to drive the magnetic amplifiers in the weld power supply. The ability of selecting a plurality of such pulses by changing the gate width provided the capability of creating current pulses with different durations.

Figure 8 shows the current trace obtained with a single $^1/_2$ wave, and Fig. 9 illustrates how two successive control pulses cause the broadening of the weld current pulse. As the pulse frequency was increased it was found to be more advantageous to use narrow pulses in order to keep the average applied welding current down.

Figure 10 illustrates a typical current trace when the pulse frequency was increased to 12 Hz.

Modulated Plasma Arc

The application of modulated energy to the plasma-arc process was investigated in a very cursory manner. Pulse frequencies of 3 and 6 Hz were both applied. It appeared that the 6 Hz frequency was to be preferred. This is possibly due to the higher travel speeds and keyholing phenomena of the plasma arc process as compared to the gas tungsten-arc. Figure 11 illustrates a typical current pulse trace at a frequency of 6 Hz.

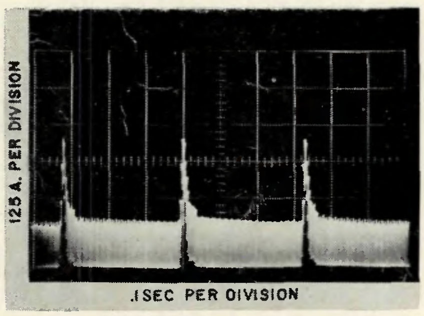


Fig. 8—Gas tungsten-arc current trace 3 Hz, 143-154 amp/13v, 450 amp pulse peak

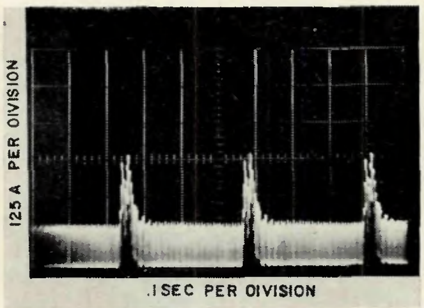


Fig. 9—Gas tungsten-arc current trace 3 Hz, 130-145 amp/13v, 400 amp pulse peak

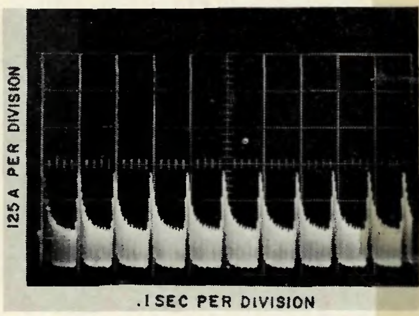


Fig. 10—Gas tungsten-arc current trace 12 Hz, 132-135 amp/13v, 350 amp pulse peak

Application of the Modulated Gas Metal-Arc Process

Arc Study

High speed photography and the optical arc monitoring system were used to observe the effects of parametric variations on pulsed gas metal-arc droplet transfer using a steel electrode (A632 wire on HY-80 steel).

It was noted that the pulse amplitude to average current ratio has a significant effect on the size, number, and velocity of droplets per pulse. A high-amplitude pulse results in the formation of many droplets. The size of the initial droplet per pulse is mainly determined by the amount of preheating which has taken place prior to the pulse and only to a minor degree by the pulse amplitude. Lower pulsing frequencies (30 and 20 Hz as opposed to the more conventional 60 Hz) cause the first detached droplet to be considerably larger for a given pulse amplitude/average current ratio. This is due to the longer preheat time between pulses.

After the first droplet is detached, the remainder of the pulse energy is applied to additional preheating and droplet transfer. Therefore, the subsequent droplets tend to be progressively smaller until the peak of the pulse has passed. Droplets which are detached while the current amplitude declines tend to become slightly larger than those detached at the peak current level.

The precise selection of moderate amplitude pulses can result in a single droplet transfer per pulse. Lower pulse peak values will tend to result in some skipping, i.e., on some pulses no droplets will transfer at all. In brief, the popular concept that one droplet is transferred per pulse in pulsed arc welding has been shown to be the exception rather than the rule. Only by a precise selection of welding parameters can this be achieved and such settings do not appear to be optimum for the process.

As noted before, the larger the droplet, the slower its transfer velocity. Hence, during a single high-amplitude pulse, the succeeding small, higher velocity droplets catch up with the first large droplet in flight. It was also seen, however, that under certain circumstances one or two of the last detached droplets lost almost all speed and did not reach the weld puddle until the accelerating force of the next pulse had been brought to bear on them.

