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THE INERT-GAS-SHIELDED METAL-ARC WELDING OF TITANIUM

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ORNL-2612

Contract No. W-7405-eng-26

METALLURGY DIVISION

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DATE ISSUED

FEB 16 1959

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THE INERT-GAS-SHIELDED METAL-ARC WELDING OF TITANIUM

E. A. Franco-Ferreira and P. Patriarca

ABSTRACT

A program was initiated by the Welding and Brazing Laboratory to study the inert-gas-shielded metal-arc welding of titanium. The basic incentive for this work was provided by the possibility of remotely repairing the leak in the Homogeneous Reactor Test core tank.

The body of the program consisted mainly of developing welding procedures for the single-pass full-penetration square butt welding of 1/4-in.-thick titanium plates in the downhand position. It was expected that the results would be applied similarly to the welding of Zircaloy-2.

Successful welding procedures were developed. The results were consistent, and various tests affirmed the excellent quality of the welds.

INTRODUCTION

With the advent of circulating fuel reactors the necessity for remote means of maintenance has become pressing. The Welding and Brazing Laboratory of the Oak Ridge National Laboratory's Metallurgy Division has surveyed the particular remote-welding needs existing at ORNL. The results of this survey have previously been reported.[1] Based on the survey, the Welding and Brazing Laboratory proposed an experimental program[2] aimed at fulfilling the remote-welding requirements at ORNL. In essence, this program consists of investigations of the welding variables to be encountered during remote operation. The main purpose of this work is to provide data on which the design of suitable equipment may be based.

The recent appearance of a leak between the fuel and blanket systems in the Homogeneous Reactor Test provided the incentive for a rather specialized series of studies by the Welding and Brazing Laboratory with the express purpose of repairing the leak. If the leak were in the core tank itself, it was considered possible for it to have any one of a number

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[1] E. A. Franco-Ferreira, An Investigation of the Applicability of Remote Welding to the Maintenance Requirements at ORNL, CF 57-9-81 (September 24, 1957).

[2] E. A. Franco-Ferreira, Tentative Project Outline for Remote Welding and Inspection Development, CF 57-12-6 (December 3, 1957).

of configurations. These are shown in Fig. 1 (ORNL-LR-DWG 33664) in which (a) represents a straight crack as in a weld, (b) represents a jagged crack, (c) shows a small, regular hole, and (d) exemplifies a large, irregular hole. The possibility of repairing such a failure by welding appeared to be real. Due to the fact that the filler wire feed is directly incorporated in the welding mechanism, it was felt that the inert-gas-shielded metal-arc process offered the most promise.

Figure 2 (ORNL-LR-DWG 33665) shows a number of proposed welding sequences for repairing the defects shown in Fig. 1. The individual and interlocking spots are made with single, short bursts from the welding torch while the single beads and overlays are made with long, continuous passes. Although a fair amount of detailed mechanical design would be required, the proposed method of torch operation, as shown schematically in Fig. 3 (ORNL-LR-DWG 33666), should not offer insurmountable difficulty.

In order to serve its specialized purpose, the experimental work was planned to have several phases. A general outline of this program is shown below.

A. Downhand Welding
   1. Bead-on-plate welds
   2. Single-pass full-penetration butt welds
   3. Spot welds
   4. Weld overlays

B. Position Welding
   1. Butt welds
   2. Spot welds
   3. Weld overlays

It was considered quite probable that during the course of this program the exact nature of the leak would be discovered and that a concerted effort on the repair welding of the specific type of defect would then be undertaken.

This report covers the steps that were taken to develop suitable welding procedures for the first two items under part A above. Since a decision was made early in this program not to attempt to repair the core vessel in any case, the remainder of the work outline was not covered.

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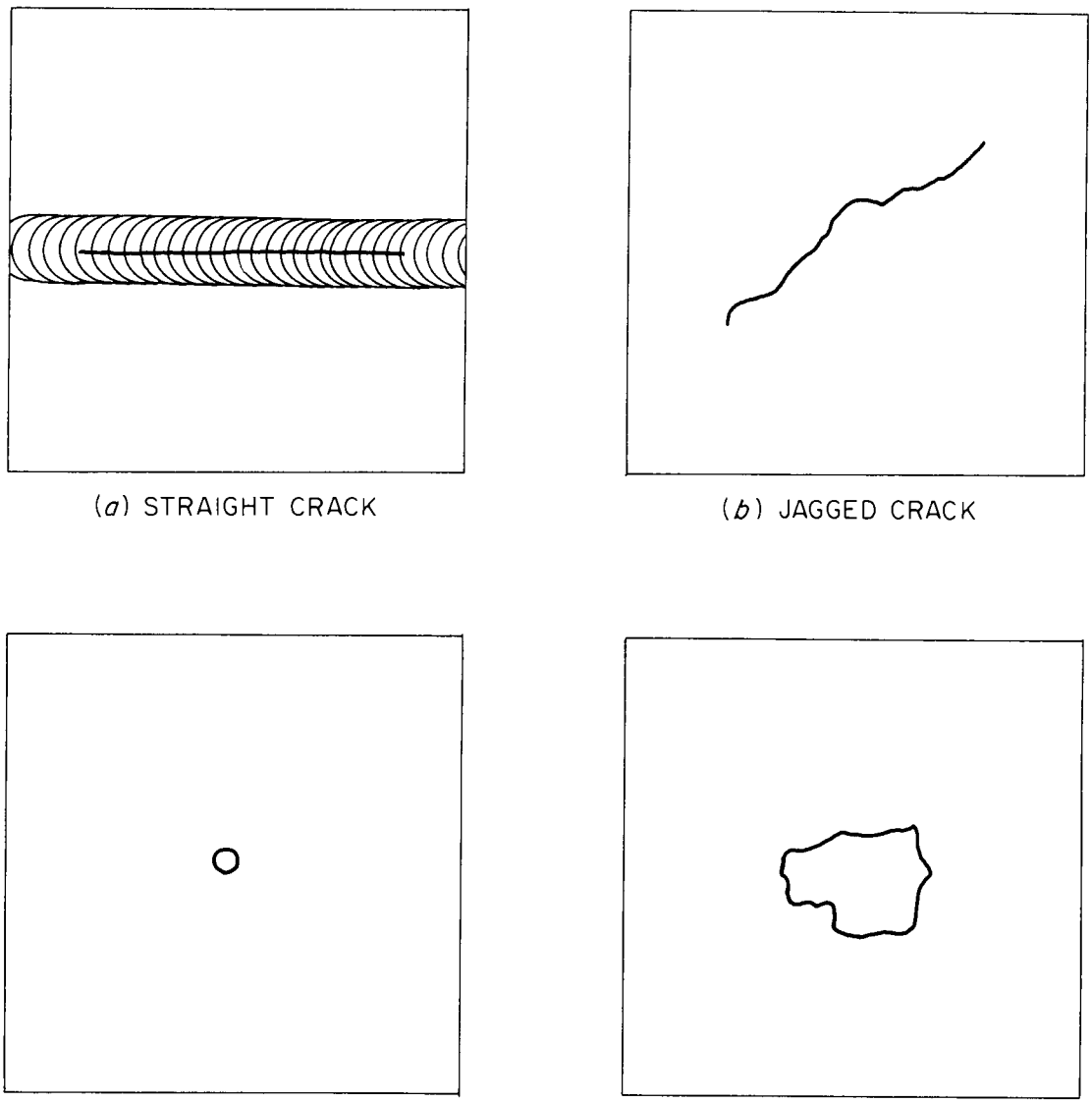

(*a*) STRAIGHT CRACK

(*b*) JAGGED CRACK

(*c*) SMALL HOLE

(*d*) LARGE, IRREGULAR HOLE

Fig. 1. The Various Possible Defects which Could Exist in the HRT Core Tank.

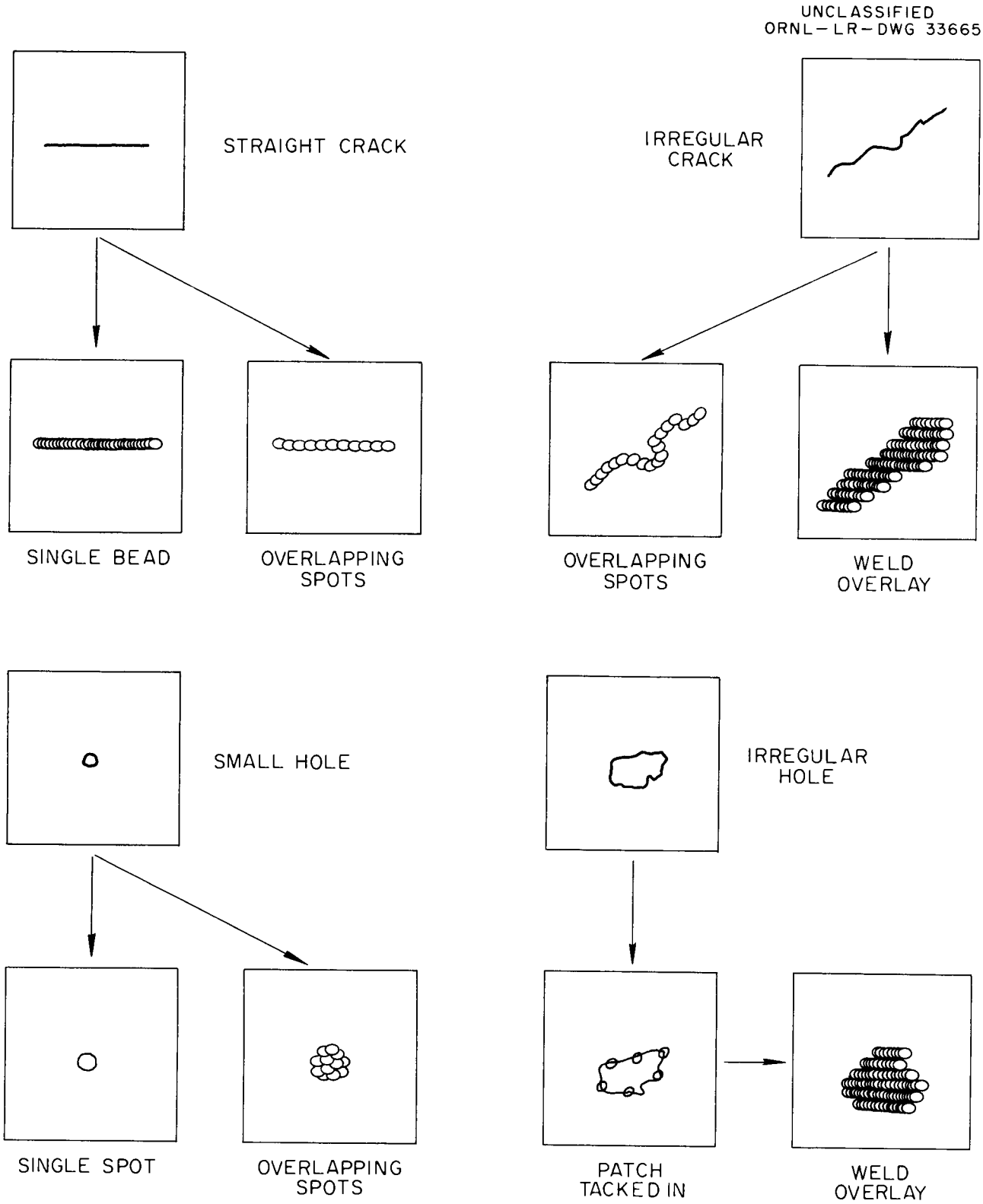

Fig. 2. Possible Methods of Repair Welding the HRT Core Tank Defects.

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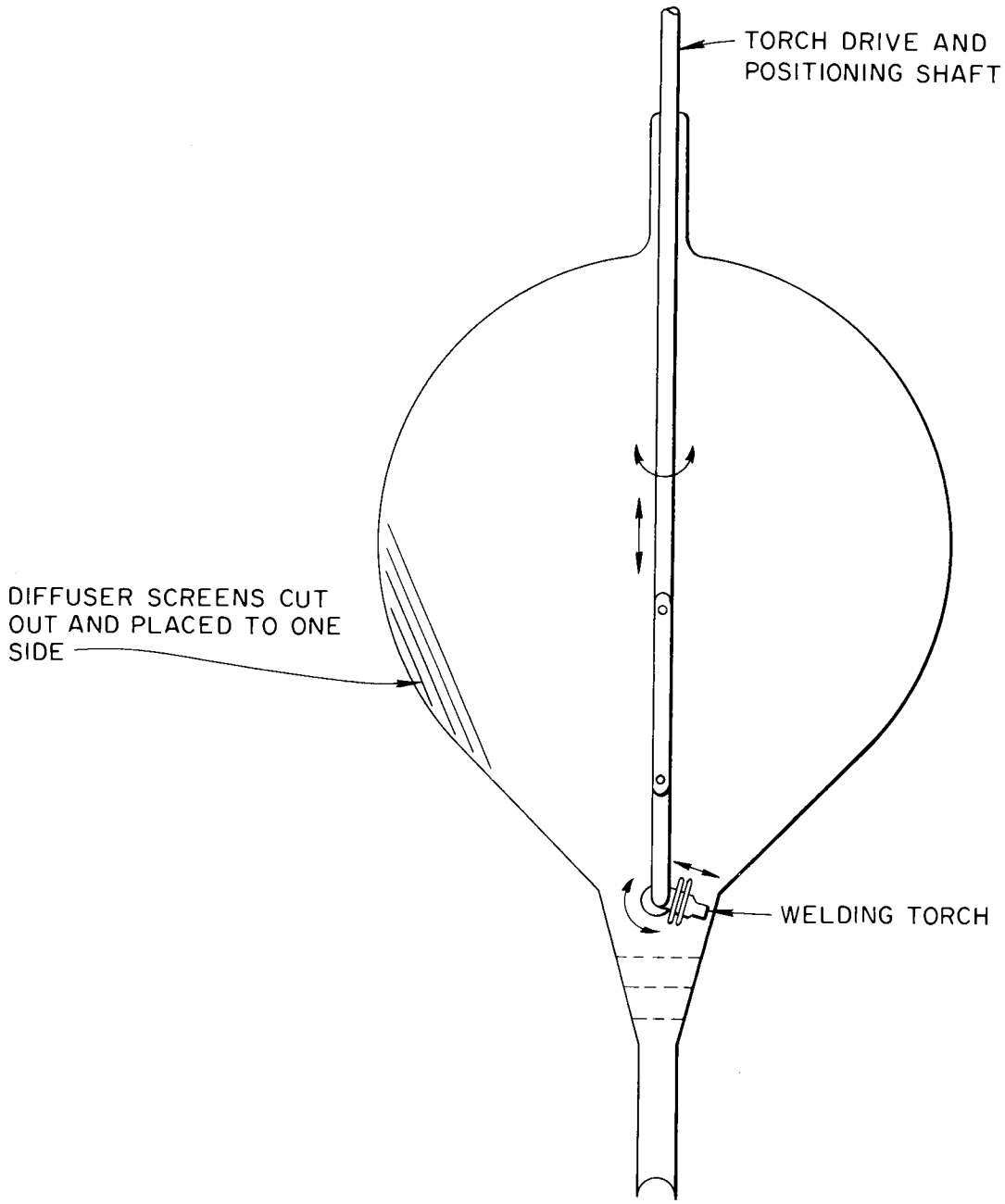

Fig. 3. Possible Method of Introducing a Welding Torch into the HRT Core Tank in Order to Repair the Leak.

