THE EFFECT OF IMPURITY GASSES ON PLASMA ARC WELDED 2219 ALUMINUM

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INTRODUCTION

Variable Polarity Plasma Arc welding has been used with considerable success by NASA for the welds on the Space Shuttle External Tank as well as by others concerned with high quality welded structures.

The purpose of this study has been to examine the effects of gaseous contaminants on the appearance of VPPA welds on 2219 aluminum so that a welder can recognize that such contamination is present and take corrective measures. There are many possible sources of such contamination including, contaminated gas bottles, leaks in the gas plumbing, inadequate shield gas flow, condensed moisture in the gas lines or torch body, or excessive contaminants on the workpiece.

The gasses chosen for study in the program were Nitrogen, Oxygen, Methane, and Hydrogen. These gasses were mixed in precise amounts (from 10 to 600 ppm) in both the argon arc gas and the Helium shield gas. Welds were made in a carefully controlled environment and comparisons were made between welds with various levels of these contaminants and welds made with research purity (99.9999%) gasses. Photographs of the weld front and backside as well as polished and etched cross sections are presented.

Plasma arc welding (PAW) differs from the more conventional gas tungsten arc welding (GTAW) in that the arc gas is constricted

by an orifice in the torch so that it forms a narrow column of high density gas. Since this gas column carries the entire weld current, it is extremely hot and the gas is sufficiently highly ionized that it becomes a plasma. The plasma column exhibits a property similar to surface tension in a liquid and is quite stiff. Although the physics of plasmas is understood, the critical plasma parameters of temperature and density in the plasma arc are not easy to measure. The arc is always surrounded by a separate stream of shield gas to prevent workpiece oxidation.

The advantages of PAW over GTAW are well documented but include:

1. A more concentrated heat source is obtained so workpiece warpage is minimized.
2. The higher gas velocity and increased power density make it possible to penetrate through thick sections so that welding can be performed in a "keyhole" mode allowing impurities to be expelled out the back of the workpiece.
3. The plasma arc is "stiffer", putting less stringent requirements on the skill of the welder and/or the intricacy of the weld joint.

Plasma arc welding is usually performed with the electrode negative so that weld power is carried by electrons moving from the electrode to the workpiece. This works well for most materials except Aluminum. Aluminum, of course, is a very reactive metal and quickly forms a tough refractory oxide skin that impedes liquid metal flow. Traditionally, aluminum has been welded in the

electrode positive mode so that ions present in the plasma are accelerated to the workpiece. The ions are much more massive than the electrons and are able to break up or sputter away the surface oxide. This so called "reverse" polarity welding results in much less of the total available weld power being transferred to the workpiece and most of the power going to the torch. Thus, short electrode life together with tungsten contamination is encountered.

A solution to this problem is to use reverse polarity at intervals during the welding. The electrode is switched positive typically 20% of the time for intervals of a few milliseconds. The weld current is usually increased during these intervals. This is known as variable polarity plasma arc welding (VPPAW) and has been used successfully by NASA on the Space Shuttle External Tank and by others for high quality Aluminum welds.

Impurities in either the arc or shield gas are expected to be particularly important in plasma arc welding because:

1. The high weld speeds attainable provide less time for impurities absorbed from the gas to effervesce.
2. The large contact area between the plasma gas and the workpiece during "keyholing" permits easy absorption in the weld pool of impurities from the gas.
3. The smaller weld puddle means that supersaturation of gasses such as Hydrogen can take place more easily and cause porosity on cooling.
4. Since an entire keyhole must re-fuse after the torch

passes, surface active gasses may alter flow patterns and cause undercutting or other weld defects.

II. EXPERIMENTAL SETUP

A. INSTALLATION AND GAS FLOW MODIFICATIONS

A Variable Polarity Plasma Arc Welding system was purchased from the Hobart Brothers Company based in Troy, Ohio. The system consists of a variable polarity 300 series power supply, control console, and water chiller. An welding torch was obtained from the B & B Company in Huntsville, Alabama. The torch, designed by both B & B and personnel at the Marshall Space Flight Center, offers the advantages of very reliable electrode alignment, no O-rings, and relatively easy modification procedures. The system was installed to make vertical bead on plate welds on 4" x 48" x .25" 2219 T-87 aluminum sheets.

Once the Hobart power supply and control console were installed, a method to allow precise gas mixing was developed. Figure 2-1 shows the current industrial installation of the VPPAW gas flow system where plastic or rubber tubing may be used. Both plasma and shield gases flow from the tanks, through the Hobart controller, and out to the torch using this tubing.

To obtain precise gas mixing and flow measurements, two mixing rotameters and two high precision 800 series electronic flow meters were purchased from the Omega Corporation. A mixing rotameter is

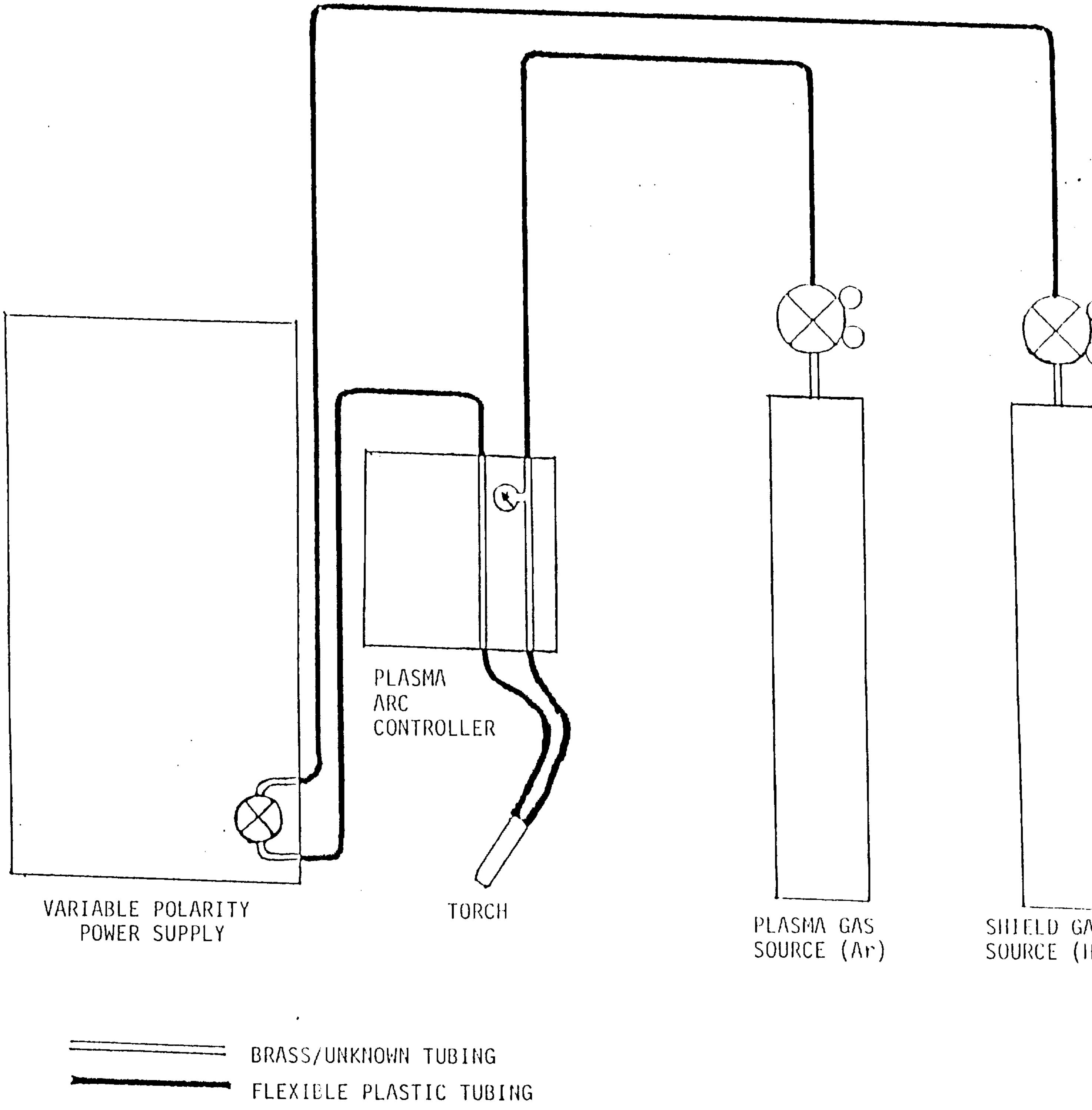

Fig. 2-1 Schematic showing gas flow in standard industrial VPPAW setup.

an instrument that allows accurate mixing of two or more distinct gases. Two high precision valves, several Swagelock fittings, and several feet of tubing, all made from stainless steel to minimize contamination, were used. Control of the gas flow system was from the above mentioned precision mixing and measurements system, referred to here as the UTEP control console, rather than the Hobart controller. The mixing rotameters allowed precise gas mixtures with an error of about 2% to be made. The electronic flow meters permitted a 1% gas flow rate repeatability.

Initially, it was proposed that gas would flow from the tanks through both the UTEP control console and the Hobart controller. Pilot arc control would be made at the Hobart controller, while gas flow adjustments would come from the UTEP control console. Figure 2-2 shows the proposed setup. The problem with this setup was that the Hobart console contains sections of brass and polymer tubing which may result in gas contamination. After a discussion with a Hobart representative, it was decided that if a 50 psi pressure sensor within the Hobart controller could be satisfied, the Hobart console could be bypassed. The pressure sensor allows the pilot arc to be activated with the correct pressure, and deactivated in case of loss of pressure. A T-connector was then installed at the plasma gas tank with one line used for the UTEP control console and the other for the plasma gas input to the Hobart controller. When the plasma gas output at the Hobart controller was capped, the pressure sensor in the Hobart controller detected a gas pressure of 50 psi coming from the T-connector at the plasma gas tank and would ignite

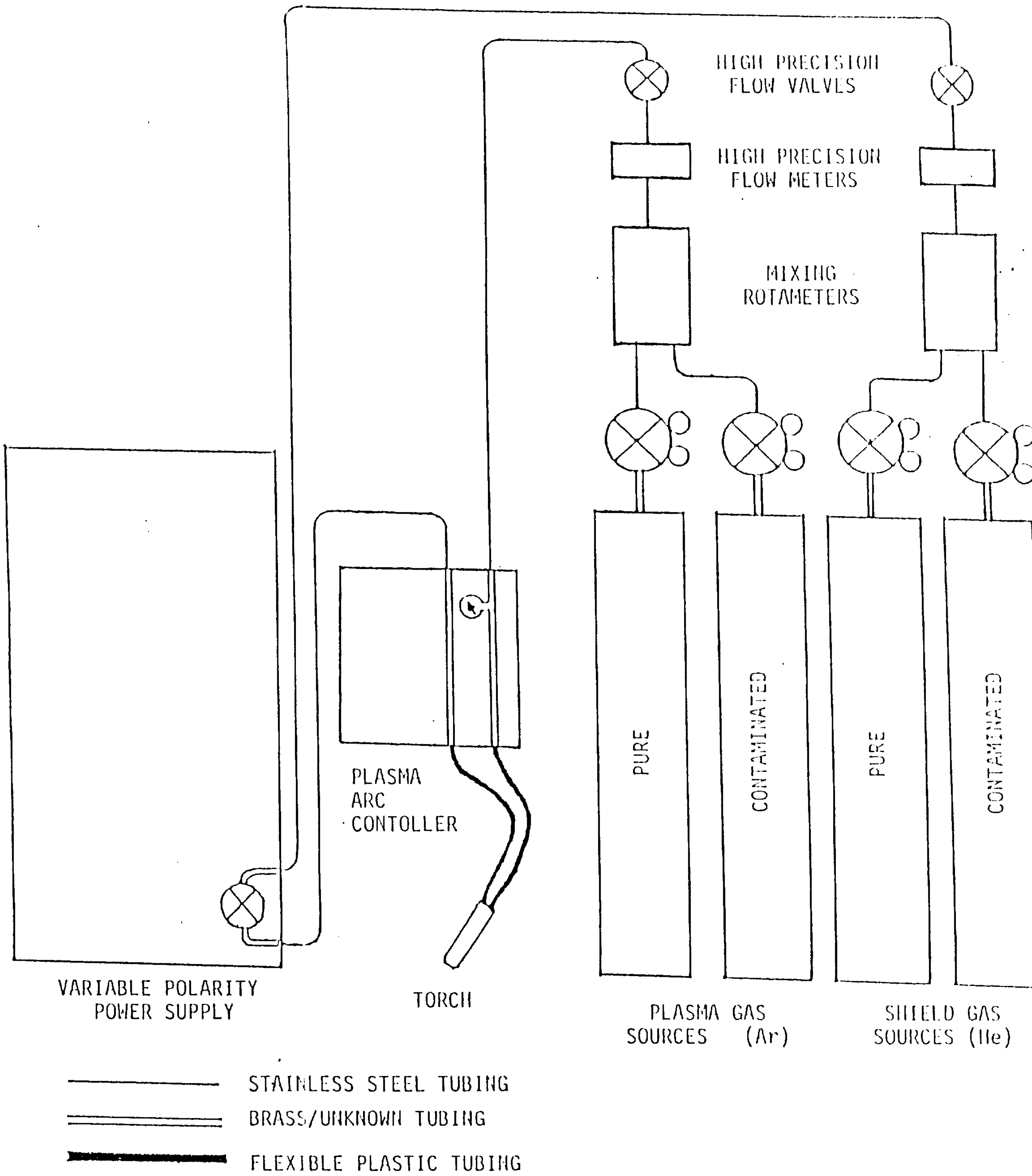

Fig. 2-2 Schematic of proposed gas flow system for this project.

the pilot arc. In this way gas flowed directly from the UTEP control console to the torch, with pilot arc control remaining with the Hobart controller. Care must be taken in this type of gas flow system. Any loss of gas flow from the T-connector to the torch would not deactivate the pressure sensor. Failure of the pressure sensor to automatically shut off the welder in either pilot arc or plasma arc mode might result in serious damage to the torch. The final experimental setup is shown in figure 2-3. Approximately one foot of brass tubing remained in the shield gas line inside the Hobart power supply. This could not be avoided. A 10′ section of plastic hose was used to activate the pressure sensor in the Hobart controller but no weld gas flowed through this line.

The gas bottle regulators had Viton seats and were recommended by the gas supplier for handling high purity gas. All tube connections were leak tested under pressure by applying a soap bubble solution. Considerable effort was required to eliminate all leaks that could inspire air.

B. TORCH AND TUBE CLEANING

Prior to installation the stainless steel tubing was cleaned by flowing Methyl Ethyl Ketone and then deionized water through the cut tube sections. Industrial helium gas was used to dry the tubing. Cut ends were bagged after cleaning. All Swagelock fittings were similarly cleaned. The welding torch lines and torch itself were cleaned by flowing ethyl alcohol through plasma and shield lines followed by a 30 minute purge. These lines were

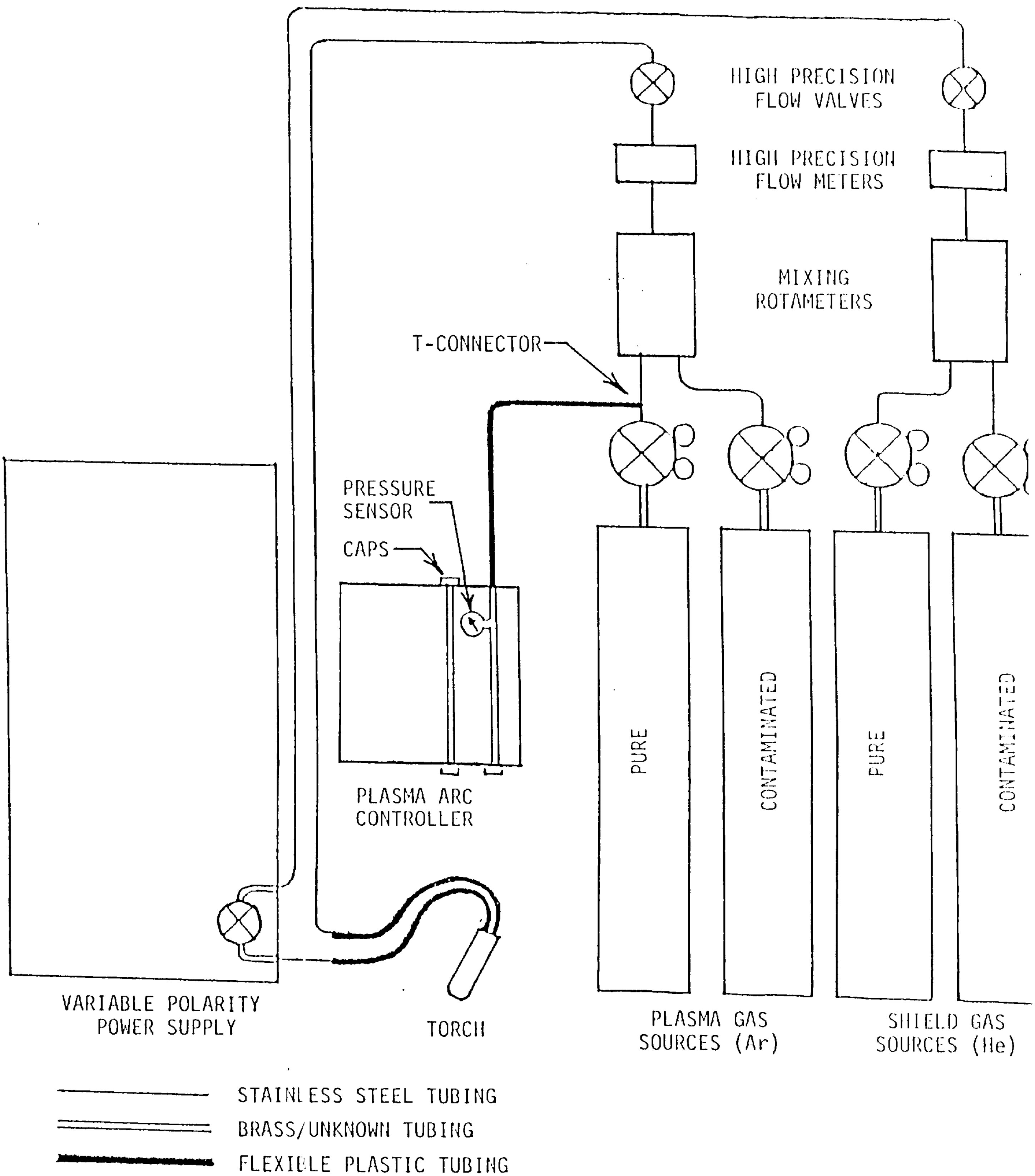

Fig. 2-3 Schematic of final gas flow system used for this project.

cleaned twice, before installation of the system and again prior to experimental weld runs.

Scott Specialty Gasses of Houston, Texas performed a purity test on the cleaned torch line. The main concern was the desorption of gases in the plastic gas line of the welding hose. Desorption of gases from the stainless steel tube sections was not considered a problem. The test carried out by Scott Specialty Gases consisted of flowing ultrapure gas into the hose and measuring the amount of oxygen, water vapor and hydrocarbons that exited the plastic hose. The results of the test are listed below.

Oxygen	-	2.4 ppm
water vapor	-	0.0 ppm
hydrocarbons	-	12.4 ppm

These results clearly demonstrated that contamination effects found in the welded samples would be the direct result of known contaminants added during experimental weld runs.

C. GASSES

All high purity gases and gas mixtures were purchased from Scott Specialty Gases. Scott Specialty Gases supplies certified purity gases to NASA and other demanding customers. The pure gases and contaminants purchased are listed below.

99.9999% pure Argon

99.9999% pure helium

500 ppm hydrogen in Argon

600 ppm nitrogen in Argon

515 ppm oxygen in Argon

500 ppm methane in Argon

500 ppm hydrogen in helium

650 ppm nitrogen in helium

520 ppm oxygen in helium

500 ppm methane in helium

Other contaminants in the mixed gases were less than 10 ppm. The above listed contamination levels were the highest conducted in this study. Lower levels were obtained by diluting the mixed gasses with either pure Argon or pure helium. Purity checks on each bottle purchased were performed by Scott before shipping. In addition the supplier included a set of certification data for each mixed and pure gas purchased.

D. MEASUREMENTS

A series of electronic meters used to monitor the gas flow rate and voltage at the torch were built into the UTEP control console. Figure 2-4 shows the various electronic measurement instruments used in the study. The electronic flow rate meters and the Hobart voltage test point are connected to a switch which in turn feeds a Keithley model 197 autoranging microvolt meter. The switch was used to analyze either plasma flow rate, shield flow rate, or weld voltage on the microvolt meter. Data from the microvolt meter was recorded on an Omniscribe chart recorder. True RMS voltage was recorded. The current waveform was monitored on a Tektronix model 2201 digital oscilloscope via a precision

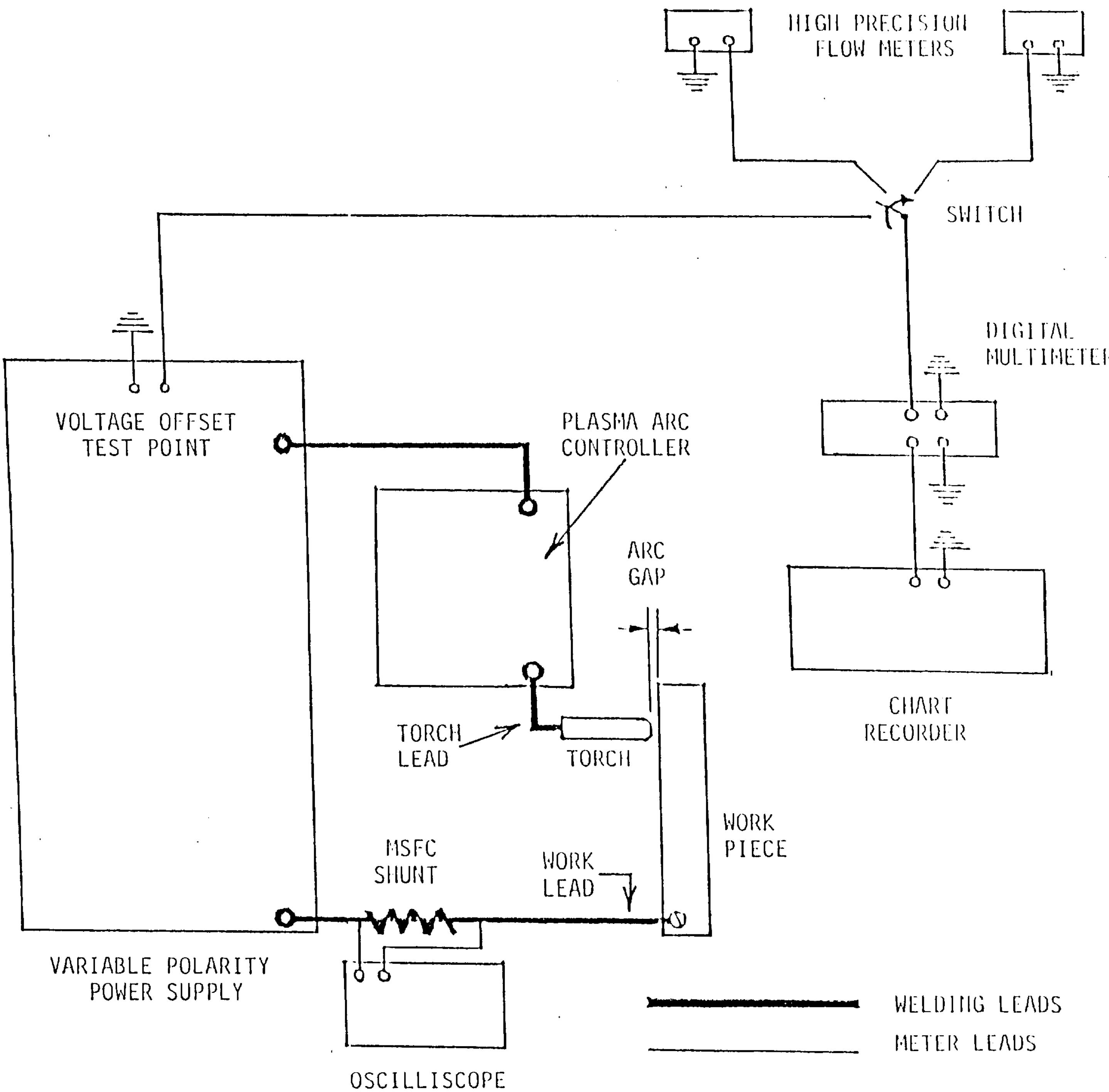

Fig. 2-4 Schematic of electrical connections used to instrument the VPPAW.

Marshall Space Flight Center current shunt. The shunt was installed on the return lead of the Hobart power supply.

The mixing rotameters, as previously mentioned, were the devices used to obtain the required gas contamination levels. Two mixing rotameters were installed, one for plasma gas mixing and one for shield gas mixing. Each rotameter was equipped with two flow rate tubes. Pure gas, either Helium or Argon, flowed through one tube while one of the mixed gasses flowed through the other. For example, to obtain a 300 ppm Nitrogen in Argon contamination level, the two gases to be mixed in the rotameter were pure Argon and the 600 ppm Nitrogen in Argon mixture. A 50% pure Argon and a 50% contaminated Argon mixture, regulated from the rotameter, would dilute the 600 ppm level to the 300 ppm level. The lower the contamination level, the more diluted the mixture.

Each of the flow tubes in the mixing rotameters had a scale from 0 to 150. The manufacturer supplied calibration sheets for each of the flow tubes. These calibration sheets gave a fairly accurate flow rate, but to assure maximum accuracy in dilution and therefore maximum accuracy in contamination levels, each of the flow tubes in the mixing rotameters was calibrated with the electronic flow rate meter. After zeroing the bob on the 0 hash mark of the flow tube, Argon or Helium, depending on which tube was being calibrated, was flowed through the tube. The bob was set at each of the major hash marks from 10 to 150 by a small valve on the mixing rotameter. A voltage from the electronic flow rate meter was recorded for each of the hash marks on the flow tube.

By using the voltage readings as a reference the accuracy of any gas mixture was maximized.

Photographs of the welder and support equipment are shown in Fig. 2-5.

E. WELDING FRAME

The welding frame, shown in Figure 2-6, is comprised of three components: the adjustable frame itself, a heat sinking and clamping system, and a mechanized welding kit. The welding frame is made of 2"x 2" rectangular steel tubing, and measures 74" high by 58" wide. The frame is bolted to the floor through anti-vibration pads. An adjustable vertical piece of the same tubing permits different widths of workpiece to be inserted. To provide a safe working area and to prevent high frequency feedback, the welding frame was installed 7′ in front of the welder.