It can be concluded that droplet velocity is directly proportional to the current amplitude after detachment due to the associated pinch effect. The higher the pinching force the less molten metal can accumulate at tht end of the electrode and hence the smaller and faster the transferred droplet.

Small and fast droplets result in better directionality, i.e., the droplets exhibit very little variation from a straight line projection of the electrode. Macroscopic examination showed that the higher the pulse (and resulting pinch force) the narrower and more crowned the weld beads tend to be. Penetration is characterized by a papillary, but porosity free welds are readily attained.

The degree of papillary appears to be a function of both pulse peak and background amperage values. The papillary tends to be greatest when high peak/low background conditions are used. This is because negligible droplet growth occurs between pulses and the early strength of the high amplitude pulse quickly pinches off a relatively small high velocity droplet with attendant penetrability. Conversely, a high background current will cause substantial inter-pulse droplet growth and a lower amplitude pulse will not detach it with as great a velocity.

One can also speculate of the interrelationship and effects of pulse peak/background current/pulse frequency ratios on weld metal properties. A. A. Smith, of the British Welding Research Association[1] has reported that the reactive additions of Co_2 or O_2 to the inert argon shielding gas will alter the weld metal chemistry due to their oxidizing effect. He further stated that "Welding conditions can also alter the chemical composition of the weld metal since it is postulated that the reactions are largely only taking place whilst the droplet of molten metal is actually on the wire tip and that metal-gas reactions whilst in the arc volume or weld pool are negligible."

It is likely then, that the retention of reactive elements such as carbon, aluminum, zirconium, titanium, silicon, vanadium, manganese and columbium could differ significantly in welds made with different pulse frequencies. Larger volumes of metal are transferred per pulse at lower frequencies. Therefore, if the current is kept sufficiently low between pulses, a minimum of molten metal will be at the anode electrode tip between pulses. The electrode behind the tip is preheated by the I^2R effect. A relatively large volume of metal can thus be quickly detached during the pulse which would be free of any oxidizing reaction due to lack of sufficient time for equilibrium at the "active" anode tip. This potential aspect of pulse arc welding is presently being explored as part of an Air Force sponsored pulsed arc research study.[2]

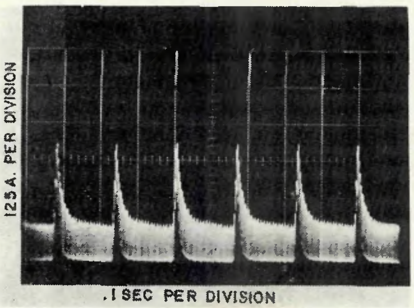


Fig. 11—Gas tungsten-arc current trace 6 Hz, 125-133 amp/½v, 430 amp pulse peak

Shielding Gas Study

Experimentation with various argon/argon-helium shielding gas compositions did not indicate sufficient arc stability for the acceptable pulsed arc welding of steel. It was determined that a 5% CO_2 or 1% O_2 addition to argon gas was necessary. The effects of these gas compositions were studied with high-speed photography. It was noted that CO_2 additions were responsible for minute gaseous explosions within the arc but that these explosions did not result in any noticeable spatter or porosity in the welds. A 1% O_2 addition resulted in a smoother acting arc column and also produced weld beads free of spatter or porosity at frequencies ranging from 15-60 Hz.

It was found that a CO_2 addition to the shielding gas permits maintenance of a shorter stable arc length for a given amperage/electrode feed speed than with oxygen additions. This enhances penetration, wetability and hence, fusion in tight corners of low included angle weld joints.

Good arc stability was obtained for aluminum welding with argon, argon—0.3% O_2 and argon-helium mixtures up to 50% helium.

Joint Geometries in Thick Sections

The pulsed gas metal-arc is capable of producing a "spray like" transfer at relatively low amperages. This is of great importance in the welding of thin sections. In order to weld thick sections at these same low amperages, a 70 deg included angle bevel has been recommended to avoid lack of fusion defects. A weave technique has also been incorporated to make excellent out of position welds with the aforementioned low amperage/wide angle joint conditions.

The difference between "threshold" currents for the pulsed gas metal-arc process and the conventional gas metal-arc process is substantial. A spray-like transfer of 0.045 in. diameter steel electrode can be affected with pulsing at approximately 110 amp whereas the conventional gas metal-arc process requires approximately 210 amp. It is reasonable to assume that intermediate weld parameters (amperage/electrode feed speed) can also be used to advantage for out of position welding which enables tighter weld joint geometries to be used. This was ultimately proven by successfully welding 1 and 2 in. thick steel sections from one side in a 20 deg included angle joint which had a root opening of $^3/_8$ in.—Fig. 12.