Due to the short supply of suitable Zircaloy-2 plate and welding wire, all of the welding covered by this report was done on titanium. It was felt that this decision was justified in light of the reported[3] similarity in weldability of zirconium and titanium. Further work to extend the present results to the welding of Zircaloy-2 should prove to be relatively simple.

The experiments conducted during this study were by no means remote in nature. As stated above, their sole function was to establish suitable welding conditions for the particular process chosen. The implementation of these conditions for remote operation must logically be left to the machine designer. Thus, the results reported herein may be useful in many applications, both remote and non-remote, wherever it is deemed that the inert-gas-shielded metal-arc process should be used.

MATERIALS

All of the welding during this investigation was done on several heats of 1/4-in.-thick titanium plate, grade A55. The as-received condition was hot rolled, annealed, and sand blasted.

The electrode wire in all cases was 1/16-in.-dia high-purity titanium.

No chemical analyses of these materials were made. It was felt that a knowledge of the nominal compositions of the materials used would be adequate for the stated purpose of the study.

The shielding gas used throughout the experiments was tank argon of 99.99% purity. The gas was used as it came from the tank with no intermediate drying operations.

EQUIPMENT

It is possible to group the welding apparatus into four general categories. These are (1) power supply, (2) welding torch complex, (3) electrode feed unit, and (4) instrumentation.

(1) Two power supplies were used at different stages of the work. For operations in the lower current ranges, a rectifier welder with a 300-amp rating was used. This unit had a drooping volt-ampere characteristic. The rectifier was capable of supplying a welding current of slightly more than 400 amp. When higher current values were required, a

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[3] B. L. Baird, "Fusion Welding Zirconium for a Nuclear Reactor," The Welding J., 35(10), 1007 – 1014 (October, 1956).

motor-generator unit of 400-amp rating was used. This power supply also had a drooping volt-ampere characteristic and was fully able to supply the maximum welding current of 470 amp used in the investigation.

(2) The welding torch complex, pictured in Fig. 4 (ORNL 44109), consisted of a torch, a gas shielding trailer, a standard machine carriage, and the holding jig for the work. The torch was a standard hand-type water-cooled torch, mounted for automatic operation. The actuating trigger on the torch was bypassed, and operation was controlled by means of a foot pedal.

Due to the active nature of titanium, high-quality inert-gas shielding was required in order that weld contamination be avoided. To provide this shielding for the face of the weld, a 12-in.-long gas trailer was made. In Fig. 4 the trailer can be seen in position on the torch. Figure 5 (ORNL 44111) shows a more detailed view of the torch and trailer. The two upright tubes at the rear of the trailer are for cooling water. Shielding gas was introduced at two places — through the torch and through the upright tube just to the rear of the torch. The gas in the rear portion of the trailer passed through a diffuser, shown in Fig. 6 (Y-26023), in order to achieve uniform coverage. During operation the lower edges of the trailer were kept uniformly within 1/32 in. of the surface of the work. Inert-gas back-shielding was admitted to the work through a groove in the stainless steel back-up plate.

The work-holding jig is also pictured in Fig. 4. It consisted of a 2-1/2-in.-thick steel strongback, a 1/2-in.-thick stainless steel back-up plate, and two 3/4-in.-thick steel hold-down plates, each secured by two large bolts. A space ~2-1/2 in. wide was left between the hold-down plates for passage of the trailer shield.

(3) The electrode feed unit is shown in Fig. 7 (ORNL 44112). It was a standard unit normally supplied with the torch which was used. In essence, the unit consisted of a reel for the electrode wire, variable speed drive rolls for feeding the wire, and control circuitry.

In the lower central part of Fig. 7, the water circulating system, which maintained the torch and trailer cooling water at room temperature, can be seen. This was found to be an important factor in avoiding the condensation of moisture inside the torch on a humid day.

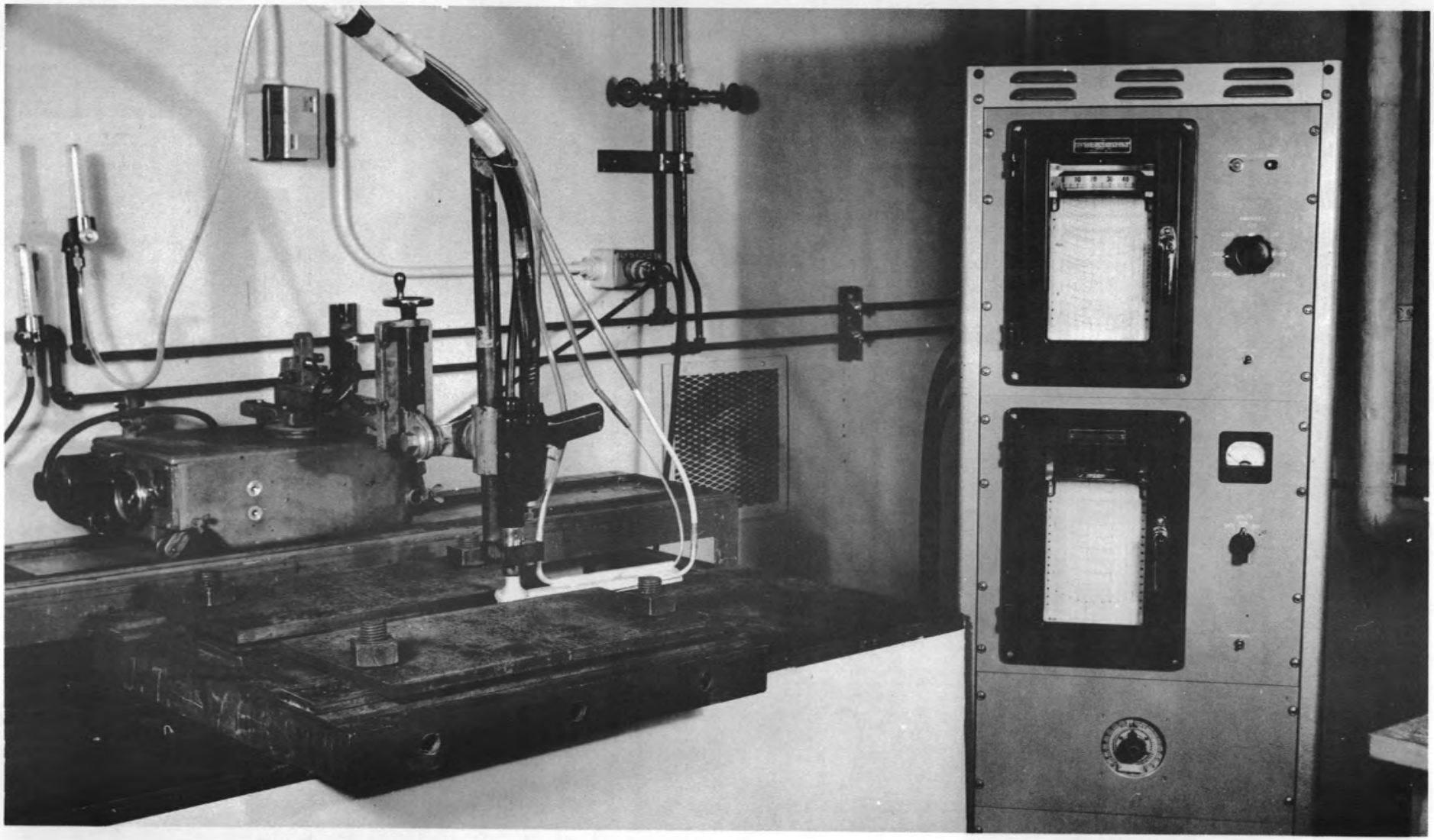

Fig. 4 (ORNL-44109) Over-all View of the Welding Torch and Instrumentation Setup.

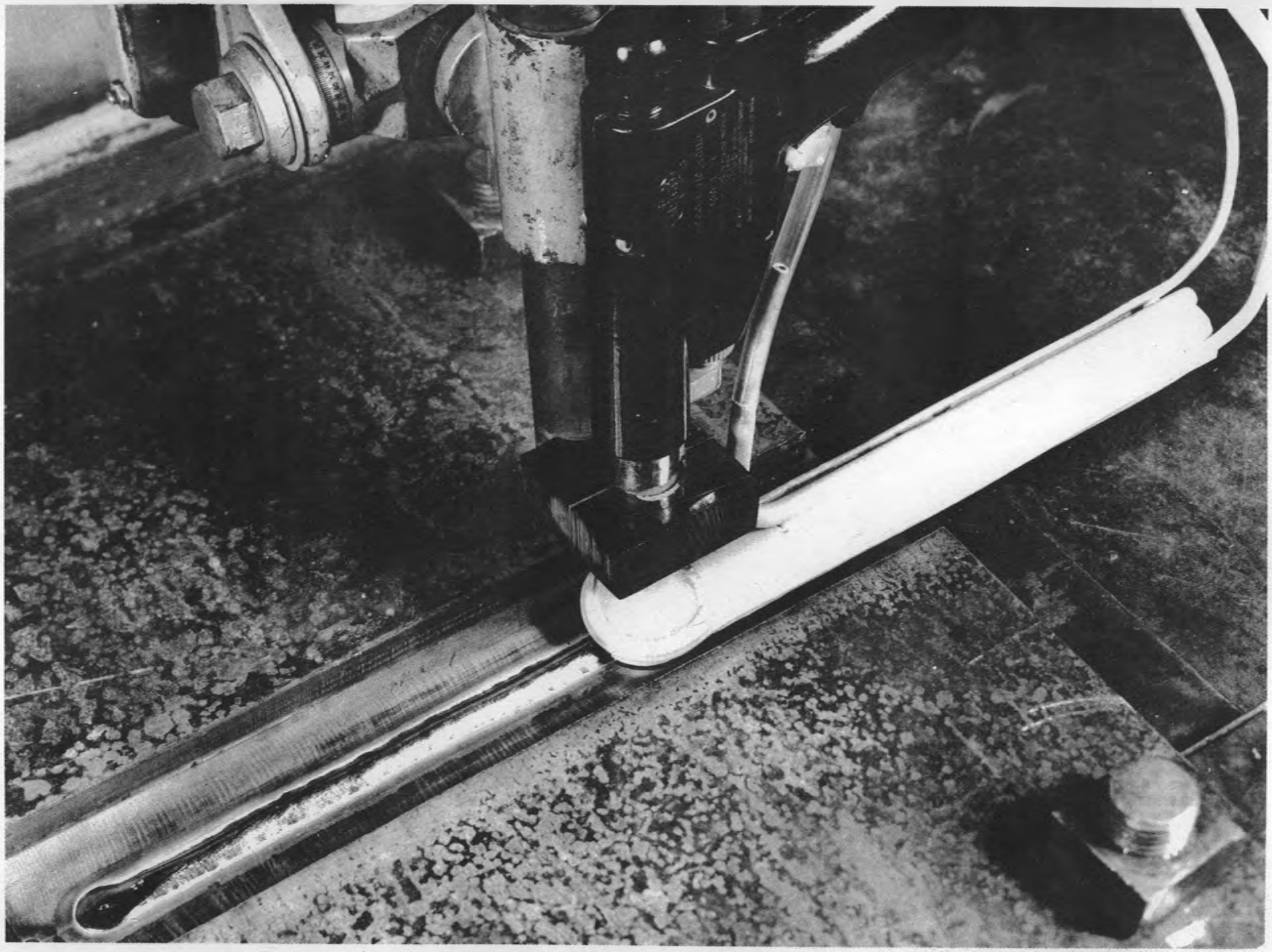

Fig. 5 (ORNL 44111) Detailed View of Torch and Trailer Shield With a Completed Weld in Place in the Hold-Down Clamps.