Two heat sinks, 35"x 9"x .5", made of 6061 aluminum plate, are bolted to the frame; one to the frame itself and one to the adjustable vertical tubing. The two heat sinks are aligned parallel to each other with no offset, and separated by 3". The adjustable vertical tubing was then secured into place. Figure 2-7A is a close-up picture at the top of the heat sink, showing the clamping system comprised of the .5" thick aluminum heat sinks, two .25" thick rectangular steel shims, two pieces of .25" thick rectangular aluminum stock, and twenty-four .25" nuts and bolts. The nuts and bolts are assembled through holes, 3" apart, in the aluminum stock and heat sink, and were tightened to sandwich and firmly hold the

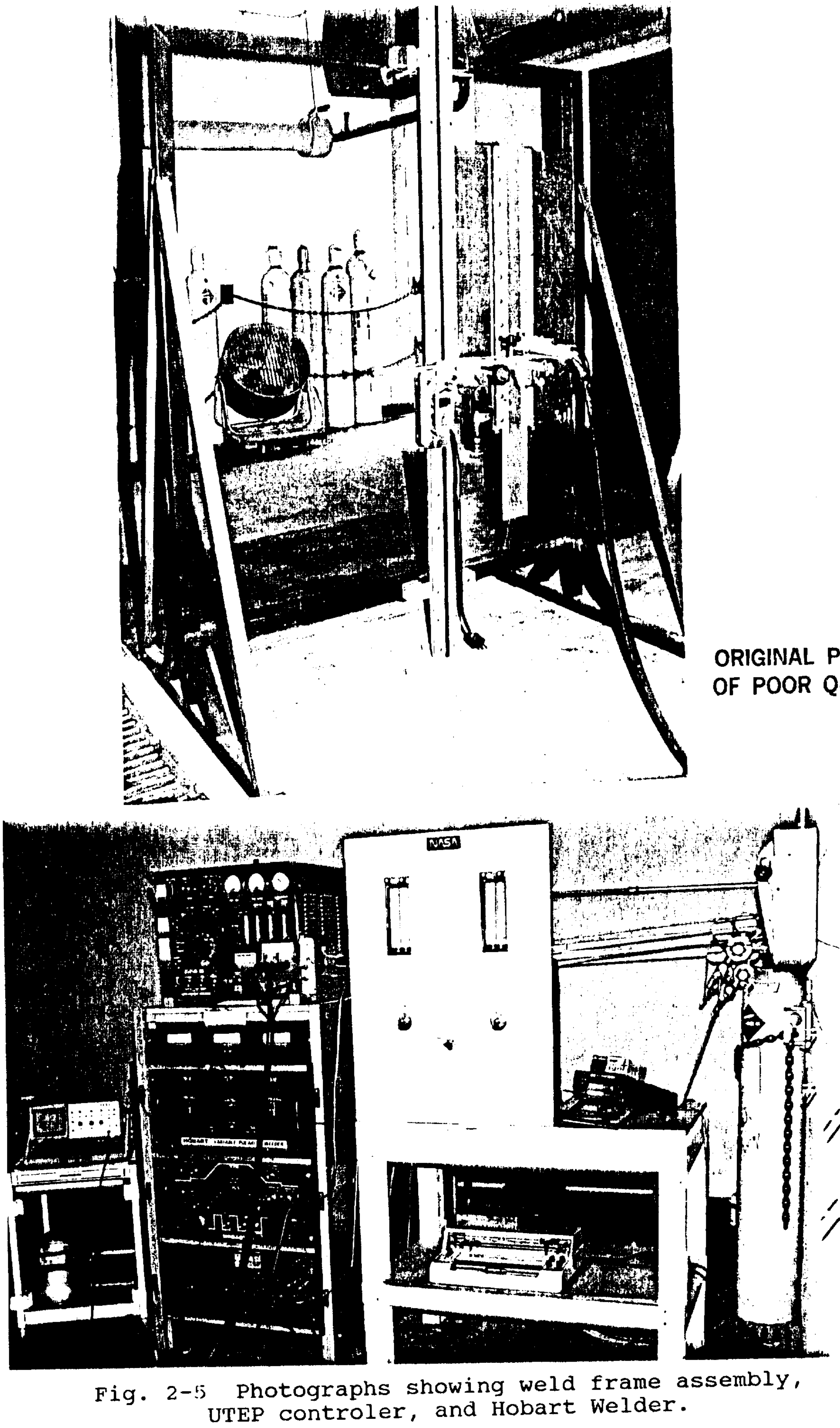

Fig. 2-5 Photographs showing weld frame assembly, UTEP controler, and Hobart Welder.

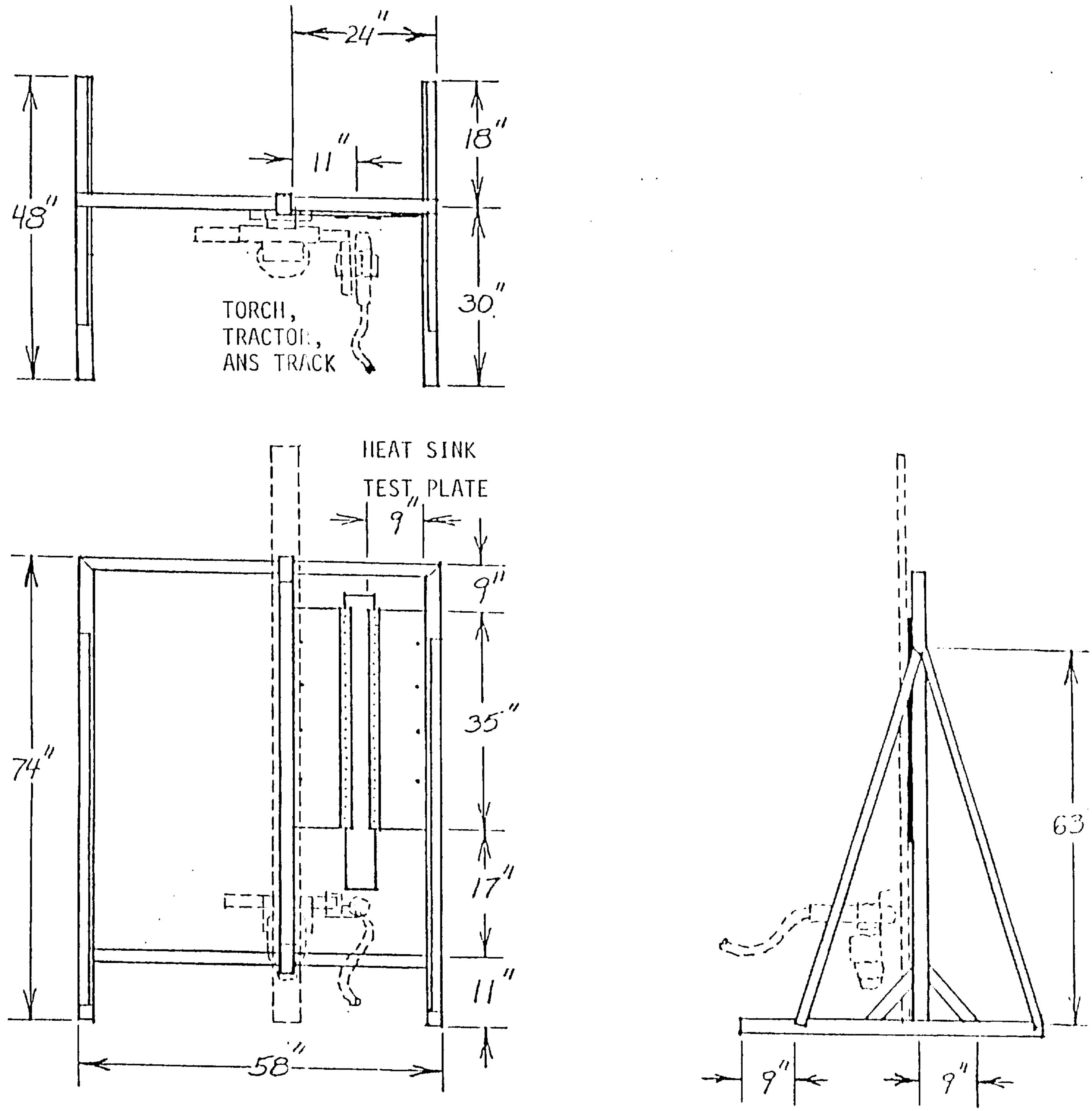

Fig. 2-6 Weld Frame Assembly

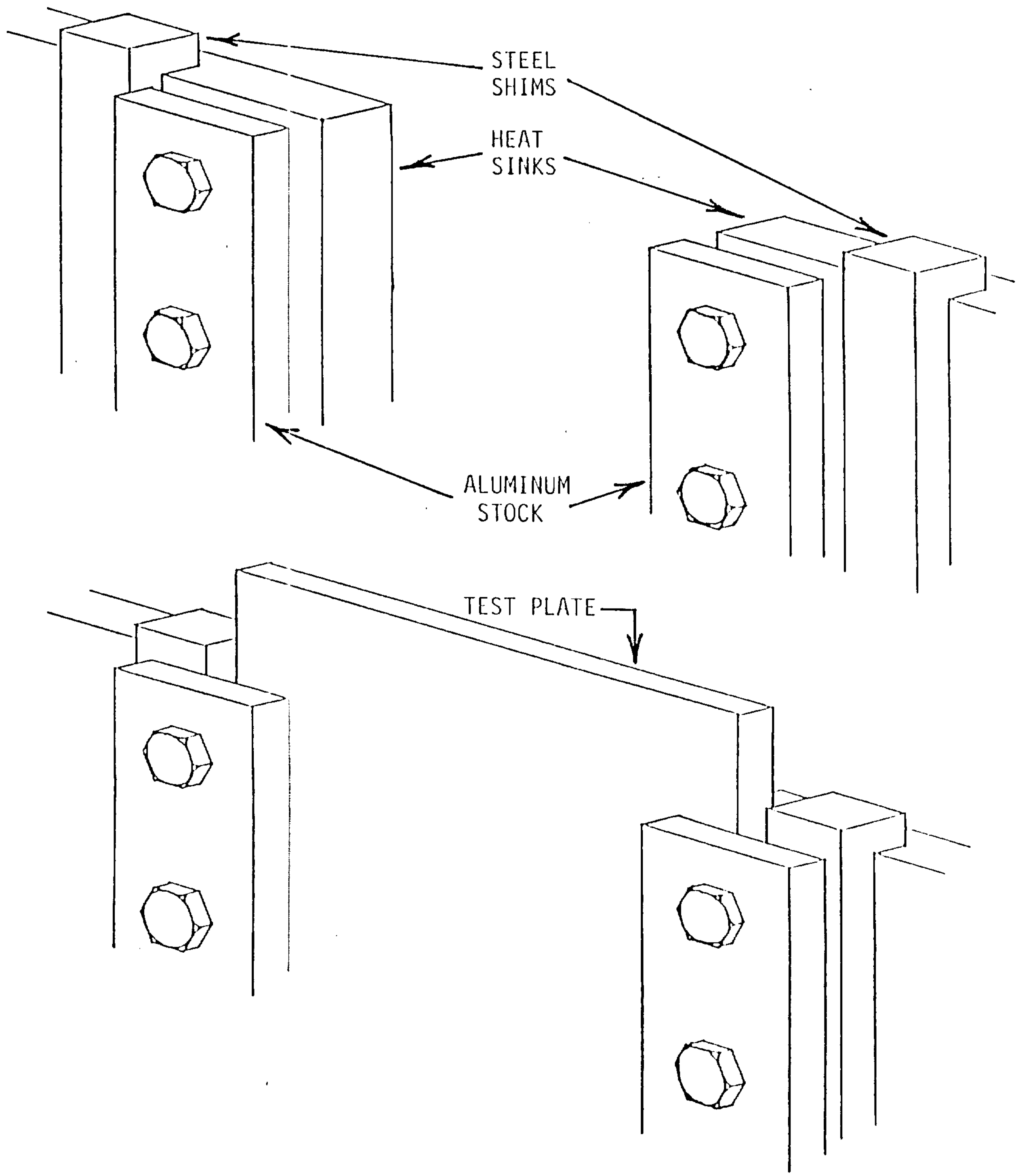

Fig. 2-7 Expanded drawing of test sheet clamping arrangement. Unassembled (above) and assembled (below).

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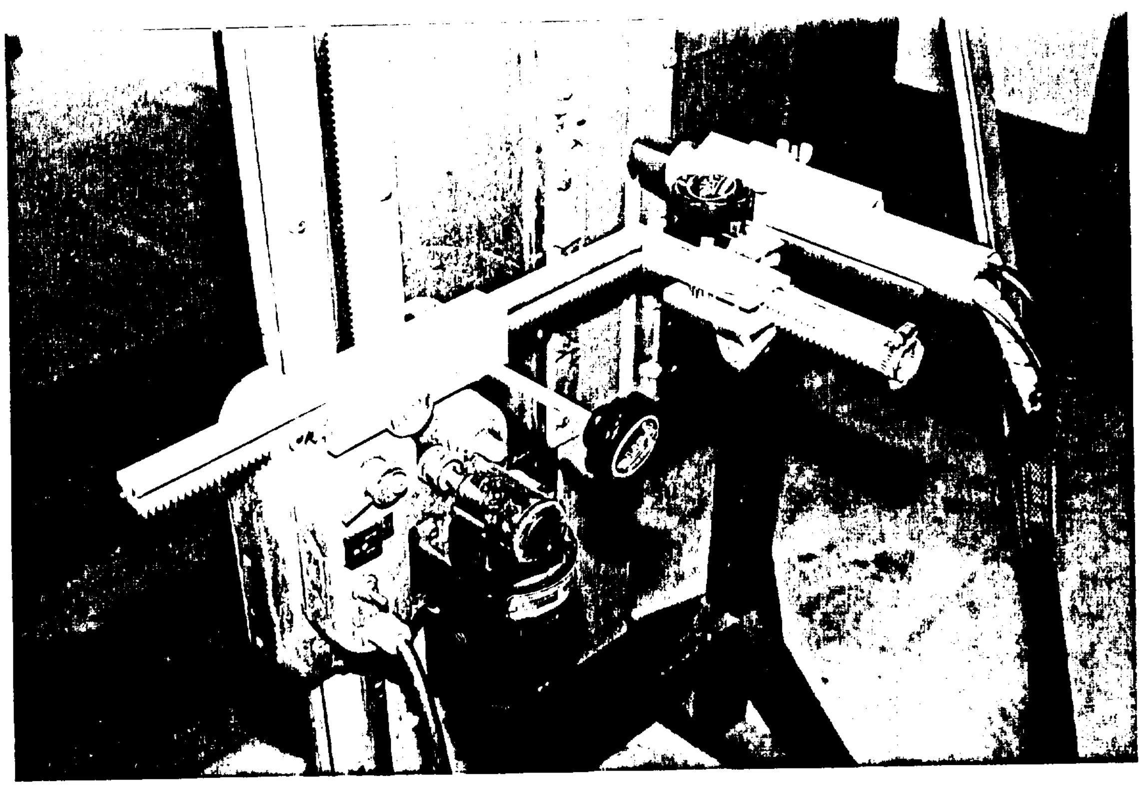

Fig. 2-8 Photograph of torch tractor and torch holder.

steel shim and the 4"x 48"x .25" 2219 Aluminum test sheets in place, as shown in Figure 2-7B. At one to two inches ahead of the torch during welding, the temperature of the workpiece was nearly ambient. Therefore, the heat sinks were judged to be very effective in removing heat horizontally.

The mechanized welding kit, seen in Figure 2-8 and made by the Weld Tooling Corporation, is comprised of three components: an ARR-1080 track, a BUG-2004 motorized carriage, and a BUG-9472 two motion torch support group with a CON-1020 swivel mount. Two pieces of 1.5"x 40" angle iron were bolted to the back of the track to increase rigidity.

F. CLEANING OF TEST PLATES

The 4"x 48"x .25" 2219 Aluminum test sheets were first wiped with Methyl Ethyl Ketone (MEK) on both sides. Next, the plates were cleaned with two different chemicals obtained from the Baron Chemical Co. The first was a Cherry Tree cleaner/degreaser (1 part cleaner to 15 parts water), and the second was an Aluminum cleaner/etchant (1 part etchant to 20 parts water). Plastic troughs were used to hold the chemicals in which the test plates were to be submerged. The test plates were submerged in the first trough, containing the degreaser, for 15 minutes. Then the plates were rinsed and agitated in the second trough, containing water, for 10 seconds. The plates were then submerged in the third trough, containing the etchant, for 15 minutes. Finally, the plates were again rinsed and agitated in water, for 10 seconds, and allowed to

air dry with a fan. Only one plate was submerged at a time per trough.

G. WELDING SEQUENCE

The cleaned 2219 aluminum test sheets were bolted between the heat sinks on the welding frame in preparation for the weld contamination tests. Normally, weld tests or runs were made in the afternoon allowing the morning to be used to calculate contamination dilution levels, dress up torch orifices and electrodes, and most importantly to purge out plasma and shield gas lines.

The purging sequence took from 20 to 30 minutes to complete. During this time one or more "morning sickness" runs were made. Morning sickness is a term used to describe the many problems associated with obtaining good repeatable welds immediately after initiating welding. The morning sickness runs allowed undercutting problems associated with torch alignment and or torch rotation to be corrected. Undercutting occurs when one side of the weld bead is more deeply penetrated than the other.

All weld runs made were bead on plate vertical up keyhole or keyhole and cover. Keyholing is the weld method used in plasma arc welding in which as the plasma torch moves, it melts or keyholes through the plate. The weld pool behind the keyhole fills up or fuses the two surfaces behind the torch. Bead on plate welds are welds used for experimental or testing purposes in which the

weld bead is established on a single base plate. To minimize contamination no filler wire was used for the weld beads.

Argon plasma gas contamination tests were performed first, with Helium shield contamination tests coming afterward. Usually a 50% pure and a 50% contaminant gas mixture was used as a reference point to determine if the contamination level mixture was to be increased or decreased. If no visible changes were noticed from this reference, then the contamination level was increased. If changes were noted, the level was decreased.

The actual welding sequence is as follows. First the pilot arc was established in the plasma gas with only pure gas flowing. The weld parameters are summarized below.

	KEYHOLE	COVER
Current (amps)	140	120
Additional Reverse Current (amps)	70	30
Voltage (volts)	31	24
Torch Speed (in/min)	9	7
Arc Gas Flow Rate (cfh)	5.2	2
Shield Gas Flow Rate (cfh)	40	40
Forward Time (msec)	19	19
Reverse Time (msec)	4	4
Orifice Diameter (in)	1/8	1/8
Electrode Diameter (in)	3/16	3/16
Continuous Pilot Arc	Yes	Yes
Source Gas Pressure (psi)	50	50

The weld start button on the Hobart power supply was depressed next. An additional 40 second gas purge was used before the plasma arc was established. The 40 second purge allowed ample time to make final adjustments on the shield gas flow rate. Once the plasma arc initiated, the offset voltage was adjusted manually.

About halfway up the aluminum test plate the gas contamination level sequence was initiated on the mixing rotameter. This process normally required anywhere from 30 seconds to 1 minute to complete. The contaminated gas was then allowed to flow until the end of the Aluminum plate was reached. Initiation of all weld beads at the bottom of the plate with only pure gas flowing through both plasma and shield gas lines established an accurate reference point for any contamination effects noted after the mixing process was complete.

The aluminum test plate was forced air cooled with a large fan after the keyhole test was complete. The cooling process required approximately 15 minutes. During this time the torch was lowered down 3/4 of the aluminum plate. Weld parameters were then readjusted for a weld cover pass sequence. A cover pass is an additional weld run that is made on an already existing weld bead. The cover pass run does not penetrate through the aluminum metal as does the keyhole. The cover pass mixing sequence was the same as that described for the keyhole. The cover pass weld run was then cooled as described for the keyhole run. Figure 2-9 summarizes the above described procedure.

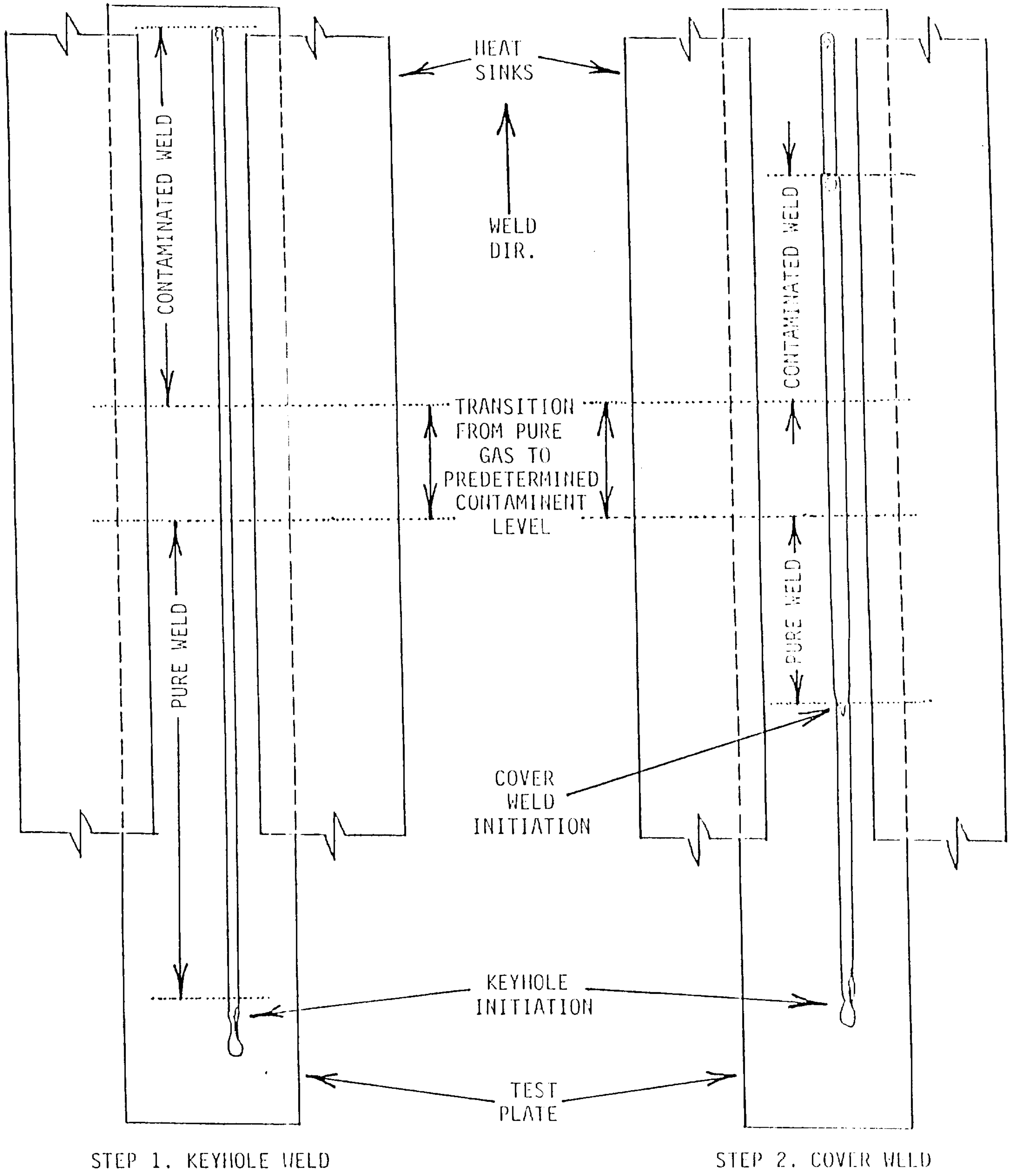

Fig. 2-9 Weld test sheet showing location of pure and contaminated welds and position of keyhole and cover passes.

Two contaminants, in keyholes and covers, were tested per weld plate. Data sheets were kept for each of the welded test plates. Humidity was measured with a sling psychrometer and was typically 20%. Welded plates were then sectioned, mounted, polished, and etched for photographs of both the weld bead and the prepared mount.

H. PHOTOGRAPHY

The photography proved to be one of the more difficult portions of the study. Because of the differences in surface weld topographies and the extremely shiny weld surfaces on some of the cover passes, it was difficult to establish the optimum lighting scheme. A 100 watt incandescent bulb was placed on each side of the weld bead and a third small microscope spot light was placed ahead of the region to be photographed with the direction of its spot along the weld. In this way weld grooves along the edges of the bead were lit by the side lights, and weld bead rippling was made apparent by the spot light.

I. RADIOGRAPHY

A Hewlett-Packard pulsed X-ray system Model 43846 was used for X-ray radiographs. 150 Kev X-rays were used from a Fexitron Model 5330 X-ray tube and Kodak Industrex AA X-ray film was used for recording. A 2% Aluminum penetrameter was discernable on the film. Crater cracks where the keyhole and cover were initiated were visible on most samples, but this is not surprising since no

special effort was taken to taper the arc gas or weld current. The pure gas samples showed no porosity, but the contaminated samples generally agreed with the assessment of porosity as seen from the polished cross sections. Porosity was easier to detect on the polished cross sections, however.

III. EXPERIMENTAL RESULTS

Experimental results will be primarily represented by photographs of the weld front, back, and a polished and etched cross section for each gas and for each level of contaminant. The weld surfaces are rather shiny and irregular so it is impossible to obtain pictures with a continuous range of grey scales between white and black on every sample. Therefore, except for extreme cases, the lighting configuration was kept constant to insure repeatable photographs.

Each contaminant gas and contaminant level will be shown by four photographs. The front and back surface photographs are shown with the weld direction up, which is how a welder would look at the weld. The cross section with the front surface is viewed with the weld direction into the page and the cross section with back surface is shown with the weld direction out of page. This allows a direct comparison of features seen on the surface views with the cross section. The two cross sections are the same photograph but one is printed with left and right reversed. This has the effect of changing the direction of the weld on that cross

section. All photographs are made to the same magnification (approximately 8X) and a ruler (each minor division is 1/64 inch) is shown in the surface photographs. All cross sections were wet ground and polished to 1.0 micron alumina. They were etched with ammonium hydroxide for about 30 seconds. The time of etch was varied slightly to obtain a uniform etch.

Before the individual photographs are presented certain interesting observations should be made. Shield gas cleanliness is extremely important to avoid porosity within the cover pass region of the weld. This porosity was observed with all contaminants except Nitrogen and Hydrogen in the arc and was usually concentrated along the bottom of the region melted in the cover pass. Results are summarized below.

POROSITY FROM SHIELD GAS CONTAMINANTS

NITROGEN	OXYGEN	HYDROGEN	METHANE
Slight at 650ppm	Slight at 520	Severe at 500	Unweldable at 400
None at 325ppm	No at 260	Yes at 250ppm	Barely weldable 250
		Yes at 50 ppm	Slight at 100 ppm
		Slight at 25 ppm	

POROSITY FROM ARC GAS CONTAMINANTS

NITROGEN	OXYGEN	HYDROGEN	METHANE
None at 600ppm	Yes at 515ppm	None	Yes at 500ppm
	Slight at 400ppm		Yes at 250ppm
	No at 250 ppm		No at 100 ppm

It is particularly significant that nearly all of these welds had a very good surface appearance and would have easily passed a visual inspection. Similar porosity was found on welds using pure gasses if the lines were not purged for about 30 minutes. Since the relative humidity in El Paso is about 20%, it seems likely that most of this contamination was from weld hose outgassing.