The following conditions were found necessary for successful mini-joint welding:

1. A $1^3/_4$ in. long piece of $^1/_2$ in. copper tubing, brazed to the end of a conventional torch barrel was used to provide the necessary shield gas coverage and also sufficient access and maneuverability in the weld joint—Fig. 13.
2. A root opening of $^3/_8$ in. was necessary so that split stringer beads could be deposited in the root of the weld. Amperage/voltage settings up to 165 amp/26 v were used for vertical up welding. For overhead welding, the range was extended to 180 amp/26 v. Bead width was kept small in order that the heat of the arc could be concentrated on a narrow zone. Good fusion and quick travel speeds could thus be attained. Any welder who was capable of semi-automatic welding had little trouble with this technique, since no significant weaving was employed.
3. CO_2 was added to the argon shielding gas for better fusion and wetability, as described above.

Subsequently, 1 in. thick plates were successfully welded in triplicate to prove reliability for each of the following alloy/position combinations:

1. High tensile steel—vertical up position.
2. High tensile steel—overhead position.
3. HY-80 steel—vertical up position.
4. HY-80 steel—overhead position.

Due to material limitations, only one 1 in. weldment was made of HY-130/150 in each position. A basic difference in the procedure was to use M-1 (1% oxygen) shielding gas with a 5% CO_2 addition rather than pure argon. This was found necessary to improve the wetting action of the molten metal. The low wetability is attributed to the greater purity of the high strength welding electrode.

The major conclusion is that pulsed gas metal-arc welding can be used out of position in joints which are significantly smaller than 70 deg. It is not intended that 20 deg included angle, $^3/_8$ in. root opening joint be construed as optimum, but it is proof that pulsed arc gas metal-arc welding need not be limited to low amperage/low wire feed parameters in large volume joint preparations. Others at Electric Boat division have successfully used the "mini-joint" technique in 40 deg included angle joints with little or no root openings.

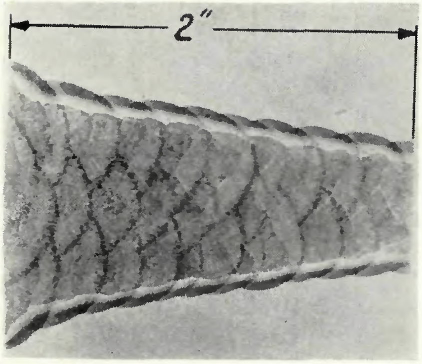


Fig. 12—"Mini-joint" weld in HY-80 steel

Selection of an optimum joint geometry is naturally prejudiced by the fabricator's desire to minimize metal deposition and distortion. To this end, "mini-joint" welding is quite advantageous. However, the narrower and deeper the joint, the more likely a problem with arc-blow and the more difficult interpass cleaning or repair becomes. Arc-blow was experienced in the laboratory when a 2 in. weldment of HY-130/150 (with the 20 deg joint geometry, stringer bead technique) was attempted. A 60 deg bevel weld was successfully completed in the same alloy and thickness without any arc-blow problems. Also, 20 deg bevel weldments were successfully made in 2 in thick HY-80 steel. Thus, the desire to minimize joint geometries must be tempered by experience and appreciation of the inherent complications.

Application of the Modulated Gas Tungsten-Arc Process

Low frequency gas tungsten-arc pulsing (3, 6 and 10 Hz) was first applied in conjunction with a fixed position pipe welding experiment. It was demonstrated that pulsing yielded greater control of the weld puddle, particularly for out of position welding. This resulted in excellent I.D. contour control during root pass welding. It is felt that the rapid solidification of the weld metal between pulses is largely responsible for the increased deposit.

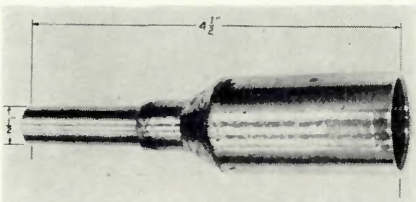


Fig. 13—Modified torch barrel for "mini-joint" welding

Dr. W. F. Savage and his associates at RPI have contributed greatly to the science of welding[3-5] and, in particular, provided a basic understanding of fusion zone solidification mechanics. In evaluating low frequency (3-10 Hz) current pulsing for the gas tungsten-arc process, it became obvious that sufficient time elapsed between pulses to cause the weld puddle to expand and contract proportionately with the magnitude of the applied current. This in turn suggested that low frequency pulsing could be used as a positive control of the solidification mode in which a higher, or more favorable $(G/(R)^{1/2}$ ratio (where G = the temperature gradient in the molten weld puddle and R = the rate of crystallographic growth) could be generated by virtue of the alternately hot and relatively cold tungsten arc.