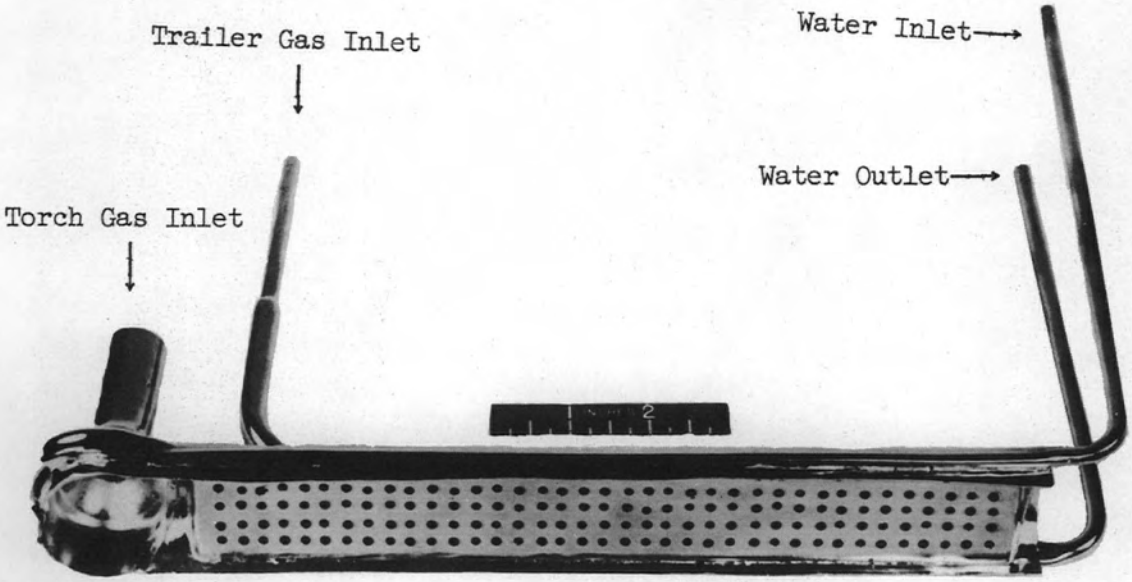

Fig. 6 (Y-26023) Underside of Trailer Shield, Showing Gas Diffuser.

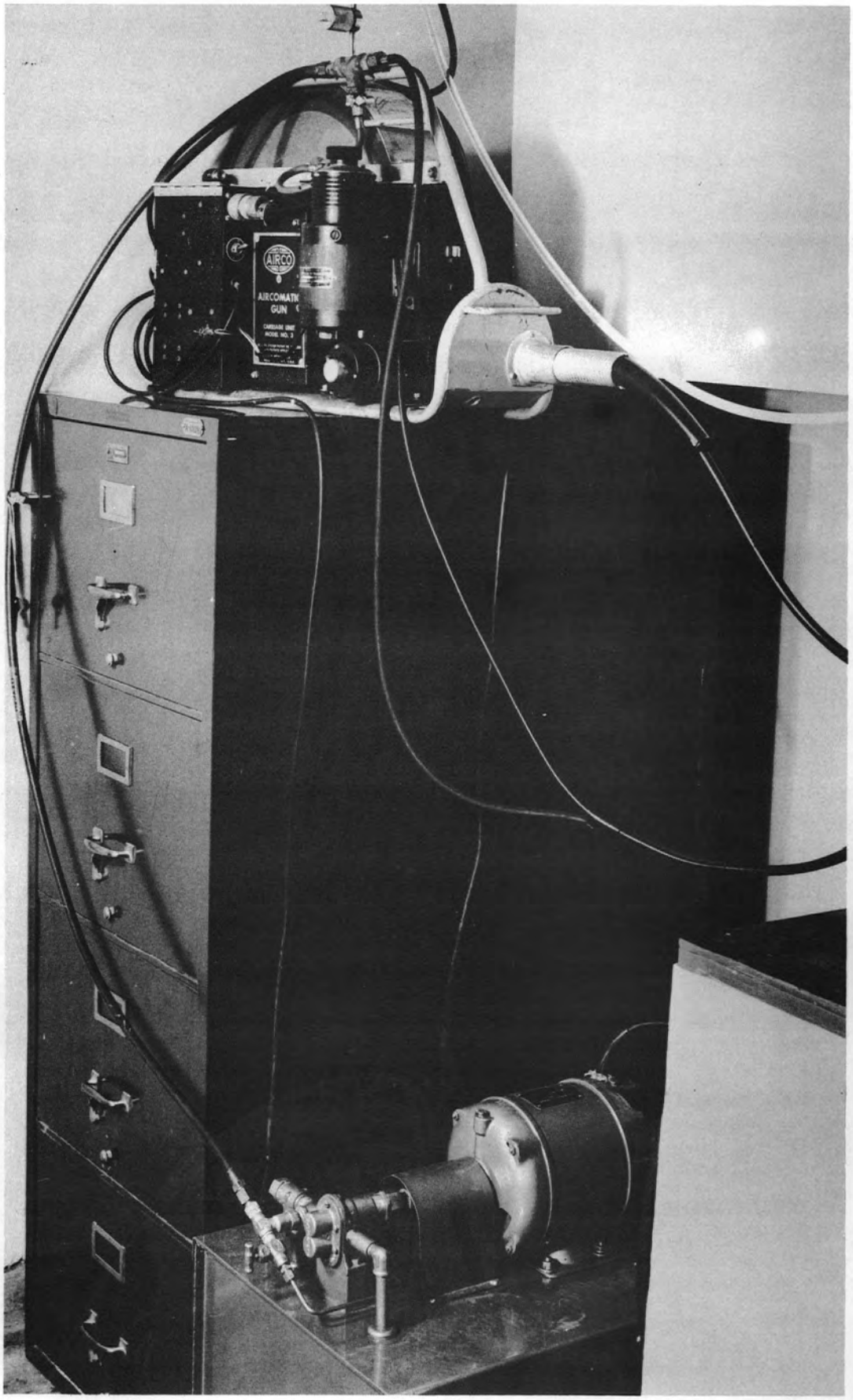

Fig. 7 (ORNL-44112) Wire Feed Unit and Cooling Water-Circulating Pump.

(4) The instrumentation consisted of a recording voltmeter and ammeter, shown in Fig. 4, and flowmeters for the shielding gas. The variables of wire feed speed and welding speed were set according to graduations on their respective dials. These dials were calibrated prior to the experimental runs and checked periodically during the investigation.

EXPERIMENTAL PROCEDURES

The use of the consumable-electrode inert-gas-shielded welding process involves a relatively large number of variables. Some of these have a direct effect on the successful operation of the process while others have marginal effects on weld quality. The variables include (1) welding current, (2) welding speed, (3) electrode feed speed, (4) electrode wire size, (5) arc length, (6) distance between the end of the contact tube and the work, (7) type of metal transfer, (8) shielding gas coverage, and (9) specimen cleaning procedure. Numbers (1) through (7) are all, to some extent, interrelated and apply directly to the welding process while numbers (8) and (9) affect weld quality without affecting the welding process to any great degree.

No attempt was made to investigate fully the effects of changing all of the above listed variables. Consequently, reasonable estimates were made for some of the welding parameters, and if the results were satisfactory these parameters were left unchanged. The mode of operation in this program was that of determining the suitable combination of welding conditions required for satisfactory, full-penetration butt welds.

The initial work took the form of bead-on-plate studies. These were used to establish conditions of deep penetration and good arc stability without the need for any joint preparation. In addition, the beads-on-plate allowed a determination of the optimum gas-shielding practice. Only when it was deemed that satisfactory penetration and good arc stability had been obtained did the work proceed to the welding of actual joints.

A stable arc is of great importance in the production of a high-quality weld, and it is thus important to consider the conditions required for arc stability. Two types of metal transfer are possible with the inert-gas-shielded metal-arc-welding process. These are droplet and spray transfer. The former is undesirable and is characteristic of an unstable arc. A

governing factor in determining the type of metal transfer is current density. For some minimum current density the metal transfer will change from drop to spray and will remain of spray type as the current density is further increased. Since current density depends upon welding current and electrode diameter, there are two means of affecting it. However, since the electrode diameter was fixed at 1/16 in., current density could be affected only by changes in current, which was varied between the limits of 315 amps and 470 amps. The resulting current densities ranged from 103,000 amp/in.^{2} to 153,500 amp/in.^{2}, and in all cases the current was d-c reverse polarity.

Welding speed normally has two effects. It will determine the effectiveness of the shielding gas coverage, and in conjunction with welding current, it governs the energy input per unit length per unit time into the work. Due to the use of a trailer shield in these experiments, gas coverage was made relatively insensitive to welding speed. On the other hand, the rate of energy input as it affects penetration is an important consideration, and for this purpose welding speed was varied from 25.0 in./min to 49.0 in./min.

The electrode feed speed or burn-off rate must be balanced with the welding current. Once this balance has been established for a given current, the arc will be self-regulating as long as a constant feed rate is maintained. This phenomenon results from the drooping volt-ampere characteristic of the power supply, which automatically adjusts the burn-off rate to maintain a constant arc length. During this study in order to balance the various current values which were used, the electrode feed rate was adjusted between the limits of 312 in./min and 488 in./min.

The distance between the end of the contact tube and the work also has an effect on arc stability. This distance must be such that a sufficient length of electrode wire is preheated by its own I^2R losses before it reaches the arc. If this preheating does not occur, arc spatter will result. On the other hand, if the distance between the contact tube and the work is too great the arc will tend to wander. Some experimentation was required to arrive at a proper value for this parameter.

Inert-gas coverage for the welds was maintained by three separate flows of argon. The first flow was through the torch and into the cup immediately surrounding the electrode and arc. The trailer shield was fed

by a separate stream of argon, and the back sides of the welds were shielded by yet another argon supply. A few initial tests were run to determine satisfactory flow rates for the gas, and once this was established the values were used throughout the experiments. In all cases the three gas systems were purged with high argon flows for a minimum of 30 sec before welding.

As with other reactive materials, the cleanliness of the work prior to welding is of great importance. Since small amounts of contaminants will exert a rather large effect on weld quality in titanium, all pieces were thoroughly cleaned prior to welding.

As stated above, the bead-on-plate studies were made to determine the optimum welding conditions. These welds were made on the same 1/4-in.-thick material which was to be used for the joint studies. Arc stability was determined by a visual examination of the arc during welding. Weld quality was evaluated by examining the surface contour of the weld bead for smoothness and uniformity. Radiography was used to detect porosity. The effectiveness of the inert-gas shielding was evaluated by inspecting the surface of the weld for discoloration and by making a microhardness traverse of a transverse section of the weld. Finally, the depth of penetration was measured by examining a transverse section microscopically.

The butt joints were made in 1/4-in.-thick plate that was 12 in. long and of varying widths. The plate edges were square and the joint gap was held as near to zero as possible. Edge preparation took two forms, as-sheared edges and milled edges. The sheared edges provided a slight vee at the joint and made it easier to get full penetration than with the perfectly square milled edges. Prior to welding the plates were tacked together by inert-gas-shielded tungsten-arc welding. This tacking was found to be necessary when it was observed that the hold-down plates were unable to prevent a slight spreading of the last part of the joint to be welded.

Weld evaluation was similar to that used for the bead-on-plate studies. The arc was observed for stability. Weld contour, both on the face and root of the weld, was evaluated. Radiography was used to detect porosity. All welds were examined for discoloration and microhardness traverses were made. The mechanical properties of representative welds were evaluated by room-temperature longitudinal guided bend testing and by room-temperature

transverse tensile testing. The bend specimens were machined flat on both faces and the position of the weld was determined by a macroetch. Tensile specimens of the type shown in Fig. 8 (ORNL-LR-DWG 33667) were machined from a welded sample plate with the weld in the middle of the gage length.

OBSERVATIONS AND RESULTS

The initial efforts during the bead-on-plate work were directed at achieving a stable arc. As indicated earlier, arc stability was judged by observing the arc in action and by examining the surface contour of the completed weld. During operation a stable arc is characterized by a constant arc length, a minimum wander, and a spray-type metal transfer. These were the features that were sought during visual observation of the arc. The variables affecting arc stability were electrode feed rate, welding current, and contact tube spacing.

It has been shown[4] that at some minimum current density varying with both electrode size and composition, metal transfer changes from large globules to a spray of fine droplets. This behavior was readily observable, and the parameters were adjusted until spray-type transfer was consistently obtained. Due to the characteristics of the power supplies that were used, it was established[5] that a given wire feed rate was useful over a relatively narrow current range. Thus, in order to achieve a spray-type transfer by increasing the current density to a suitable value, the wire feed rate also had to be changed in some cases. The values of current and wire feed rate, as they were found to affect arc stability, are summarized in Table I.

With the drooping characteristic power supply, the arc length for a given wire feed rate depended upon welding current. The arc length was variable with current over only a small range, however, due to the onset of burnbacks (wire fusing to contact tube) when the current became too high. Once satisfactory spray-type metal transfer was established and the current and wire feed rate held constant, the arc length remained at a constant value. However, from time to time slight variations in arc

[4] W. H. Wooding, "The Inert-Gas-Shielded Metal-Arc Welding Process," The Welding J., 32(5), 407-423 (May, 1953).

[5] A. Lesnewich and E. Cushman, "Power Supplies for Gas-Shielded Metal-Arc Welding," The Welding J., 35(7), 655-664 (July, 1956).

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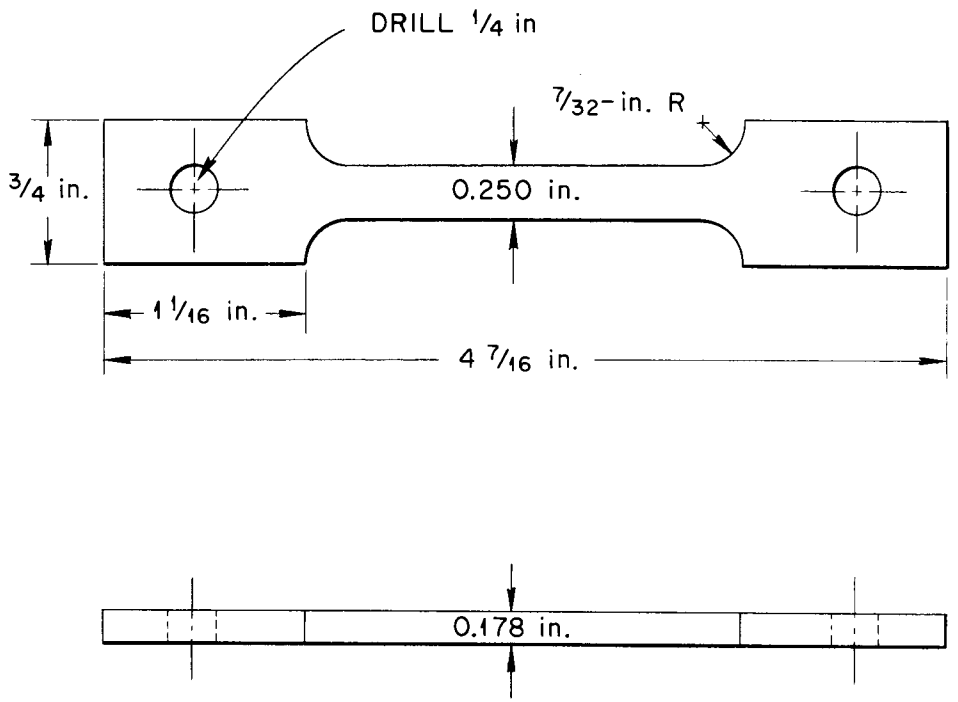

Fig. 8. Tensile Specimen used in the Mechanical Testing of Welds.