As mentioned in the experimental section, the standoff (and hence the voltage) was set to obtain a 31 volt arc using pure gas. A record of voltage during the each weld run was made and no changes were made to keep the voltage constant. The torch track and workpiece were aligned parallel within approximately .01 inch on a cold sheet, but the voltage nevertheless varied by about 1 volt in an irregular fashion during runs. There were two probable sources of this variation: the hot sheet may warp slightly (despite the narrow three inch unsupported region between the large heat sinks) and there was some unexplained variation in voltage caused by a change in flow rate during the changeover from pure to contaminated gas. The flow rates during the pure and contaminated runs were easily kept constant to 1% during the pure and contaminated runs. However, during the changeover period the flow rate sometimes varied up or down by as much as 10% for perhaps 20 seconds while the mixing rotameters were varied to obtain the desired mixture. These voltage changes were at first taken to be true changes in voltage due to the contaminated gas since they would remain after changeover was complete and the standard flow rates were reestablished.

A series of experiments were performed to explore this voltage change phenomenon. Three keyhole welds were made with pure gas. After several inches of stable weld, the arc gas flow rate was changed (twice upwards and once down) by 10%. for about 20 seconds. The voltage always lowered by about 1 volt during this change. The flow rate was then reset to standard conditions but the voltage remained at its lower value. In other words, there seemed to be some latching mechanism which, once activated by a flow rate change, permanently lowered the voltage.

To further explore this latching mechanism the following experiment was performed: A keyhole weld was established at standard 31 volts and then the torch was moved in and out and rotated in an attempt to flip the voltage into its lower mode. Naturally, this lower mode could not be detected since the actual standoff changed. Next the standard 31 volt standoff was reestablished (the keyhole was never lost during the torch movement) and the flow rate was briefly changed as described above. Two out of three times, the flow rate surge did not lead to a permanent reduction in voltage and the third time it did. We were, evidently, partially successful in causing a latch down of the voltage. A possible explanation of this phenomena is that, although in principle the arc strikes the surface of the sheet at the front of an elliptical keyhole, the arc may strike slightly beneath the rim of the keyhole at differing points depending on where it comes to rest. Normally, one would expect the arc to take the shortest path (which of course is to the surface) but it would

actually prefer to take the lowest resistance path and the resistance may be slightly lower inside the keyhole where pressure is higher and ionized aluminum is present.

In any case, because of these voltage changes no conclusive proof of greater heating with any of the contaminant gasses was observed. Certain of the fusion zones (mainly from the keyhole pass) are wider than others, but in all cases the voltage recording showed a change in voltage. An automatic voltage control that continually adjusts the standoff to keep constant voltage would be needed to further explore this phenomena. The AVC should be instrumented so that a chart of torch movement can be obtained. It can be concluded on the basis of fusion zone width, however, that no large temperature changes were associated with these low levels of contamination. A possible exception to this is the higher levels of Hydrogen in the arc which produced an unweldable condition. Even here, however, the primary difficulty seems to be poor wetting of the aluminum surface due to increased surface tension.

Another unexpected phenomena found in this study is the occurrence of small angular shiny particles that form along the front side edges of the weld bead and occasionally within the weld bead itself. These can be seen in the electron micrographs of Fig. 3-1A. These particles will be called granular extrusions and their presence is noted for each contaminant. These particles are enriched in Copper to about 12% to 18% (the nominal Copper in 2219 Aluminum is 6%). Those at the edges of the weld are only slightly

richer in Copper than the surrounding Copper enriched aluminum at the edge of the weld. Those in the center of the weld bead do, however, differ considerably in composition from the surrounding metal. They are easily seen by a welder because of their sparkling appearance. Their probable cause is Copper rich eutectic liquid being squeezed to the surface by compressive stresses during cooling. They clearly cool quickly within the shield gas envelope since a dull oxide does not form over them. Fig. 3-1B shows optical micrographs of what is thought to be a part of a granular extrusion seen in profile on a polished surface. We were unable to section through the center of a large granular extrusion possibly because of poor edge retention in the mount. In any case, the upper picture shows the light colored copper enriched liquid between the grains near the surface and a channel leading to the surface through which the liquid was exuded. The lower picture in 3-1B shows a similar region in a sample welded with pure gasses and an absence of the surface bumps and the copper rich channels. Both picture were taken from the central weld bead rather than the edge of the weld.

The next page shows an index to the photographs of the welds. To summarize this data several tables are included after the photographs. Most of the tables are self-evident. Notice that there is a table rating the brightness of the welds. This table was made by choosing the brightest and dullest welds as extremes and comparing all the other welds against these. There is some subjectivity in the assignment as dull or bright, and trying to

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discern more than two levels of brightness was not reliable. We tried to remove the optical effects of different degrees of rippling on brightness, but that made the decision on brightness even more uncertain. Nevertheless, our assignments as bright or dull, we believe, are useful in judging the welds.

The extent of rippling on both cover and keyhole passes is to a certain extent affected by the heat input to the weld which, of course, depends on voltage. The primary cause of the different rippling patterns that have been observed, however, is the different impurity gasses that were used. Bead curvature is, likewise, dependent on heat input with hotter welds being flatter.

Some observations useful to a welder trying to asses the purity of his weld gas can be drawn from these summary tables. The welds made from the pure gasses had the dullest, perhaps described as a "mat", finish in both the keyhole and cover pass. They, likewise, had the smoothest finish with the least rippling. Notice that the arc and shield with oxygen contamination also produced a very smooth surface. Oxygen contamination, however, is indicated by a rough irregular back surface particularly when the oxygen contamination occurs in the arc. This is consistent with aluminum oxide fragments forming that serve as solidification nuclei. Since solidification can start at many places, the fine, regular ripples seen on the backside of pure gas welds do not occur. This is particularly striking if the metal flow out the back of the keyhole is observed during welding. With pure gas there is a continuous (perhaps described as a waterfall) flow of metal appearing to come out of the keyhole. With Oxygen

contamination, the flow is intermittent and sometimes it appears that chunks of already solidified metal are flowing out.

The smooth mat finish of the pure gas welds probably results from the homogeneous distribution of native solidification nuclei in the metal. Various contaminants that may form at the surface of the weld pool and be swept into the liquid, such as aluminum oxide, aluminum nitride, or carbon from dissociated methane, can serve as nucleation centers for solidification and reduce undercooling in the melt. Solidification can start sooner behind the arc where the isotherms still have the tear drop shape characteristic of the keyhole or cover pass melted bead. The isotherms farther behind the weld are not only flatter, but are closer together so the rippling would be finer and contribute to the mat finish. Notice, however, that of all the contaminants, Oxygen produced the least rippling on both the cover and keyhole passes. The coarse backside of Oxygen contaminated welds leaves no doubt that Oxygen reacts with the aluminum. Perhaps a tenacious aluminum oxide skin forms on the bead and suppresses the rippling or perhaps the aluminum oxide is simply not as efficient a solidification nucleator as some of the other contaminants that are in the weld. Notice that Hydrogen in the arc gas causes both severe lack of fusion in the weld (due to high surface tension of the Aluminum behind the weld) and severe rippling on the cover pass front surface. A high surface tension could make small ripples more difficult to form in the liquid but when the solidification front does reach the surface, a larger ridge would exist.

Undercutting on keyhole passes proved to be one of our experimental difficulties. Several welds had to be redone because of unacceptable undercutting and a few of our cross section still show slight undercutting. Undercutting from torch misalignment could always be detected since each weld run was started by several inches of pure gas weld. If undercutting was present in this pure section, we were certain that the torch was misaligned. Magnified cross sections will, of course, highlight undercutting that may not be apparent on the surface of a weld. The torch had to be rotated manually which caused some difficulties for the welder, but did not significantly affect the quality of the final welds. Outside of the higher concentrations of Methane in the shield and Hydrogen in the arc, which caused disastrous welds, clear evidence of contamination induced undercutting was observed with 650 ppm and 325 ppm Nitrogen in the shield and with 100 ppm Hydrogen in the shield. Fig. 3-7 shows three cross sections which were made respectively with pure gas, 650 ppm Nitrogen in the shield, and pure gas. These sections were made from one pass and are only a few inches apart. Notice that the undercutting changes from minor to significant and back to minor as the purity of the gas is changed. This was repeated several times and proved to be a pattern. Apparently, a thin layer of adsorbed Nitrogen (or aluminum nitride) has a larger rate of change of surface tension with temperature and causes faster convection on one side of the weld. This faster convection can cause a Bernouli reduction in pressure over the liquid and lead to an undercut. It is known that

a reduction in shield gas flow rate or simply jerking the torch away from the workpiece can cause undercutting. It was assumed that Oxygen introduced into the weld caused this. Our data, however, suggest that Nitrogen is more effective in causing undercutting. The very poor welds made with a high concentration of Hydrogen also indicate changes in surface properties that manifested themselves as undercutting at 100 ppm Hydrogen in the arc.

Another interesting observation from the undercut Nitrogen welds is that the ridges on the backside are slanted toward the undercut indicating asymmetric fluid flow. This can be very significant to a weld inspector since a cover pass will smooth out undercutting, but not change the ridges on the backside. Our data indicate that slanted backside ridges should be a warning of keyhole undercutting.

The summary sheets on granular extrusions indicate that contaminants in the shield gas cause the most problem. The shield gas flow rate is about five times that of the arc gas and less shield gas flows out the keyhole so just from a volumetric standpoint, shield contamination would be expected to be worse. The granular extrusions typically appear at the edge of the weld, but in severe cases such as Methane arc contamination and Hydrogen shield contamination, appear also as small particles in the bead. It was found that if the gas lines were inadequately purged, even using the pure gasses, granular extrusions formed. Their presence, in fact, could be used as an indicator of insufficient purge. It

is not certain what the contaminants are that are purged each morning, but the low humidity in our laboratory and the fact that Methane is a strong promoter of granular extrusions suggests that hydrocarbon desorption from the weld hose is a significant contamination. Our lines were purged each morning both by flowing gas through them and by making several feet of test weld to insure that everything was working properly. In a few cases the test welds had a very poor appearance (sometimes called "morning sickness") and poor fusion similar to (but not as bad as) the test welds with Methane in the shield or Hydrogen in the arc. This is further indication that hydrocarbon contamination is a problem in unpurged systems. An interesting and useful study would be to examine the kinds and amounts of gasses given off by various weld hose materials when they are purged.

A review of the summary tables on granular extrusions shows that shield gas impurities during the cover pass produce the most granular extrusions with Nitrogen, Methane, and Hydrogen causing the most problems. Notice that the Nitrogen weld at 325 ppm which showed undercutting had most of the granular extrusions on the undercut side which is consistent with the theory that they are squeezed up from the interior. On the thin undercut side the compressive stress is greatest and should exude the greatest amount of liquid. Since our test sheets were clamped very tightly (a 1/4 inch bolt every 3 inches), we may have seen more than the usual amount of granular extrusions.

The optical micrograph of Fig. 3-1B shows the copper rich intergranular channel through which the granular extrusion, presumably flowed. Clearly, unless there is something solid for the liquid to flow through, there can be no extrusion. Since these granular extrusions seem to be a fairly general phenomenon with contaminated gasses, perhaps the adsorbed contaminants cause a quicker skinning over of the weld pool so that copper enriched liquid can be squeezed up rather than just pooling at the surface.

Many of the phenomena taking place during welding depend on surface properties of liquid aluminum alloy and how these properties change with adsorbed gasses. Such data is simply not available but would be extremely useful (if difficult to obtain) for better understanding of weld phenomenon.

IV CONCLUSIONS

To have confidence that weld gas is of sufficient purity to produce good porosity free welds, this study suggests that a welder should look for:

1. A smooth almost ripple free keyhole pass. The cover pass should show even less rippling.

2. The weld backside should have fine, regularly spaced ridges. When the finger is run along the weld backside, the welder will feel the ridges, but no sharp crests on the ridges.

3. At most, slight granular extrusions will be present on the edges of the weld bead, and none will be present in the weld bead itself. This is by no means a sufficient condition, however.

4. The weld frontside will have a dull mat appearance.

5. The backside ridges should be normal to the weld direction. If they are slanted, it is an indication that the keyhole pass was undercut.

6. Increased rippling on the front surface seems to be one of the first indications of any impurity except Oxygen. Oxygen can be detected readily by a significantly rougher backside.

7. Methane (and presumably other hydrocarbon) contamination, such as might occur from unpurged or oily gas lines, produces noticeable granular extrusions at the edges of the weld and in severe cases also in the weld bead itself.

This study has raised many questions about the VPPA weld process. To mention just a few:

1. It is still not clear why the weld voltage changes when gas flow rate is momentarily changed. In addition to this change, is there a true change in arc resistance due to impurities?

2. Exactly what is on the surface of the molten Aluminum when various gasses are over the Aluminum? Is this coating solid enough to resist breakup due to convection and how fast does it sputter away during the reverse polarity cycle?

3. How does the temperature rate of change of surface tension change with adsorbed species on aluminum? The extent of Marangoni flow will depend on this parameter.

4. Is there a better weld hose material available? Could hoses be bagged or otherwise wrapped when not in use in order to reduce contamination? If a valve is placed just before the torch, would keeping positive pressure on the hose overnight reduce contamination?

The authors are grateful for the many stimulating conversations we have had during this work with Dr. Arthur Nunes at Marshall Space Flight Center. His patience and many helpful suggestions have been a source of pleasure, inspiration and encouragement during this project.

We also wish to acknowledge the advice in gas handling and the gas purity measurements that Scott Specialty Gasses of Houston, Texas has provided for us.

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3-42	25ppm Hydrogen in arc, Cover.
3-43	10ppm Hydrogen in arc, Keyhole.
3-44	10ppm Hydrogen in arc, Cover.
3-45	Pure gasses - Keyhole.
3-46	Pure gasses - Cover.

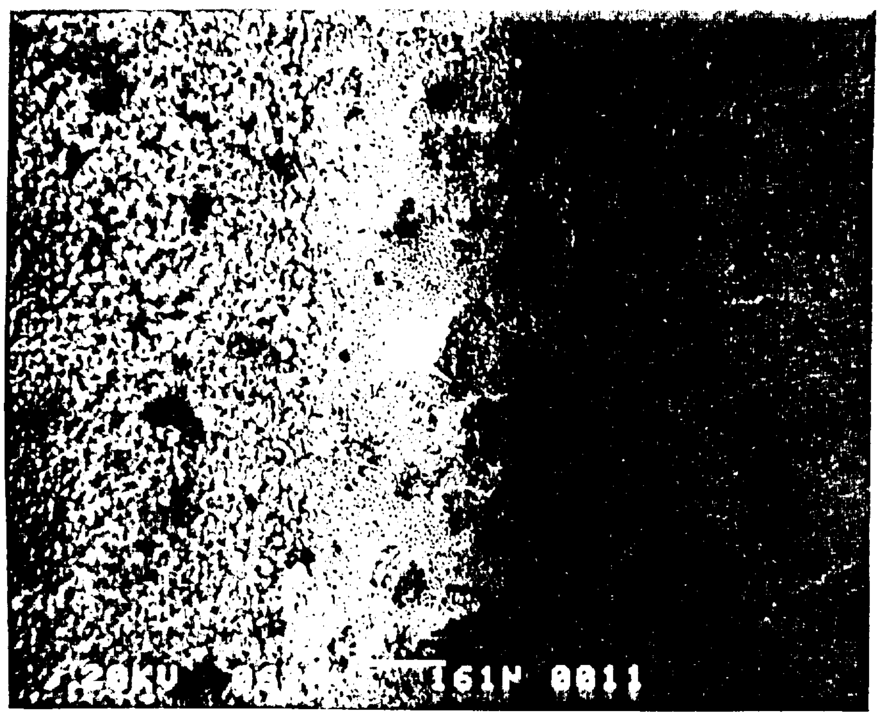

Fig. 3-1 SEM micrograph of typical granular extrusions seen at edge of weld.

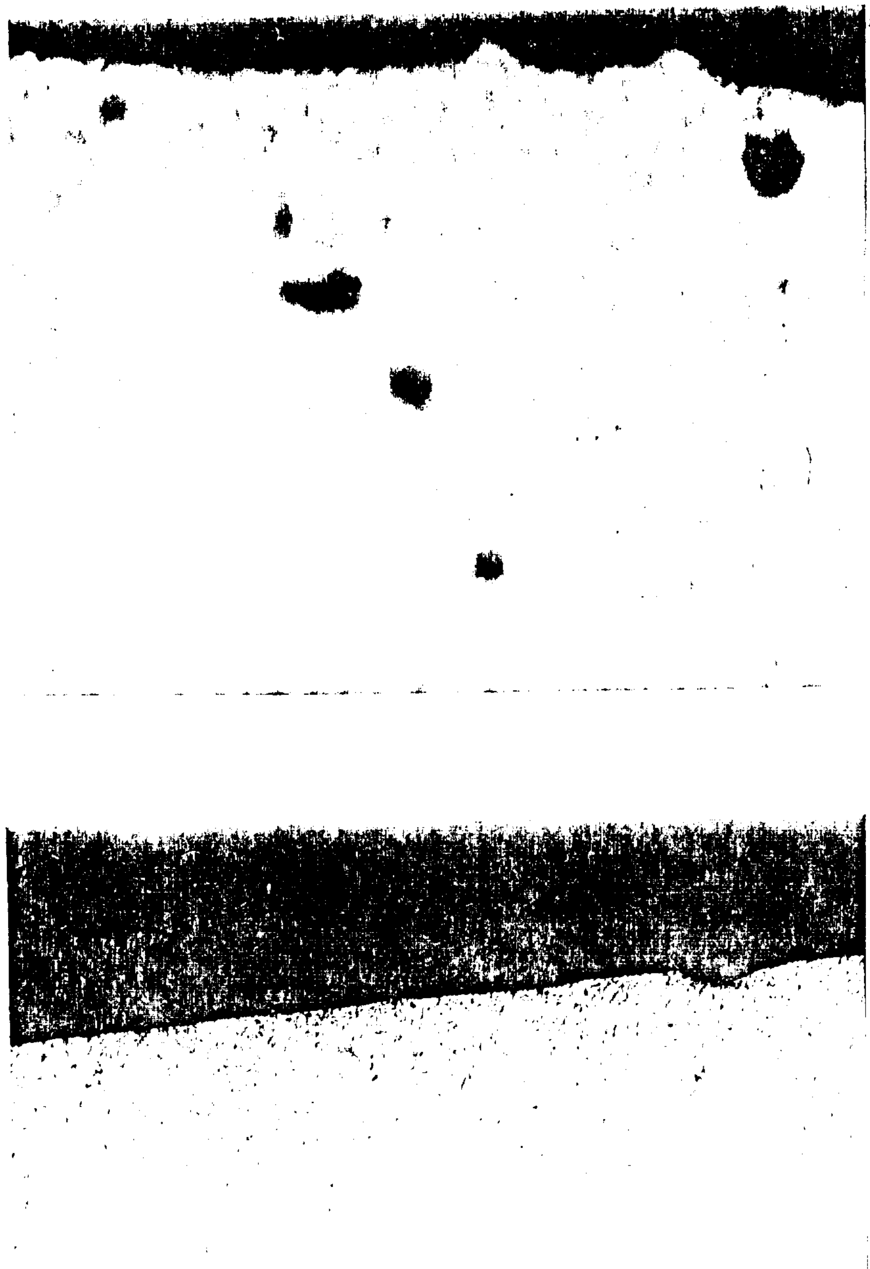

Fig. 3-1B Optical micrographs showing a granular extrusion at the surface of a weld (top) and a similar section through a weld without granular extrtusions. Note light Copper enriched region around extrusion. (500X, Ammonium Hydroxide etch)

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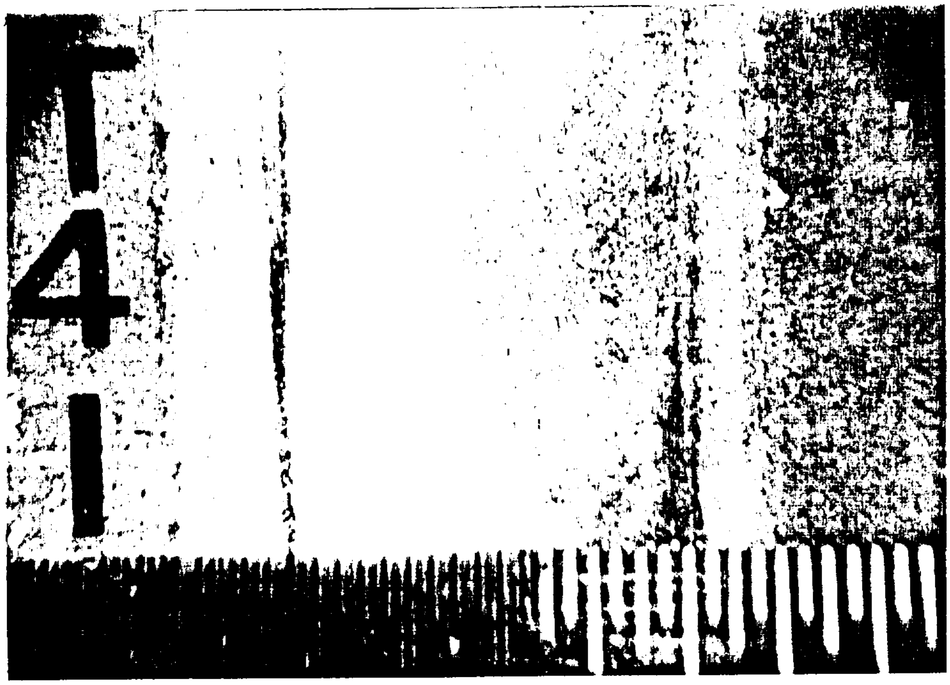


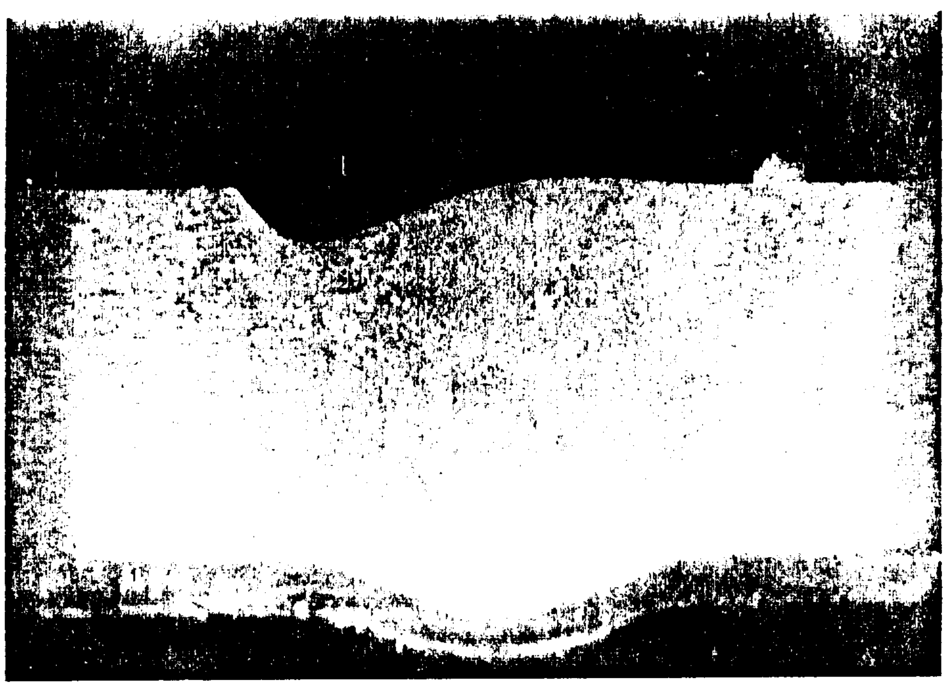


Fig. 3-2A Weld made with 650 ppm Nitrogen in Shield. Keyhole. Front
t4i,t4m

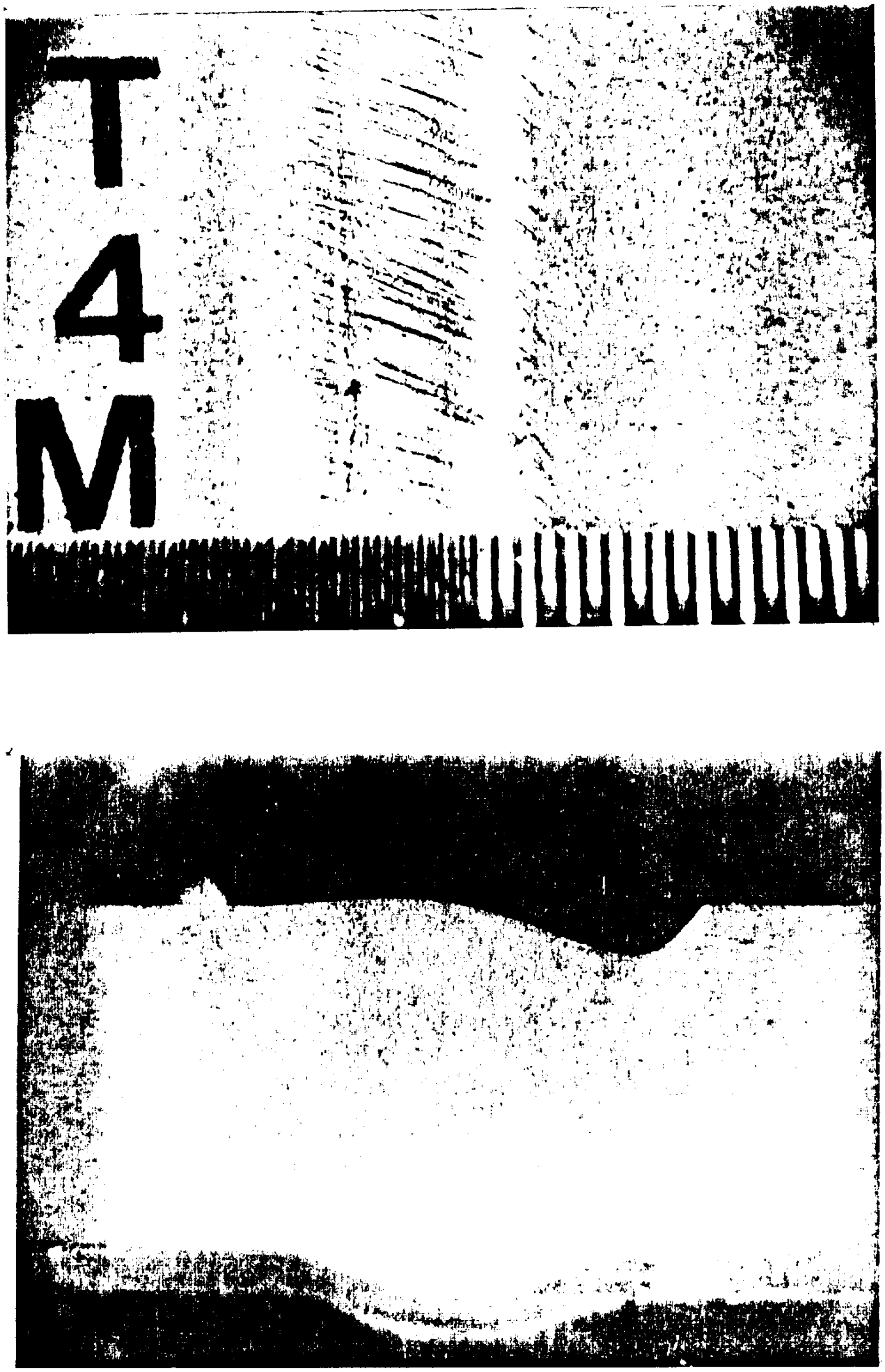
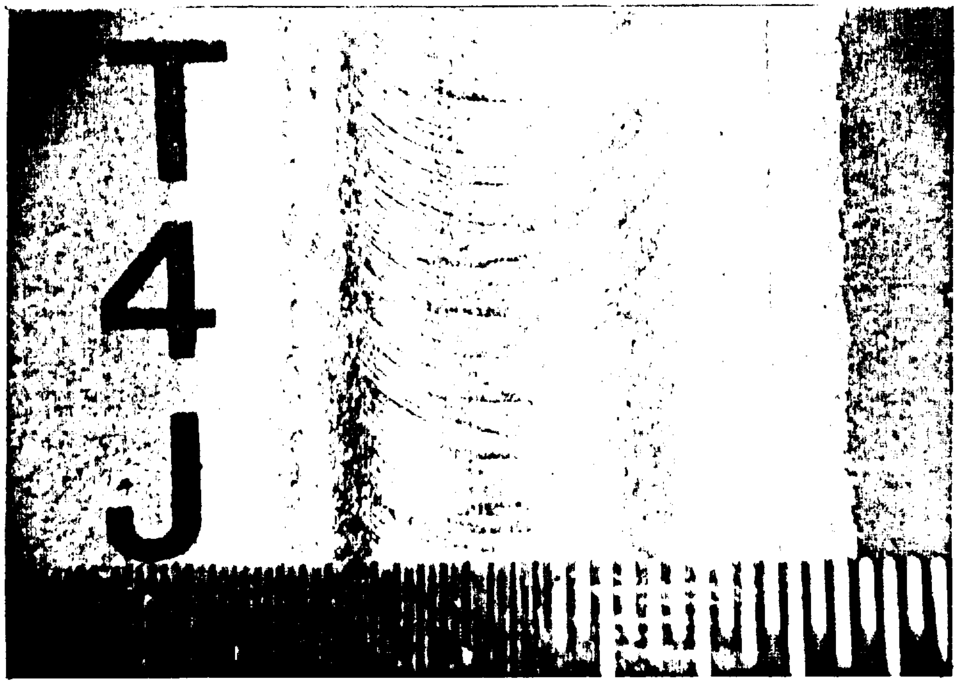


Fig. 3-2B Weld made with 650 ppm Nitrogen in shield. Keyhole. Back.