It was felt that a judicious selection of pulse amplitude to background current ratio, pulse shape, and pulse frequency would help to optimize gas tungsten-arc welding procedures and result in one or more of the following fusion zone benefits as suggested by Savage et al.:

1. Reduction of microporosity.
2. Reduction in the degree of alloy segregation.
3. Reduction in tendency for dendritic growth to occur.
4. Reduction of the superheat meltback region due to an increase of puddle agitation and a reduction of lamellar flow at the edges of the weld puddle.
5. Reduction in the tendency for hot-cracking.

To date, it has been established that the pulsed gas tungsten-arc process can reduce the tendency for hot-cracking. The Varestraint test was used for this determination.

Materials used in this investigation were 2 x 12 in. strips of:

1. 0.090 in. 4130 steel.
2. 0.090 in. D6AC steel.
3. 0.250 in. 9Ni-4Co-.25C steel.
4. 0.500 in. 2014-T6 aluminum.

Parametric variables such as shield gas composition and flow rate, voltage, amperage, travel speed and radius block over which the specimens were bent were adjusted to produce a low, but significant degree of cracking under conventional gas tungsten-arc welding conditions. Specimens were tested in triplicate and then 3 more series of triplicate tests were made using pulse frequencies of 3, 6 and 10 cps. All variables (volts, average amperage, travel speed, radius block,

Table 1—Average Crack Lengths and Pulse Conditions

Alloy	Avg. crack length for condition shown, in. No pulse	3 Hz	6 Hz	10 Hz
0.090 in. 4130	0.093	0.064	0.045	0.081
0.090 in. D6AC	0.083	0.053	0.087	0.075
0.0250 in. 9Ni-4Co-.25C	0.075	0.053	0.053	0.070
0.500 in. 2014 aluminum	0.320	0.205	0.226	0.265

etc.) were kept identical to the control series for each alloy. Pulse peak to average current ratios were kept constant for all three frequencies and a controlled pulse width was used throughout. All specimens were prepared for crack measurement by etching the weld bead surface to reduce the oxide coating and glare. Crack measurements were made at 40× magnification with a calibrated filar eyepiece.

Average crack lengths (per specimen) for each alloy and pulse condition are presented in Table 1.

Examination of the data shows that the conventional or non-pulsed welds cracked to a greater extent than the pulsed welds in all but one case. Pulsing at 6 Hz in D6AC resulted in a larger average crack length than its non-pulsed counterpart specimens. However, this was largely due to one (6 Hz) specimen which cracked far more than any of the other 11 D6AC specimens.

Furthermore, pulsing at 3 cps showed the lowest incidence of hot cracking in 3 of the 4 alloys tested; the only exception being the 4130 alloy where a pulse frequency of 6 cps appeared best.

It should be emphasized that this investigation was extremely cursory in nature and conclusions must thus be tempered with caution. The results, however, do strongly indicate that:

1. Low frequency pulsing of the power source can reduce the hot cracking tendency of the four tested alloys and presumably many others.

2. Maximum benefit can probably be gained from pulsing at 6 Hz or lower.

The encouraging results of the Varestraint test have prompted further efforts to establish the effect of low frequency pulsing on the mechanical properties of weldments. This program is being conducted concurrently with the Laboratory's Air Force sponsored pulsed arc research program. Results are expected to be published at a later date.

Application of the Modulated Plasma Arc Process

Although the investigation[6] was very limited in scope, it was demonstrated that the modulated plasma arc process appears to provide some worthwhile advantages. They are:

1. Increased parametric tolerance level.

2. Capability to maintain a smaller keyhole.

3. Improved underbead contour.

4. Stiffer, more defined plasma columns for the average applied current level.

5. Deeper penetration capability for an average applied current level.

Conclusions

Equipment

This program resulted in the design and construction of a versatile, multipurpose, low-cost add-on pulse control system which, in conjunction with commercial type weld power supplies, is applicable to the gas metal-arc, gas tungsten-arc and plasma arc processes.

Processes

The modulated gas metal-arc process using the described equipment provides an economical means of producing high quality weldments in all positions. The attendant highly directional deposit capability permits consumable electrode welding of narrow joint configurations. These combined capabilities also permit the substitution of a large number of manual production welding practices with faster, more economical mechanized and/or automatic weld techniques.