TABLE I

THE EFFECTS OF WELDING CURRENT AND WIRE FEED RATE ON ARC STABILITY

Bead No.	Current (amp)	Current Density $\frac{\text{amps}}{\text{in.}^2}$	Wire Feed Speed in./min	Remarks
1	200	65,000	136	Globular transfer with wander
4	320	104,000	320	Spray transfer with small amount of spatter and arc wander
8	330	107,000	320	Spray transfer with decreased wander
10	340	111,000	320	Spray transfer with nil spatter and wander
15	350	114,000	312	Spray transfer with nil spatter and wander

length were noted under conditions which would otherwise be considered ideal. This behavior was probably due to minor instabilities in the speed of the wire feed motor. It was found also that the arc length depended to a certain extent upon the spacing between the end of the contact tube and the work. For given values of current and wire feed rate and a drooping characteristic power supply, it has been shown[6] that an increase in contact tube-to-work spacing produces a smaller, but proportional, increase in arc length. Further, it was seen that the contact-tube spacing had an important effect upon the presence or absence of weld spatter. When the spacing was decreased spatter decreased, whereas increasing the spacing beyond a certain point virtually eliminated spatter. This phenomenon was explained by reasoning that with increased electrode "stick out" (increased spacing between contact tube and work) the wire was preheated by its own I^2R losses to a higher temperature. It appeared that spatter could be eliminated by eliminating "cold metal" in the arc. Unfortunately, it was also seen that contact-tube spacing had an opposite effect upon arc wander. That is, as the distance between the end of the contact tube and the work increased, arc wander increased. Thus, a balance was required which would minimize both arc wander and weld spatter, and while neither was eliminated entirely, they were held to a satisfactorily low level. Table II summarizes the effects of contact-tube spacing on arc stability.

A portion of a typical bead-on-plate is shown in Fig. 9 (Y-26815). Good arc stability was characterized by the smooth bead contour and by the absence of spattered metal. The fact that the edges of the bead appear to be uniformly linear and parallel shows that arc wander was held to a minimum. The brightness of the weld surface and the lack of porosity, as indicated by x-ray, show that the inert-gas shielding of the bead was satisfactory. Argon flow was maintained at 45 cfh through the torch and 80 cfh through the trailer.

Figure 10 (Y-26809) shows a cross section of the same weld. In this the depth of penetration is evident and the extent of the heat-affected zone can be seen. The results of a microhardness traverse of the weld are shown in Fig. 11 (ORNL-LR-DWG 33668) giving further evidence of the effectiveness of the inert-gas shielding.

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[6] A. Lesnewich and E. Cushman, Ibid.

TABLE II

THE EFFECT OF THE SPACING BETWEEN THE END OF THE CONTACT TUBE AND THE WORK PIECE ON ARC STABILITY

Bead No.	Current amp	Wire Feed Speed in./min	Contact Tube Spacing in.	Remarks
1	200	136	11/16	Considerable wander
4	320	320	5/8	Some spatter and some wander
8	330	320	1/2	Wander decreased
10	340	320	3/8	Wander and spatter both minimized
15	350	312	7/16	Wander and spatter both minimized

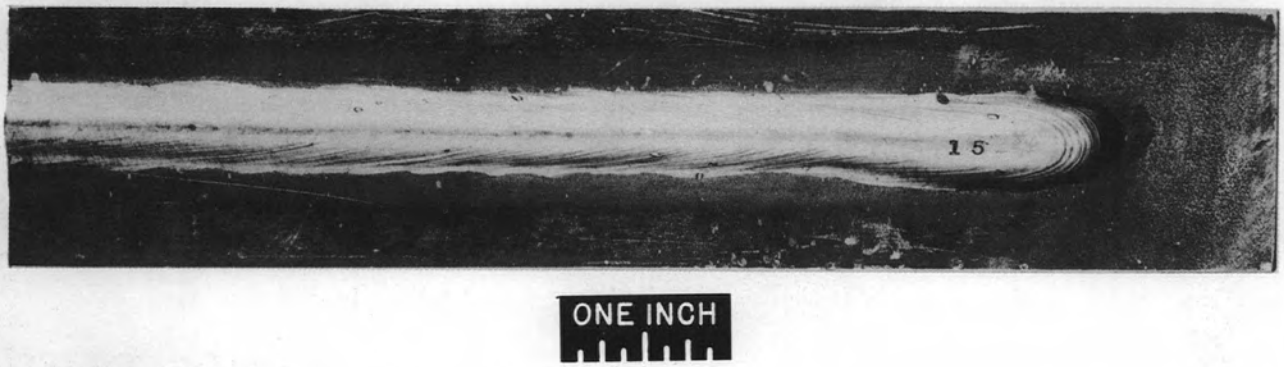

Fig. 9 (Y-26815) A Portion of a Typical Bead-on-Plate.

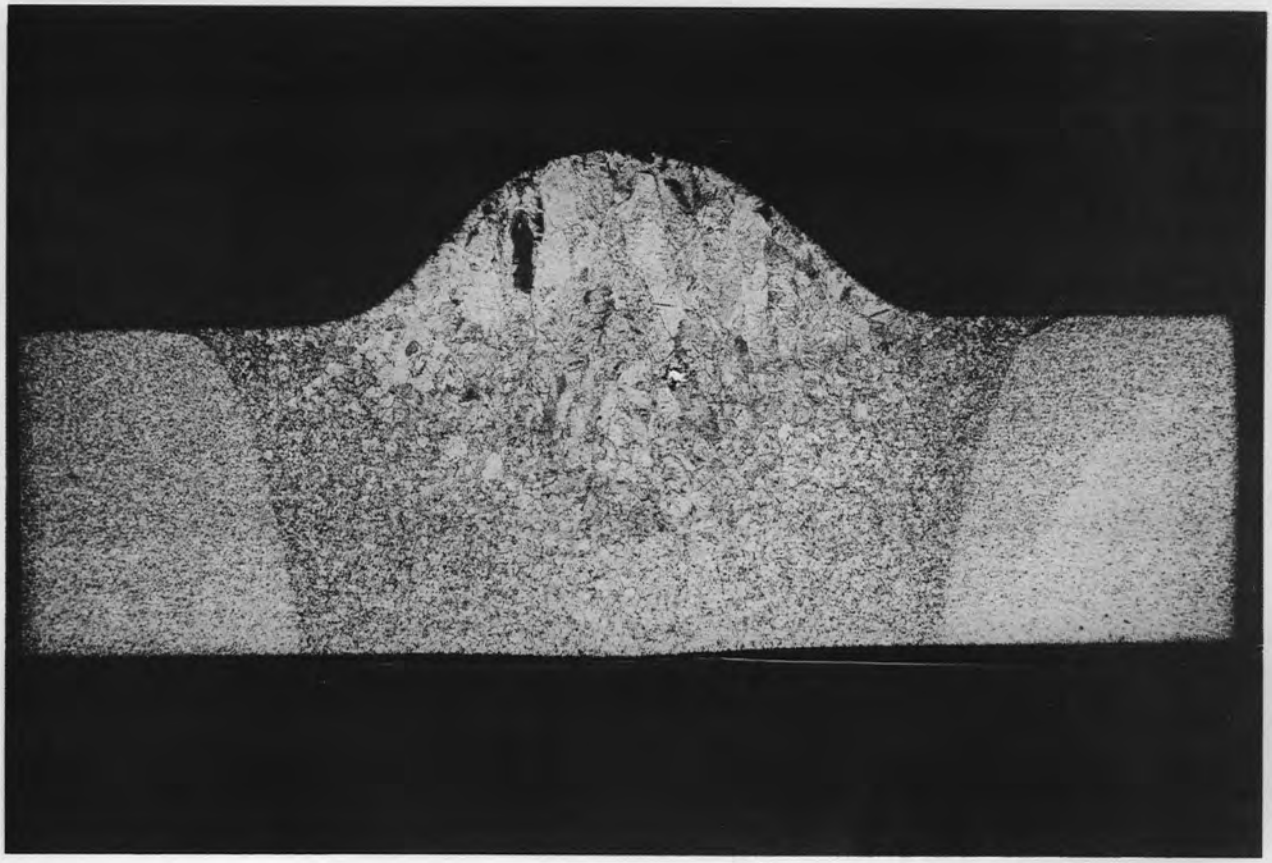

Fig. 10 (Y-26809) Cross Section of a Satisfactory Bead-on-Plate Weld. Etchant: HNO_3 + HF + Glycerine. 6.5X

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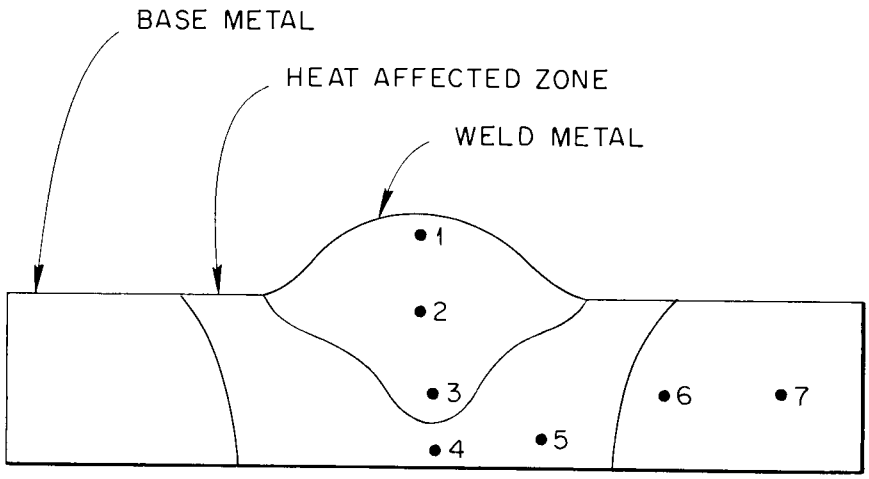

HARDNESS TESTING DONE ON A TUKON TESTER. 10 kg LOAD AND 16 mm OBJECTIVE USED.

POINT NO.	HARDNESS
1	166 DPH
2	181 DPH
3	164 DPH
4	146 DPH
5	146 DPH
6	145 DPH
7	142 DPH

Fig. 11. The Distribution of Test Points, and the Results of a Microhardness Traverse of a Bead-on-Plate Weld.

As pointed out previously, Fig. 9 shows the results of satisfactory arc stability. Figure 12 (Y-26814), on the other hand, shows a bead produced by an unstable arc. The high and uneven contour denotes a rather large degree of arc wander. Some spatter is evident, although in this case it was not as pronounced as in others.

Once satisfactory arc stability had been established, efforts were made to secure deep penetration in the bead-on-plate studies. Since the ultimate aim of the program was a full-penetration butt weld, it was felt that the criteria for deep penetration in the bead-on-plate work could be applied to the welding of joints.

The variables having the greatest effect upon energy input and, hence, the depth of penetration were found to be welding speed and welding current. During this study the welding speed was varied only slightly while the welding current was varied over a much wider range.

Table III lists these variables and their values in the bead-on-plate penetration studies. The variation of penetration with welding current is presented in graphical form in Fig. 13 (ORNL-LR-DWG 33669). The penetration is expressed as per cent of total plate thickness. Although there is considerable scatter, the expected trend is noted. That is, penetration increases directly with welding current for constant welding speed and wire feed speed. Although no extensive data were taken to show it, penetration decreased, as expected, with increasing welding speed.

The bead shown in Fig. 10 exhibits 80% penetration. No effort was made to push much further than this since some of the conditions influencing penetration for the butt joints were expected to be different from those for the bead-on-plate welds. Thus by the time that penetrations on the order of 70 – 80% had been reached, it was deemed that welding conditions had been established which would be suitable for the initiation of butt-joint studies.

An interesting corollary of the penetration measurements in the bead-on-plate work is the way in which the size of the heat-affected zone varied with penetration. For this purpose the widths of the heat-affected zones were measured at the points where the zones intersected the top (weld face) and bottom (weld root) surfaces of the plates. Table IV presents this data, while Fig. 14 (ORNL-LR-DWG 33670) shows the results in graphical form.

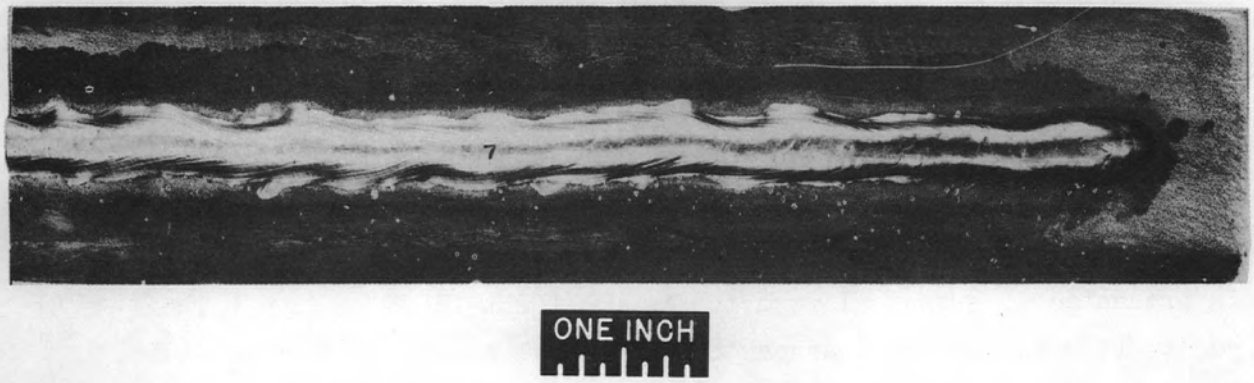

Fig. 12 (Y-26814) Bead-on-Plate Weld Produced by an Unstable Arc.

