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5456 and 5086 Aluminum alloys were welded at 1.2-7.2 cm/s with a continuous CO_2 laser operated at beam powers of 5-9 kW. Difficulty was experienced in reproducing weld bead geometries and depths of penetration from weld to weld. Control of the helium shield gas flow rate and flow pattern were observed to be particularly critical for maintenance of full penetration of the fusion zone in both 0.64 and 0.95 cm plates. The 5456 alloy was found to be more easily welded

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ABSTRACT - Cont'd

than 5086, presumably because of the approximately 1% greater magnesium content of the 5456. Full penetration butt welds were achieved with both alloys, but fusion zone drop through and weld bead porosity, in addition to consistency and reproducibility, remain as problems at this stage of the program. This report contains a detailed summary of the test welds produced and evaluations of these test welds to date.

UNITED TECHNOLOGIES RESEARCH CENTER

UNITED TECHNOLOGIES

East Hartford, Connecticut 06108

Report R78-911989-14

Evaluation of Basic Laser Welding Capabilities

Technical Report
Contract N00014-74-C-0423

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Report R78-911989-14

Evaluation of Basic Laser Welding Capabilities

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INTRODUCTION AND BACKGROUND

This report constitutes the third technical report on a program whose primary objective is the Evaluation of Basic Laser Welding Capabilities. The initial phase of the program, carried out in 1974 and 1975, consisted of a fundamental study of the deep penetration laser welding process. This was a broad-based study, with emphasis on the physical properties of elemental metals, but conducted with the realization that the eventual output of this program should contain information on the applicability of laser welding to materials of interest to the Navy.

The fundamental phase of the program was centered around two main areas:

1 - Determination of the influence of laser parameters on welding performance, using a standard model material (type 304 stainless steel).

2 - A study of the effect of the physical properties of a range of elemental metals on their laser welding performance.

In the course of these studies, speed/power relationships were determined, along with the effects of laser operating mode and focusing optics on weld penetration, bead shape, and fusion zone volume. The results of these studies were detailed in report R76-911989-4, issued in early 1976 (Ref. 1).

During the remainder of 1976 and the first part of 1977, the first welding tests on an alloy of potential interest to the Navy were conducted. HY-130 alloy steel was laser-welded in a series of thicknesses ranging from 0.64 cm to 1.27 cm. Welds were characterized by visual, X-ray, magnaflux and metallurgical inspection; and were also subjected to a thorough series of mechanical tests which included hardness, bend, tensile, impact, and dynamic tear tests. All of the laser welded specimens performed well in these mechanical tests, and it was concluded that the laser welding process is capable of making mechanically excellent and generally acceptable welds in HY-130 steel plate up to and including thicknesses of 1.27 cm. It was further noted that the laser weldability of the alloy improved with improved deoxidation practice in the original steel making (rare-earth treatment); and that, to the extent that inclusions continued to be present in the alloy, the numbers of such inclusions remaining in the fusion zone could be substantially reduced during laser welding by a process known as Fusion Zone Purification. This effect apparently consists of selective heating and vaporizing of ceramic inclusions within the fusion zone by the 10.6μm CO_2 laser radiation which is more efficiently absorbed by ceramics than by metal. The Fusion Zone Purification of the HY-130 steel was quantitatively verified for all weld specimens during this study, and was identified as a significant contributor to the excellent mechanical properties of autogenous HY-130 laser welds. This study was reported in detail in technical report R77-911989-10, March 1977 (Ref. 2).

Following the HY-130 work, two additional alloys were identified as being of substantial current interest to the Navy. They were HY-80 steel, an important hull construction alloy, and the two aluminum alloys 5456 and 5086, important candidates for surface effects ship hull construction. A large joint program to evaluate HY-80 laser welding for ship construction was already in the "talking stages". As a result of a small amount of promising previous HY-80 laser welding results, and the substantially successful background in HY-130 laser welding, the industrial welding of HY-80 steel was considered to be a promising candidate for a primary development program.

By contrast, the laser welding of aluminum and its alloys, while of substantial interest, has been a problem area. This has been thought to be primarily due to the physical properties of aluminum, as compared to other metals which are readily weldable with 10.6μm CO_2 laser radiation. Aluminum has a high surface reflectivity for 10.6μm radiation, and as a result, increased power density is necessary to initiate penetration. There is also an increased tendency for diffusion of heat away from the weld point due to the high thermal conductivity of aluminum. As far as the initiation of penetration is concerned, the stable, refractory oxide which forms on aluminum in the atmosphere is also a factor, since the oxide has a substantially higher absorptivity for 10.6μ radiation than does the metal itself.

Upon consideration of the status of the two potential alloy systems of interest to the Navy (HY-80 and aluminum), it was decided based on the information summarized above that the laser welding of aluminum alloys was the more appropriate area for study under this contract.

The history of aluminum welding to date has been as follows. The initial problems in welding aluminum alloys appeared to be porosity and bead surface appearance and were attributed to the presence of sources of hydrogen and to the tendency for refractory oxide formation respectively. Solutions were expected to be found, and were proposed in terms of elimination of sources of hydrogen and elimination or control of surface contamination during welding, with the possibility of improving the flow and puddling characteristics also being considered. A search for solutions to these problems was, naturally, based on the assumption that aluminum alloys could be laser welded in approximately the same procedures utilized for other alloy systems studied to date.

Experience during 1977 has been largely to the contrary. The welding of aluminum alloys has proved to be significantly more difficult than the laser welding of nickel, cobalt, iron, or titanium base alloys. Using initial parameters and techniques based on previously optimized conditions determined earlier in this program as a starting point for welding of 5086 and 5456 aluminum alloys, it was determined that laser optical arrangement and the resultant distribution of energy intensity at the focal point are critical factors which influence the quality of the welds produced. The hollow beam (Unstable Resonator) output mode appeared to couple more easily with both aluminum alloys than did the Gaussian energy distribution produced by the oscillator/amplifier. This was in sharp contrast to the deeper penetration normally obtained with Gaussian optics in materials such as 304 stainless steel (Ref. 1), where coupling is more readily accomplished. It was concluded that the improved coupling is most likely due to the very high energy density at the center of the unstable resonator focal spot.

The two aluminum alloys studied appeared to differ in welding response to a greater degree than was previously expected, both in ability to penetrate under a given set of conditions, and also in bead appearance. Penetration in 5456 was substantially greater, the difference being primarily attributed to the 1.5% greater magnesium content of this alloy.

Adequate penetration was eventually achieved in both alloys, and effects linking gas atmosphere and shielding to both penetration and bead surface appearance began to be observed. Beads produced, however, have not exhibited substantial improvement over those made previously (Ref. 1). Butt welding has usually resulted in fusion zones of somewhat lower quality than have been produced by "bead-on-plate" techniques.

The principal difficulty in welding of aluminum alloys is now considered to be the result of the extreme sensitivity of the alloys to the intensity of the input energy. In order to produce adequate initial coupling, i.e., to overcome the surface reflectivity and penetrate the refractory oxide coating and the alloy beneath, high powers are required; however, once penetration has been initiated and a radiation trap (the deep penetration cavity) capable of greater energy absorption is formed, excessive penetration and "drop-through" of the fusion zone can and often does result. The high fluidity of the molten aluminum, combined with the sensitivity of coupling to energy input, has made it very difficult to produce an acceptable bead shape in aluminum alloys while still producing adequate penetration. The interaction of shielding gas and/or plasma with the beam and the workpiece is very much a part of this phenomenon. The other problem, that of porosity, while still considered important, has been relegated to secondary status, since the necessity of producing an acceptable penetration and weld bead configuration must take precedence over the internal structure of the weld.

The bulk of the welding work conducted during the past period was directed at developing a means of consistently producing acceptable penetration and fusion zone configurations. The main areas of investigation included refinement of the laser beam itself, and attempts to develop an adequate and reproducible shielding setup. These experiments are described in the body of this report. It should be noted that gas shielding development is one of the most difficult areas to make quantitative.

The results produced to date are also summarized herein. Although information has been obtained, and some fairly good welds have been produced, we are still without a means to consistently make acceptable butt welds in the two aluminum alloys under study. Efforts in this area are continuing, since we cannot sensibly proceed to mechanical property measurements without first establishing a consistent welding technique.

EXPERIMENTAL PROCEDURE AND RESULTS

Phase I

The preliminary phase of the aluminum alloy welding program was intended to duplicate the nominally acceptable bead-on-plate laser welds of 5456 which had been previously achieved both in Ref. 1 and in other laser welding trials at UTRC. To this end, the initial attempts to laser weld 5456 and 5086 aluminum alloy plate were made with the continuous, cross-beam carbon dioxide laser, mirror train, and work station described in Ref. 2. The laser was operated in the oscillator/amplifier mode, and thus produced an approximately Gaussian energy distribution at the focal point of the beam. The fixed shielding enclosure was also similar to that used previously (Fig. 2, Ref. 2), but was operated with 100% helium as a shield gas, instead of 100% argon or an argon-helium mixture. A 17.1 cm diameter focusing mirror with a 45.7 cm focal length was used throughout the program.

Bead-on-plate welds were made in the downhand position on 10.2 x 20.3 x 0.64 cm specimens of 5456 and 5086 aluminum alloy plate. The top surface of each specimen was cleaned along the path of the weld seam immediately before welding by scraping to bare metal with the sharpened end of a steel file. Variation of the welding speed was achieved by traversing the specimens beneath the focusing mirror. The specimens were clamped to a Bridgeport machining table, which was equipped with a motorized x-axis drive and manual controls for the y and z (height) positions. The table height was set so that the focal plane of the laser beam lay 3.2 $\pm$ 0.2 mm below the upper surface of each specimen. During Phase I of the investigation, the effects of varying the beam power, beam traverse speed, and shielding configuration were evaluated by examining bead-on-plate welds for quality of bead surface appearance and adequacy of penetration. Butt welds were made only under conditions which had previously resulted in acceptable bead-on-plate penetration using the same alloy and plate thickness.

Slight changes in both the internal and external laser optics and the consequent variations of the energy intensity distribution at the focal point proved to be very critical factors. The approximately Gaussian radial energy distribution in the focal plane produced by the oscillator/amplifier laser operational mode did not couple reproducibly with the specimens of 5456 alloy; and only rarely and after extensive table height adjustment, with the 5086. Inadequate beam coupling was characterized by the virtual absence of complete fusion zone penetration, a narrow and unusually smooth bead surface, and extensive back reflection of the beam into the laser cavity with consequent damage to the potassium chloride beam output window. The factors which caused the day-to-day (and sometimes hour-to-hour) variation in the degree of beam coupling with the specimen surface when using this laser were never satisfactorily isolated, despite repeated attempts to measure and control critical parameters such as laser output energy, focal plane position, shielding geometry, and specimen surface preparation (Table I). Consequently, it was decided to shift the work station to a different continuous, cross-beam carbon dioxide laser, operating in the unstable resonator mode. It was expected that the change to a hollow-beam energy distribution, with its associated high intensity at the center of the focal spot, would couple more easily and perhaps more reproducibly with the aluminum.