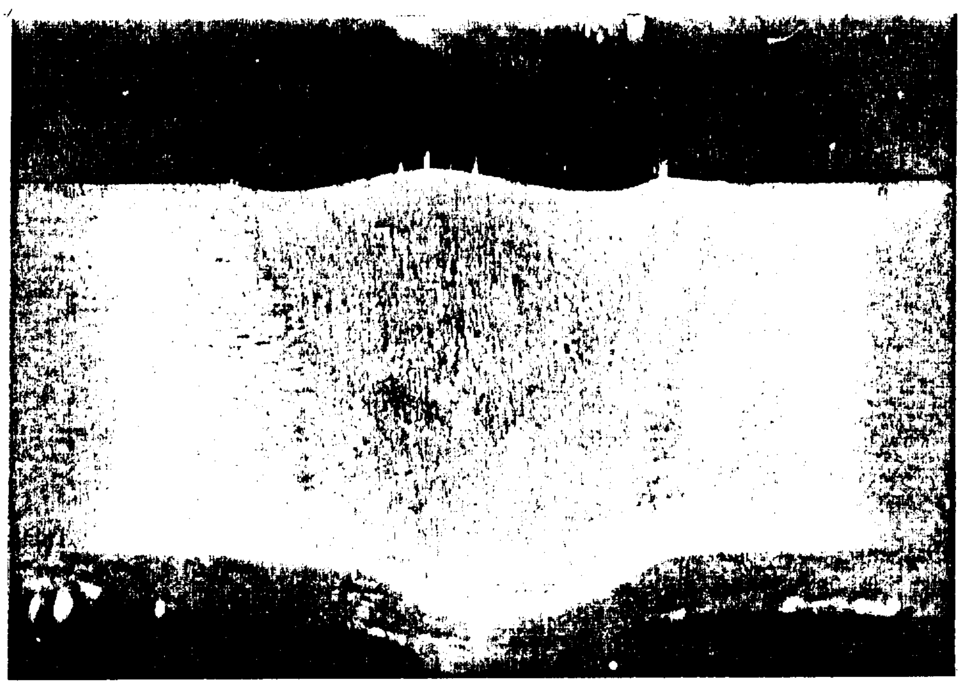


Fig. 3-3A Weld made with 650 ppm nitrogen
in shield. Cover. Front.
t4j, t4n

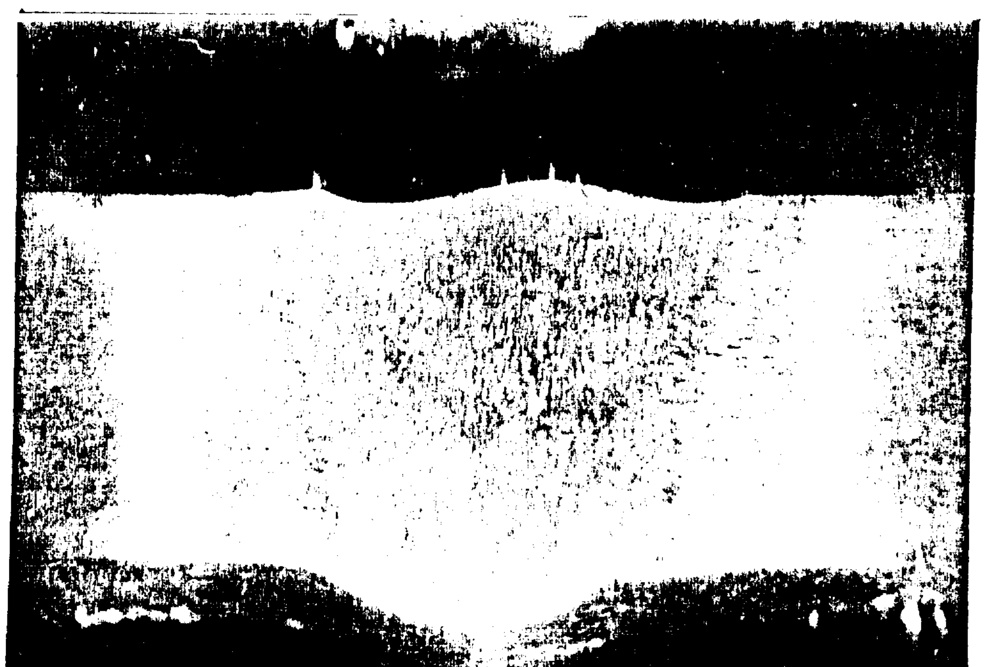


Fig. 3-3B Weld made with 650ppm nitrogen
in shield. Cover. Back.

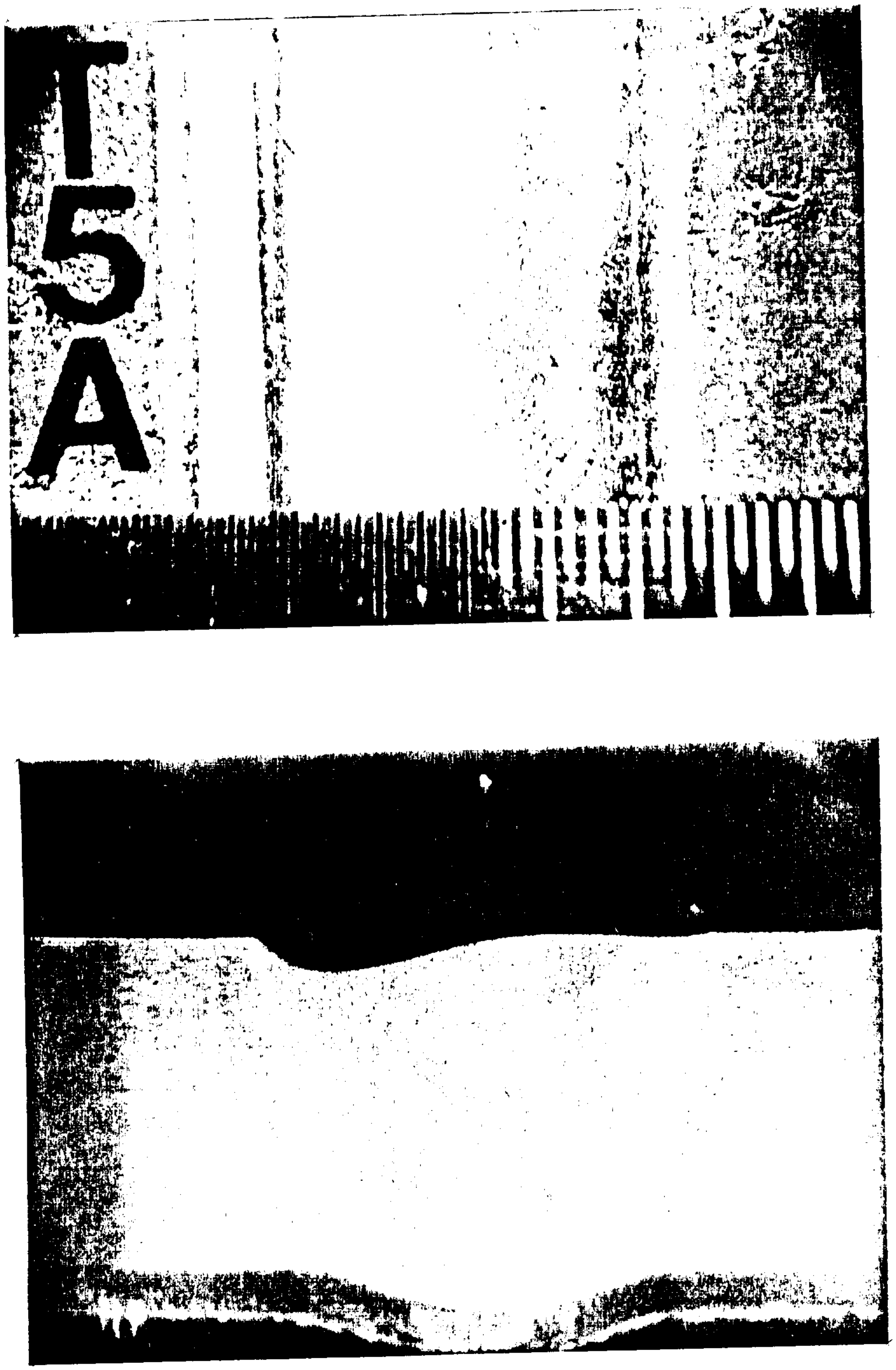
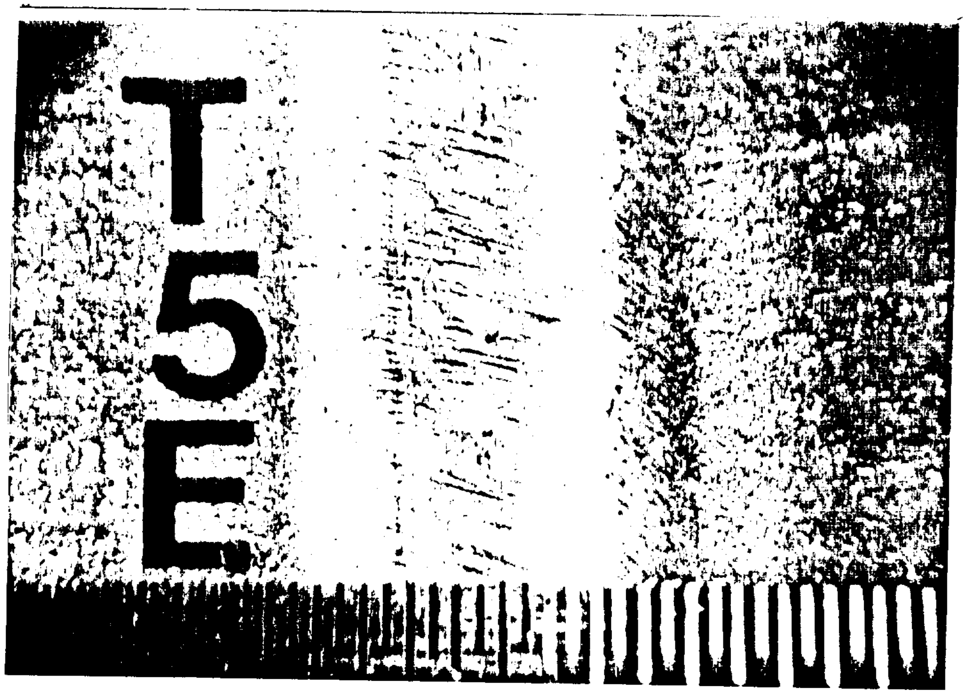


Fig. 3-4A Weld made with 325 ppm Nitrogen
in shield. Keyhole. Front
t5a,t5e



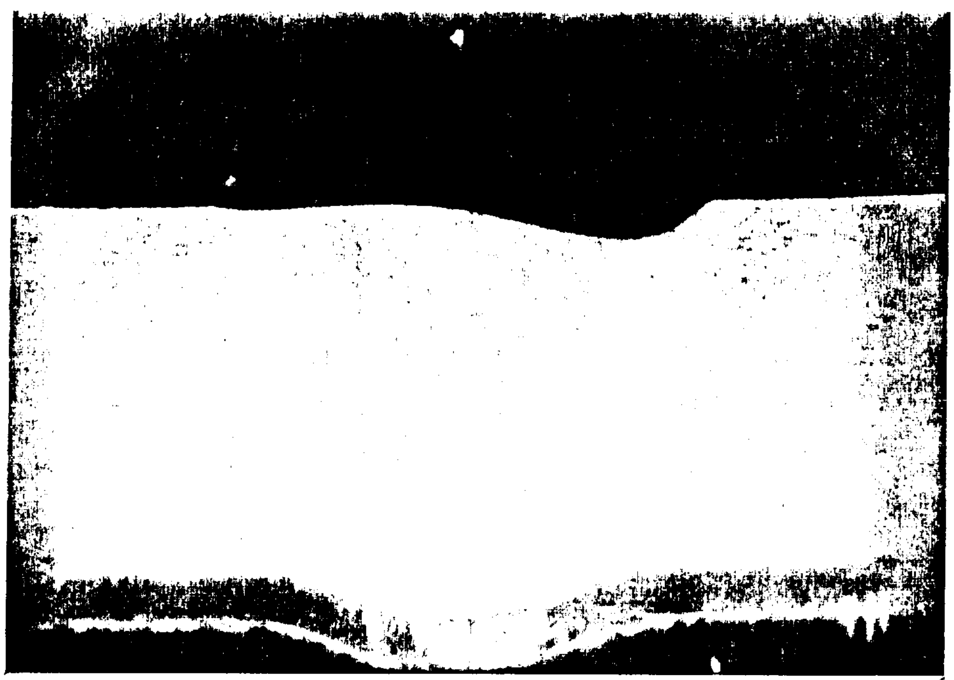


Fig. 3-4B. Weld made with 325 ppm Nitrogen in shield.
Keyhole. Back.

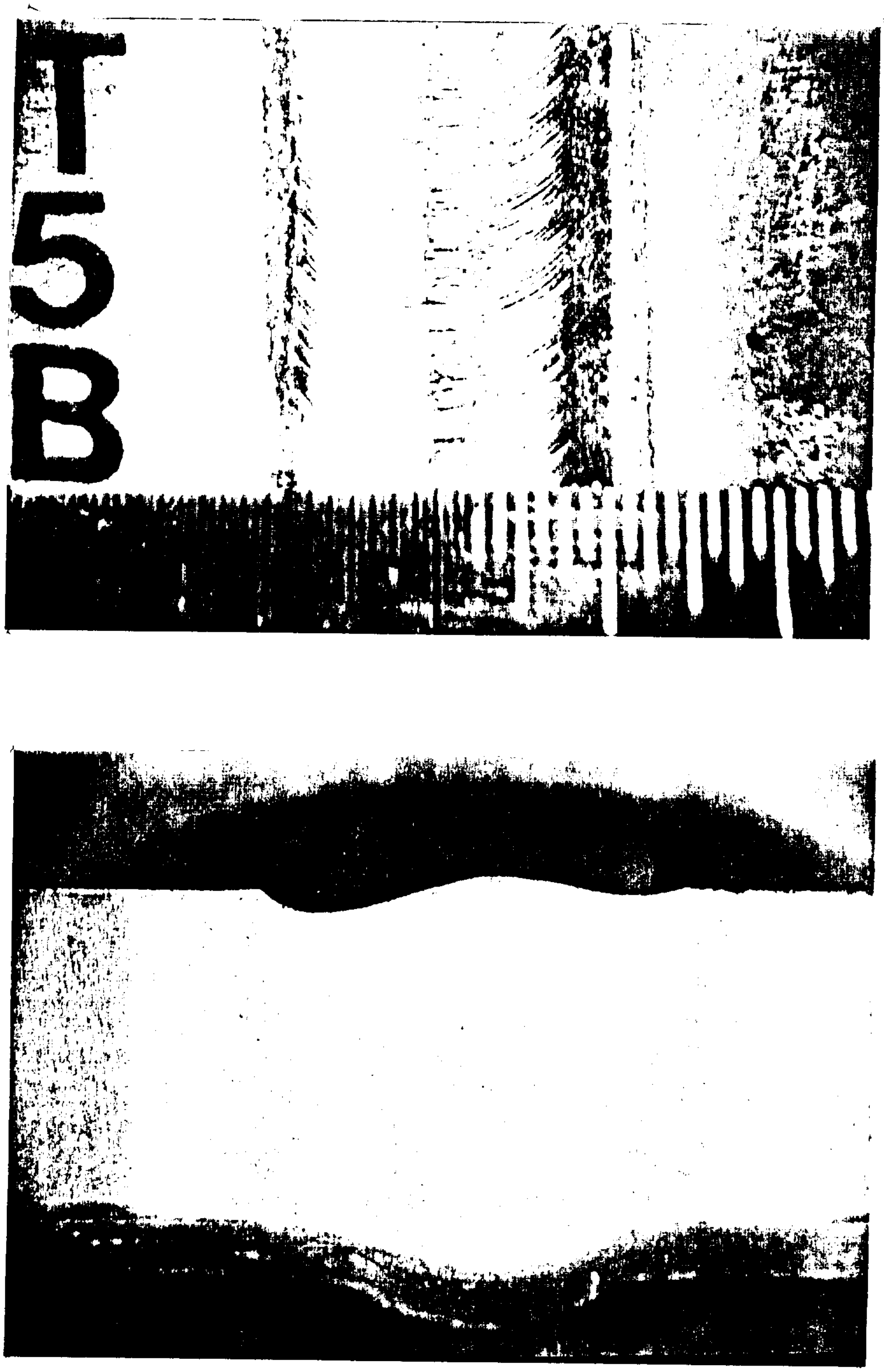


Fig. 3-5A Weld made with 325 ppm Nitrogen in shield.
Cover. Front.

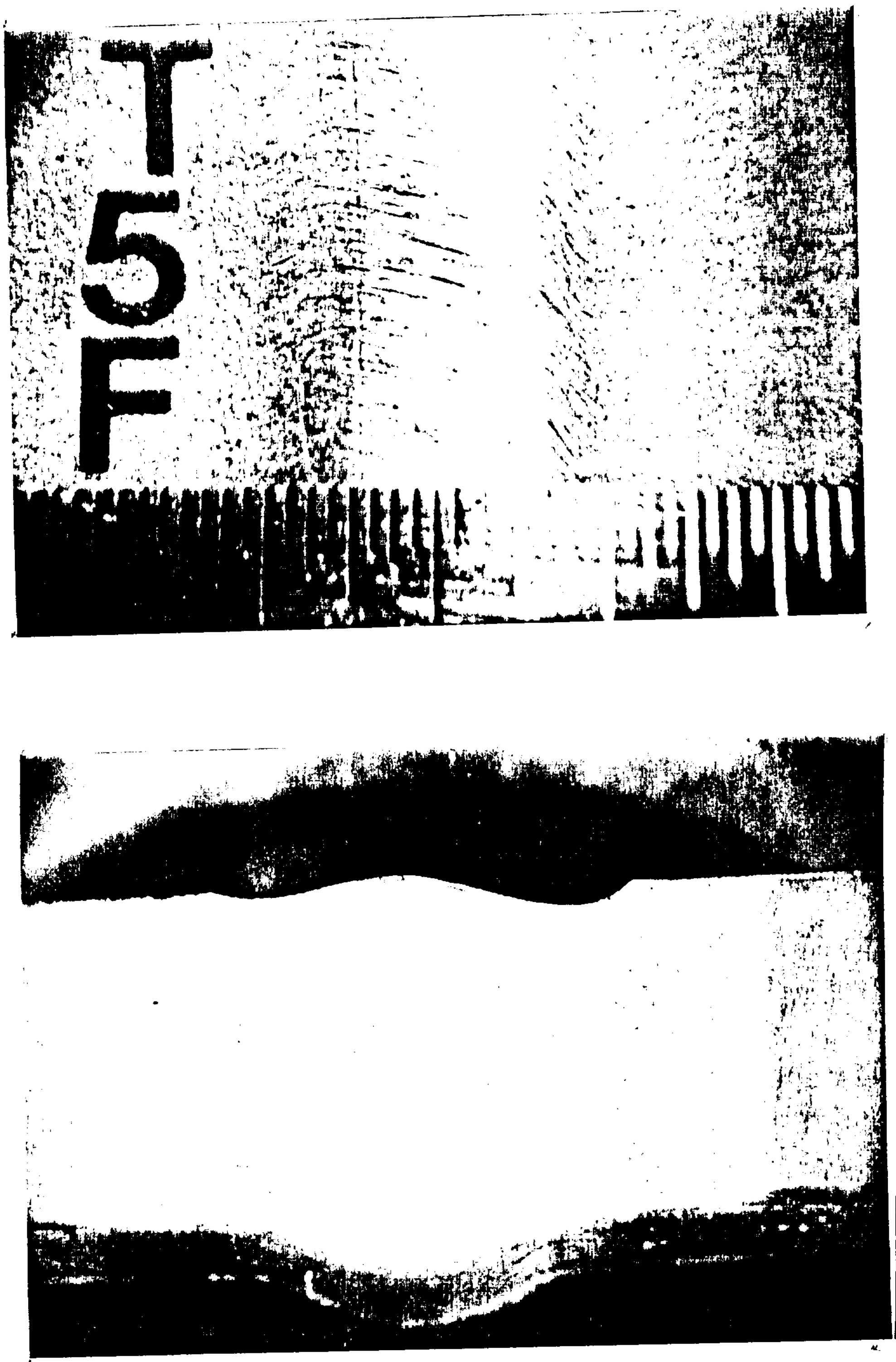
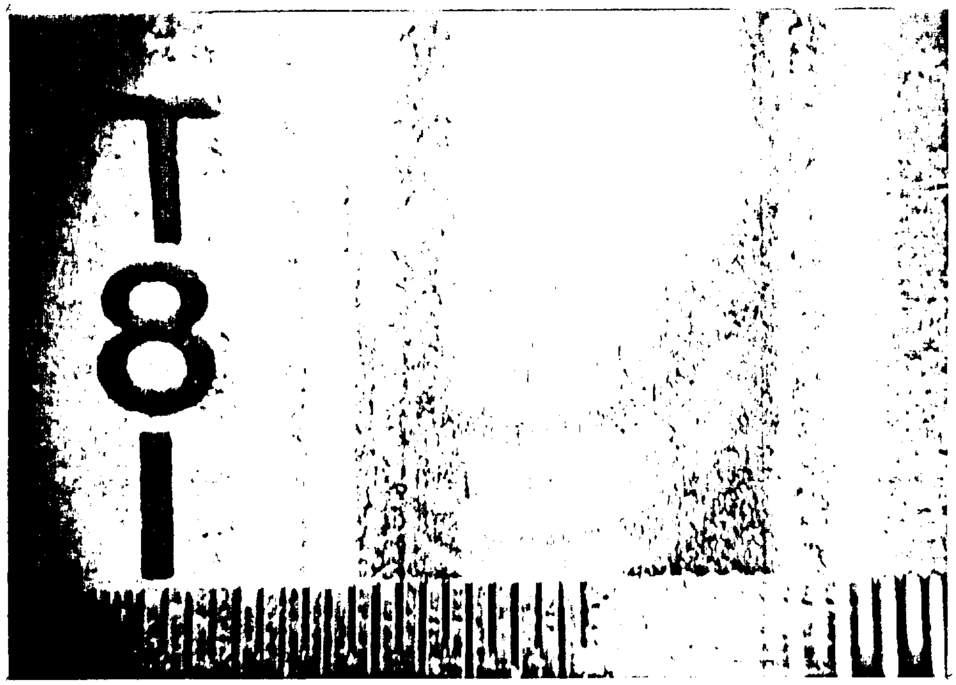


Fig. 3-5B Weld made with 325 ppm Nitrogen in shield.
Cover. Back.