TABLE III

THE VARIATION IN DEPTH OF PENETRATION WITH CHANGES IN THE WELDING CONDITIONS

Bead No.	Current amp	Wire Feed Speed in./min	Welding Speed in./min	% Penetration
1	200	136	29.5	32
2	200	136	29.5	40
3	315	320	29.5	44
4	320	320	27.5	48
5	325	320	27.5	48
6	330	320	27.5	48
7	330	320	34.0	56
8	330	320	29.5	40
9	330	320	27.5	52
10	340	320	27.5	68
11	345	320	27.5	56
12	350	320	27.5	72
13	350	320	27.5	60
14	350	320	27.5	72
15	350	312	27.5	80
16	350	320	27.5	64
17	360	320	27.5	56
18	360	320	27.5	68
42(2G)	375	360	49.0	36
43	440	440	27.5	76

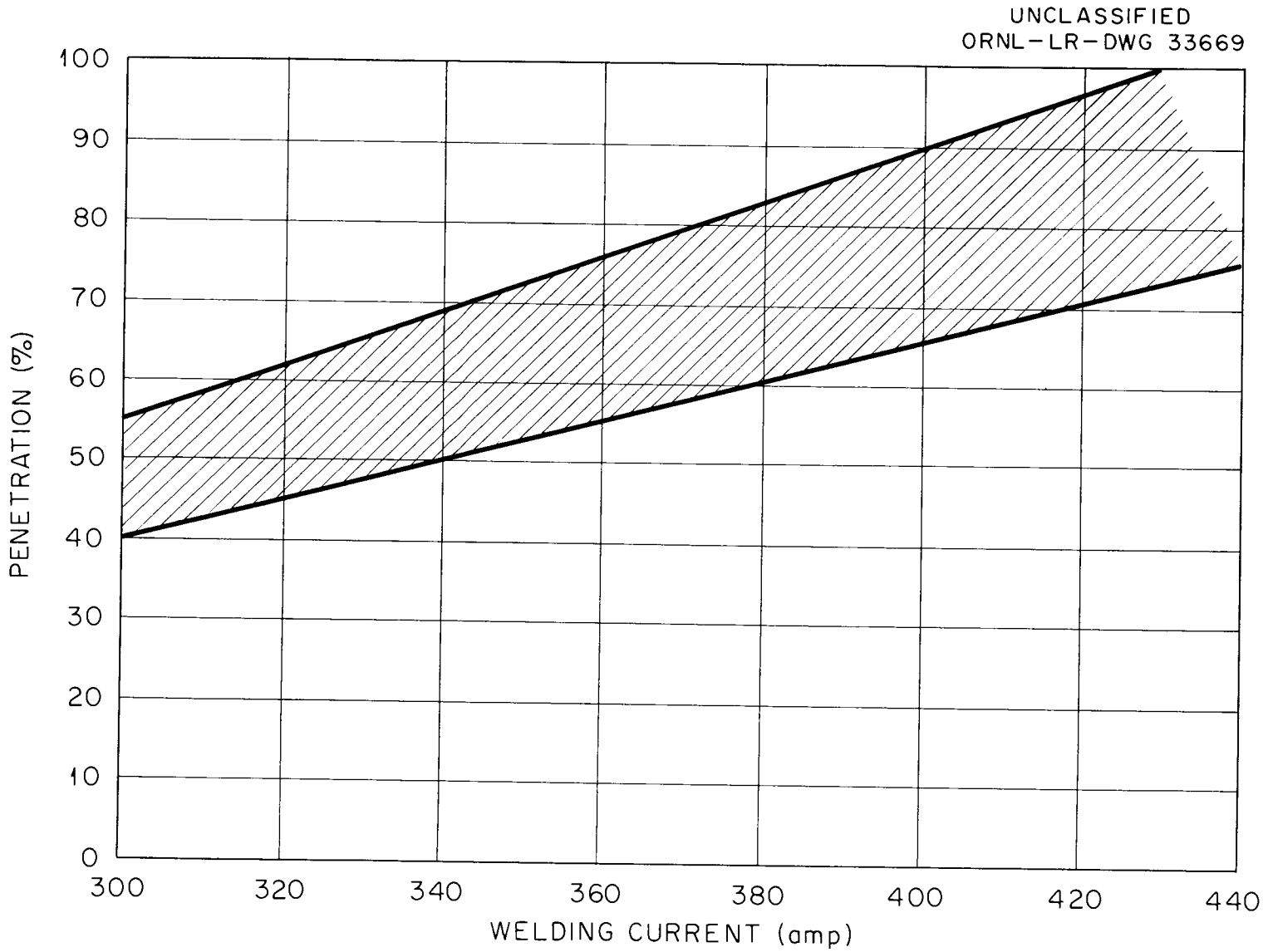

Fig. 13. The Variation of Depth of Penetration with Welding Current for the Bead-on-Plate Welds.

TABLE IV

THE SIZE OF THE HEAT-AFFECTED ZONE FOR EACH BEAD-ON-PLATE

Bead No.	HAZ Face (in.)	HAZ Root (in.)
1	0.31	--
2	0.38	--
3	0.52	0.05
4	0.64	0.33
5	0.59	0.31
6	0.62	0.39
7	0.55	0.13
8	0.60	--
9	0.58	0.40
10	0.57	0.36
11	0.58	0.41
12	0.59	0.45
13	0.64	0.51
14	0.63	0.45
15	0.66	0.50
16	0.61	0.43
17	0.61	0.45
18	0.62	0.48
42(2G)	0.48	--
43	0.65	0.48

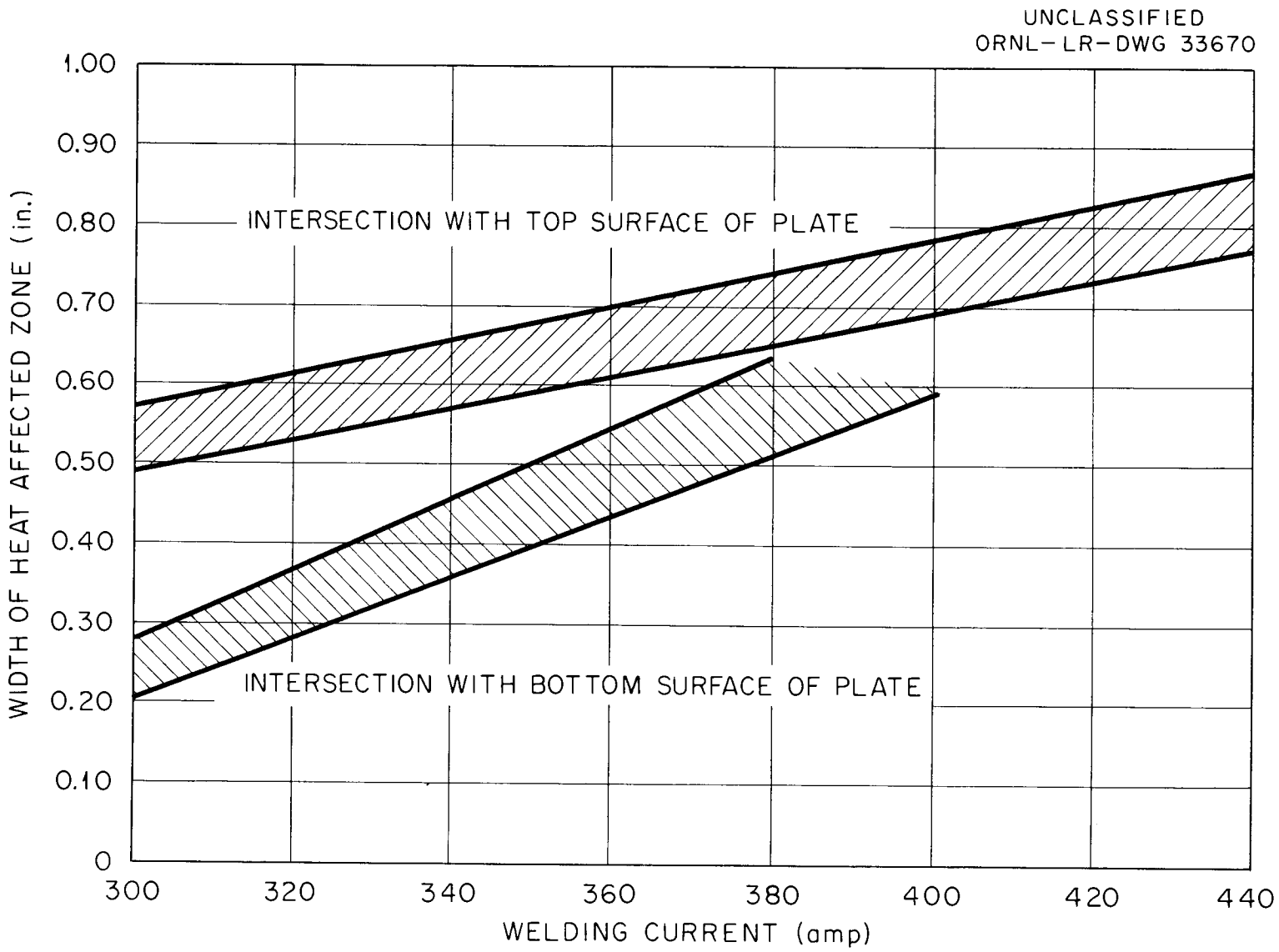

Fig. 14. The Variation of the Size of Heat Affected Zone with Current for the Bead-on-Plate Welds.

Once again, scatter is noticeable; however, the same trend exists as did with the penetration. That is, the size of the heat-affected zone increased with increasing current. The scatter band for the bottom of the heat-affected zones has a slightly greater slope than that for the top. However, it appears that this is due merely to the geometry of the heat-affected zones rather than to any inherent feature of the welding process.

During the experimental work, it was found, as expected, that the same factors influenced arc stability for the welding of joints as for deposition of a bead-on-plate. Even though the welding conditions were somewhat different (higher currents, etc.) for the joint welding, the proper relationships among parameters had to be maintained in order to realize arc stability. It was interesting to note the manner in which the character of the arc was revealed by the current and voltage traces. Figure 15 (ORNL-LR-DWG 33671) shows the current and voltage traces produced by a stable arc. On the other hand, Fig. 16 (ORNL-LR-DWG 33672) illustrates traces characteristic of an unstable arc.

For the most part, as a result of the application of the experience gained during the bead-on-plate work, arc stability was readily attained. As before, it was necessary to strike a balance between arc wander and weld spatter. It appeared, too, that the effects of excessive arc wander were more serious during the joint studies as it was necessary for the arc to be aligned quite accurately with the joint crack in order to secure uniform 100% penetration for the full length of the weld. Thus, it was expedient to tolerate slightly more weld spatter in order to hold arc wander to an absolute minimum.

The question of penetration maintained its position of importance throughout. The requirements for the joints differed somewhat from those for the bead-on-plate work in that a satisfactory joint was expected to show a 100% penetrated root bead with a uniform contour for the length of the joint. Originally, it had been thought that if the same conditions which resulted in 80% penetration of a bead-on-plate were used in welding a joint, full penetration would be secured. It was found, however, that the depth of penetration was quite dependent upon joint geometry, and for a tight butt joint, consistent full penetration required much more current than was needed for an 80% penetration bead-on-plate.

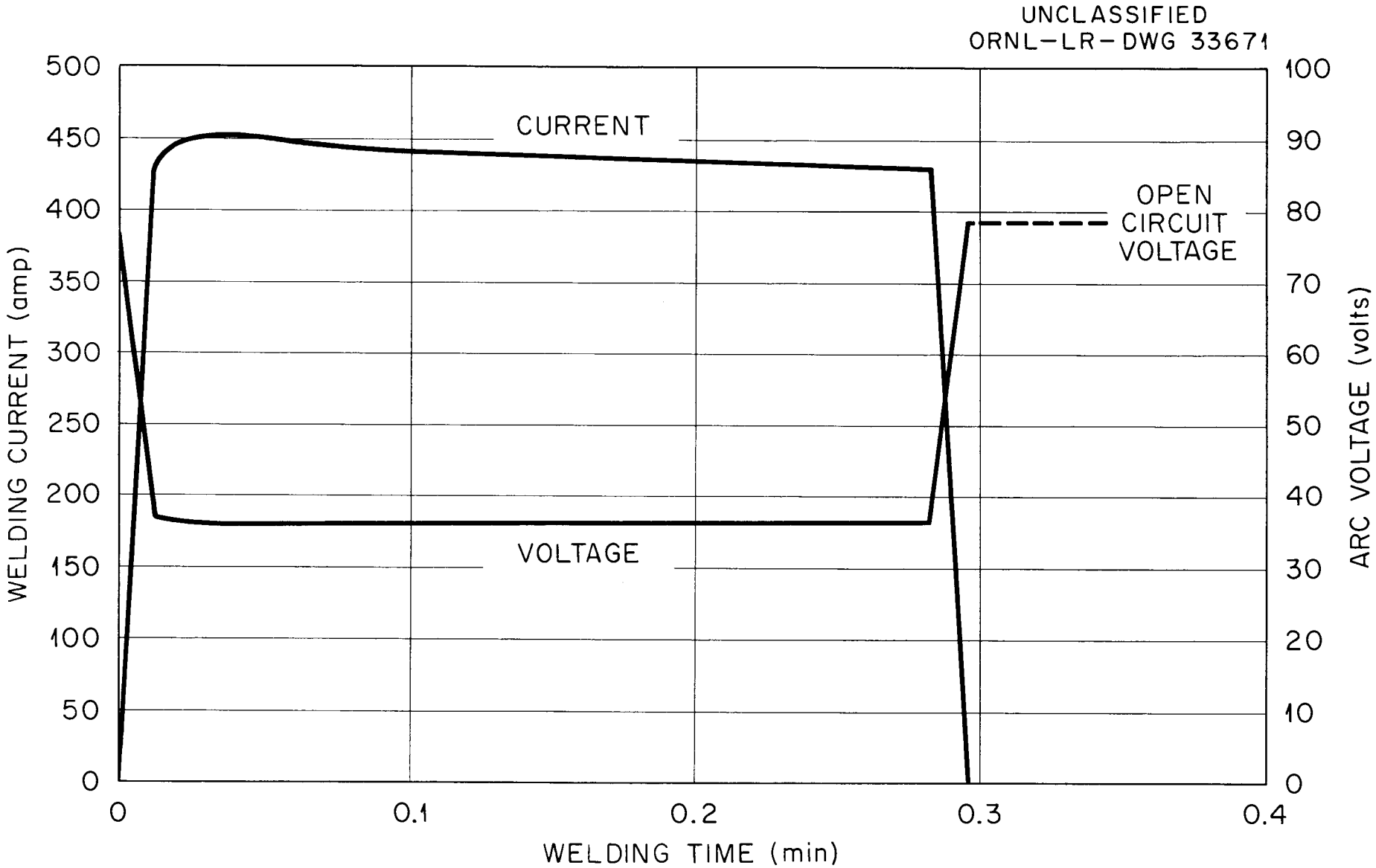

Fig. 15. Current and Voltage Traces Produced by a Stable Arc.