Phase II

The change to a laser operating in the unstable resonator mode (hollow beam) virtually eliminated the difficulties experienced previously in obtaining adequate coupling between the laser beam and the aluminum alloy surface. In addition, it was possible to couple while utilizing 2-3 kW less of beam power. However, complete penetration of the fusion zone continued to be a problem in that it could not be achieved reproducibly at the same power input (Table II). Furthermore, the depth of penetration often varied between complete and partial along the length of the weld, whether in butt or bead-on-plate configuration. In an attempt to improve this lack of reproducibility of the depth of penetration, the main effort of the next phase of the program was directed toward plasma suppression and/or plasma removal from the beam path by altering the shielding.

Soon after the change of lasers which initiated Phase II of the program, it became apparent that there was a marked difference in the response of 5456 as opposed to 5086 to CO_2 laser welding. This was manifested as a greater depth of fusion zone penetration in the 5456, as well as a somewhat smoother bead surface. This difference in response did not appear to be associated with the change in the lasers utilized for the welding.

To ensure that undetected variations in extrinsic welding parameters were not responsible for this phenomenon, 0.64 cm thick specimens of each alloy were placed end-to-end, and a bead-on-plate weld was made in one continuous traverse perpendicular to this butted interface (Run 18-1, Table II). The weld was started in the 5086 at 5.08 cm/s with a laser power setting of 7.5 kW (~5.9 kW at the specimen surface). No through penetration was observed along the 5.7 cm length of the weld bead in the 5086 specimen, only a slight outward bulge of the bottom surface. However, full penetration was achieved in the 5456 as soon as the beam crossed the interface and entered that specimen. Irregular drop-through of the fusion zone averaging 1.3 mm occurred, with two gaps of no penetration, each about 2 mm in length, along the 5.7 cm bead length in the 5086. These results strongly suggest that a change in the magnesium content of <1.5% (the maximum difference inherent in the nominal range of magnesium content of 5456 and 5086) can significantly affect the weldability of aluminum alloys. In this case, a greater degree of beam penetration and a somewhat smoother bead surface were observed to coincide with an increase in magnesium content, whereas the small differences in all other alloying elements appear to be insignificant. This deduction is admittedly qualitative, but it is consistent with the prior observation that commercially pure magnesium exhibits much greater fusion zone depth than other commercially important alloys laser welded under the same conditions (Ref. 1).

Phase III

Examination of the effects of shielding changes on plasma suppression and fusion zone depth were conducted with the same shielding enclosure utilized in the previous experiments (Fig. 2, Ref. 2). The shielding enclosure was positioned so that it cleared the workpiece by 0.05 in. A small nozzle was added which was positioned to direct a jet of helium across the workpiece surface, perpendicular to the beam traverse direction, at the point of beam inpingement. Welds were made in the bead-on-plate configuration on 0.95 cm plate, using various laser beam power settings and beam traverse speeds, with the beam focal plane set 4.8 $\pm$ 0.2 mm below the upper surface of the workpiece (Figs. 1-7 and Table III).

Use of the helium cross-jet to sweep plasma to one side of the beam path appeared to also aspirate air into the beam impingement area (Figs. 1-2 and run 35-1, Table III). However, considerable improvement in overbead surface appearance was achieved for both 5456 and 5086 by increasing the top surface shield gas flow through the diffuser plate surrounding the beam part (Figs. 3-7 and Table III). Under these shielding conditions, full penetration of 0.95 cm plate was achieved with 8 kW power setting at 1.19 cm/s traverse speed in 5456 and 9 kW, 1.48 cm/s in 5086.

Phase IV

Following a period of laser down time for maintenance and internal alignment, a new series of bead-on-plate welds was conducted using a new circular shield enclosure designed by UTRC laser engineer, C. O. Brown. This shield enclosure was intended to maximize the shield gas flow rate surrounding the beam entry path (shield throat), as well as the area around the point of beam impingement (Fig. 8). The shield height was set to give a 1.8 mm clearance above the workpiece. The focal plane of the beam focusing mirror (focal length, 45.7 cm) was set 3.2 mm below the upper surface of the specimens. A new surface cleaning procedure was also introduced in an attempt to generate a cleaner and more reproducibly smooth and uniform surface. A shallow, flat-bottomed channel of 0.13-0.18 mm depth was milled in the top and bottom surfaces of each specimen along the intended weld path with a portable router equipped with a tungsten carbide bit. Welding was subsequently conducted not more than one minute after router cleaning.

As indicated by the data recorded in Table IV, small changes in shield gas flow rate resulted in substantial variation in fusion zone depth. In 0.64 cm 5456, an increase in the helium flow rate to the throat area from 1.42 to 2.12 m^3/hr had approximately the same effect on depth of penetration as an increase in beam power setting from 5.5 to 7.5 kW. It also became evident that it was important to maintain a steady helium flow pattern across the specimen surface during welding. This condition was greatly facilitated by the use of end and side plates of 0.64 cm aluminum stock butted against the sides of the specimen to be welded. This maintained a constant gap between the bottom edge of the shield enclosure during the welding. As with the throat area flow rate, a rapid and steady flow of helium was essential for consistent depth of fusion zone penetration, presumably by removing plasma from the beam path.

Phase IV of this program served to demonstrate that very careful control of the shield gas flow pattern was required to achieve consistent depth of fusion zone penetration. The shield alignment, side plate position and accumulation of splatter in the shield throat all proved to have a strong influence on this parameter, and required constant attention from run to run. When acceptable weld profiles were obtained, it was hoped that weld porosity would be minimal as a result of the thorough router-cleaning of the top and bottom aluminum surfaces immediately prior to welding. Radiography demonstrated that this was not the case, however (Figs. 9B and 10B), and further work in the area of porosity control is required. If it is assumed that this porosity is caused by the rejection of hydrogen dissolved in the liquid aluminum and it solidifies, it is still not clear whether the observed weld porosity was produced by dissolved hydrogen present before welding, or whether hydrogen sources from the external environment (water vapor) had been inadequately controlled.

Additional problems were encountered when full penetration was achieved due to the low viscosity of the liquid aluminum. The fusion zone was sufficiently fluid to cause a significant amount of drop-through in all cases. Surface tension forces did not appear to be adequate to control the weld pool. This phenomenon does not seem to be associated with a more efficient absorption of beam energy due to a deeper vapor cavity, since drop-through was always observed even over short distances along a weld which displayed intermittent full penetration.

Phase V

The final phase of the experimental program was designed to achieve the best possible bead-on-plate and butt welds in both alloys, using those parameters judged to be optimum based on the results described previously. The 0.95 cm thick plate was chosen to determine whether any of the results of Phase IV were unique to 0.64 cm plate. The bead-on-plate welds essentially duplicated the results obtained previously (Table V, Figs. 11-13). Alloy 5086 required higher energy to weld than 5456, and complete fusion zone penetration was accompanied by drop-through and an underfilled bead on the top surface.

Drop-through during butt welding was eliminated by the use of two-sided welding (Figs. 14-15). However, fusion zone porosity continued to occur, together with the intermittent appearance of porosity at the root of the second weld (Fig. 14).

Lack of reproducibility of welding results was often noted in tests where no experimental parameters were deliberately altered. This indicated that some variation in the experimental conditions was occurring. The two areas which are most difficult to quantitatively monitor experimentally are the detailed nature of the laser beam itself (energy distribution at the focal point, mode purity), and the specifics of the gas shielding arrangement. It has already been noted that both of these areas are quite critical to the welding results.

In order to reduce variations in the laser beam to the minimum possible with the present state-of-the-art, a thorough engineering study of the cross beam unstable resonator laser presently in use for this study has been made. A slight drifting problem resulting from mechanical instability of the internal optical mounts was identified and corrected. The changes in beam energy profile, focusability, and output mode purity which resulted from this problem are expected to be eliminated in the reworked laser. In addition, the entire laser has been totally refurbished, including mirrors and mounts, discharge cathodes, and heat exchangers. Subsequently, the laser has been fine-tuned for maximum beam quality and consistency of operation.

Although it is not possible within the present state-of-the-art of high power laser technology to absolutely guarantee complete stability, uniformity, perfection, and reproducibility of the beam at multikilowatt power levels, all reasonable steps have now been taken to improve the laser beam to the maximum extent possible. This should serve to minimize the effects of beam instability and/or variability on experimental results, so that the influence of gas shielding, the other difficult and critical factor in the physical aluminum welding process, can be better isolated and more meaningfully investigated.

SUMMARY OF PERTINENT OBSERVATIONS AND CONCLUSIONS

1. Small changes in internal and external laser optics, and the consequent variations of the energy distribution at the focal point had large effects on the ability of the laser to couple with aluminum alloys and produce deep penetration welds.

2. The Gaussian energy distribution characteristic of a focussed laser operating as an oscillator amplifier was less effective in coupling with aluminum alloys 5456 and 5086 than was the energy distribution which was characteristic of a focussed laser operating as an unstable resonator.

3. When inadequate coupling occurred, it was accompanied by extensive back reflection into the laser cavity which was potentially damaging to both the cavity optics and the output window.

4. Variations in the degree of coupling were encountered which, to date, have not been satisfactorily explained, despite repeated attempts to measure and control critical parameters including laser output energy, focal plane position, gas shielding and shielding geometry, plasma suppression and control, and specimen preparation.

5. The unstable resonator coupled relatively easily with the aluminum alloys under study. This was attributed to a sharp, high energy spike at the center of the focal point. Coupling generally required between 2 and 3 kW less of beam power than was required of the oscillator-amplifier.

6. Penetration was often observed to be nonuniform along the weld length. This was attributed to intermittent plasma effects. It was improved, but not completely controlled, by improving plasma suppression techniques.

7. 5456 Alloy proved to be substantially more weldable than 5086 alloy, using a CO_2 laser. The difference in weldability was attributed to the 1% greater magnesium content of the 5456 alloy.

8. A clean surface with a reproducible finish could be obtained on aluminum samples immediately prior to welding by router finishing with a carbide bit. This procedure produced noticeable improvement in process reproducibility.

9. Small changes in shielding gas flow rate resulted in substantial changes in penetration depth and bead appearance, indicating the criticality of shielding to the laser welding process. A rapid, steady flow of helium gas appeared to produce the best results. Shield alignment and accumulation of splatter within the shield also proved to be important variables.