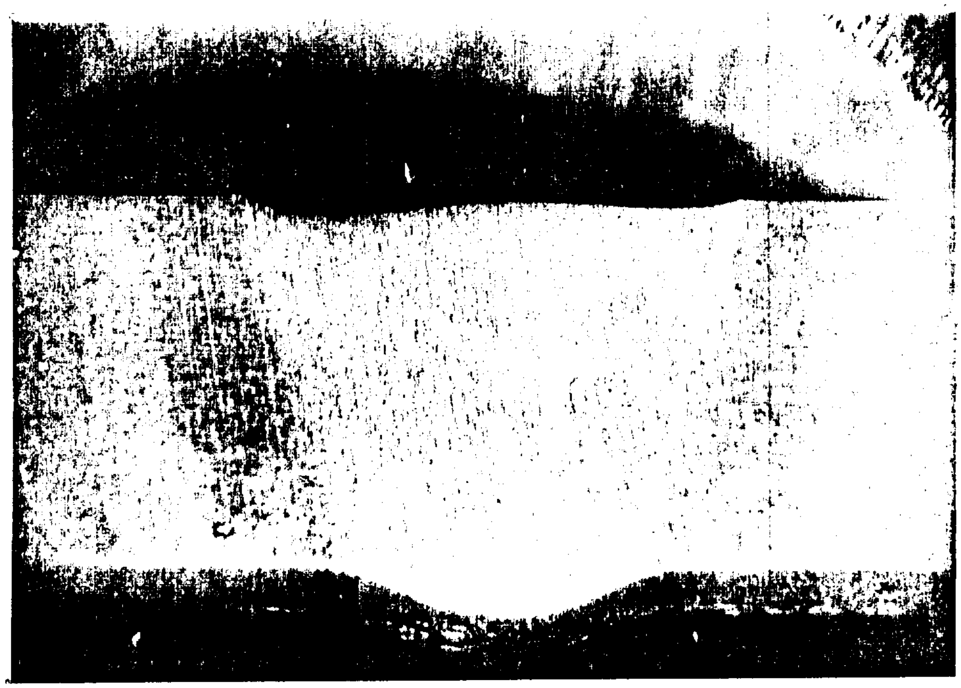
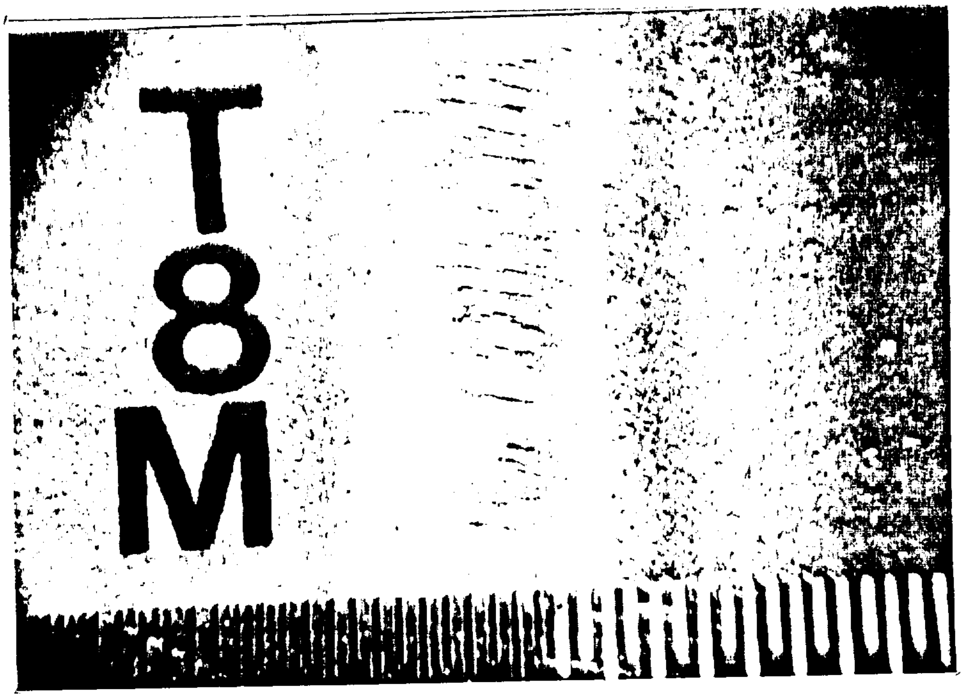


Fig. 3-6A Weld made with 100 ppm Nitrogen
in shield. Keyhole. Front
t8i,t8m



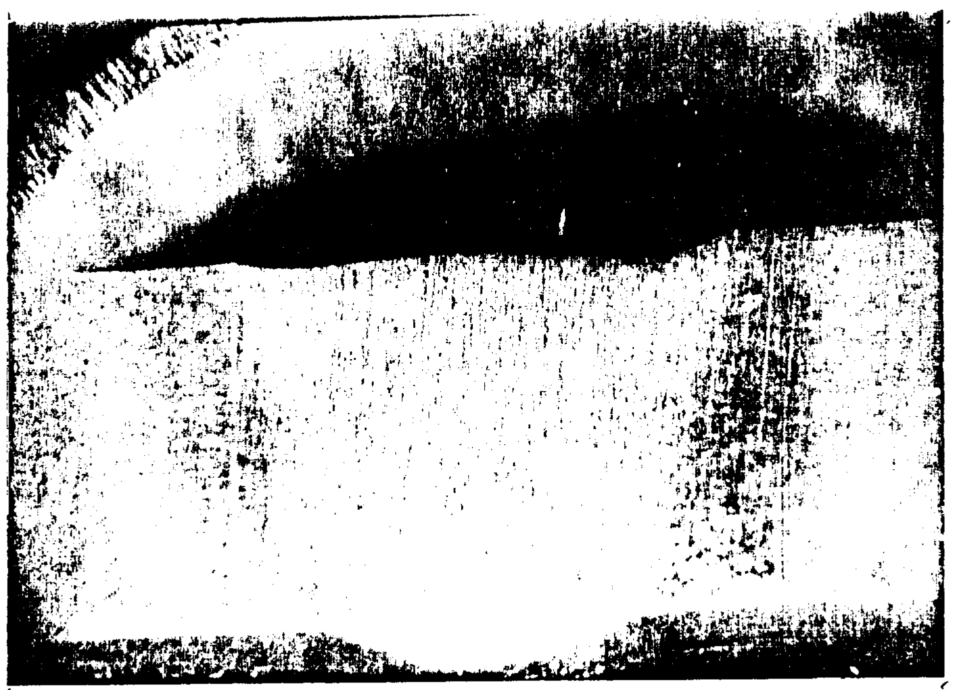


Fig. 3-6B Weld made with 100 ppm Nitrogen in shield. Keyhole. Back.

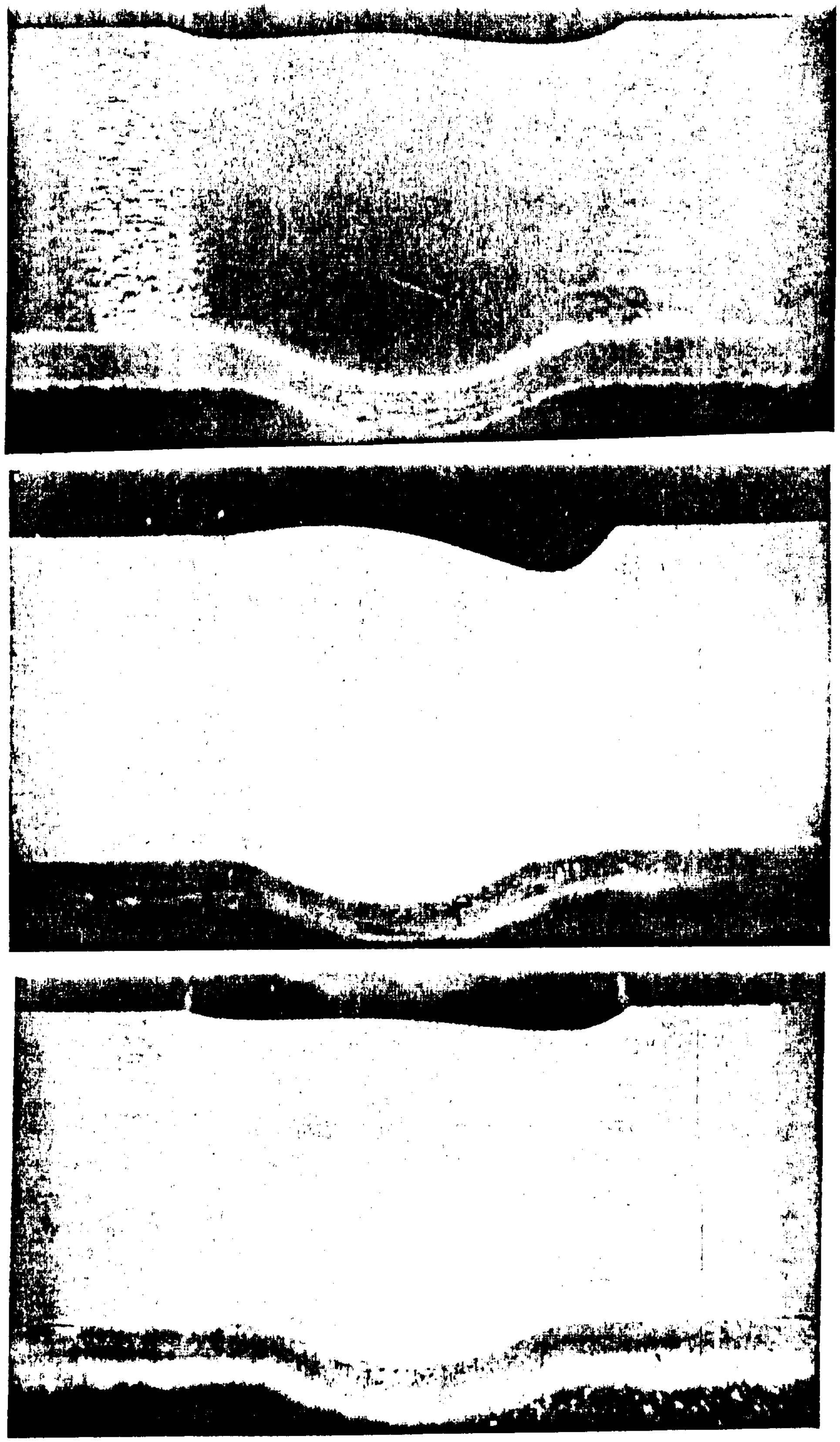
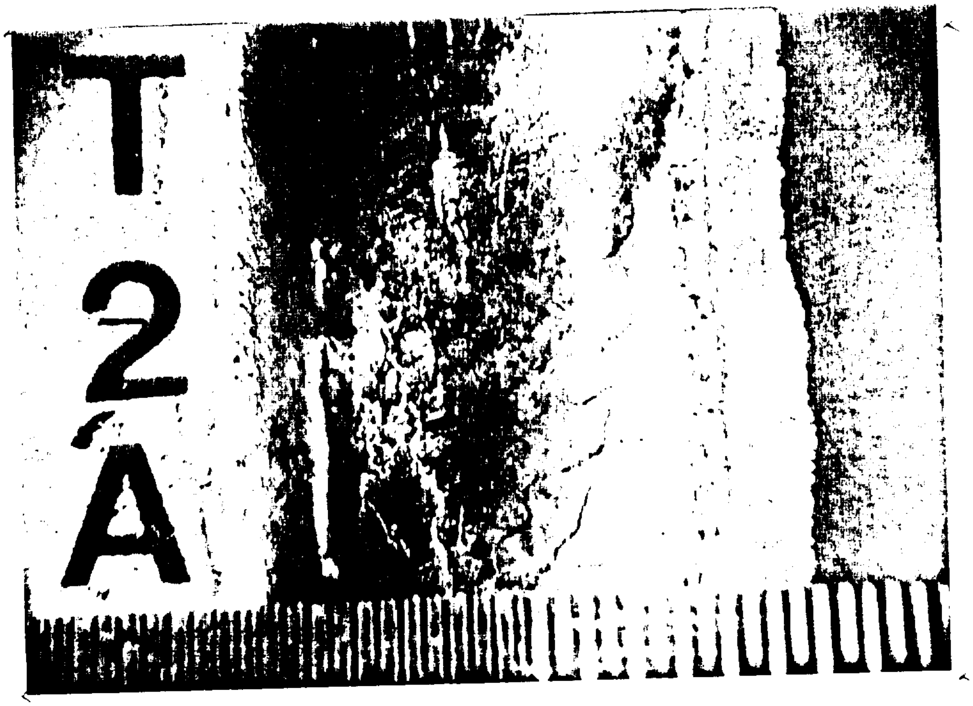


Fig. 7 Welds made with 650 ppm Nitrogen in shield gas (center) and with pure gas (top and bottom). Note undercutting during contaminated runs.



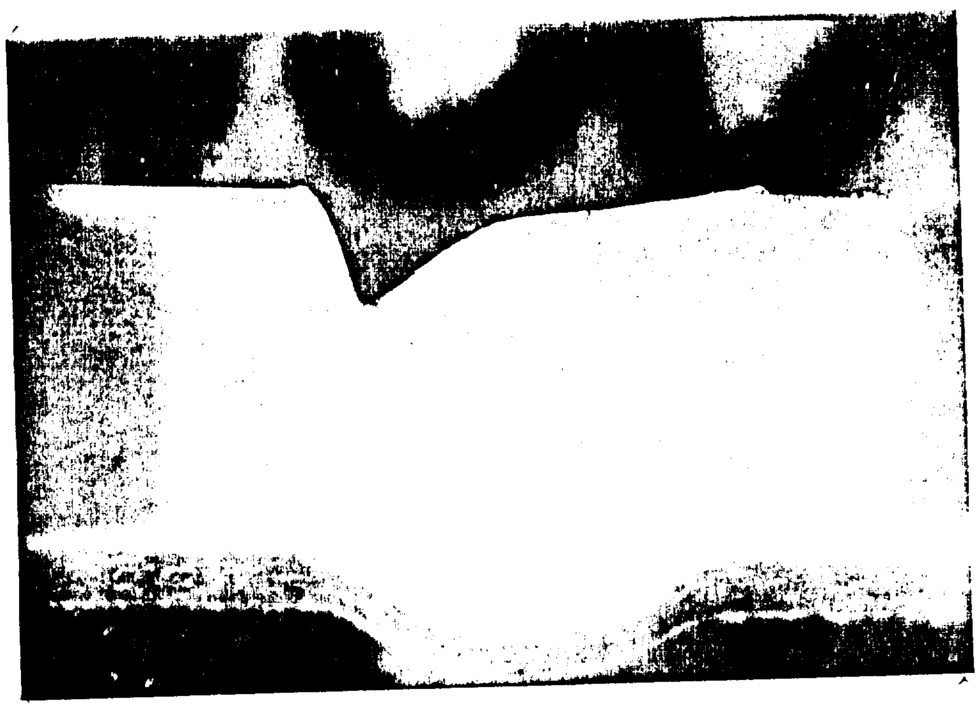
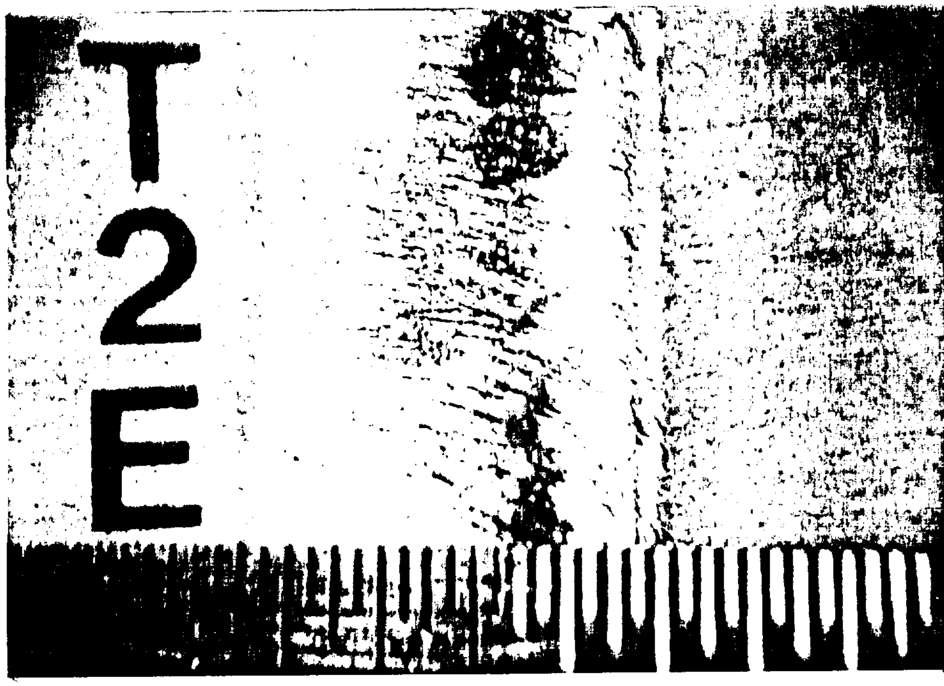


Fig. 3-8A Weld made with 400 ppm Methane in shield. Keyhole. Front
t2a,t2e



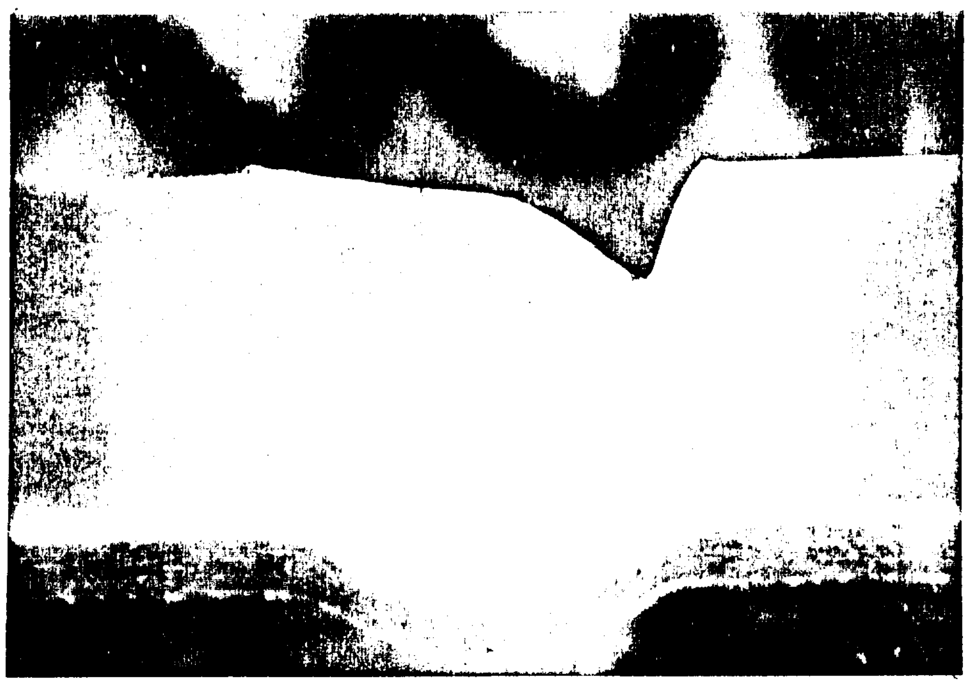


Fig. 3-8B Weld made with 400 ppm Methane in shield. Keyhole. Back.

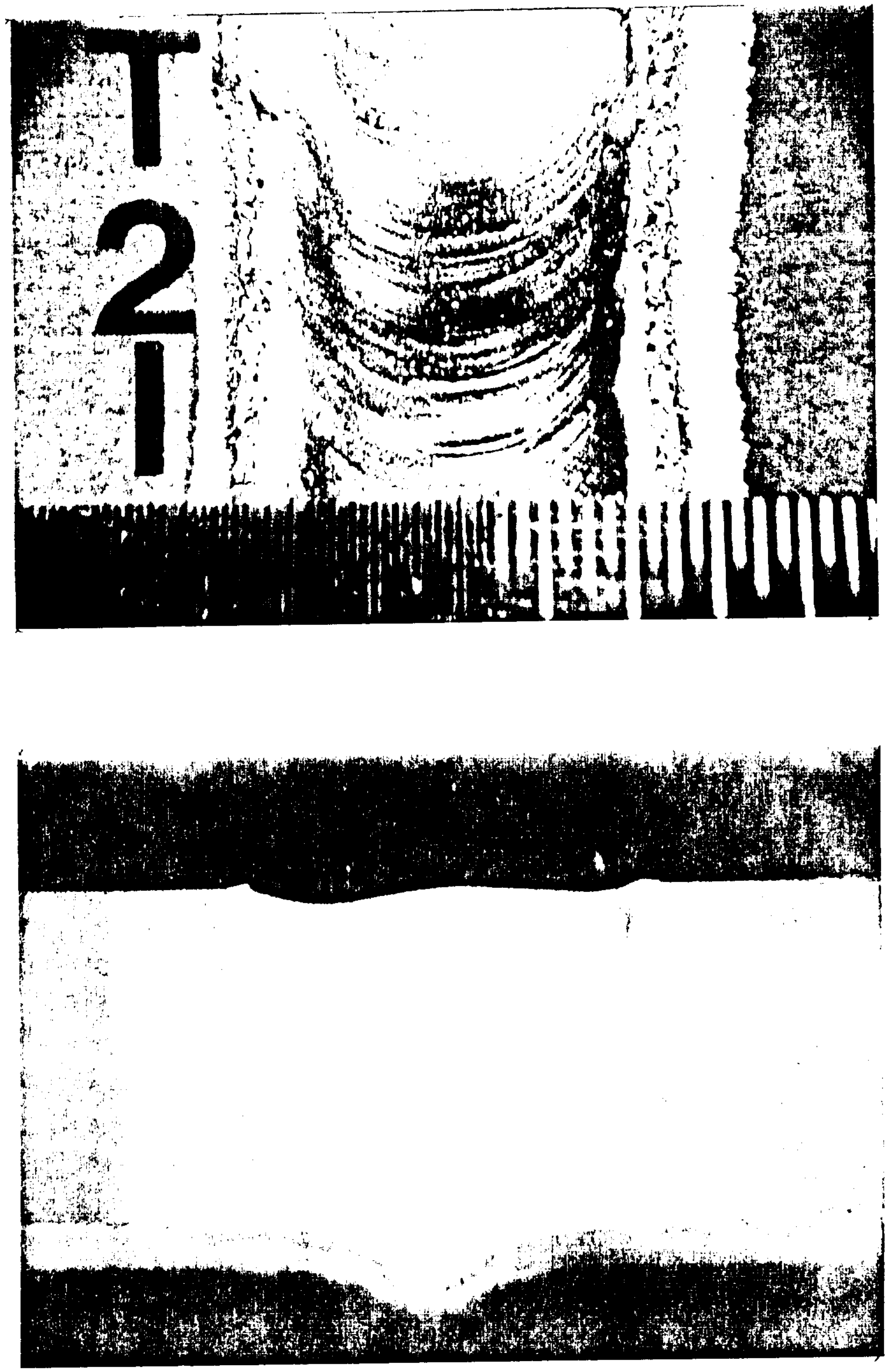
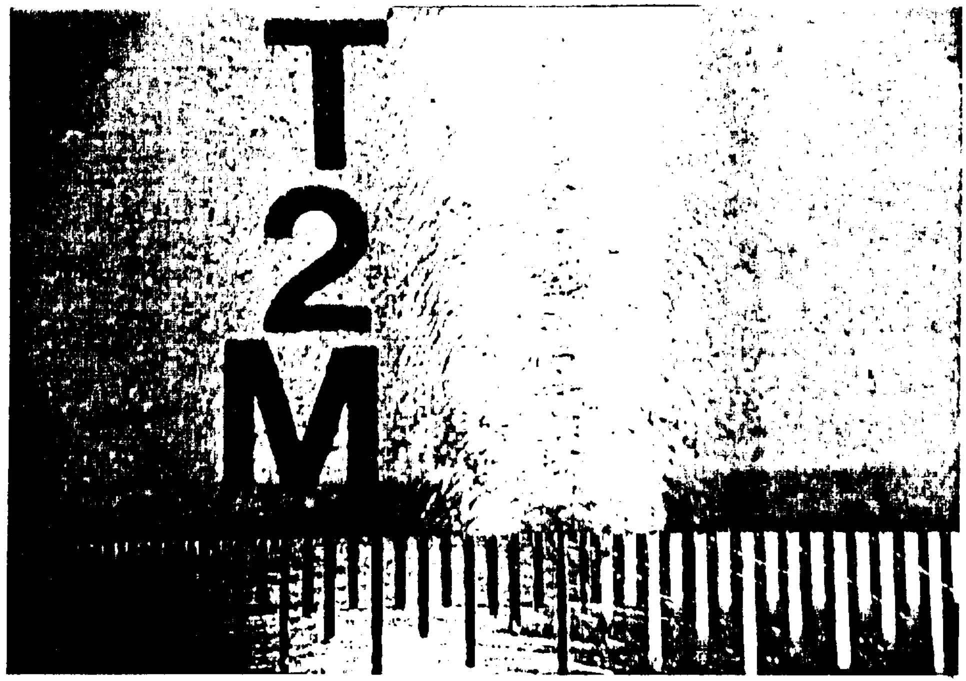


Fig. 3-9A Weld made with 250 ppm Methane
in shield. Keyhole. Front
t2i,t2m



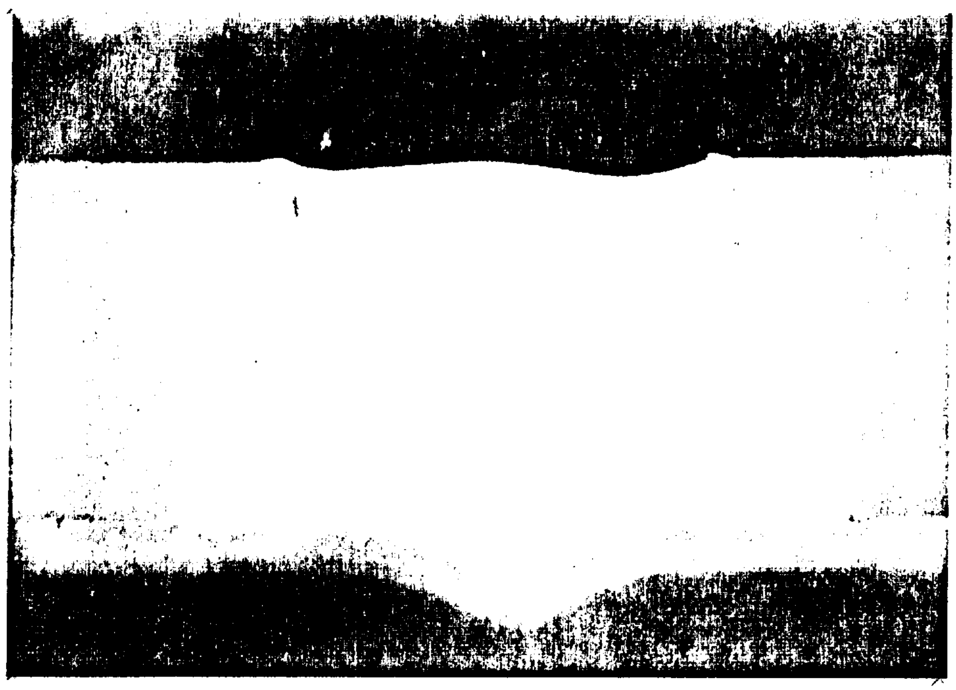
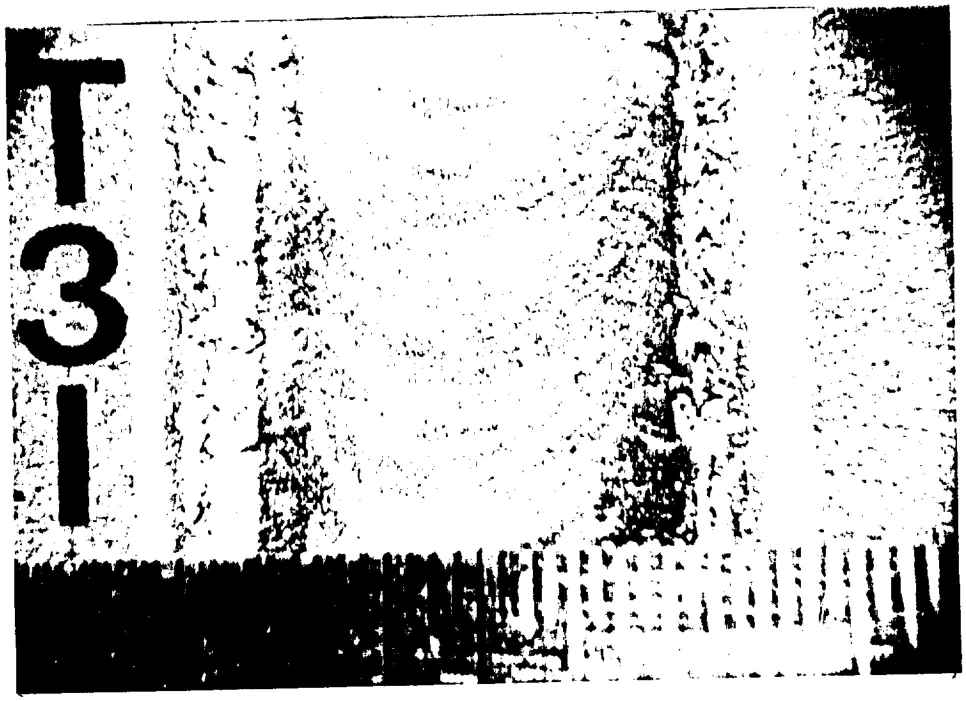


Fig. 3-9B Weld made with 250 ppm Nitrogen in shield. Keyhole, Back.