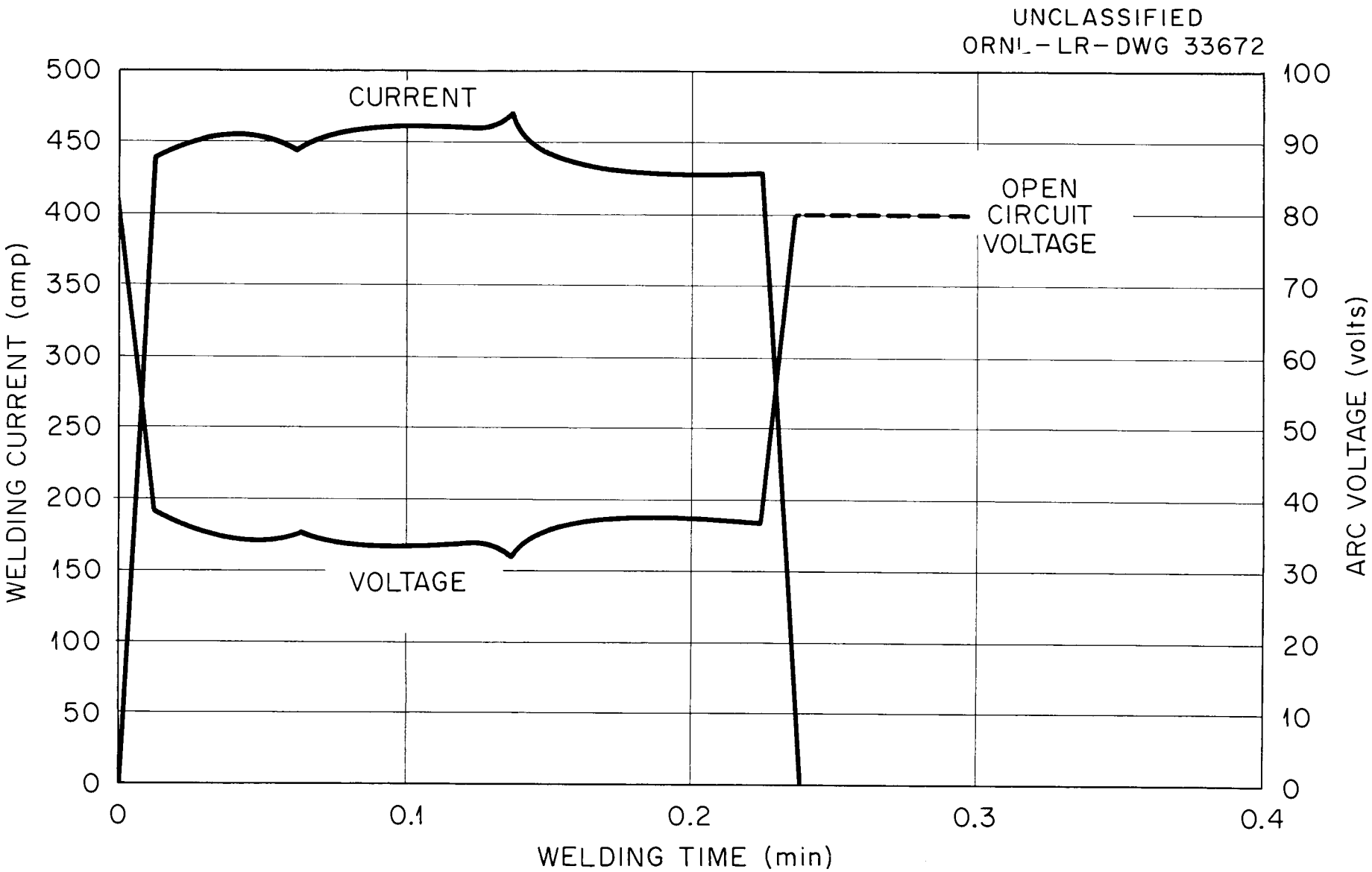

Fig. 16. Current and Voltage Traces Produced by an Unstable Arc.

During the joint studies, the welding current was varied from 365 amps to 470 amps. Welds with satisfactory penetration were produced at the upper end of this range.

The means by which inert-gas coverage was maintained were identical to those used during the bead-on-plate work. It was not found to be necessary to modify the shielding procedure in any way as the results of the bead-on-plate work had proven them to be quite satisfactory. The argon flow rates were maintained constant at 45 cfh through the torch, 80 cfh through the trailer, and 30 cfh into the back-up cavity. Before each weld was started, a high flow-rate purge was maintained for at least 30 sec through each of the three gas systems.

The effects of gas coverage upon weld quality were the same here as previously discussed. However, the requirements became somewhat more stringent due to the need for good shielding at the root of the weld. Satisfactory root shielding was of great importance to the production of sound, smoothly contoured root beads. In general, the gas-shielding practice outlined above proved to be satisfactory.

As mentioned earlier, the joint edge preparation was of two types, as-sheared edges and milled edges. There was a definite difference in performance between the two types of preparation. The sheared edge joint required less current for full penetration than did the milled edge joint. An example of this type of behavior is given in Table V in which are listed the welding conditions for two fully penetrated joints, one with sheared edges and one with milled edges.

When viewed from the standpoint of remote repair operations, the behavior discussed above has serious implications. Since the success of the joining operation depends upon joint geometry, it is necessary that this geometry be accurately known before welding commences. Once this has been established, the proper welding conditions may be selected so that an adequately penetrated joint will result.

It was recognized that the degree of surface cleanliness of the base material would affect weld quality. With this in mind a number of different precleaning procedures were tried: (a) as-received plate cleaned in acetone, (b) as-received plate wire brushed and cleaned in acetone, (c) as-received plate ground and cleaned in acetone, (d) as-received plate sand blasted and cleaned in acetone, and (e) as-received plate chemically cleaned and rinsed with water and alcohol.

TABLE V

WELDING CONDITIONS FOR TWO FULLY PENETRATED JOINTS WITH DIFFERENT EDGE PREPARATIONS

Weld No.	Current amp	Current Density $\frac{amp}{in.^2}$	Wire Feed Speed in./min	Welding Speed in./min	Remarks
25	385	125,000	360	25.0	Plate with sheared edges. 100% penetrations. Stable arc.
38	430	140,000	440	27.5	Plate with milled edges. 100% penetration. Stable arc.

Since the as-received plate was already in the sand-blasted condition, all of the cleaning methods served merely to remove any contamination which had been picked up subsequent to mill processing. The two least severe of the methods tried, that is cleaning in acetone and wire brushing followed by an acetone rinse, both produced satisfactory results. The two more stringent approaches of grinding followed by an acetone rinse and sand blasting followed by an acetone rinse likewise produced satisfactory results. The chemical cleaning method consisted of pickling the plates in a 46% H_2O – 36% HNO_3 – 18% HF solution, followed by water and alcohol rinses. Welds in these samples, under conditions which had previously produced satisfactory results, were very poor. The bead contour was quite irregular, penetration was erratic, and the final color of the weld bead indicated contamination. As a further check of the source of trouble, two pickled plates were sand blasted and welded without difficulty. It appeared that the pickling operation produced a residue on the plates which was not removed by the subsequent rinses.

The experimental work on butt joints produced at its culmination welding conditions which would result in a highly satisfactory joint. An example of such a joint is given in Figs. 17 (Y-26534) and 18 (Y-263535) showing the face and root, respectively. The bead face exhibited a smooth, uniform contour. There was very little spatter present and the brightness indicated adequate gas shielding. The root bead showed uniform and continuous penetration once the arc had stabilized. Once again, the brightness of the bead indicated adequate back-up gas shielding.

The welding conditions which produced the above joint are listed in Table VI. Table VII presents various combinations of welding conditions, all of which resulted in successful joints.

A number of tests were used to evaluate the acceptability of the butt-welded joints.

An example of a joint which passed the visual inspection is shown in Figs. 17 and 18 and was discussed above.

Radiographic examination was performed on each of the joints. The primary purpose of this was to detect porosity in the weld zone. No acceptance standards were established regarding porosity, but it was felt that an indication of the incidence of porosity would be useful.

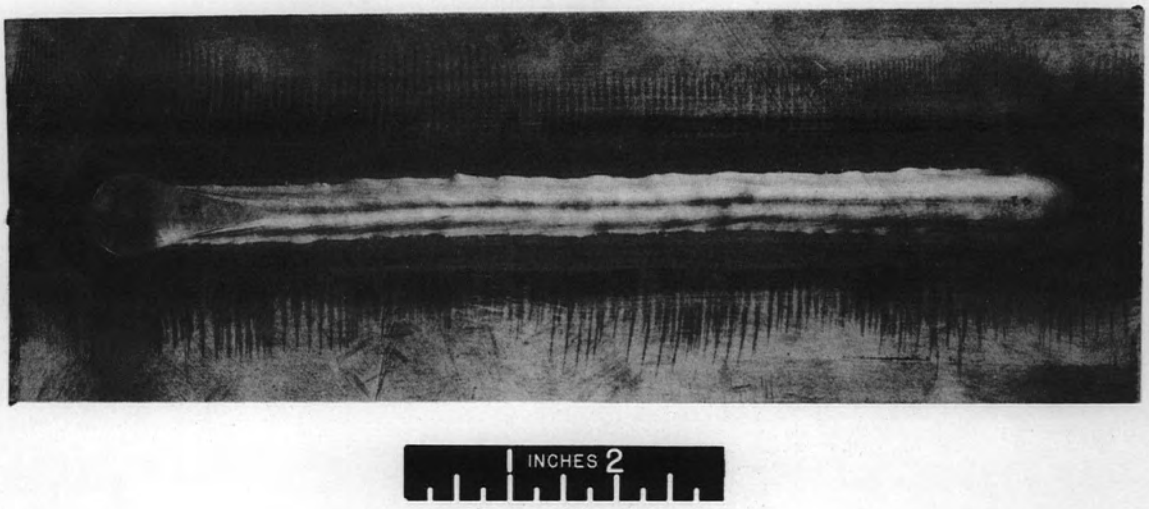

Fig. 17 (Y-26534) View of the Face Bead of a Satisfactory Square Butt-Welded Joint.

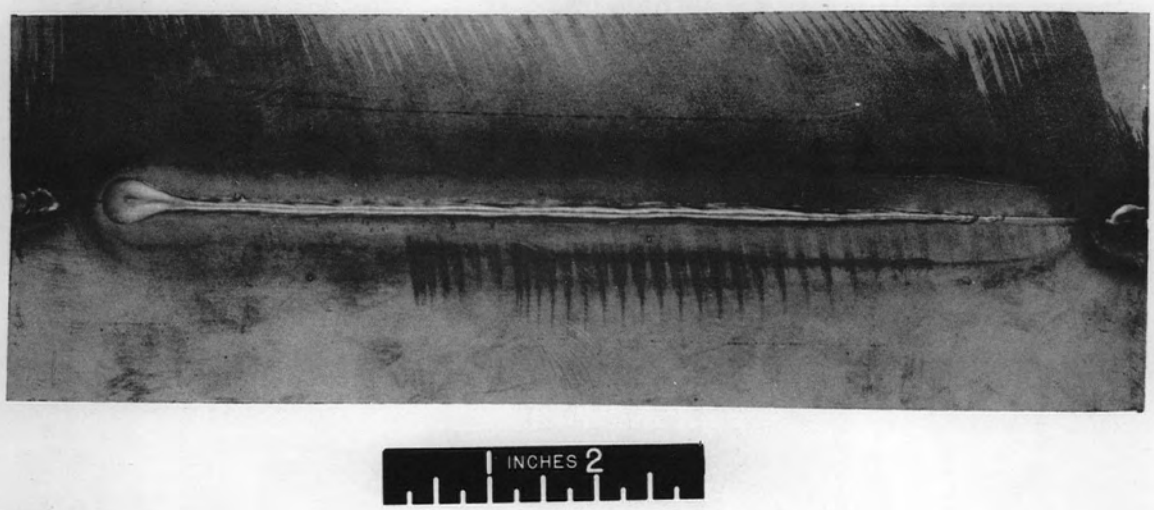

Fig. 18 (Y-26535) View of the Root Bead of the Joint Shown in Fig. 15.