10. Porosity was present in unacceptable amounts in all weld specimens, indicating that the router cleaning procedures in themselves, were not sufficient to eliminate porosity. Sources of hydrogen, both internal and external, bear future investigation.

11. Excessive "drop-through" of the bead was encountered in all full penetration welds. This problem, which is related to liquid metal viscosity and surface tension, has not been solved. It does not appear to be related to increased absorption of energy following formation of the deep penetration cavity.

12. Attempts to eliminate "drop-through" by use of two-sided partial penetration welding produced improved bead contours, but the welds exhibited excessive root porosity at the base of the second (blind) weld pass.

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The authors wish to acknowledge the significant contributions of Clyde O. Brown, Senior Research Scientist, United Technologies Research Center, in the areas of laser engineering, operation, and application, as applied to this program as well as in the design of gas shielding apparatus. Mr. Brown was responsible for laser operation and delivery of the energy to the workpiece, and assisted in the majority of the welding tests. He was also wholly responsible for the laser evaluation and overhaul which should pave the way for progress in the continuation of this aluminum-welding study.

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Table I

Representative Laser Welds, 0.64 cm Plate, Preliminary Series Using Oscillator/Amplifier Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	Weld Configuration Bead-on Plate	Weld Configuration Butt	Comments
9-6		x	11	4.66		x	Coupling only at 20.3 cm butt seam; none on lead-in or run-off plates. Incomplete penetration.
9-7		x	11	4.66	x		Raised workpiece 0.127 cm. Good coupling.
9-8		x	11	4.66	x		Raised workpiece 0.127 cm. Good coupling with some full penetration.
9-9		x	11	4.66	x		Raised workpiece 0.127 cm. Good coupling but little full penetration.
9-10		x	11	4.23	x		Lowered workpiece 0.127 cm. Same position as run 9-8, but less penetration despite slower speed.
9-11		x	11	3.81	x		Same height as 9-10. Full penetration but too much drop-through.
10-11	x		9	3.81	x		Extensive prior laser alignment. No full penetration.
10-12	x		9	3.81	x		Virtually no coupling until last half of 15 cm run.
10-13	x		9	3.81	x		Lowered workpiece 0.254 cm. 80% penetration; irregularly.
10-19		x	10	3.39		x	Good coupling; both butt seam and run-off plates. Virtually no full penetration.

Table II

Representative Laser Welds, 0.64 cm Plate, Preliminary Series Using Unstable Resonator Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	Weld Configuration Bead-on Plate	Weld Configuration Butt	Comments
17-14	x		7.5	7.20		x	No full penetration. Good coupling.
17-15	x		7.5	5.08		x	Mostly full penetration with one small gap. Overbead is underfilled. 18 cm bead.
17-16		x	7.5	5.08	x		Very little full penetration.
17-17		x	7.5	4.23	x		No apparent increase in penetration with respect to run 17-16.
18-1	x	x	7.5	5.08	x		5456 + 5086 plates butted, BOP weld perpendicular to seam. Started in 5086; no full penetration. Full but somewhat irregular penetration with drop-through in 5456. Implies difference in welding response between alloys.
18-10		x	7.5	3.39	x		Partial and very irregular full penetration along weld bead.
18-11		x	8	3.39	x		Mostly full penetration. Underfilled and dropped through.
18-12		x	8	3.39		x	20.3 cm butt seam, plus BOP run-out plates. Full penetration, both ends of butt seam; incomplete penetration, center 7.6 cm.

Table III

Laser Bead-on-Plate Welds of 0.95 cm Plate, Shielding Variation Seires, Unstable Resonator Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	Top He Shield Gas Flow Rate (m^3/hr)	Comments
35-1		x	8	1.48	1.27	Plasma-sweeping cross-jet on. No full penetration. Much fine porosity on bead surface.
35-2		x	8	1.48	1.27	Cross-jet off. Much plasma generation visible. No full penetration. Very grey, oxidized bead surface.
35-3		x	8	1.48	2.83	Cross-jet off. Much plasma during run. Bead surface much better, shiny.
35-4		x	8	1.19	2.83	Cross-jet off. Wider overbead than run 35-3. No full penetration but some peek-through. Good looking bead surface.
35-5		x	9	1.48	4.25	Cross-jet off. 10 cm bead. Full penetration along center 4 cm only; this region underfilled and dropped through.
35-6	x		8.2	1.69	2.83	Cross-jet off. No full penetration.
35-7	x		8	1.19	2.83	Cross-jet off. Incomplete penetration, first 1.9 cm; then full penetration remainder of 10 cm bead. Extensive drop-through. Relatively smooth overbead.

Table IV

Data from Selected Bead-on-Plate Laser Welds of 0.64 cm Plate, Circular Shield, Unstable Resonator Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	He Shield Gas Flow Rates (m^3/hr) Top	Throat	Comments
62-11	x		7.1	1.19	5.66	1.42	Full fusion zone penetration; second half of bead only.
62-12	x		6.5	1.19	5.66	1.84	Full penetration.
62-13	x		5.5	1.19	5.66	1.84	Full penetration.
62-14	x		5.5	1.19	5.66	1.84	Full penetration.
62-15	x		5.0	1.19	5.66	1.84	Intermittent full penetration.
62-16	x		6.0	1.19	5.66	1.84	Full penetration. Removed Al splatter buildup from throat.
62-17	x		6.0	1.19	5.66	1.84	Intermittent full penetration.
62-18	x		7.5	2.20	5.66	1.84	Good weld. Some drop-through.
62-19	x		7.5	2.50	5.66	1.84	Intermittent full penetration. Some back reflection.
62-20	x		7.5	2.20	5.66	1.84	Full penetration, one hole created.
62-21	x		7.5	2.20	5.66	1.42	Full penetration, one hole created.
62-22	x		7.5	2.20	5.66	0.85	Intermittent full penetration.
62-23	x		7.5	2.20	5.66	1.13	Full penetration; center 1/3 of bead only.
62-24	x		7.5	2.54	5.66	1.27	Full penetration, entire length.
62-25	x		7.5	2.54	5.66	1.27	Full penetration, butt weld.
62-26	x		7.5	2.54	5.66	1.27	Two overlay bead-on-plate welds. Full penetration, second half only, both welds.
63-27	x		6.0	1.19	5.66	1.42	No full penetration.
63-28	x		6.0	1.19	5.66	1.98	Full penetration, entire length.
63-29	x		5.5	1.19	5.66	1.98	Intermittent full penetration.
63-30	x		5.5	1.19	5.66	1.98	Removed Al buildup from throat. Full penetration, last half of weld only.
63-31	x		5.5	1.19	2.83	2.27	Full penetration. Clean overbead, sooty deposit to side of weld.

Table IV (Cont'd)

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	He Shield Gas Flow Rates (m^3/hr) Top	He Shield Gas Flow Rates (m^3/hr) Throat	Comments
63-32	x		5.5	1.19	4.25	2.21	Full penetration. Wider overbead. Shield hit workpiece near end of traverse.
63-33	x		5.5	1.19	4.25	2.21	Shield leveled. Full penetration. Sooty deposit.
63-34	x		5.5	1.69	4.25	2.21	Full penetration. Best looking overbead of series. Cleaned out shield throat.
63-35	x		5.5	1.69	4.25	2.21	Duplicated run 63-34.
63-36	x		5.5	2.12	4.25	2.21	Some spots of incomplete penetration. Shield caught on weld bead.
63-37	x		5.5	1.69	4.25	2.21	Incomplete penetration. Suspect hydrocarbons in atmosphere beginning to absorb beam energy.
64-40	x		5.5	1.69	4.25	2.21	Intermittent full penetration, first 1½ in. Full penetration, remainder of weld.
64-41	x		5.5	1.69	4.25	2.21	Full penetration after first 1/8 in. Substantial fusion zone drop-through.
64-42	x		5.5	1.69	4.25	2.21	Duplicate run 64-41.
64-43		x	5.5	1.69	4.25	2.21	Very shallow penetration.
64-44		x	6.0	1.69	4.25	2.21	Full penetration only along 2.5 cm at center zone.
64-45		x	6.0	1.69	4.25	2.21	Intermittent full penetration.
64-46		x	6.3	1.69	4.25	2.21	Very intermittent full penetration. Suspect side plates tilted.
64-47		x	6.3	1.69	4.25	2.21	Full penetration. Side and end plates tightly butted for more constant gas flow over top surface of workpiece.
64-48		x	6.3	1.69	4.25	2.21	Duplicate run 64-47.

Table V

Data from Selected Bead-on-Plate and Butt Laser Welds of 0.95 cm 5456 and 5086 Plate, Circular Shield, Unstable Resonator Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	He Shield Gas Flow Rates (m^3/hr) Top	He Shield Gas Flow Rates (m^3/hr) Throat	Welding Configuration Bead-on Plate	Welding Configuration Butt	Comments
65-71	x		7.9	1.69	4.25	2.21		x	Butted seam tack welded before butt weld. Full penetration. Considered drop-through of fusion zone.
66-72	x		7.9	1.69	4.25	2.21		x	Duplicated results of run 65-71.
66-73	x		7.9	1.69	4.25	2.21	x		Virtually complete absence of full fusion zone penetration. Butt seam present in previous runs may act as radiation trap.
66-74	x		7.9	1.69	4.25	2.21	x		0.025 in. groove cut in top for radiation trap. Virtually no full penetration.
67-76	x		7.9	1.69	4.25	2.21	x		Smooth top surface. Virtually no full penetration.
68-83	x		7.0	1.69	4.25	2.21		x	Full penetration along butt seam; 1/2 of bead length fully penetrated on trail bead-on plate piece.
68-84		x	7.0	1.69	4.25	2.21		x	Virtually no full penetration along butt seam; none through bead-on-plate lead and trail plates.
68-85		x	7.5	1.69	4.25	2.21		x	Same results as run 66-84.