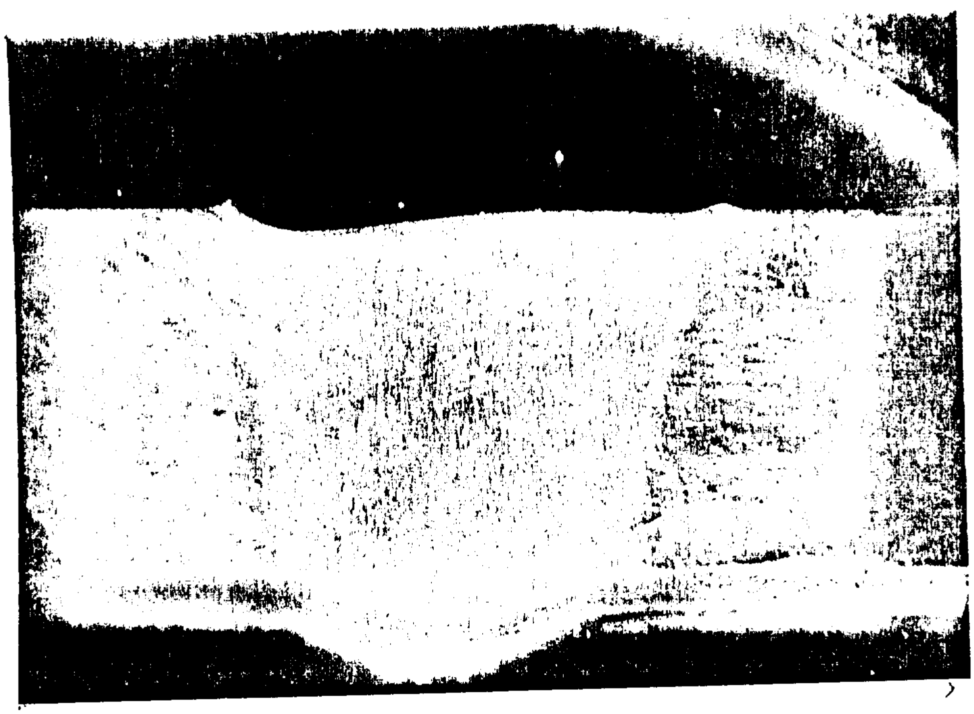


Fig. 3-10A Weld made with 100 ppm Methane
in shield. Keyhole. Front
t3i,t3m

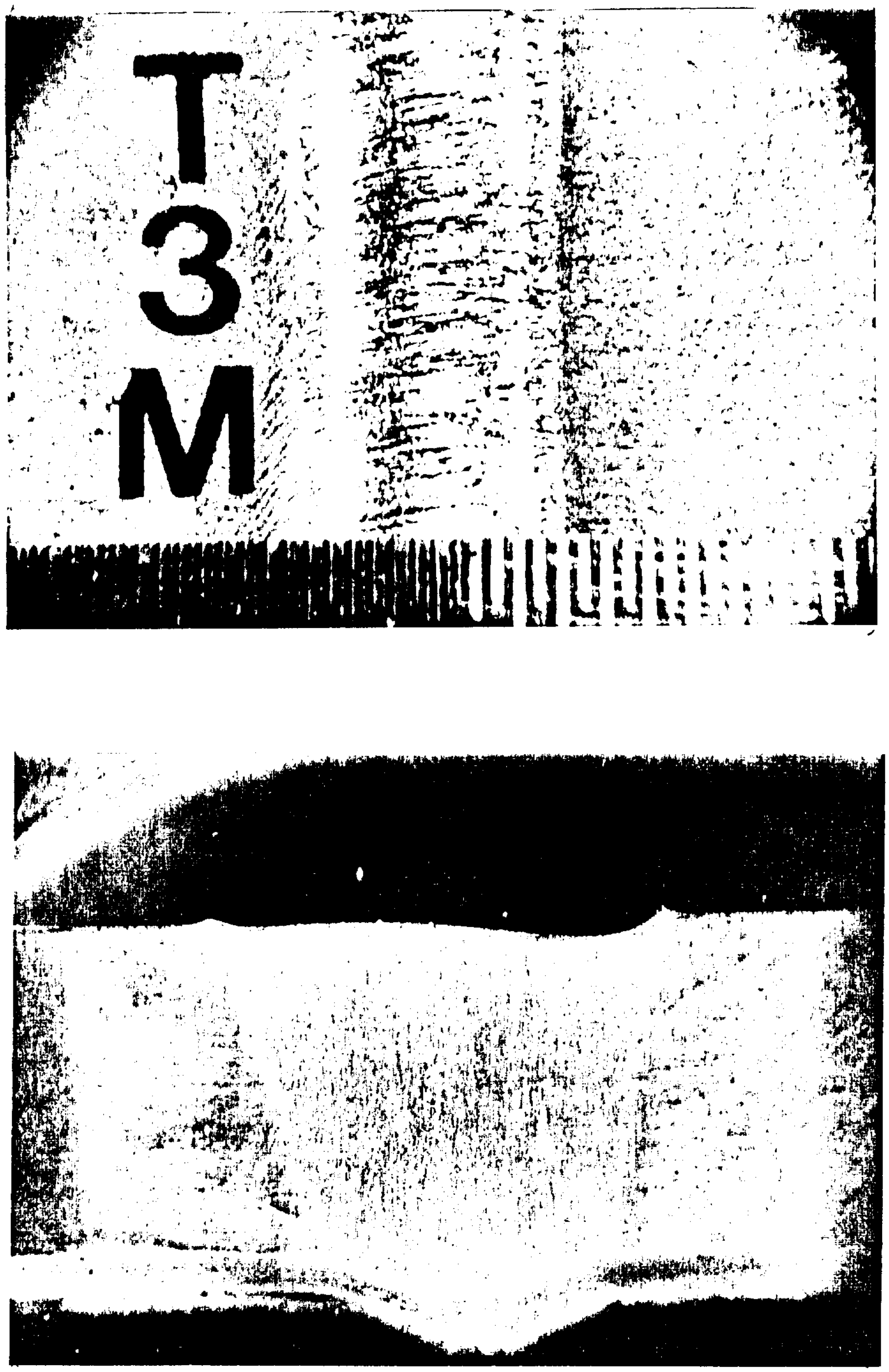
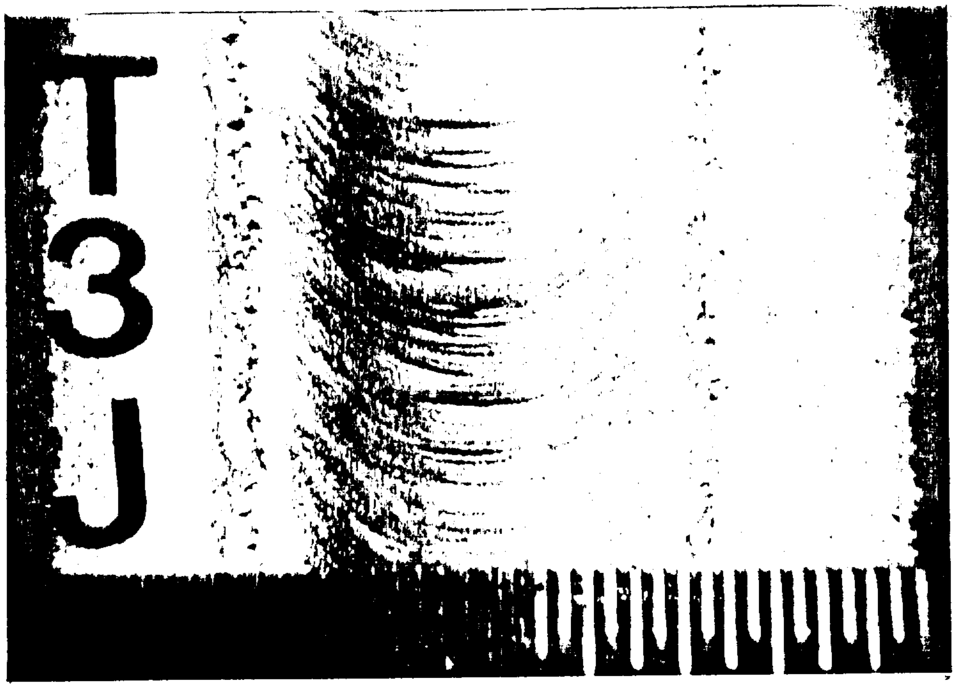


Fig. 3-10B Weld made with 100 ppm Methane in shield. Keyhole. Back.



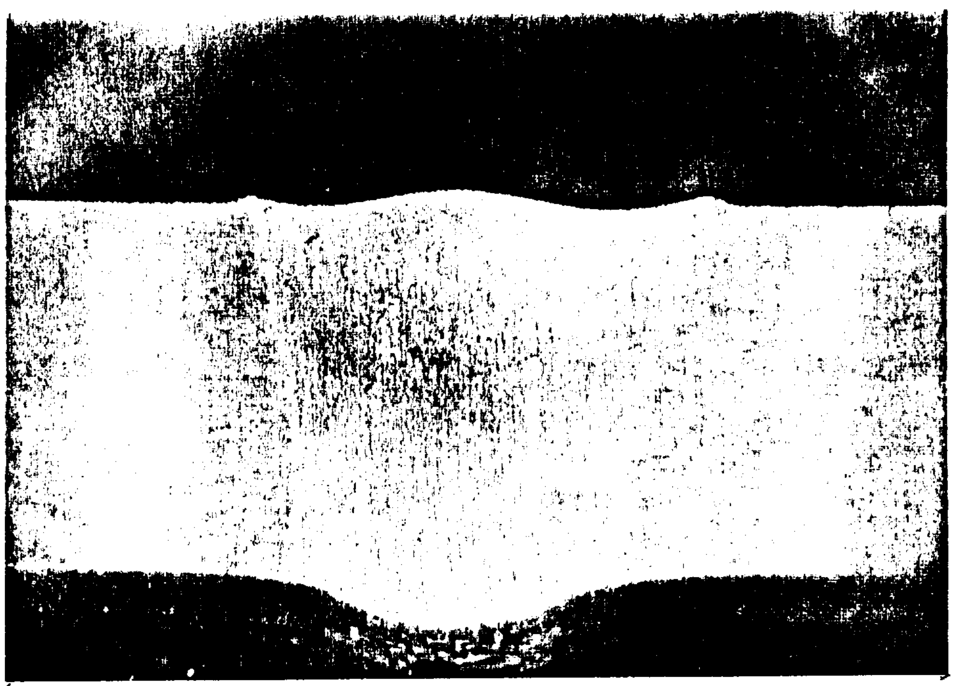


Fig. 3-11A Weld made with 100 ppm Methane in shield. Cover. Front.
t3j,t3n

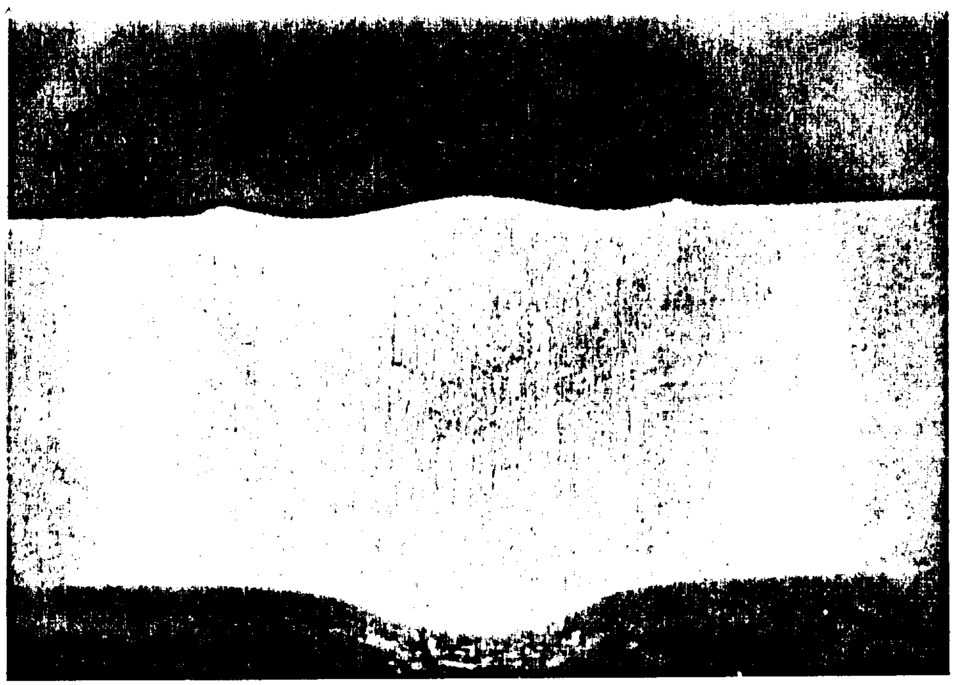


Fig. 3-11B Weld made with 100 ppm Methane in shield. Cover. Back.

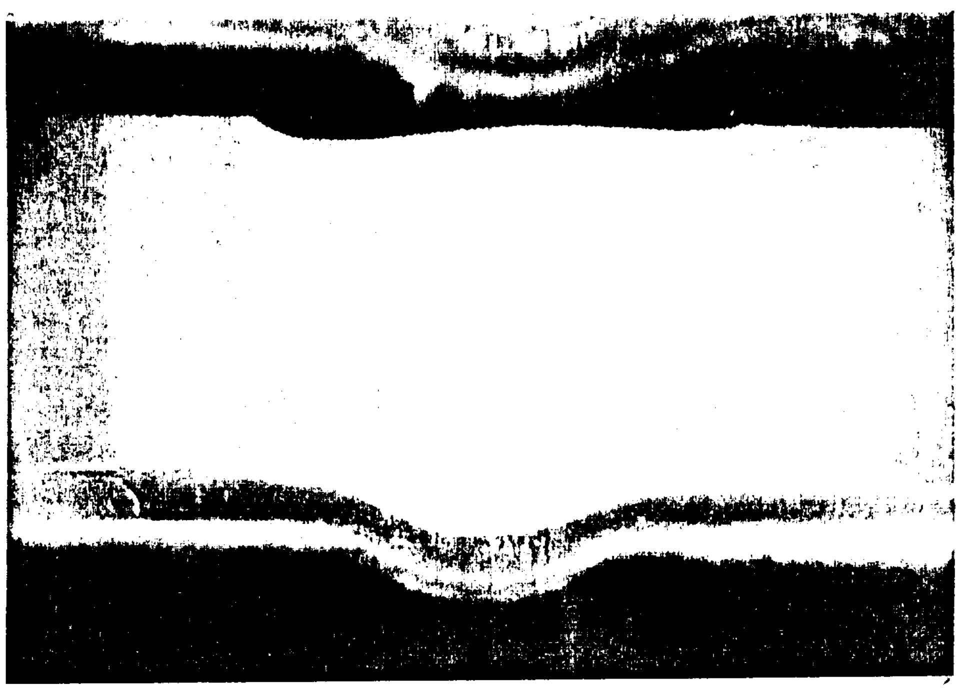


Fig. 3-12A Weld made with 520 ppm Oxygen in shield. Keyhole. Front.
t7a,t7e

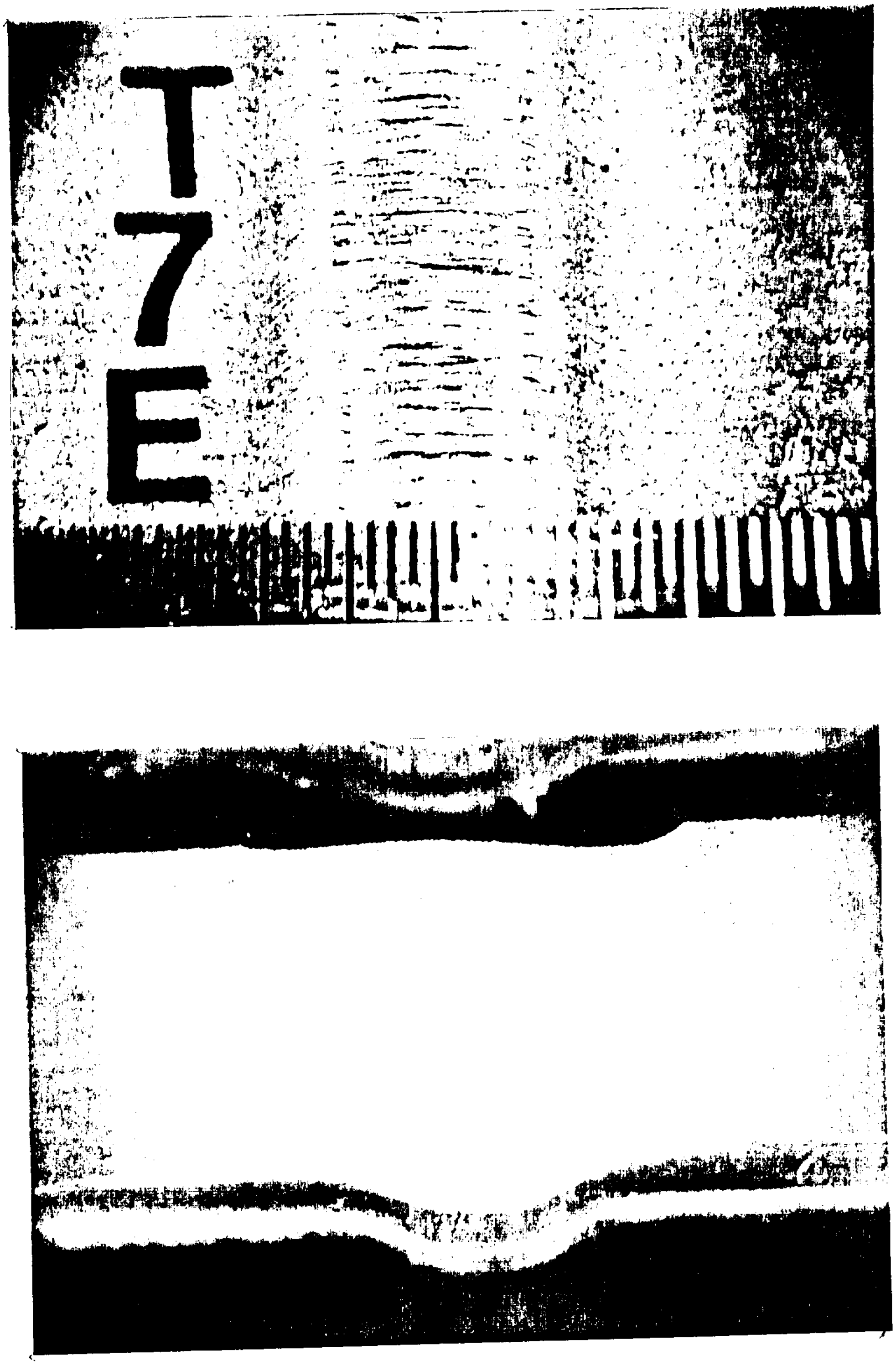


Fig. 3-12B Weld made with 520 ppm Oxygen in shield. Keyhole. Back.

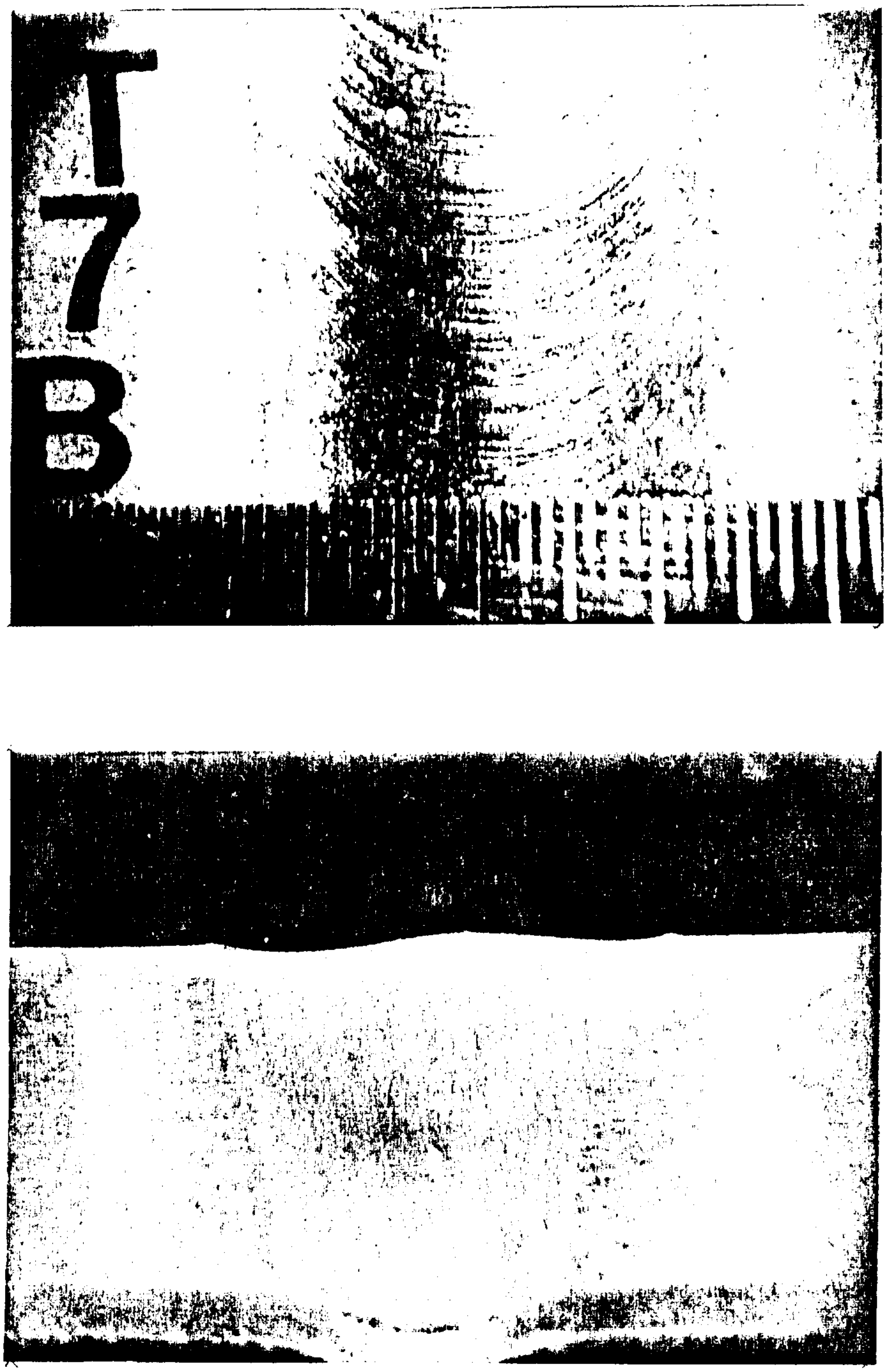
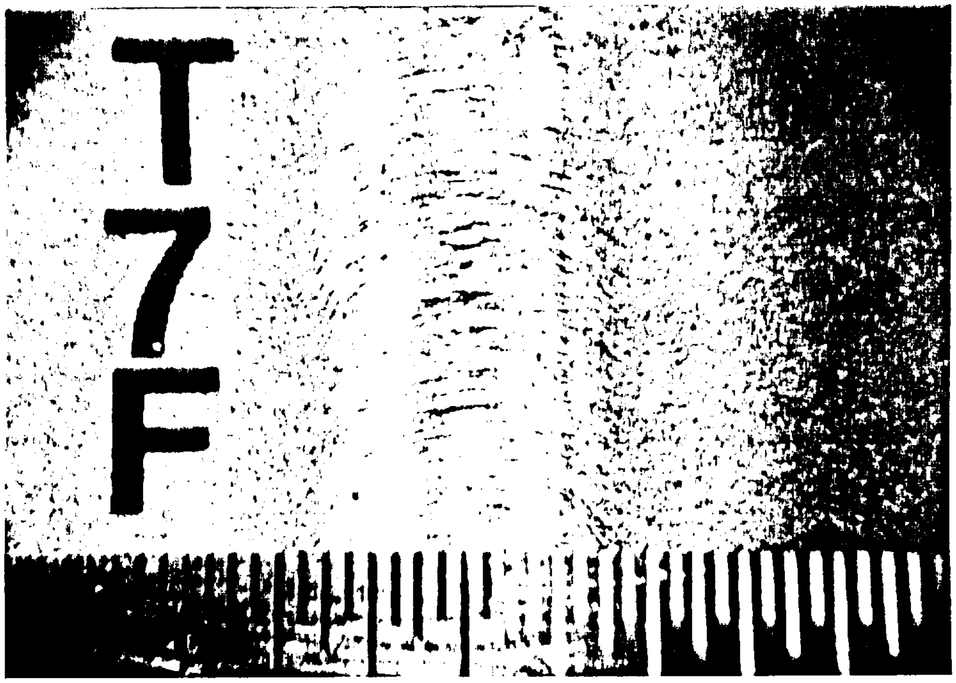


Fig. 3-13A Weld made with 520 ppm Oxygen in shield. Cover. Front.
t7b,t7f



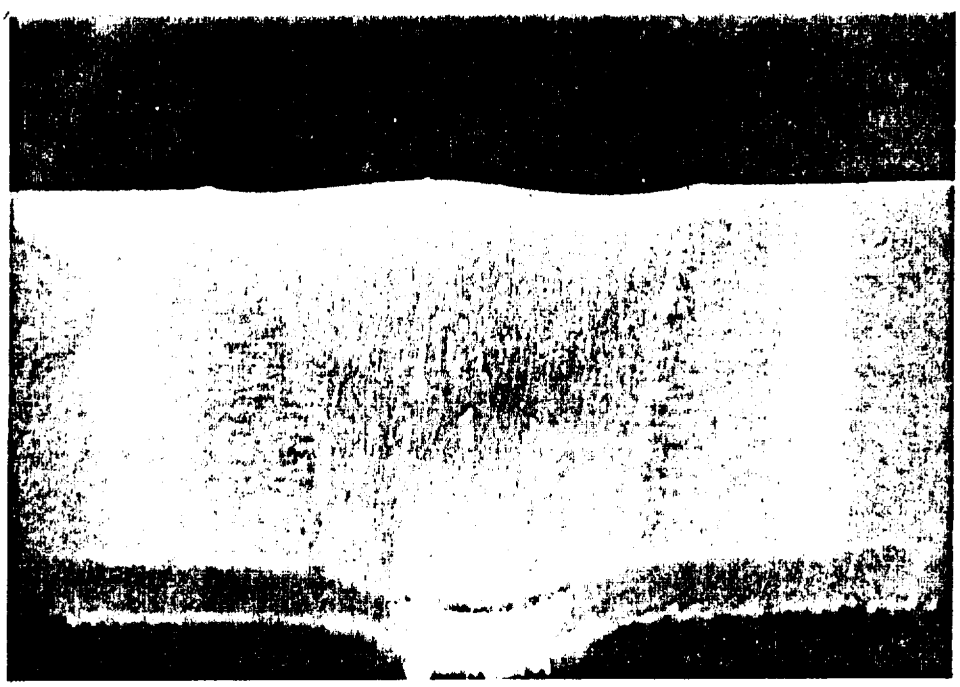


Fig. 3-13B Weld made with 520 ppm Oxygen in shield. Cover. Back

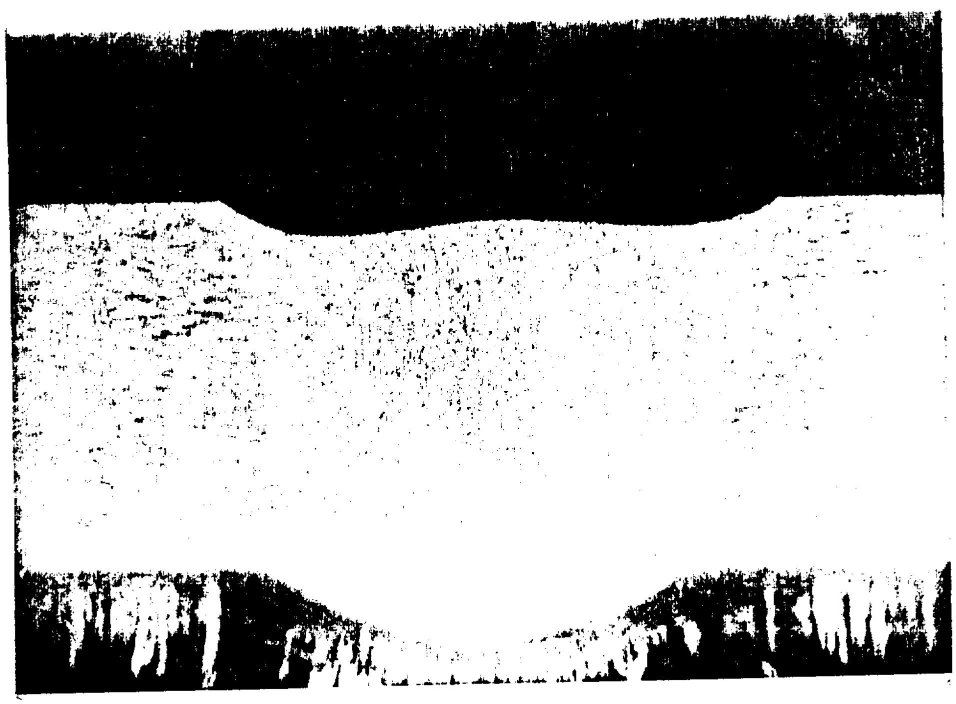


Fig. 3-14A Weld made with 260 ppm Oxygen in shield. Keyhole. Front.
t7i,t7m

Fig. 3-14B Weld made with 260 ppm Oxygen in shield. Keyhole. Back.