Gas Tungsten-Arc. The modulated gas tungsten-arc process enhances the non-consumable electrode capability for all position welding. It improves process capabilities as evidenced by improved weld bead uniformity, consistency of penetration, grain refinement and reduction of hot cracking tendency. In certain applications a reduction in average weld current level (heat) requirements can be realized.

Plasma Arc. This cursory investigation provided a number of favorable observations. The most significant ones appear to be the ability to maintain more accurate control of the underbead contour and the broadening of parametric tolerances.

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Technical Note: Fatigue Crack Propagation in Zircaloy-2 Weld Metal

(*Continued from page* 206-s)

plate-bending machine modified to accept a three-zone, split-shell resistance furnace. Surface strain was measured during the first few cycles of each test using elevated temperature strain gages. The specimens were cycled at a rate of ~700 per minute.

It should be noted that since the primary emphasis in this investigation was placed on determining the conventional fatigue properties of the material, the specimens were designed for that purpose. The use of this specimen design and loading mode is not conducive to fundamental studies of crack propagation because of the difficulties associated with analysing and interpreting the varying strain field as the crack penetrates the specimen.

The crack propagation data collected during this investigation were obtained using visual measurements made with a × 20 telescope having a resolution of about 0.001 in. The measurements were made through a viewing port in the furnace on only the upper side of the specimens. Cycling was stopped while an observation was made.

For the type of specimens employed, initiation and propagation of cracks was limited to two positions on the hole periphery, thus restricting the area to be watched. Surface-crack length, load, and number of cycles, were recorded periodically during testing. Observations were performed approximately every 5–10% of life-to-specimen rupture.

Typical crack propagation data which were collected are shown in Fig. 2. These data are reported in cycles versus a normalized total surface crack length, obtained by dividing the total surface crack length ($2a$) into the specimen width (w) at the cross section of the hole-type notch. The total crack length is a summation of the hole diameter and the crack lengths extending radially from each side of the hole perpendicular to the applied stress. The raw data were least-squares fitted to produce best-fit smooth curves for use in calculating fatigue crack growth rates. The corrections of the raw data by these manipulations were slight. At selected values of cycles, the equations for the smooth curves were differentiated to obtain da/dN, the fatigue crack growth rates.

For the conditions of these tests where there was a substantial amount of gross plastic strain, it appeared reasonable to assume that the growth of the fatigue cracks was governed primarily by the applied plastic strain and not by the stress field at the crack tip, as required by the linear elastic fracture mechanics criterion. The correlation of the crack growth data on the basis

(*Continued on page* 234-s)

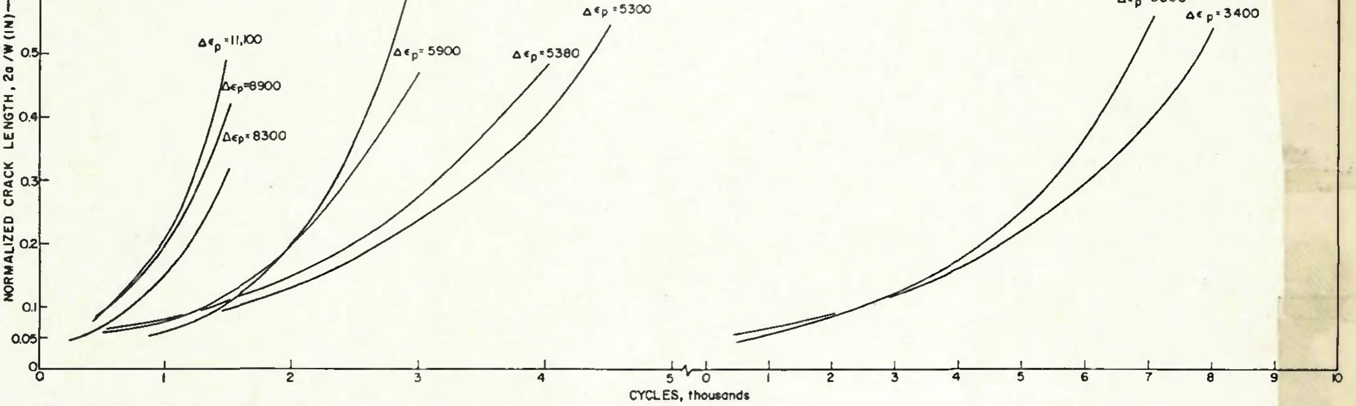

Fig. 2—Crack growth curves for Zircaloy weld metal