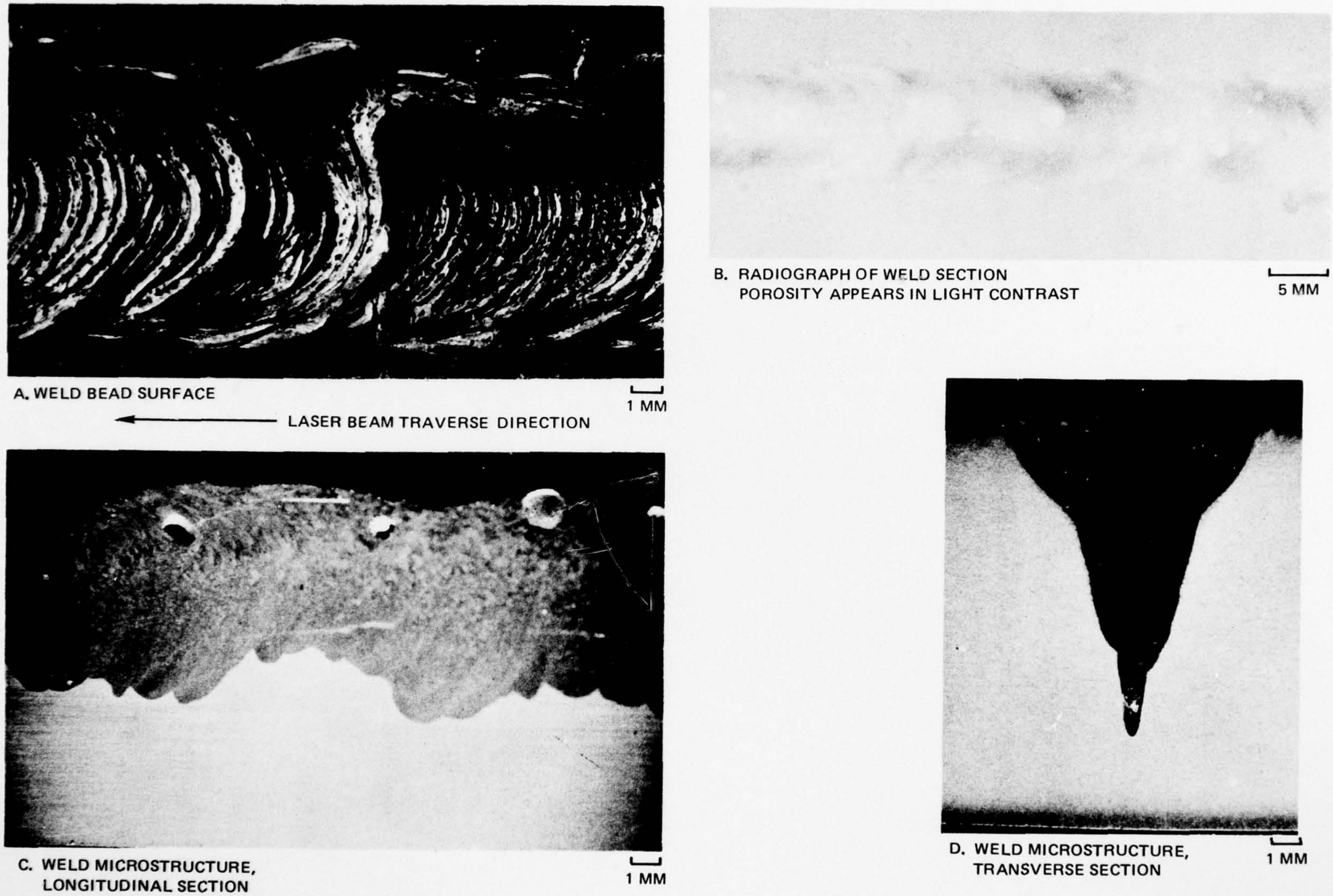
Table VI

Data from Selected Two-Sided Butt Laser Welds of 0.95 cm 5456 and 5086 Plate, Circular Shield, Unstable Resonator Mode

Run	Alloy 5456	Alloy 5086	Set Power (kW)	Beam Traverse Speed (cm/s)	He Shield Gas Flow Rates (ft^3/hr) Top	Throat	Comments
70-86	x		7.0	3.39	4.25	2.21	First pass (top): Nominal. No full penetration, as expected. Second pass (bottom): Shield off (error) for 1/3 of butt weld bead.
70-87	x		7.0	3.39	4.25	2.21	Both top and bottom over-beads look good.
70-88		x	7.0	3.39	4.25	2.21	About same as run 70-87, but both bead surfaces rougher.

STRUCTURE OF WELD 35–1, 5086, TABLE III

TOP SHIELD HELIUM FLOW RATE: 1.27 M^3/HR. CROSS–JET ON. 8kW; 1.48 CM/S



A. WELD BEAD SURFACE

B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

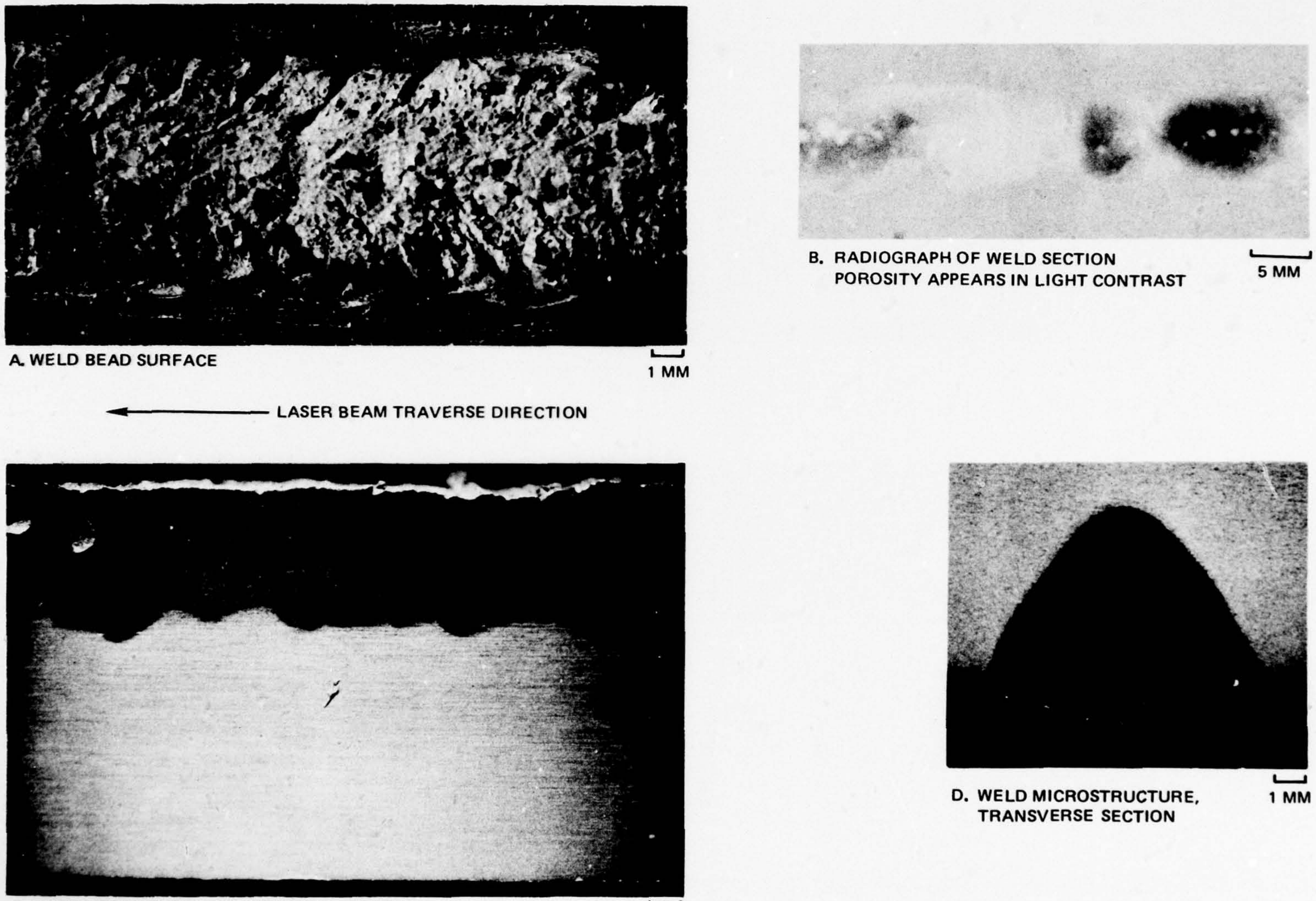
C. WELD MICROSTRUCTURE,
LONGITUDINAL SECTION

D. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

FIG. 1

STRUCTURE OF WELD 35–2, 5086, TABLE III

TOP SHIELD HELIUM FLOW RATE : 1.27 M^3/HR. CROSS–JET OFF. 8 kW; 1.48 CM/S



A. WELD BEAD SURFACE

B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

C. MICROSTRUCTURE, LONGITUDINAL SECTION

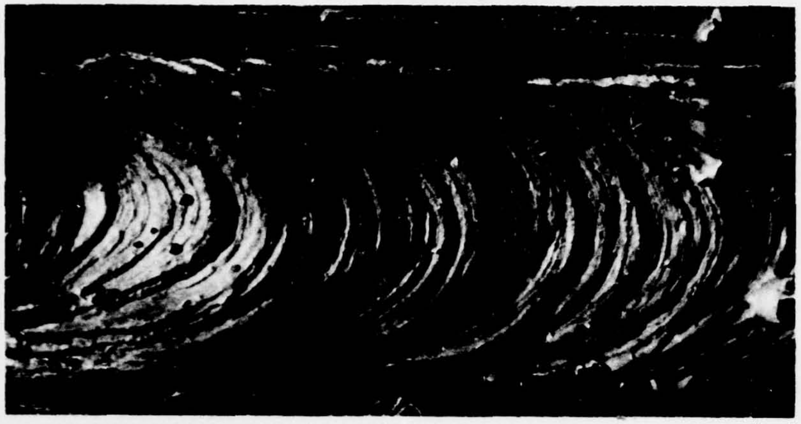
D. WELD MICROSTRUCTURE, TRANSVERSE SECTION