TABLE VI

WELDING CONDITIONS FOR AN ACCEPTABLE JOINT

Weld No.	Current amp	Current Density $\frac{amp}{in.^2}$	Wire Feed Speed in./min	Welding Speed in./min	Remarks
41	440	143,000	440	27.5	Arc stable, spatter and wander minimized. Milled edges on plates. Plates pickled and sand blasted before welding.

TABLE VII

WELDING CONDITIONS WHICH RESULTED IN ACCEPTABLE JOINTS

Weld No.	Current amp	Current Density $\frac{amp}{in.^2}$	Wire Feed Speed in./min	Welding Speed in./min
24	385	125,000	360	27.5
25	385	125,000	360	25.0
27	400	130,000	360	25.0
30	400	130,000	360	25.0
33	450	146,000	408	27.5
37	430	140,000	440	27.5
38	430	140,000	440	27.5
41	440	143,000	440	27.5

Practically every joint showed some porosity. However, the joints which were discarded for other reasons tended to exhibit more porosity than did acceptable joints. In no case did the amount of porosity present in the acceptable joints approach the average amount of that in the rejected joints. On the other hand, a few of the otherwise unacceptable joints showed very little porosity.

In most instances the porosity was limited to the fusion line and appeared to be situated primarily at the root of the weld. It can be recalled that a comparatively high welding speed was used, and in addition, high backing-gas flow was employed. It was reasoned that the high backing-gas flow introduced gas into the molten metal and that this gas was subsequently trapped by the high rate of solidification of the weld. Since there was usually no porosity at the faces of the welds, it was reasoned that any gas close to the surface had an adequate chance to escape.

A microhardness survey of the metal around a cavity was used to determine whether or not it had been formed by inert gas. Since the weld remained at an elevated temperature a sufficient length of time for any gas-metal reactions to proceed, any increase in hardness around the cavity would indicate that it was formed by a contaminant such as nitrogen or oxygen rather than an inert gas. Such a survey was made and the results, as shown in Fig. 19 (ORNL-LR-DWG 33673), verify the above reasoning. In addition, the results of the tensile and bend tests on specimens containing some porosity showed no decrease in weld ductility. Thus, the porosity encountered in this study, while it did detract from the load-bearing cross section of the weld, did not appear to have any deleterious effect upon the material itself.

Metallographic examination of each of the joints was conducted to determine whether or not the weld structure was normal and sound. Figure 20 (Y-26839) shows a cross section of a typical acceptable joint. This joint was made under the conditions given in Table VIII. The grain size of the weld zone was not excessive, and the heat-affected zone did not extend an inordinate distance into the base material. The width of the heat-affected zone at its intersections with the top and bottom of the plate were 0.65 in. and 0.58 in., respectively. This may be compared with

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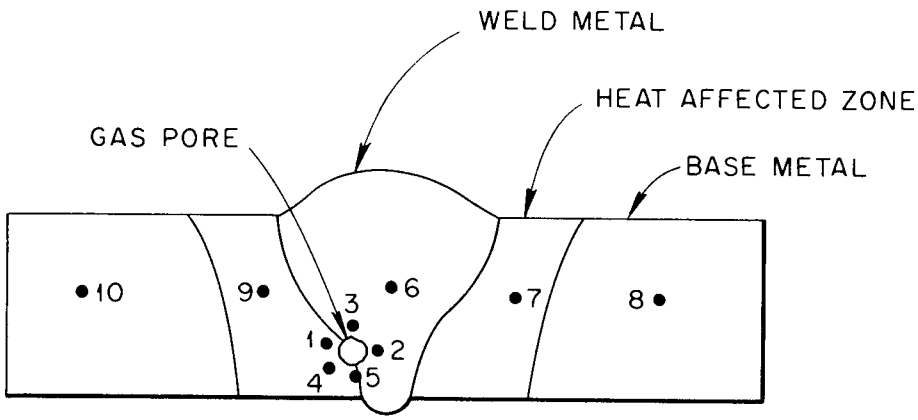

HARDNESS TESTING DONE ON A TUKON TESTER. 10 kg LOAD AND 16 mm OBJECTIVE USED.

POINT NO.	HARDNESS
1	186 DPH
2	160 DPH
3	147 DPH
4	185 DPH
5	182 DPH
6	177 DPH
7	151 DPH
8	142 DPH
9	151 DPH
10	151 DPH

Fig. 19. The Distribution of Test Points, and the Results of a Microhardness Traverse Around a Gas Pore.

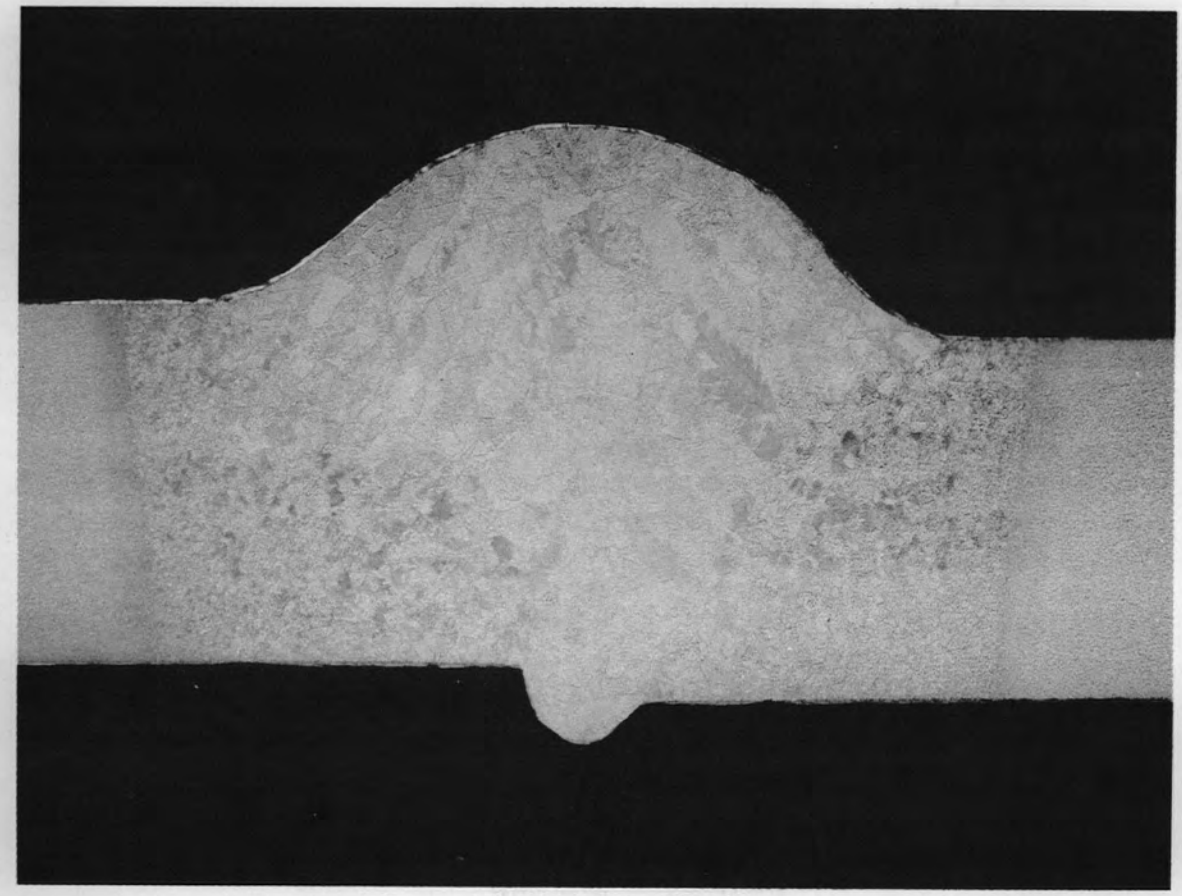

Fig. 20 (Y-26839) Cross Section of a Sound Square Butt-Weld. Etchant: HNO_2- HF-H_2SO_4-Lactic-H_2O (Goniff's Reagent). 7X.

TABLE VIII

WELDING CONDITIONS FOR THE JOINT SHOWN IN FIG. 20

Weld No.	Current amp	Current Density $\frac{amp}{in.^2}$	Wire Feed Speed in./min	Welding Speed in./min	Remarks
27	400	130,000	360	25.0	Stable arc, spatter and wander minimized. Milled edges on plates. As-received plate cleaned in acetone.

similar figures of 0.66 in. and 0.50 in. for a bead-on-plate which showed 80% penetration. In general, all the welds showed suitable microstructures. Except for an occasional bit of porosity, no gross defects were observed. In no case was any weld cracking found.

By way of further comparison, the joint cross section pictured in Fig. 21 (Y-27101) is a multipass, manually welded butt joint in 1/4-in.-thick titanium plate. The welding conditions are shown in Table IX. It is interesting to note that for the manual weld the width of the heat-affected zone at its intersection with the top of the plate is 0.75 in. and at the bottom of the plate is 0.45 in. In addition, the structure of the weld appears to be somewhat more coarse grained in the manual case. Thus, it may be generalized that the inert-gas-shielded metal-arc process, due to its high rate of energy input, might be utilized to produce higher quality welds in materials in which large heat affects are undesirable.

Microhardness traverses of the welded joints gave support to the other evidence that the gas-shielding practice was fully successful in preventing harmful contamination of the welds. The results of a typical microhardness traverse are presented in Fig. 22 (ORNL-LR-DWG 33674). This traverse was made on the same sample that is pictured in Fig. 20. The absence of a marked increase in the hardness of the weld zone as compared to the base material attests to the lack of embrittling contamination.

In order to verify the quality of the acceptable welds, their mechanical properties were tested in two ways. A room-temperature, transverse tensile test and a room-temperature, longitudinal guided bend test were used. Due to the limitation on the availability of material, the sizes of the welded specimens were such that it was impossible to include longitudinal tensile or transverse bend testing in the program. However, the tests that were used were sufficient to point up any basic weaknesses and when used in conjunction with the other points of evaluation, gave a realistic picture of the quality of the welds.

The tensile specimens were machined from strips which were cut from the welded plates. The strips were machined smooth on both surfaces as shown in Fig. 23 (Y-26712). The macroetch was used to insure that the weld would be in the center of the strip with its axis at right angles to that of the strip. Figure 24 (Y-26816) shows the tensile specimen as it

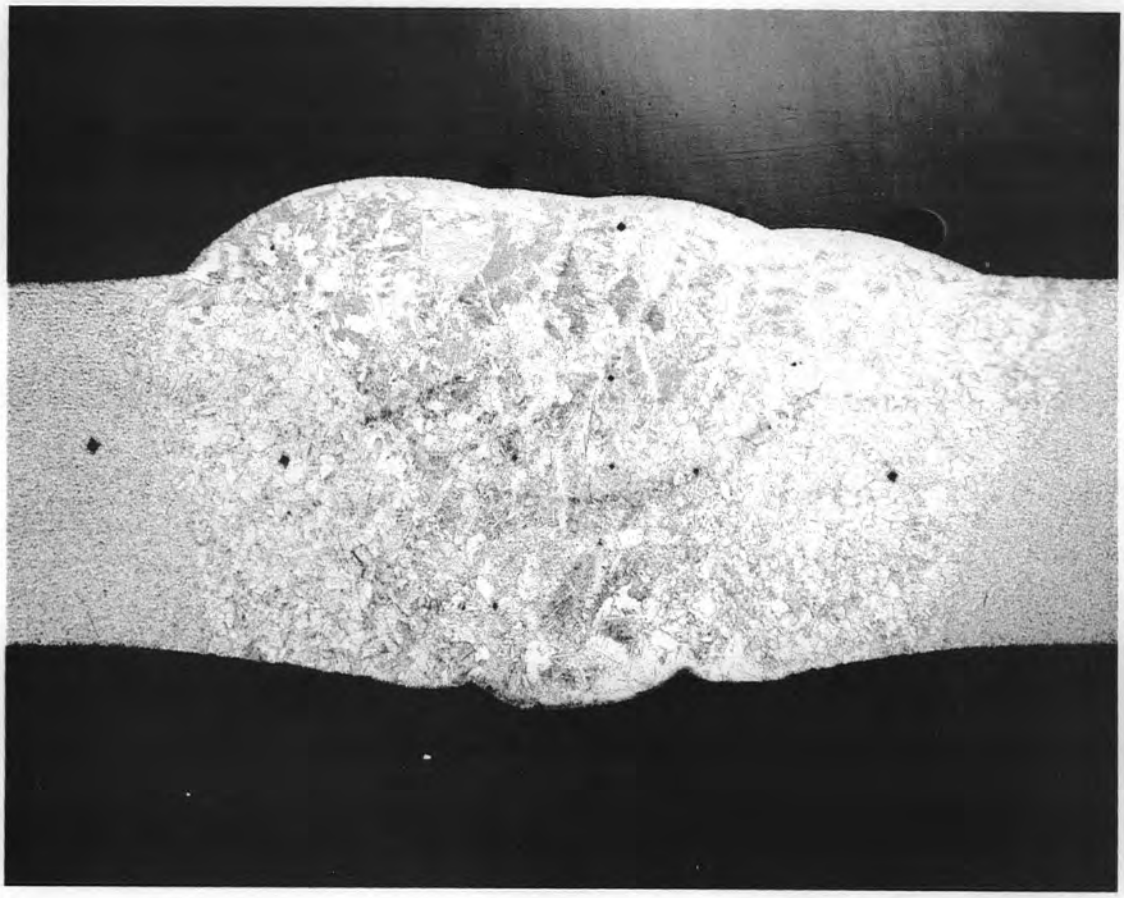

Fig. 21 (Y-27101) Cross Section of a Manually Welded Titanium Joint. Etchant: Goniff's Reagent. 6X.