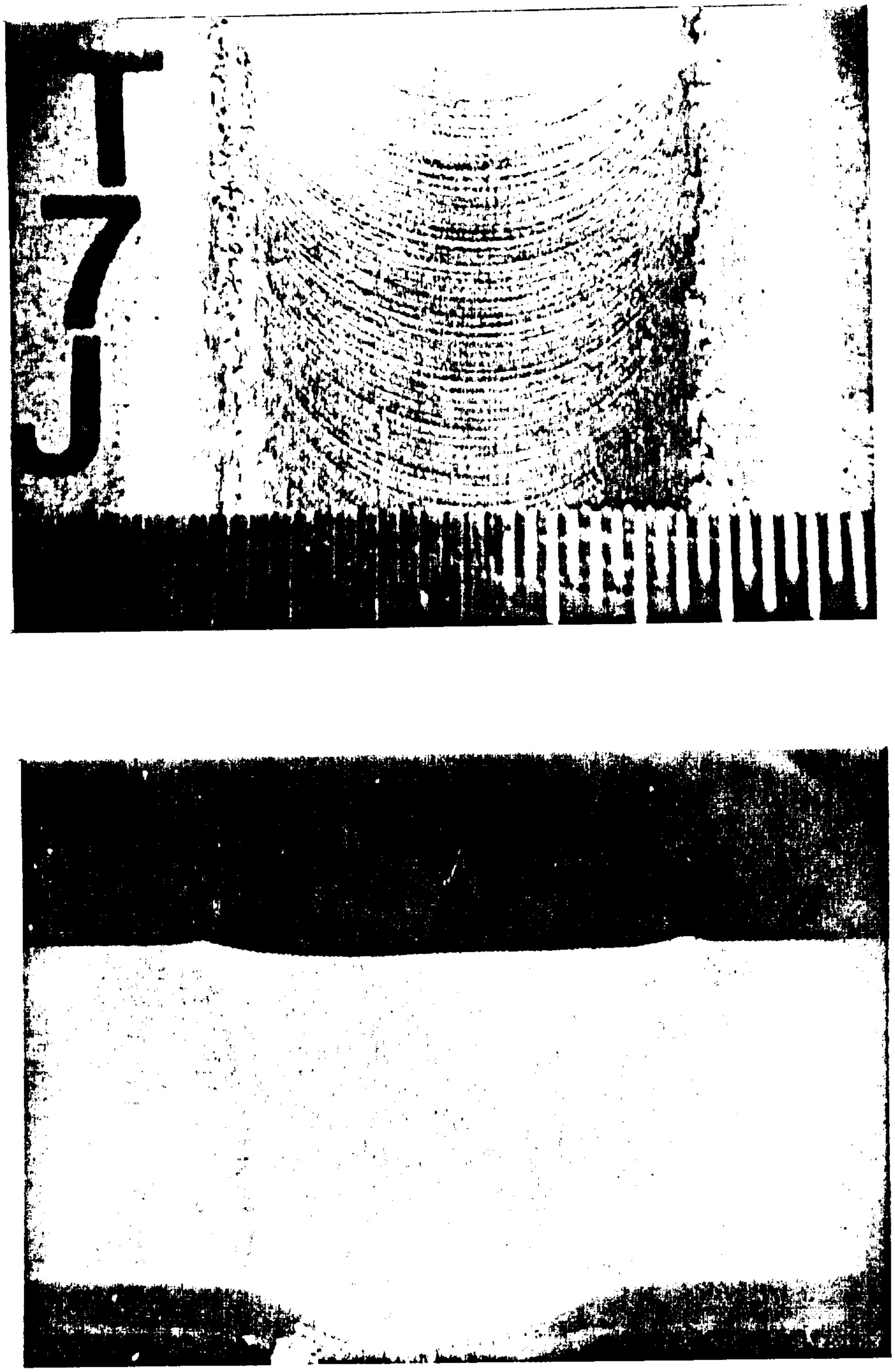


Fig. 3-15A Weld made with 260 ppm Oxygen
in shield. Cover. Front.
t7j,t7n

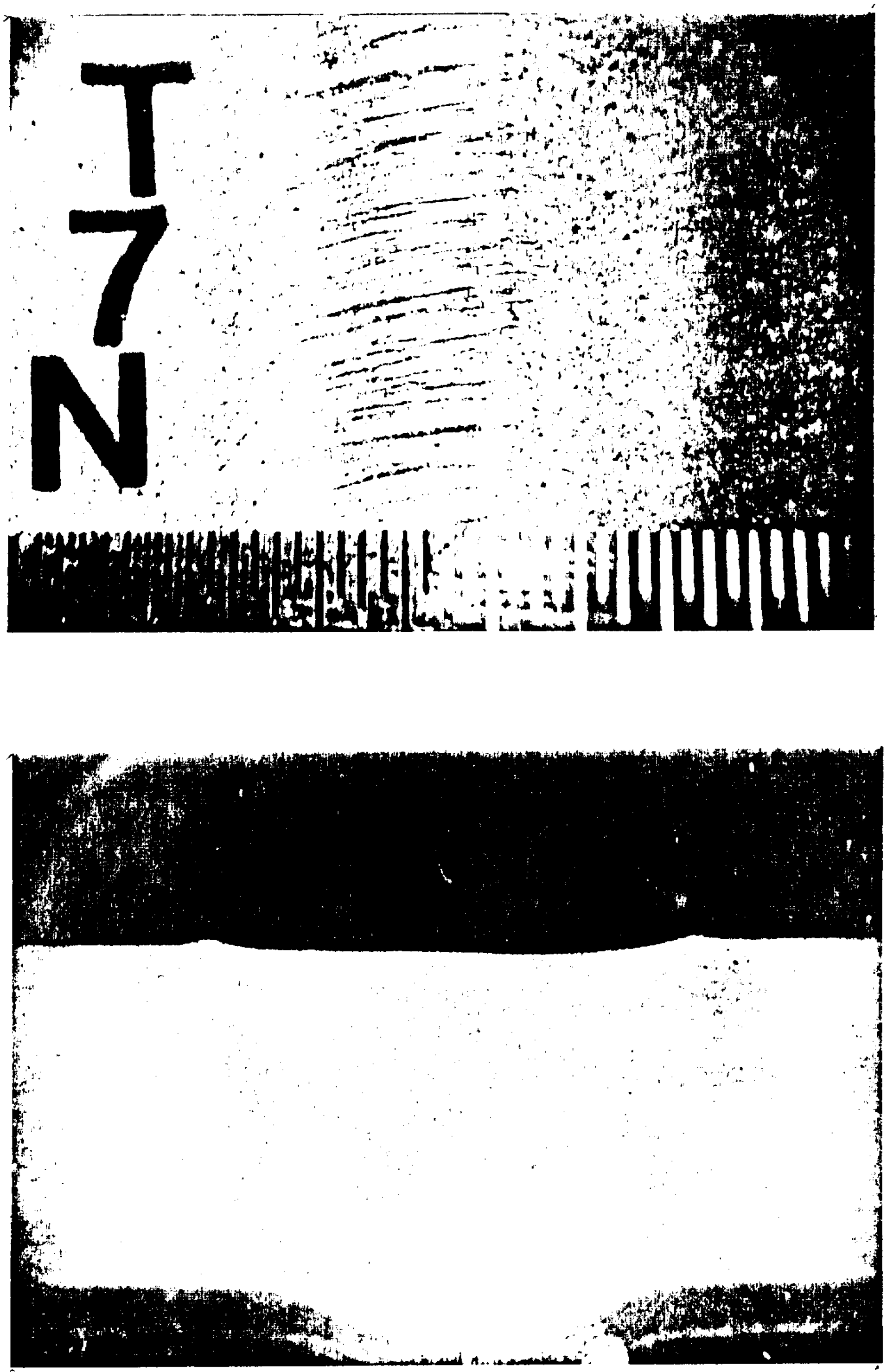


Fig. 3-15B Weld made with 260 ppm Oxygen in shield. Cover. Back.

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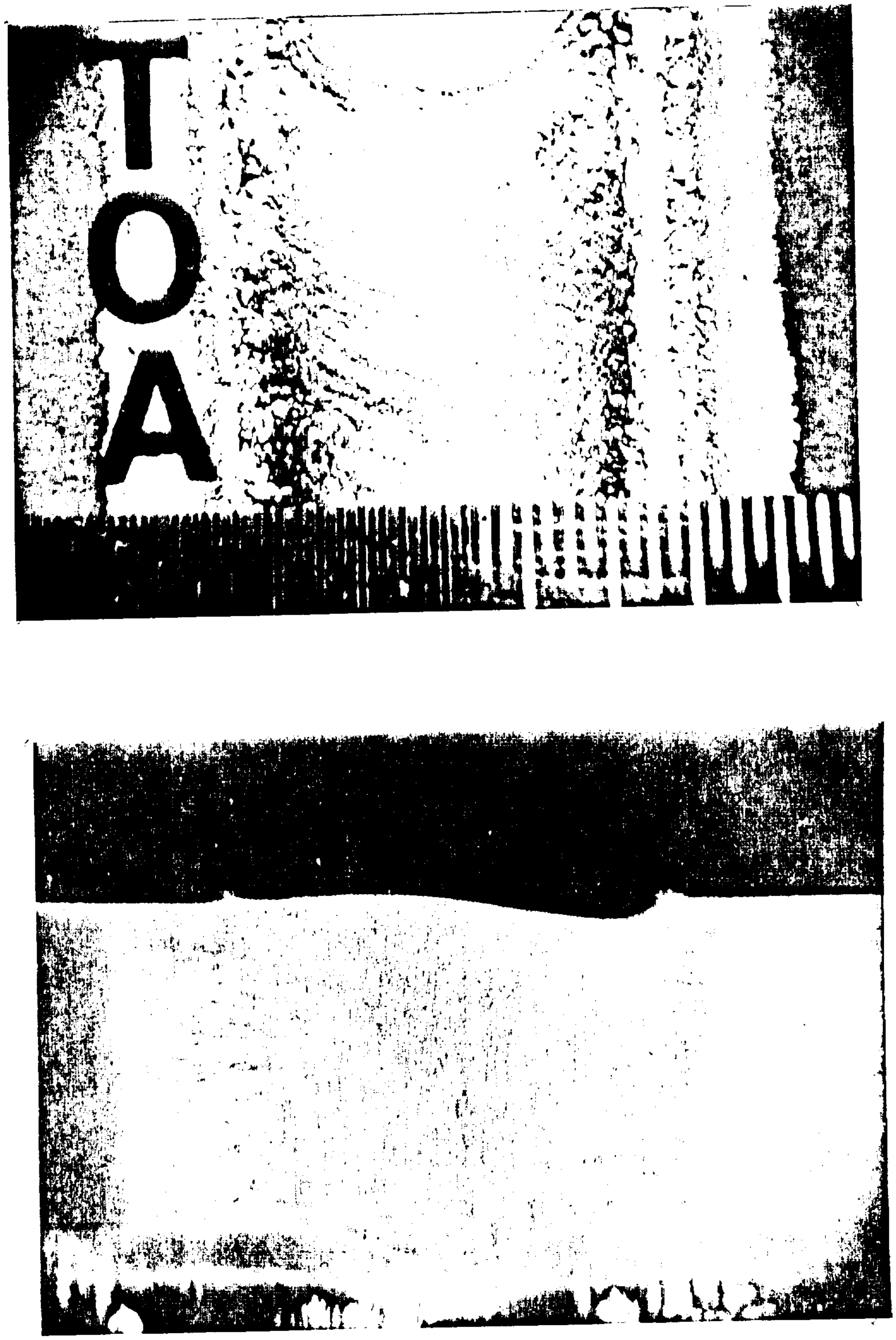


Fig. 3-16A Weld made with 500 ppm Hydrogen in shield. Keyhole. Front.
toa,toe

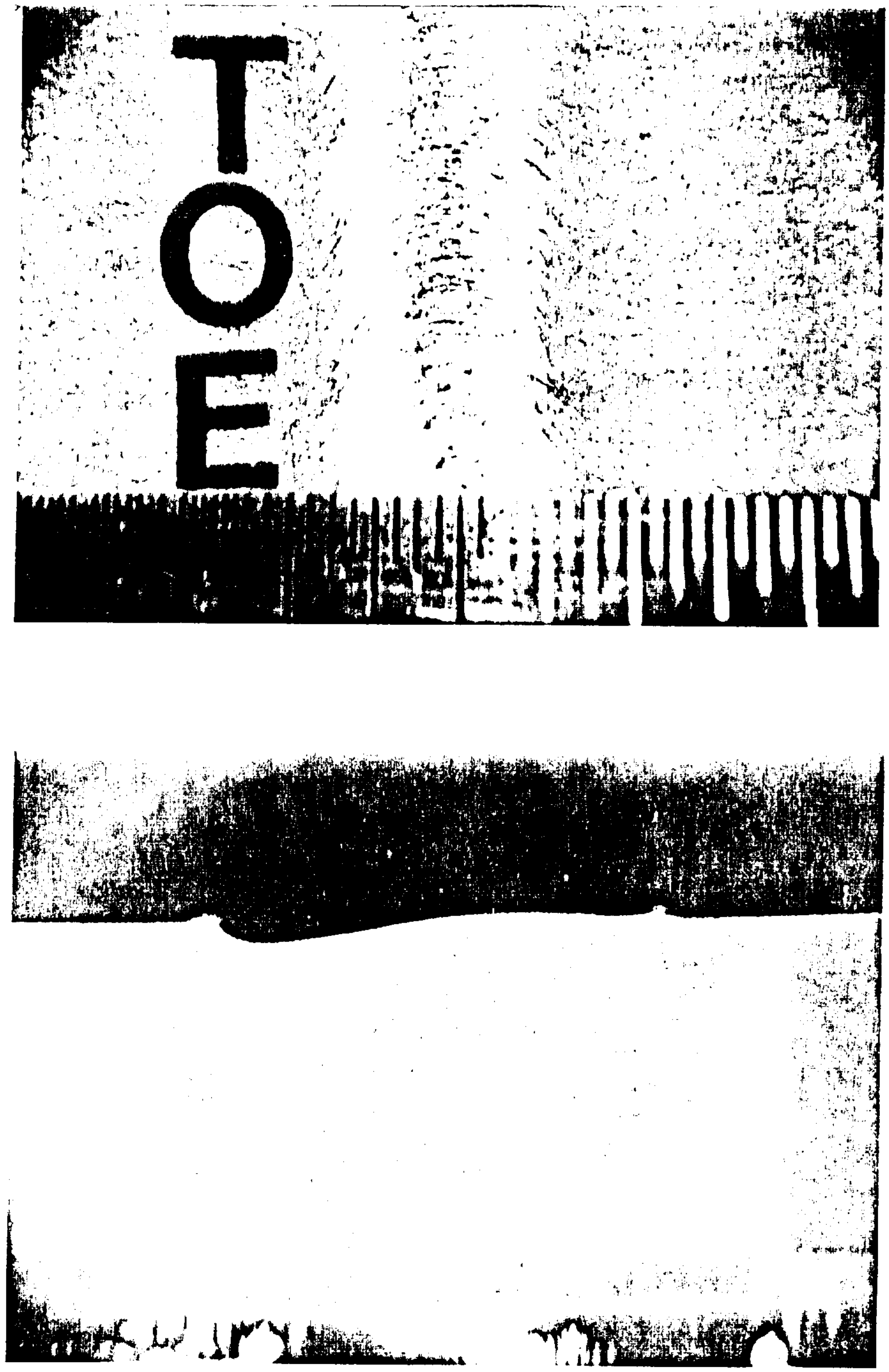


Fig. 3-16B Weld made with 500 ppm Hydrogen in shield. Keyhole. Back.

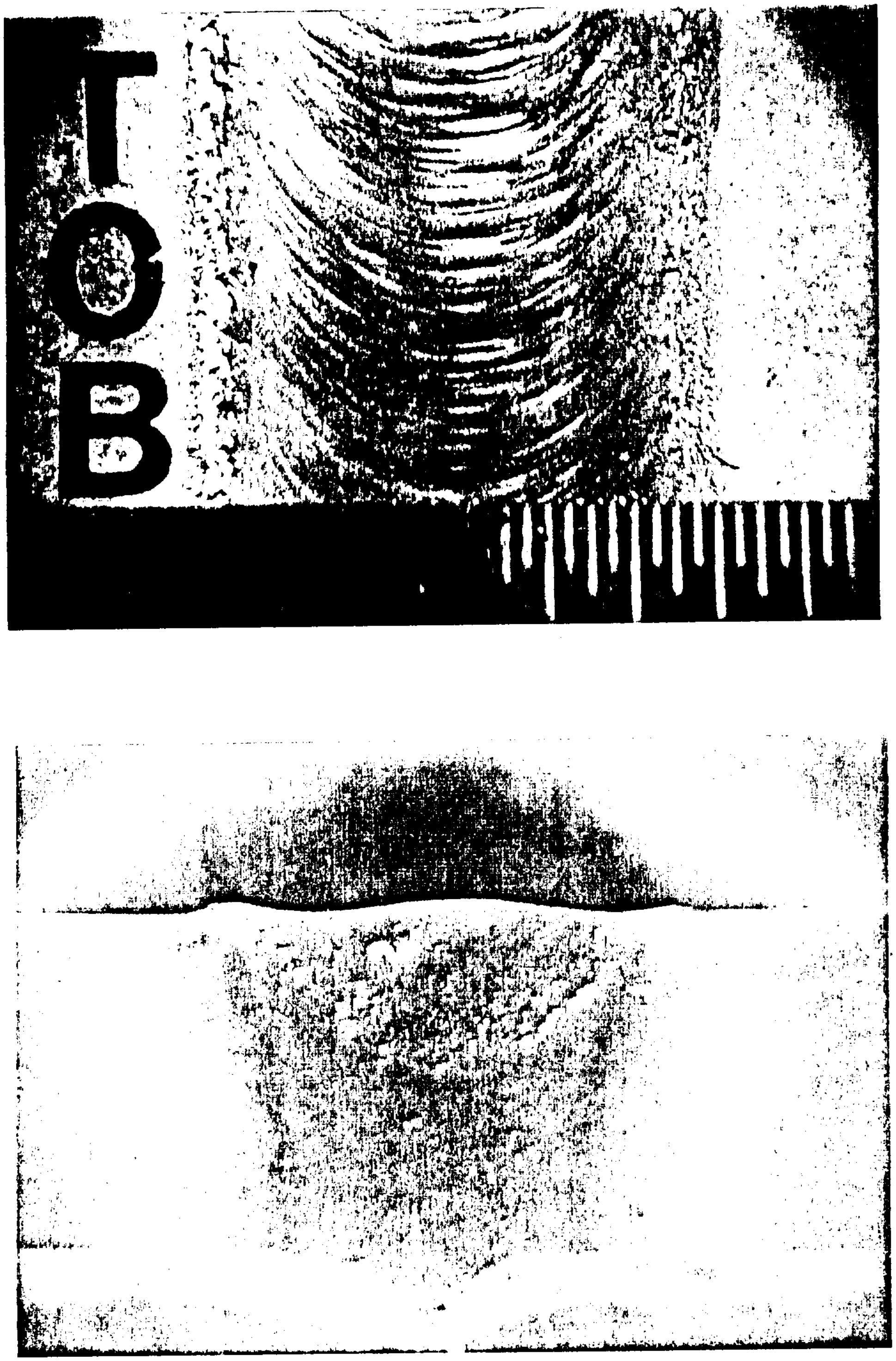
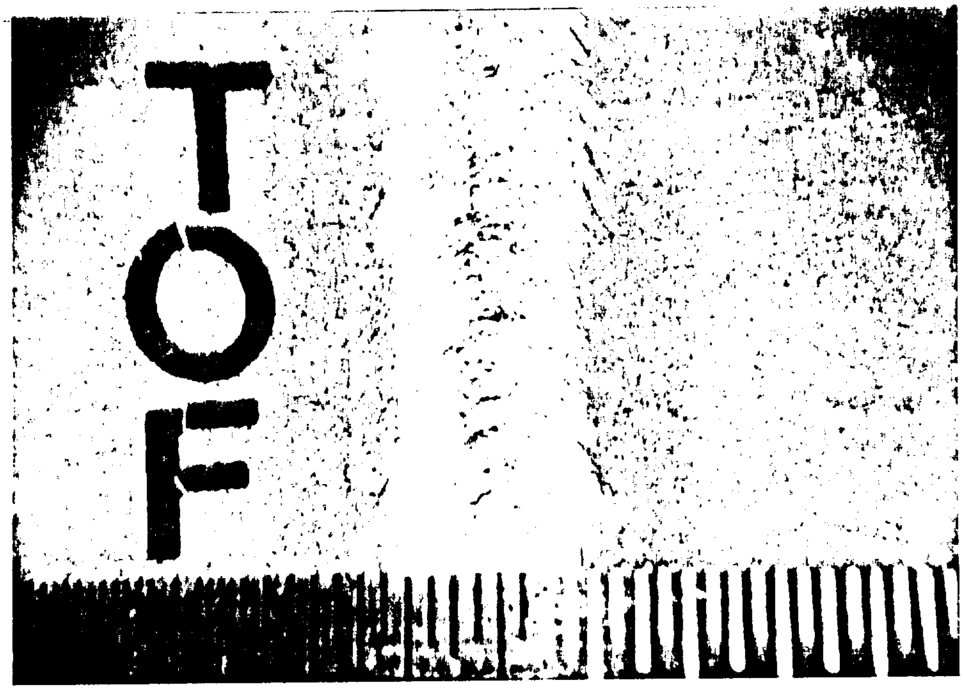


Fig. 3-17A Weld made with 500 ppm Hydrogen in shield. Cover. Front.
tob,tof



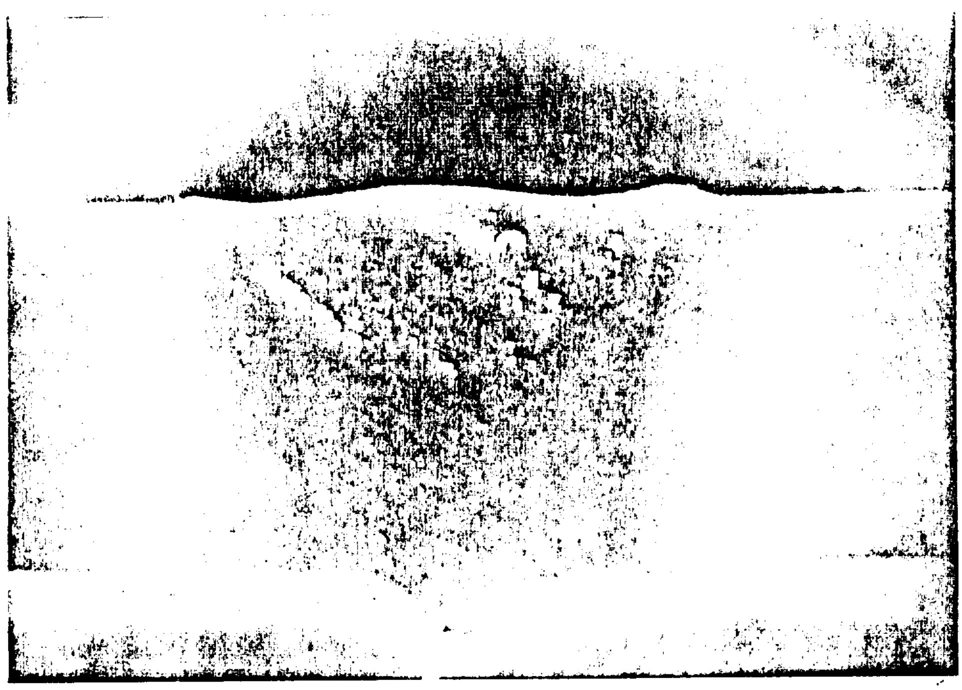


Fig. 3-17B Weld made with 500 ppm Hydrogen in shield. Cover. Back.