78–07–248–13

FIG. 2

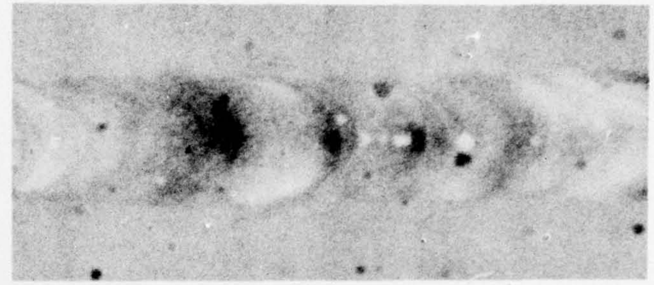
STRUCTURE OF WELD 35–3, 5086, TABLE III

TOP SHIELD HELIUM FLOW RATE: 2.83 M^3/HR. CROSS–JET OFF. 8 kW; 1.48 CM/S



A. WELD BEAD SURFACE

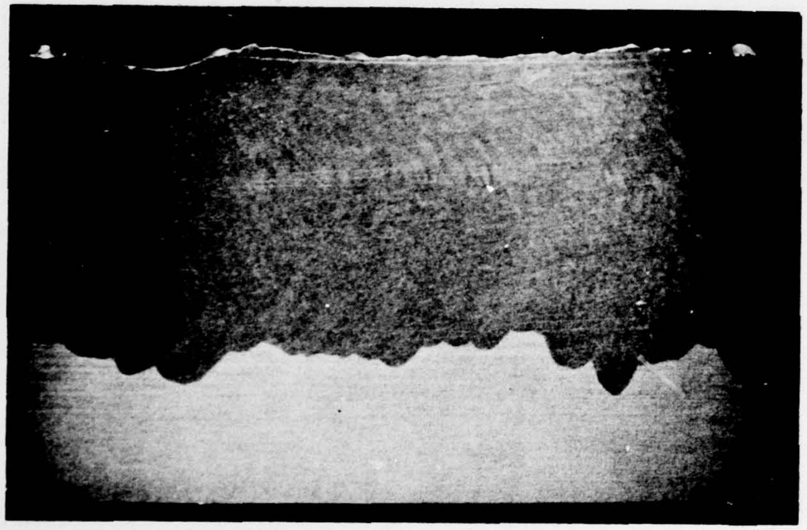
1 MM



B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

5 MM

← LASER BEAM TRAVERSE DIRECTION



C. WELD MICROSTRUCTURE, LONGITUDINAL SECTION

1MM

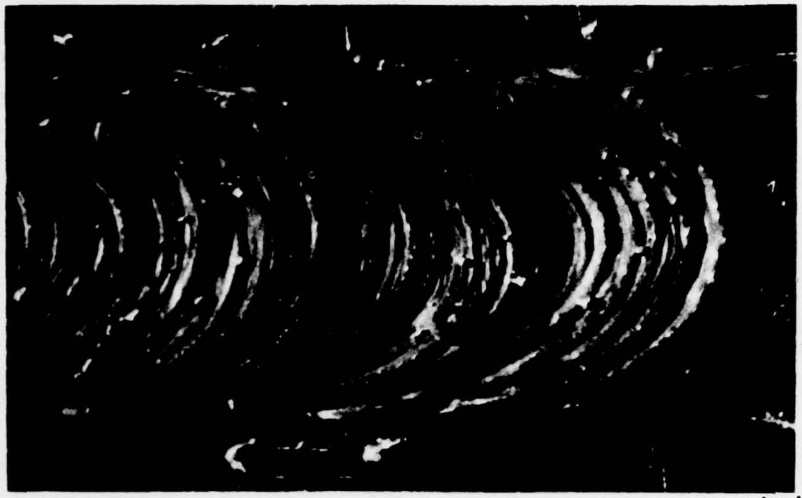
D. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

1 MM

FIG. 3

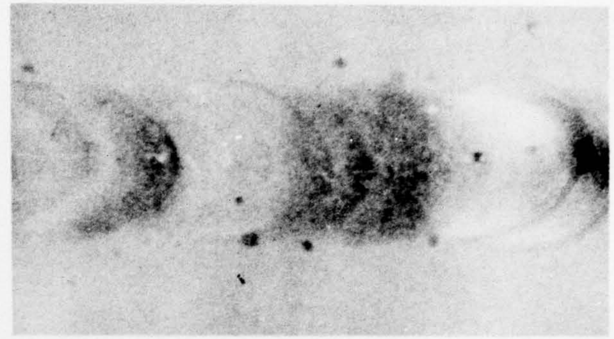
STRUCTURE OF WELD 35–4, 5086, TABLE III

TOP SHIELD HELIUM FLOW RATE: 2.83 M^3/HR. CROSS–JET OFF. 8 kW; 1.19 CM/S



A. WELD BEAD SURFACE

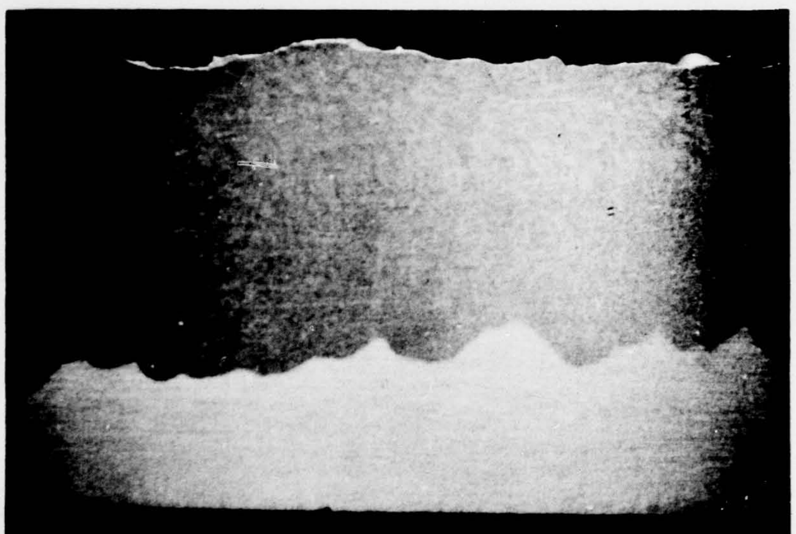
1 MM



B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

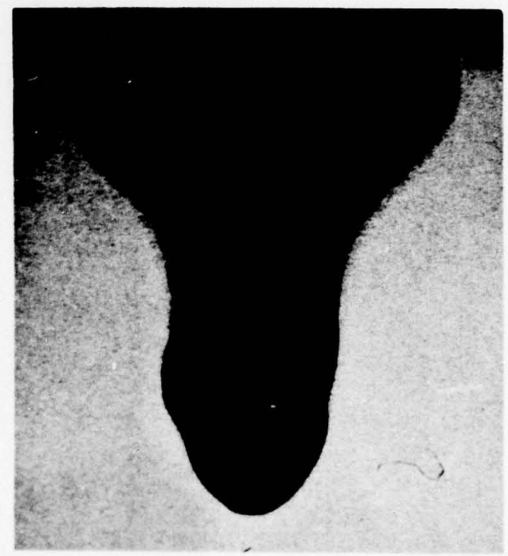
5 MM

← LASER BEAM TRAVERSE DIRECTION



C. WELD MICROSTRUCTURE, LONGITUDINAL SECTION

1 MM



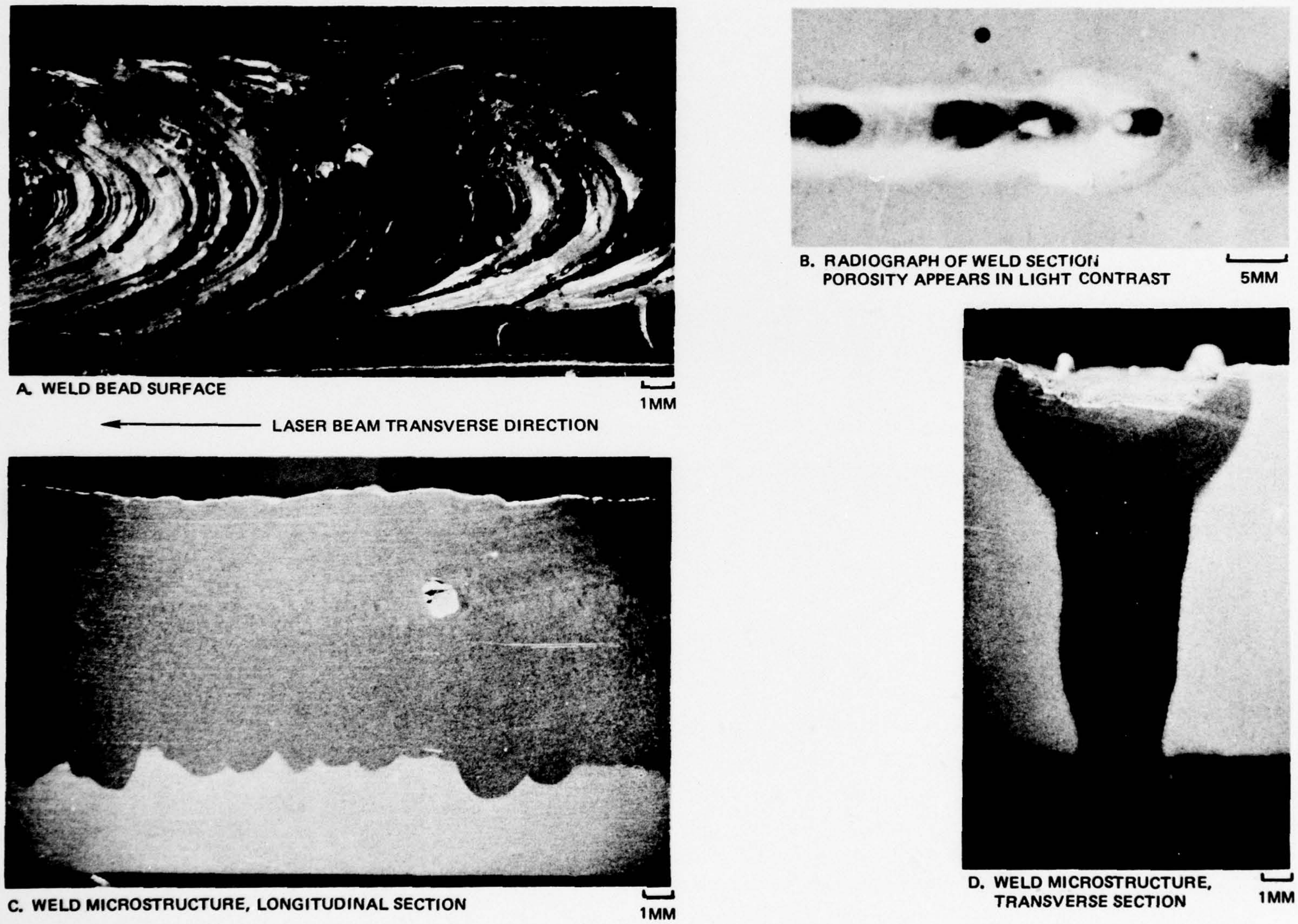
D. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