TABLE IX

WELDING CONDITIONS FOR A MANUALLY WELDED TITANIUM JOINT

		Root Pass		Filler Passes			
Weld No.	No. of passes	Current amp	Welding Speed in./min	Current amp	Welding Speed in./min	Back-up Gas	Torch Gas
Manual	15	65	1	85	1.5	He	A

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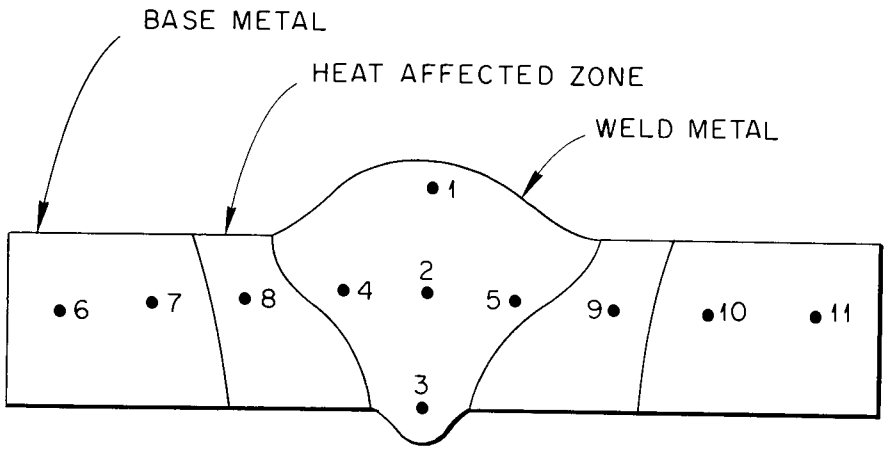


HARDNESS TESTING DONE ON A TUKON TESTER. 10 kg LOAD AND 16 mm OBJECTIVE USED.

POINT NO.	HARDNESS
1	194 DPH
2	201 DPH
3	191 DPH
4	209 DPH
5	192 DPH
6	201 DPH
7	197 DPH
8	206 DPH
9	197 DPH
10	201 DPH
11	205 DPH

Fig. 22. The Distribution of Test Points, and the Results of a Microhardness Traverse of a Square Butt-Welded Joint.

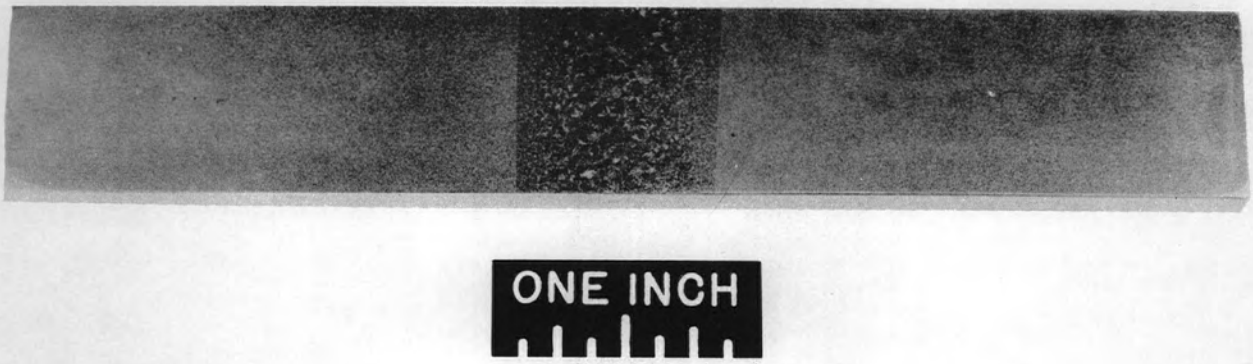


Fig. 23 (Y-26712) Welded Blank From Which Tensile Specimens Were Machined.

Fig. 24 (Y-26816) Welded Tensile Specimen Before Testing.

was machined from the strip before testing. Figure 25 (Y-26919) is a view of the fractured specimen. The welding conditions for the particular specimen shown in the foregoing illustrations are to be found in Table X. Table XI shows the mechanical-property data for two similar specimens, both welded under the conditions given above.

As can readily be seen, the tensile test became, in essence, a test of the base metal. The appearance of the fractured specimens shows that the weld ductility was less than that of the base metal, but that its strength was higher. This is usually the case for many welds, and the mode of failure indicated that there was no danger of a brittle fracture in the weld zone. The elongation exhibited in the 1-in.-gage length gave some indication of the weld ductility, since most of this gage length was taken up by the weld and heat-affected zone. However, since the fracture occurred outside the 1-in.-gage length, one can assume that the weld elongation would have been greater than 7.5%.

The bend tests were made on specimens which were machined from the welded plates. Both face and root beads were removed and the specimen machined smooth as shown in Fig. 26 (Y-26817). As can be seen, the weld axis was parallel to the longitudinal axis of the specimen. The specimens were 3/4 in. wide, 3/16 in. thick, and 7 in. long. Bending was done in such a way as to put the face of the weld in tension. The bend radius was 2T and the bend angle 180 deg.

Figure 27 (Y-27005) shows a specimen in the bent condition. No defects are noticeable and adequate ductility is exhibited. As could be expected, all the joints which were able to pass the previous tests also proved to be satisfactory on the basis of the bend test.

This phase of the joining program was concluded with the successful production of several satisfactory joints as discussed in the preceding pages. The joints made according to the listed welding procedures were shown by the several tests performed on them to be sound, and thus the validity of the welding procedures was established.

It was recognized that downhand welding represented a comparatively limited application of this process. Successful repair of the Homogeneous Reactor Vessel would require an extension of this work to welding in the

Fig. 25 (Y-26919) Welded Tensile Specimen After Testing.

TABLE X

WELDING CONDITIONS FOR THE JOINT SHOWN IN FIGS. 21, 22, AND 23

Weld No.	Current amp	Current Density $\frac{amp}{in.^2}$	Wire Feed Speed in./min	Welding Speed in./min	Remarks
37	430	140,000	440	27.5	Stable arc, spatter and wander minimized. Milled edges on plates. As-received plate cleaned in acetone.

TABLE XI

RESULTS OF ROOM-TEMPERATURE TENSILE TESTING OF WELDED SPECIMENS

Spec. No.	Width in.	Thick-ness in.	Max Load lb	Rupture Load lb	(2% Offset) Yield Strength psi	Tensile Strength psi	% Ext. in 1 in.	% Ext. in 2 in.
1	0.249	0.167	2400	1550	48,120	58,180	7.50	18.75
2	0.248	0.161	2350	1600	48,335	58,855	7.50	17.50

Fig. 26 (Y-26817) Welded Bend Specimen Ready for Bending.

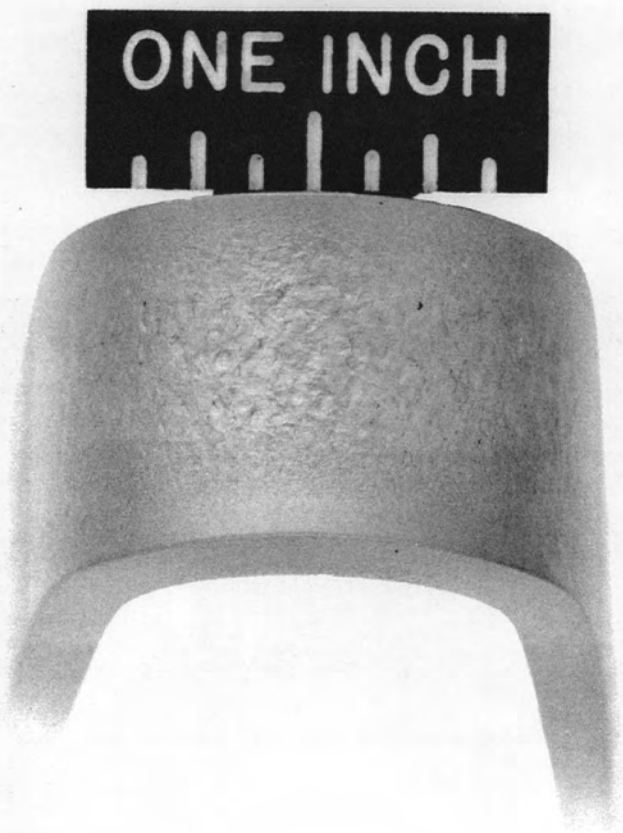


Fig. 27 (Y-27005) Welded Bend Specimen After Bending.

horizontal fixed (2G) position. A limited number of beads-on-plate were made as a part of the current study in order to provide an indication of the problems to be encountered in position welding.

The most important source of difficulty was anticipated to be the high fluidity of the molten weld metal. As a result, the welding conditions were changed from those required for downhand welding. In order to minimize "sag" of the bead, welding conditions which would result in a more or less "cold" deposit were required. It was recognized that it would be much more difficult to achieve deep penetration in position welding with the process under study than in downhand welding.

A portion of a 2G weld sample is shown in Fig. 28 (Y-26818). The uneven bead contour indicates some lack of arc stability. The conditions under which the weld was made are shown in Table XII. The "cold" deposit was achieved by increasing the welding speed to nearly twice that used for the downhand welds. The high, narrow bead contour, in addition to the fact that the penetration was 36%, shows that the heat input was considerably reduced.

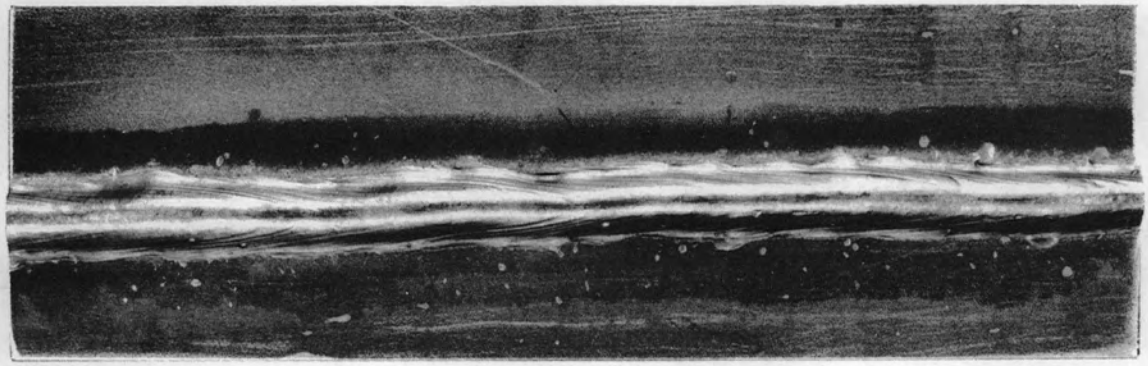
The foregoing observations indicated that a considerable amount of work would be required to establish suitable conditions for all-position welding of titanium with the inert-gas-shielded metal-arc process.

CONCLUSIONS

1. This study has shown that it is possible to produce sound, high-quality single-pass full-penetration butt welds in 1/4-in.-thick titanium plate in the downhand position with the inert-gas-shielded metal-arc (consumable electrode) process. The quality of the welds is attested to by their performance under the tests discussed in the body of this report. This quality was consistently obtained once the proper welding procedure had been developed.

2. The given welding procedures are applicable only to the downhand welding of titanium plate. Modification of procedure would be required for position welding. The scope of this study did not permit an investigation of such modifications.

3. A limitation which appears to be inherent is that the process variables require rather rigid control. Thus, one might conceive that



ONE INCH

Fig. 28 (Y-26818) Bead-on-Plate Weld Made in the 2G Position.

TABLE XII

WELDING CONDITIONS FOR A BEAD-ON-PLATE MADE IN THE 2G POSITION

Weld No.	Current amp	Wire Feed Speed in./min	Welding Speed in./min	Contact Tube Spacing in.	Current Density $\frac{amp}{in.^2}$	Remarks
42	375	360	49.0	1/2	122,000	Spray transfer with slight arc wander

the greatest use for this method would be in a machine-welding situation. As stated at the outset, however, the original motive for undertaking this study was the development of a remote-welding repair technique. It is quite apparent that by its very nature remote welding must take the form of an automatic or semi-automatic machine operation.

RECOMMENDATIONS

During the course of this investigation, the problems associated with the leak in the Homogeneous Reactor core vessel were reviewed and an alternate solution was proposed and accepted which eliminated the need for repair. Consequently, the study as outlined in this report may be undertaken at a more favorable pace at some future date. In this event the following recommendations should be considered:

1. As discussed earlier, the power supplies used were of the drooping voltage type. During the period when a great deal of experimentation was being done with current values and wire feed rates, burnbacks were a constant annoyance. Further, with this type of power supply, it is almost impossible to fill the crater which occurs when the arc is extinguished. This would be highly undesirable where run-off tabs cannot be provided, such as in the repair of a crack. It has been shown[7] that the above difficulties may be overcome by the use of a constant-voltage transformer-rectifier unit with automatic regulation for line voltage changes. In addition, it is considered[8] that this is the best available type of power source for inert-gas-shielded metal-arc welding.

2. It was impossible to make a full investigation of all the welding variables involved. Such an investigation would, however, be quite worthwhile as the application of the process to actual operating situations would thereby be greatly facilitated. An adequate supply of material should be provided to allow a complete investigation of variables and a comprehensive mechanical-testing program. Position welding should be stressed, and complete and reliable instrumentation should be employed to record all welding variables.

---

[7] A. Lesnewich and E. Cushman, "Power Supplies for Gas-Shielded Metal-Arc Welding," The Welding J., 35(7), 655 – 664 (July, 1956).

[8] Ibid.

ACKNOWLEDGMENTS

The author wishes to thank B. McDowell of the Welding and Brazing Laboratory for his extensive assistance in all the experimental phases of this study.

Metallographic work was done by R. A. Bowman and the macrophotographs were prepared by J. C. Gower and E. P. Griggs, all of the Metallography Group.

Mechanical testing was performed by C. W. Dollins and C. K. Thomas of the Mechanical Properties Group.

Typing and preparation of the report for reproduction was done by W. D. Mason of the Metallurgy Reports Office.

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