1 MM

FIG. 5

STRUCTURE OF WELD 35–5, 5086, TABLE III

TOP SHIELD HELIUM FLOW RATE: 4.25 M^3/HR' CROSS–JET OFF. 9 kW; 1.48 CM/S



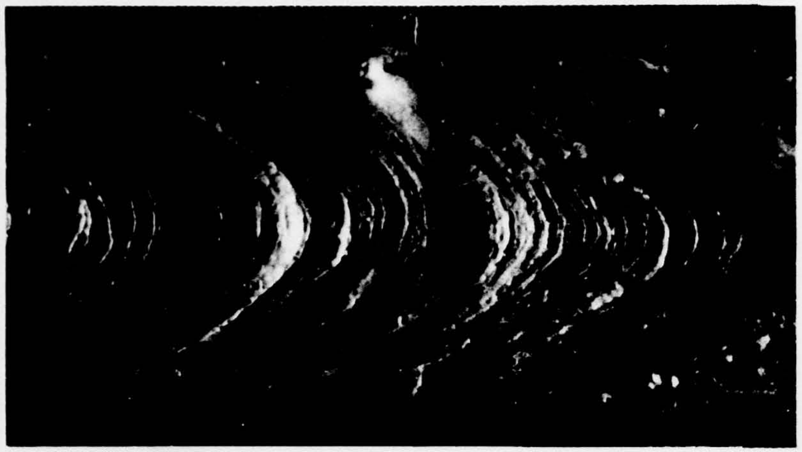
A. WELD BEAD SURFACE

B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

C. WELD MICROSTRUCTURE, LONGITUDINAL SECTION

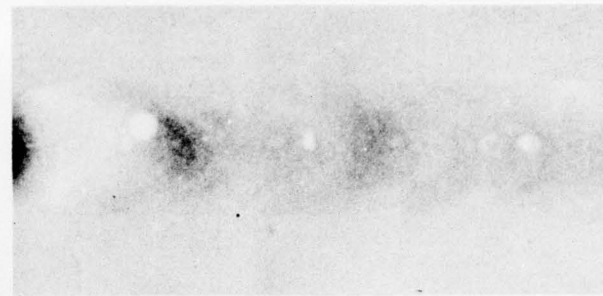
D. WELD MICROSTRUCTURE, TRANSVERSE SECTION

STRUCTURE OF WELD 35–6, 5456, TABLE III
TOP SHIELD HELIUM FLOW RATE: 2.83 M^3/HR. CROSS–JET OFF. 8.2 kW; 1.19 CM/S



A. WELD BEAD SURFACE

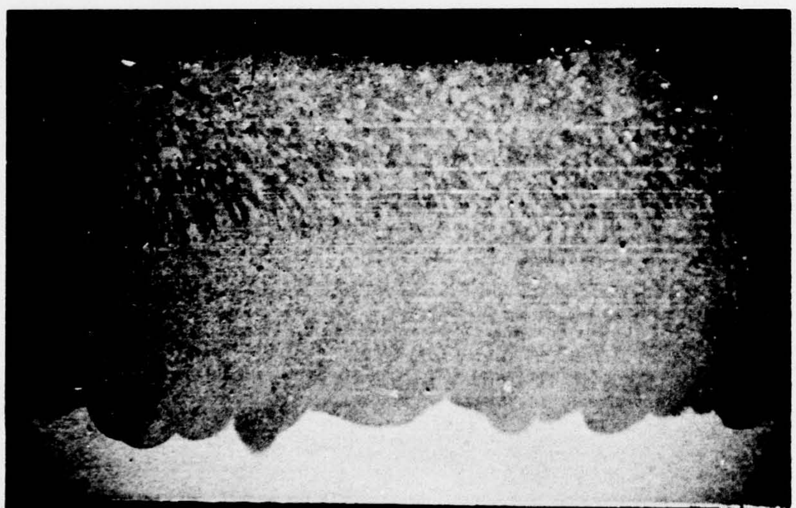
1MM



B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

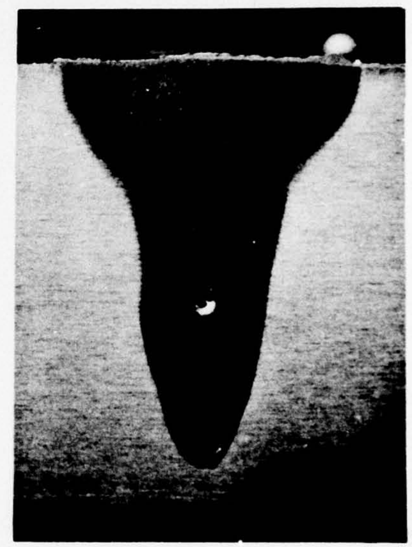
5MM

LASER BEAM TRANSVERSE DIRECTION



C. WELD MICROSTRUCTURE, LONGITUDINAL SECTION

1MM



D. WELD MICROSTRUCTURE, TRANSVERSE SECTION

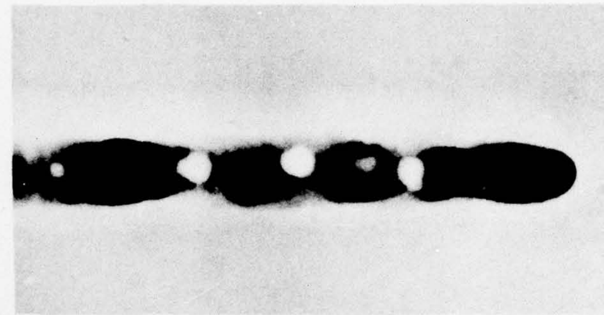
1MM

78–07–248–11

STRUCTURE OF WELD 35–7, 5456, TABLE III
TOP SHIELD HELIUM FLOW RATE: 2.83 M^3/HR. CROSS–JET OFF. 8kW; 1.19 CM/S

A. WELD BEAD SURFACE

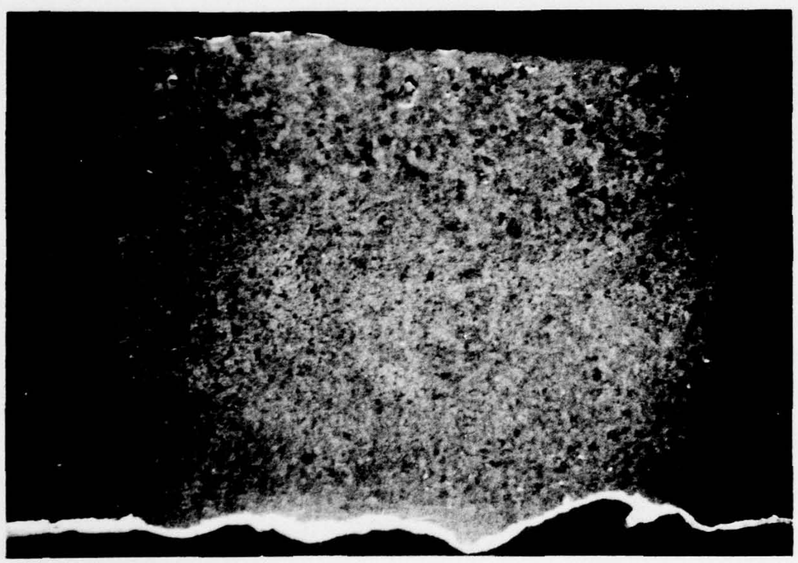
1MM



B. RADIOGRAPH OF WELD SECTION
POROSITY APPEARS IN LIGHT CONTRAST

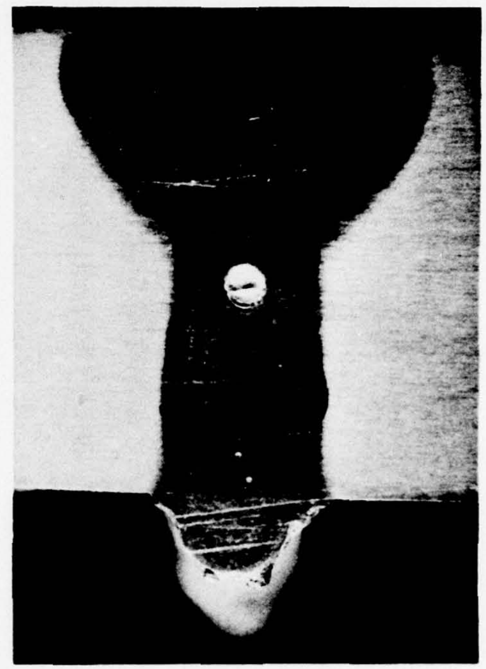
5MM

← LASER BEAM TRAVERSE DIRECTION



C. WELD MICROSTRUCTURE, LONGITUDANAL SECTION

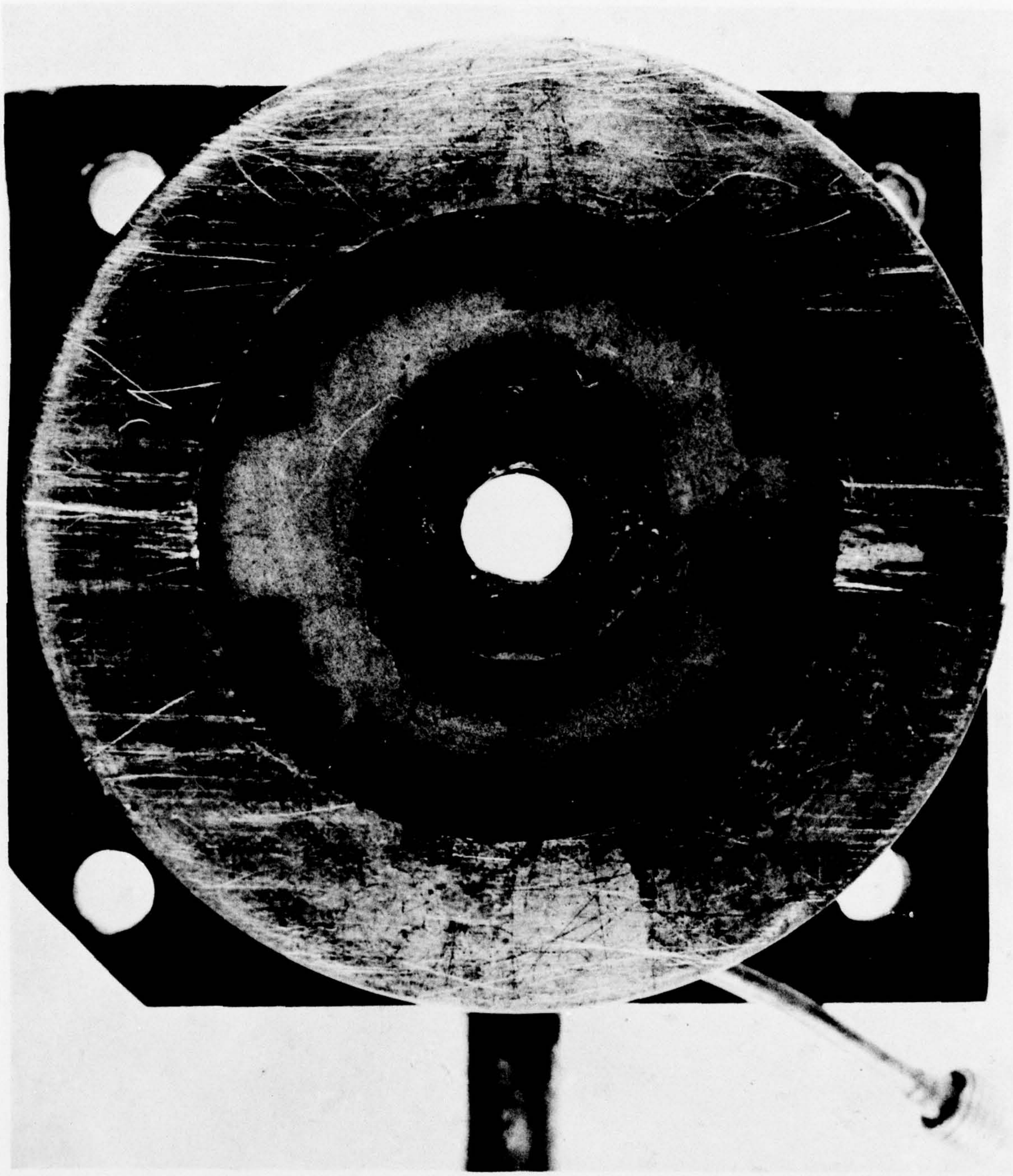
1MM



D. WELD MICROSTRUCTURE, TRANSVERSE SECTION

1MM

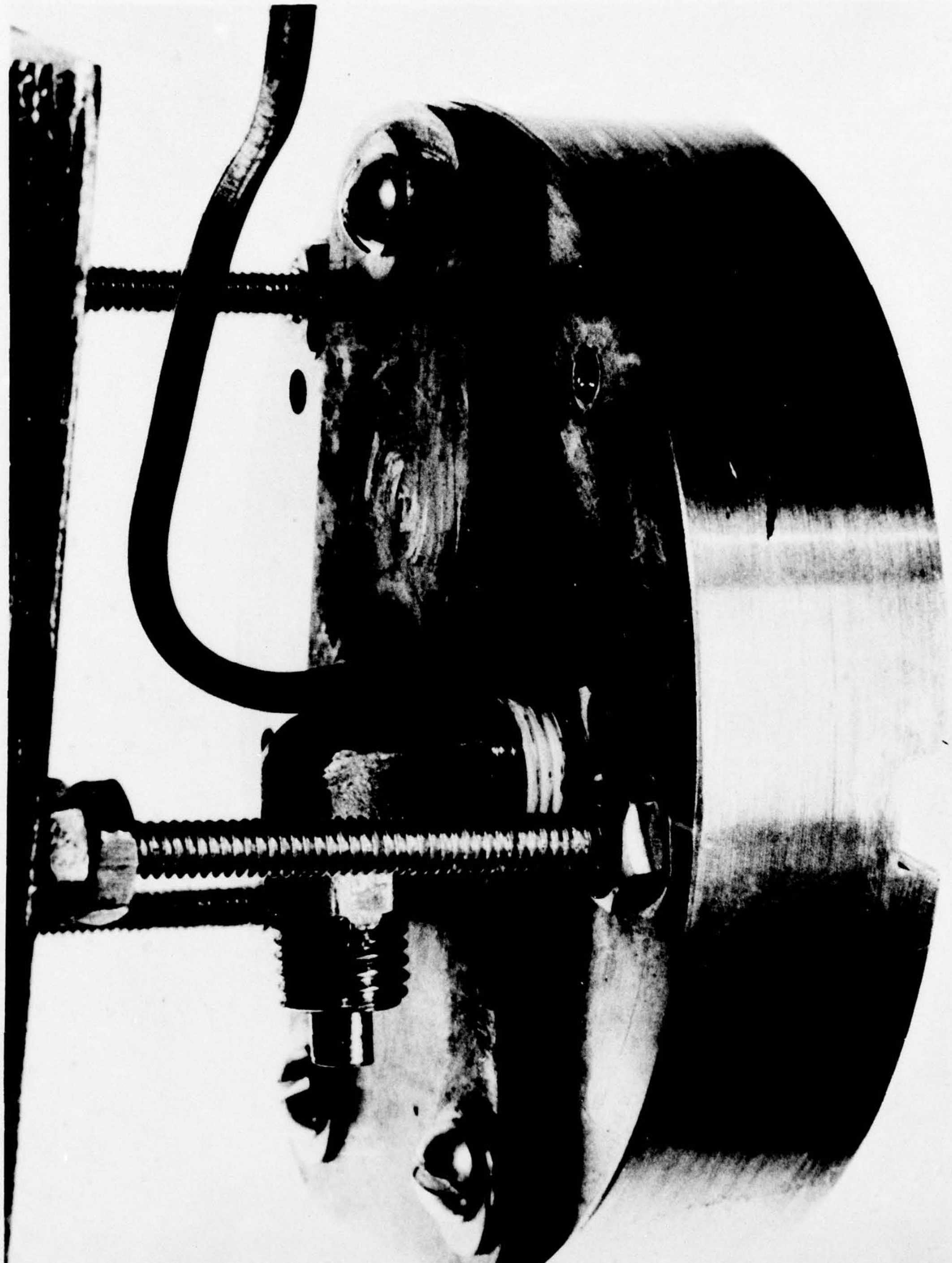
CIRCULAR SHIELD USED FOR PHASES IV AND V
OF ALUMINUM WELDING PROGRAM
(BOTTOM VIEW)



OUTER DIAMETER 8.9CM
GAS DIFFUSER PLATE SURROUNDING THROAT IS ATTACHED WITH SCREWS
GROOVE IN OUTER RING ACCOMMODATES WELD BEAD

CIRCULAR SHIELD USED FOR PHASES IV AND V OF ALUMINUM WELDING PROGRAM

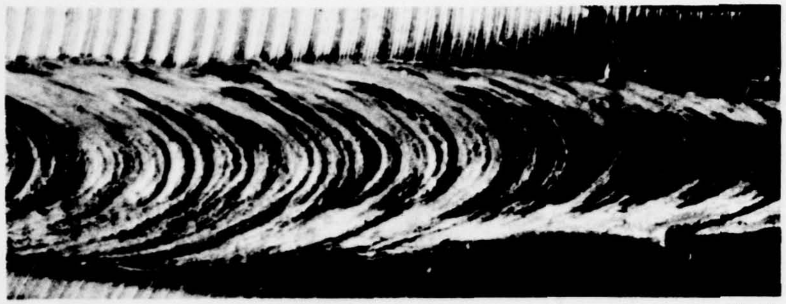
(SIDE VIEW FROM REAR)



LONG SCREWS ATTACH SHIELD TO MOUNTING BRACKET
FRONT (LARGER) INLET PORT FEEDS SHIELD GAS TO DIFFUSER PLATE
SOLDERED (SMALLER) INLET TUBE FEEDS SHIELD GAS TO THROAT AREA

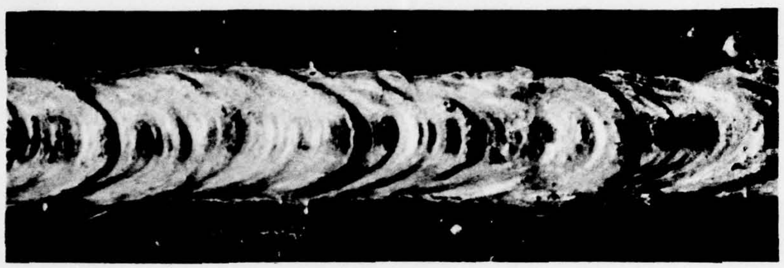
STRUCTURE OF WELD 64–41, TABLE IV

BEAD–ON–PLATE WELD OF 0.64–CM, 5456, 5.5 kW, 1.69 CM/S



1MM

TOP SURFACE

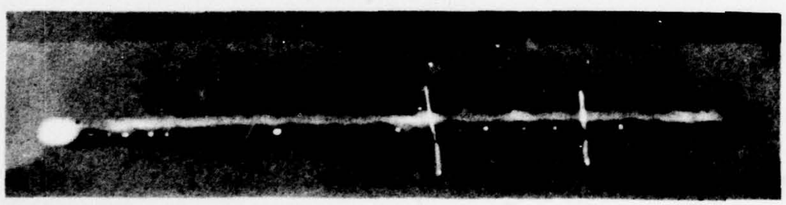


1MM

BOTTOM SURFACE

A. WELD BEAD SURFACES

← LASER BEAM TRAVERSE DIRECTION



10MM

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

1MM

C. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

STRUCTURE OF WELD 64–47, TABLE IV

BEAD–ON–PLATE WELD OF 0.64–CM, 5086, 6.3 kW, 1.69 CM/S

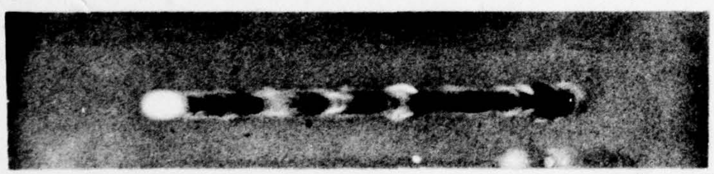
TOP SURFACE

BOTTOM SURFACE

1MM

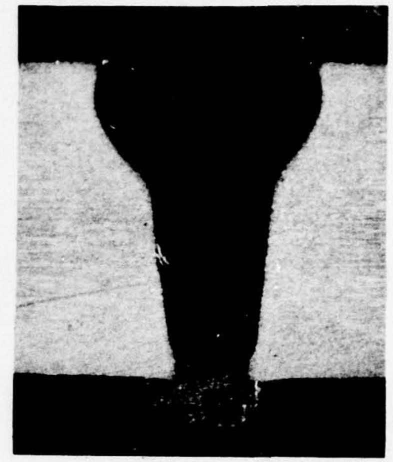
A. WELD BEAD SURFACES

← LASER BEAM TRAVERSE DIRECTION



10MM

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)



1MM

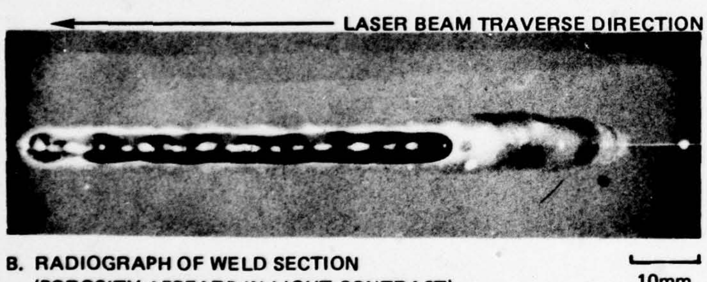
C. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

STRUCTURE OF WELD 66–72, TABLE V

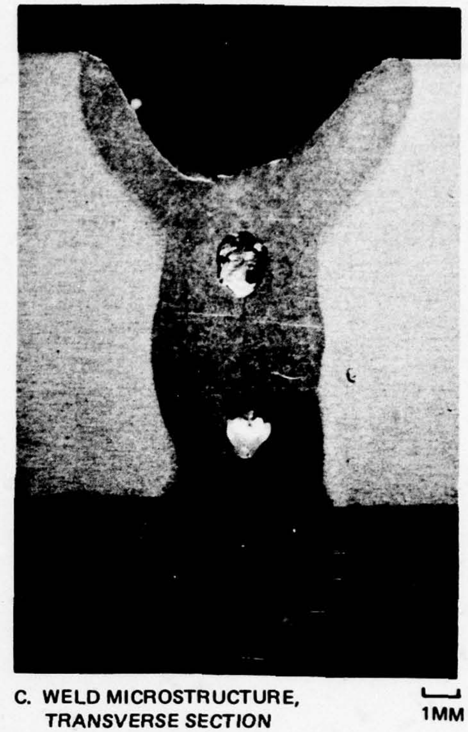
BUTT WELD OF 0.95–CM, 5456, 7.9 kW, 1.69 CM/S

BOTTOM SURFACE

A. WELD BEAD SURFACES



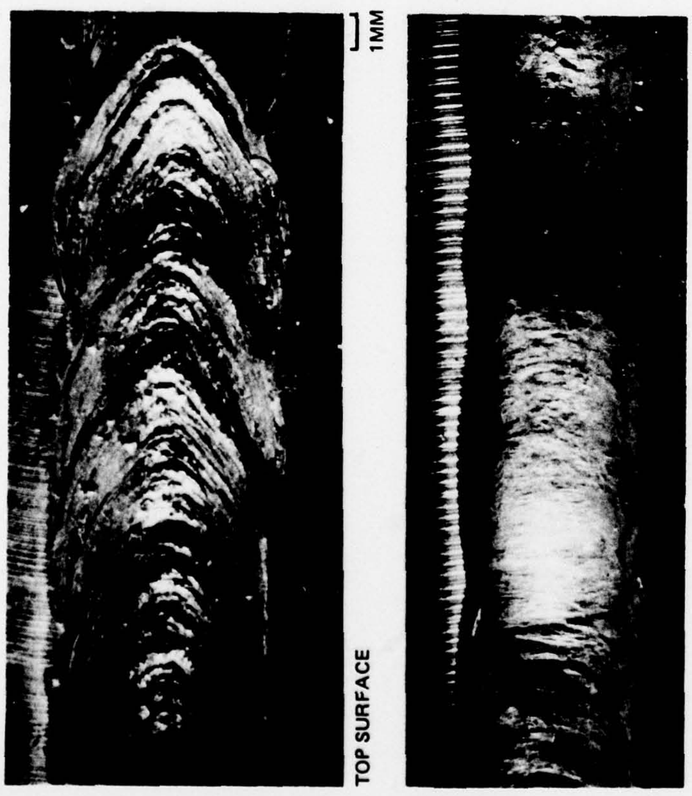
B. RADIOGRAPH OF WELD SECTION (POROSITY APPEARS IN LIGHT CONTRAST)



C. WELD MICROSTRUCTURE, TRANSVERSE SECTION

FIG. 12

STRUCTURE OF WELD 68–83, TABLE V
BUTT WELD OF 0.95–CM, 5456, 7.0 kW, 1.69 CM/S

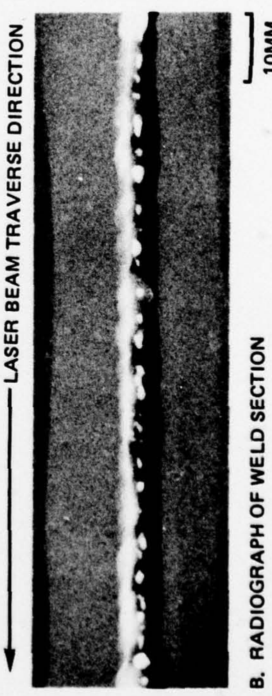


TOP SURFACE

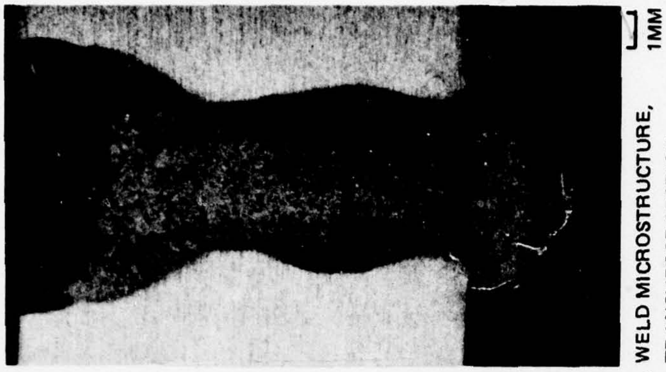
BOTTOM SURFACE

A. WELD BEAM SURFACES

← LASER BEAM TRAVERSE DIRECTION



B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)



C. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

STRUCTURE OF WELD 68–85, TABLE V
BUTT WELD OF 0.95–CM, 5086, 7.5 kW, 1.69 CM/S

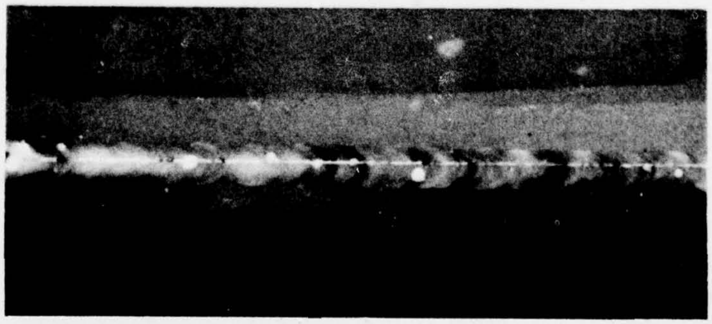
← LASER BEAM TRAVERSE DIRECTION

A. WELD BEAD SURFACE

1MM

B. WELD MICROSTRUCTURE, LONGITUDINAL SECTION

1MM



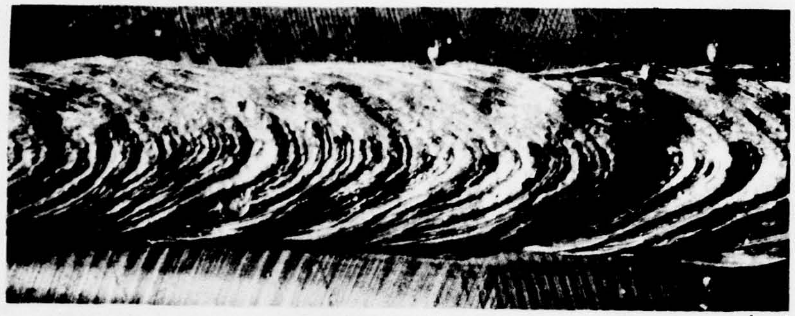
C. RADIOGRAPH OF WELD SECTION (POROSITY APPEARS IN LIGHT CONTRAST)

10mm

78–07–248–6

STRUCTURE OF WELD 70–87, TABLE VI

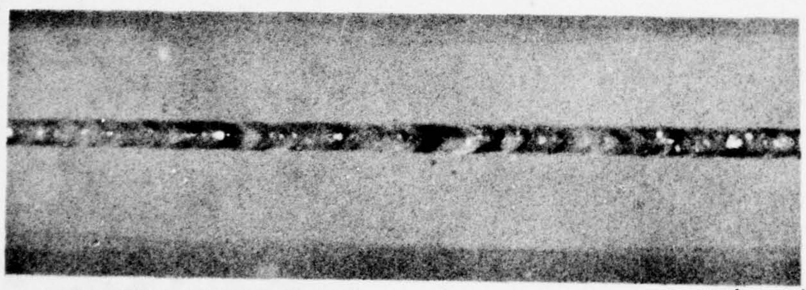
TWO–SIDED BUTT WELD OF 0.95–CM, 5456, 7.0 kW, 3.39 CM/S



A. WELD BEAD, TOP SURFACE (FIRST PASS)

1MM

LASER BEAM TRAVERSE DIRECTION



B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

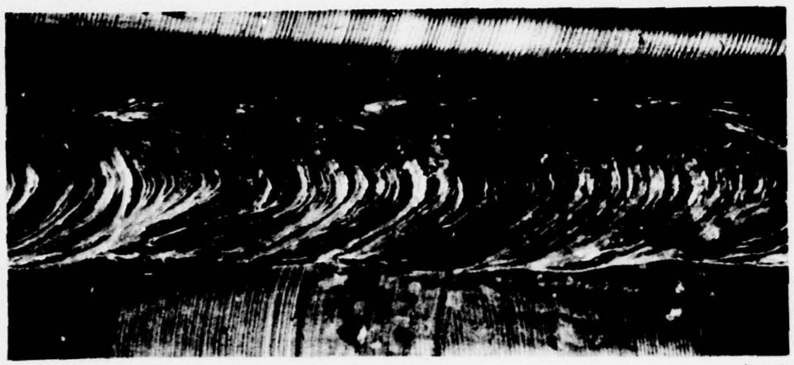
10MM

1MM

C. WELD MICROSTRUCTURE,
TRANSVERSE SECTION

STRUCTURE OF WELD 70–88, TABLE VI

TWO–SIDED BUTT WELD OF 0.95–CM, 5086, 7.0 kW, 3.39 CM/S



1MM

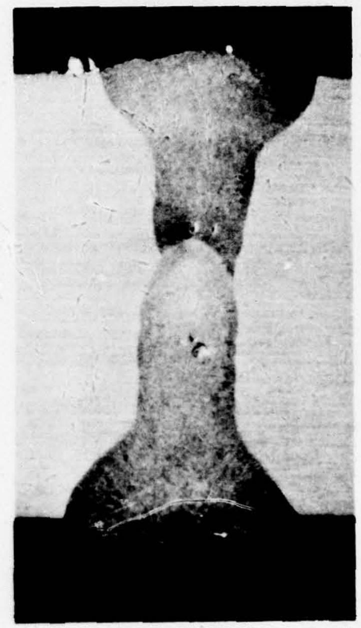
A. WELD BEAD, TOP SURFACE (FIRST PASS)

← LASER BEAM TRAVERSE DIRECTION

10MM

B. RADIOGRAPH OF WELD SECTION (POROSITY APPEARS IN LIGHT CONTRAST)

FIRST PASS



SECOND PASS

1MM

C. WELD MICROSTRUCTURE, TRANSVERSE SECTION