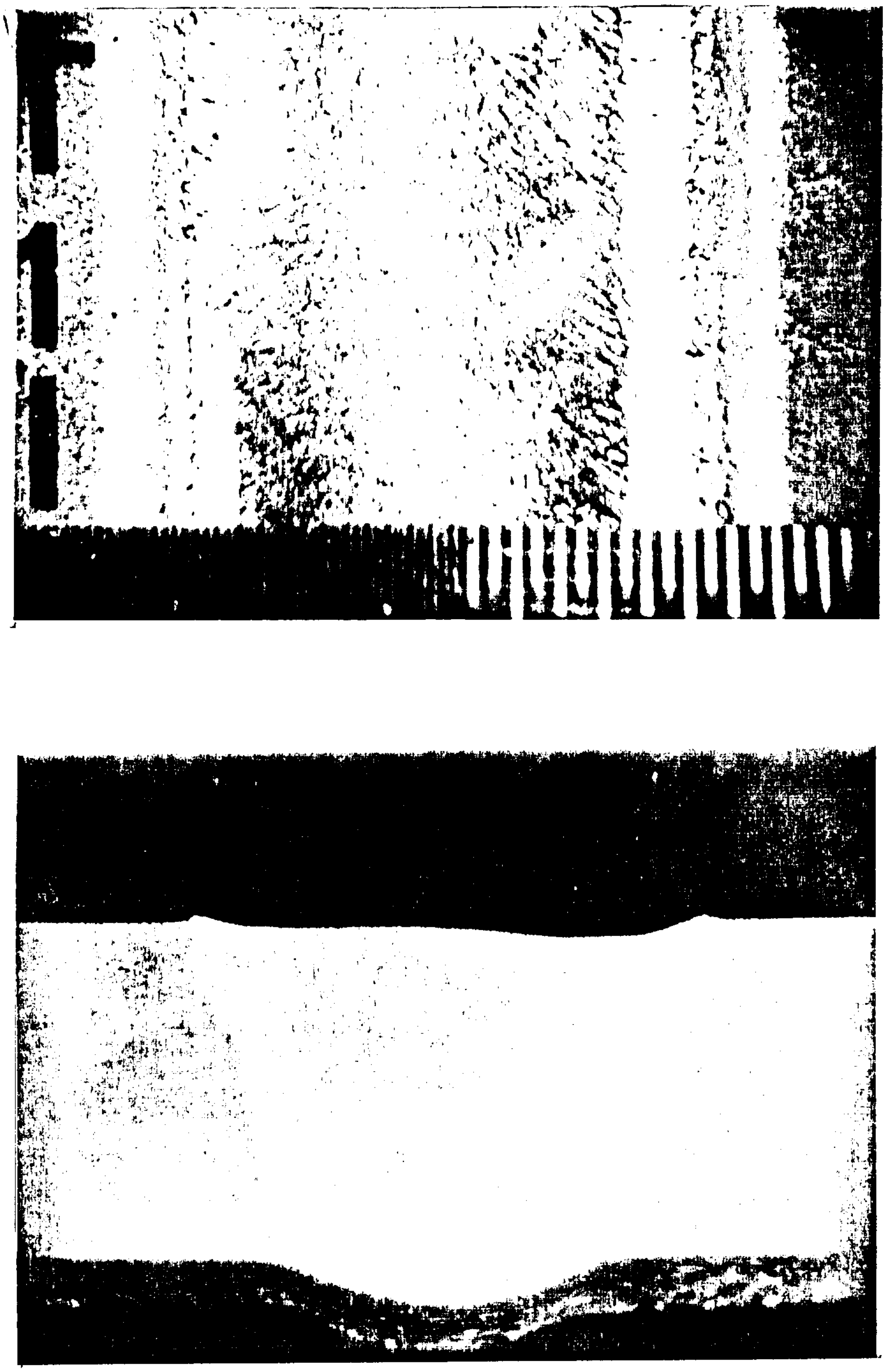


Fig. 3-18A Weld made with 250 ppm Hydrogen in shield. Keyhole. Front.
t1i,t1m

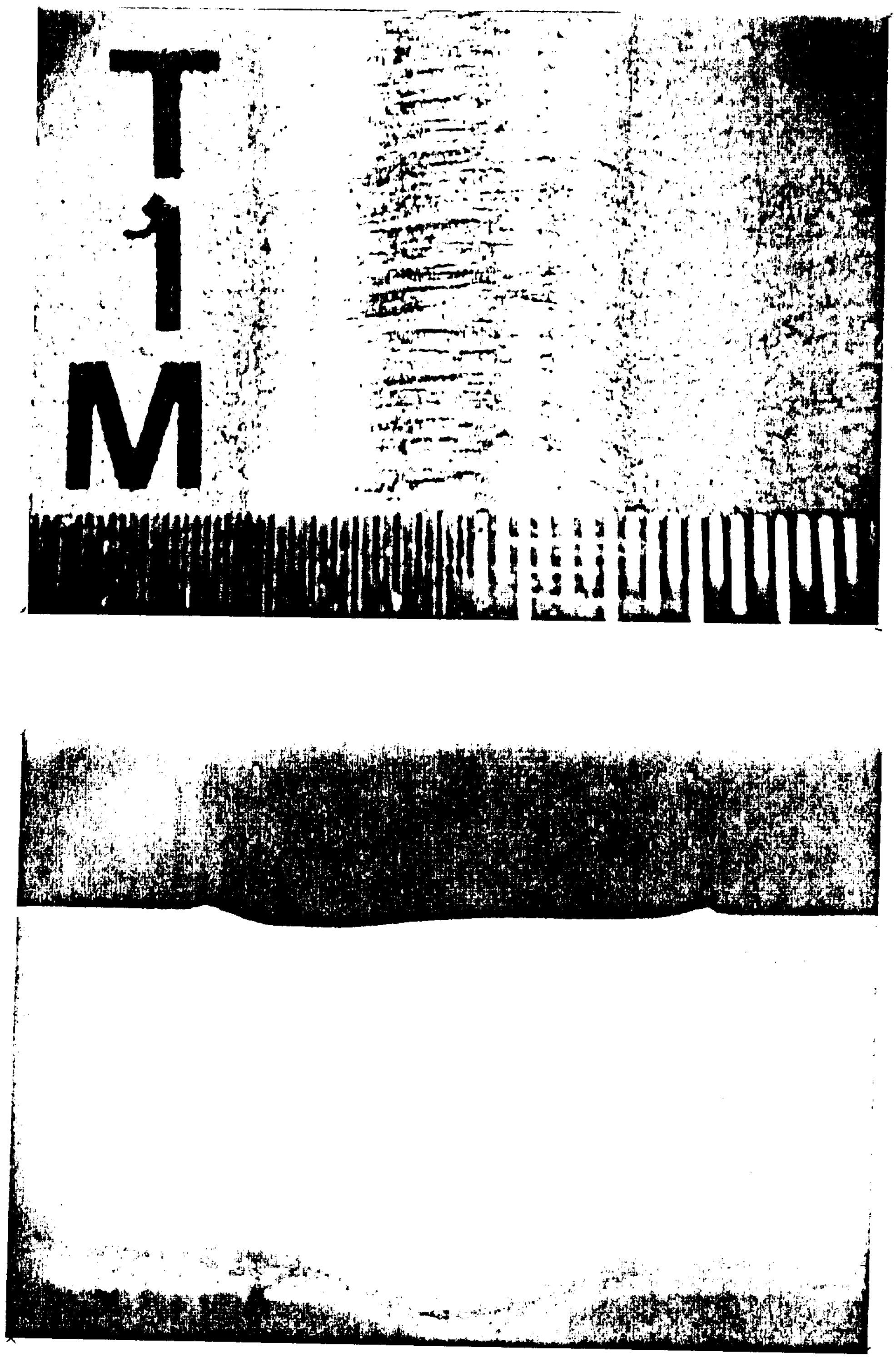
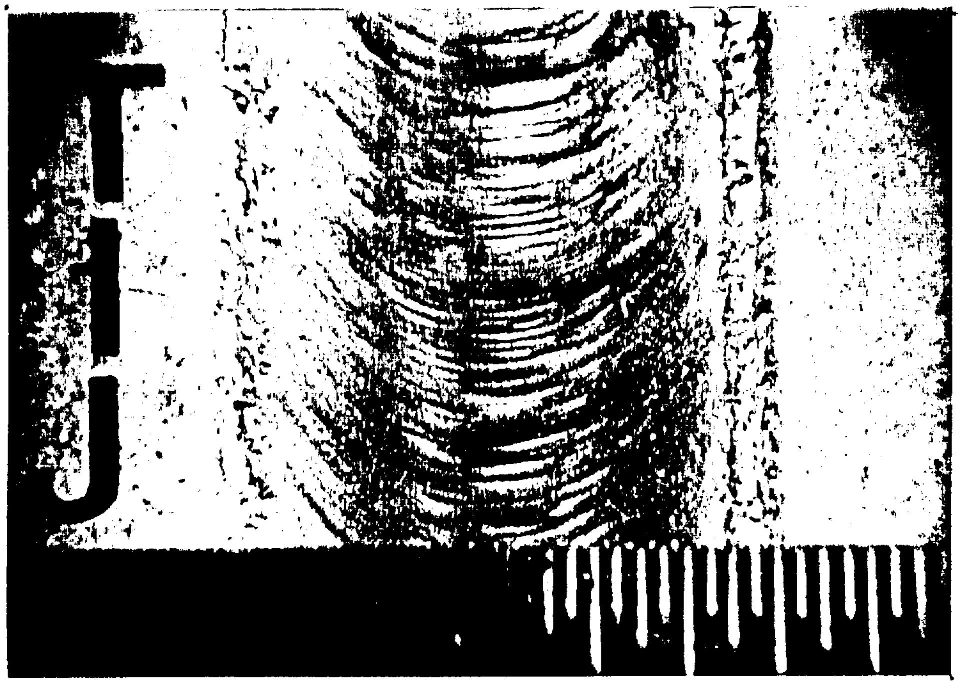


Fig. 3-18B Weld made with 250 ppm Hydrogen in shield. Keyhole. Back.



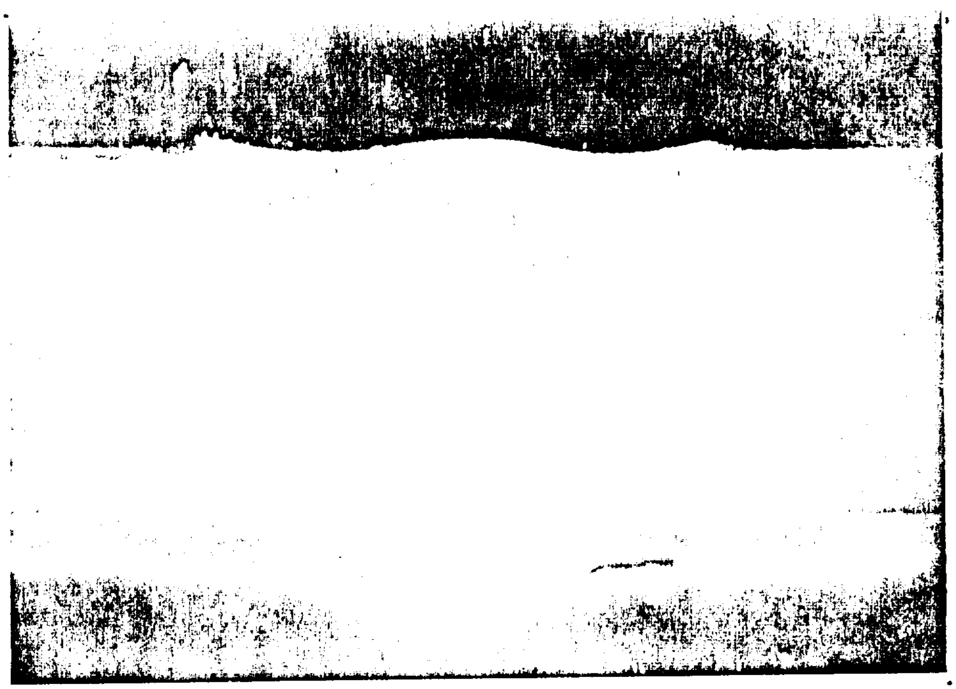


Fig. 3-19A Weld made with 250 ppm Hydrogen
in shield. Cover. Front.
t1j,t1n

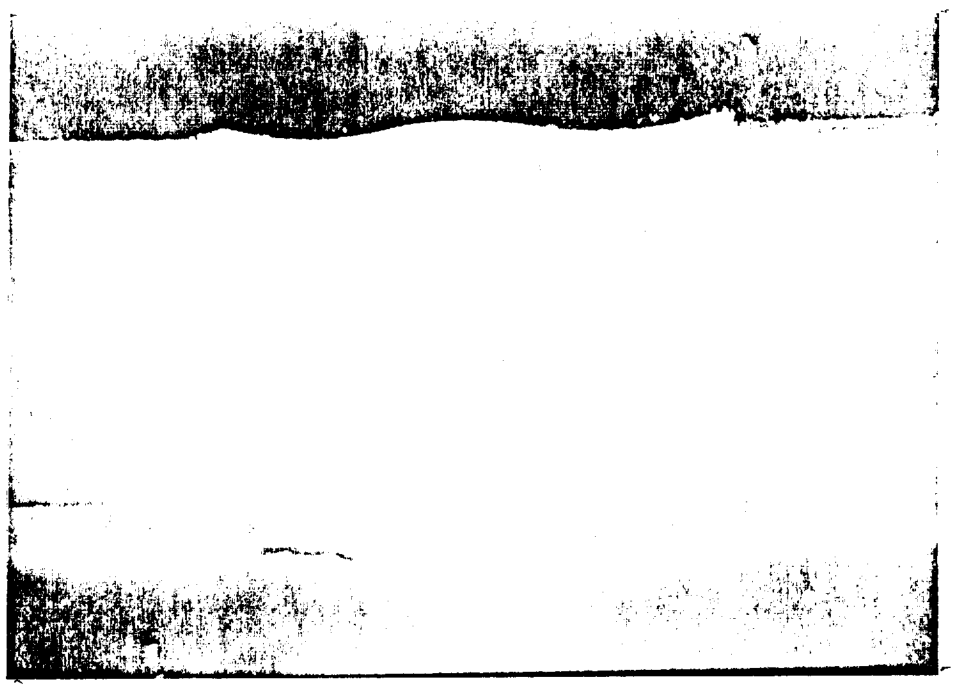


Fig. 3-19B Weld made with 250 ppm Hydrogen in shield. Cover. Back.

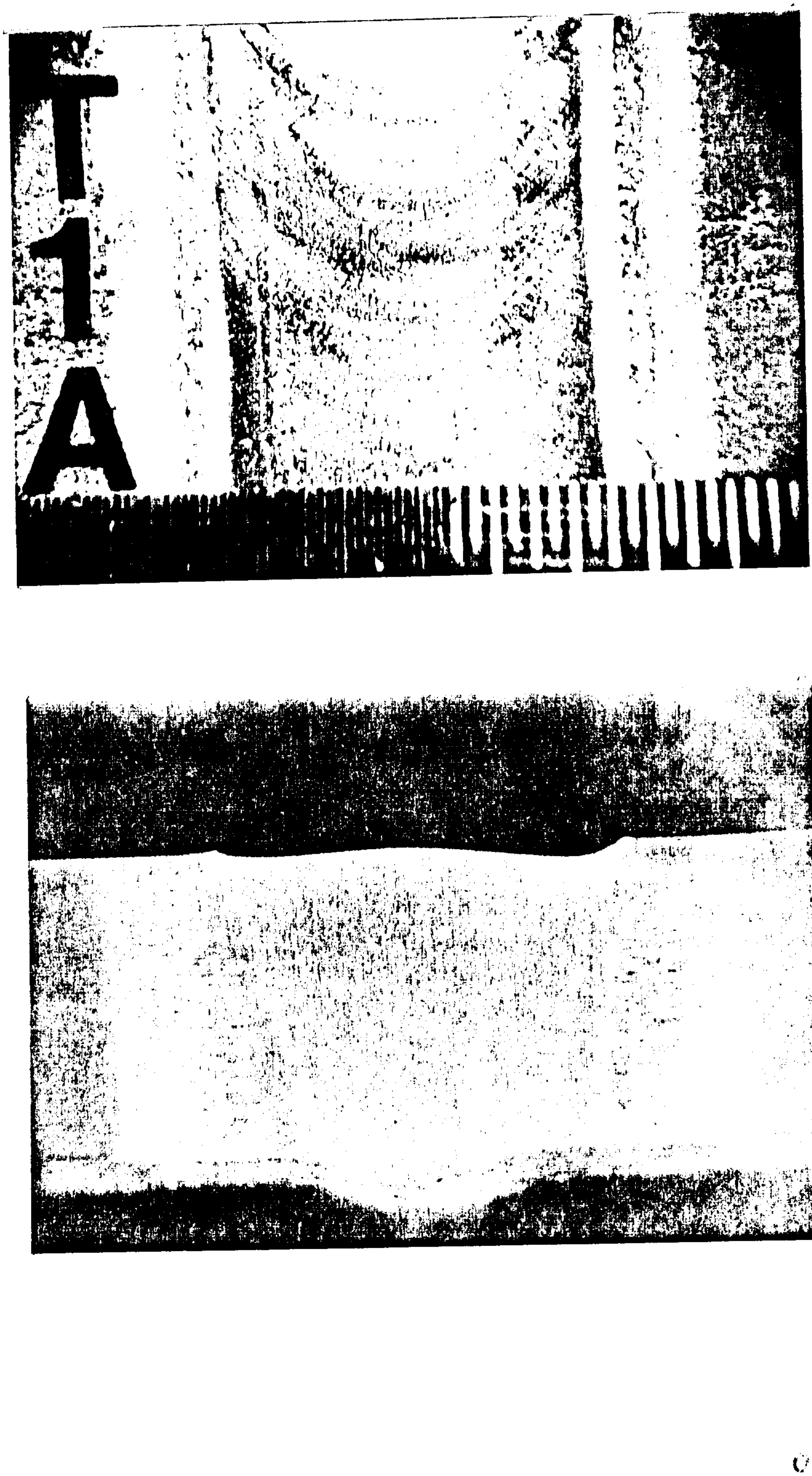
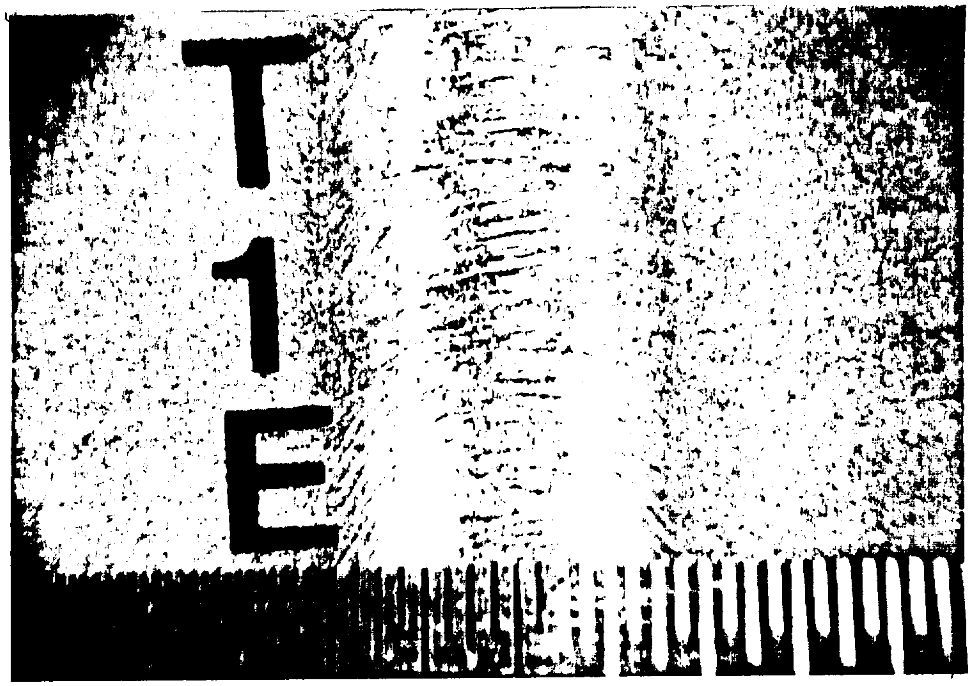


Fig. 3-20A Weld made with 50 ppm Hydrogen in shield. Keyhole. Front



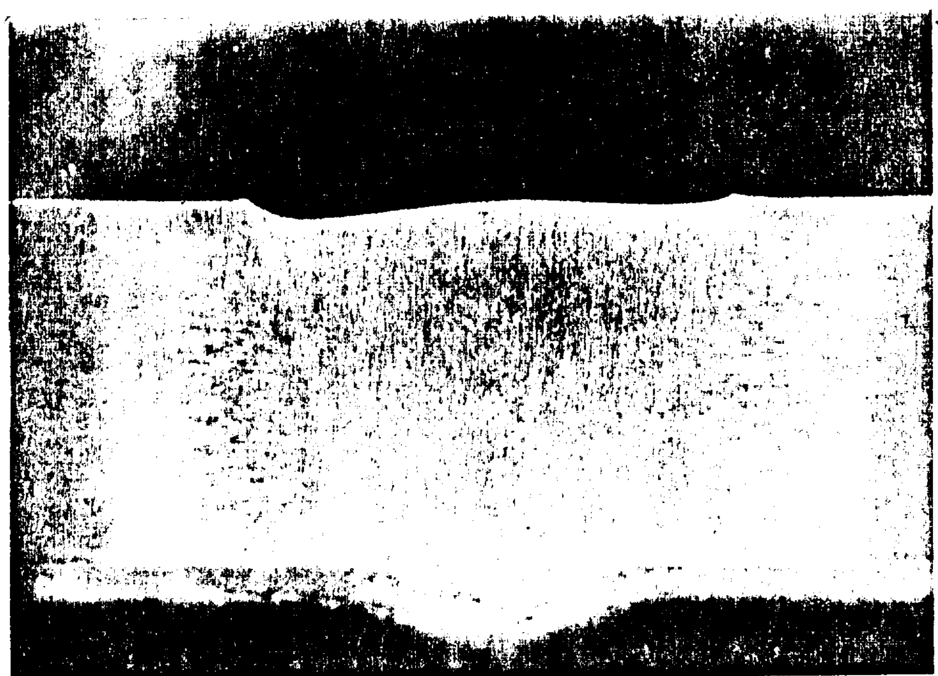
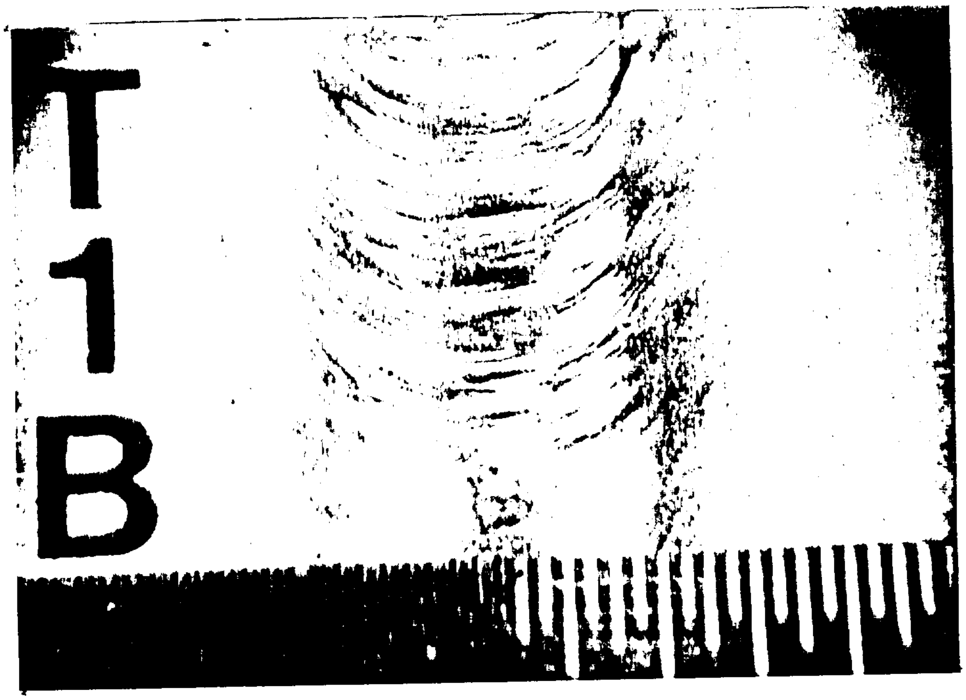


Fig. 3-20B Weld made with 50 ppm Hydrogen in shield. Keyhole. Back.



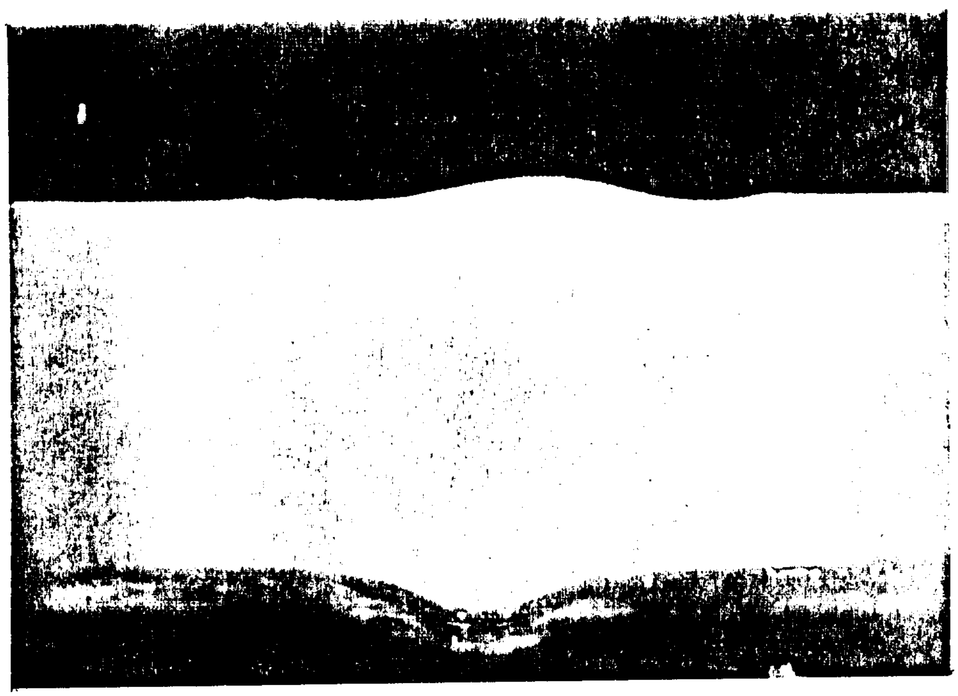


Fig. 3-21A Weld made with 50 ppm Hydrogen
in shield. Cover. Front.
t1b,t1f

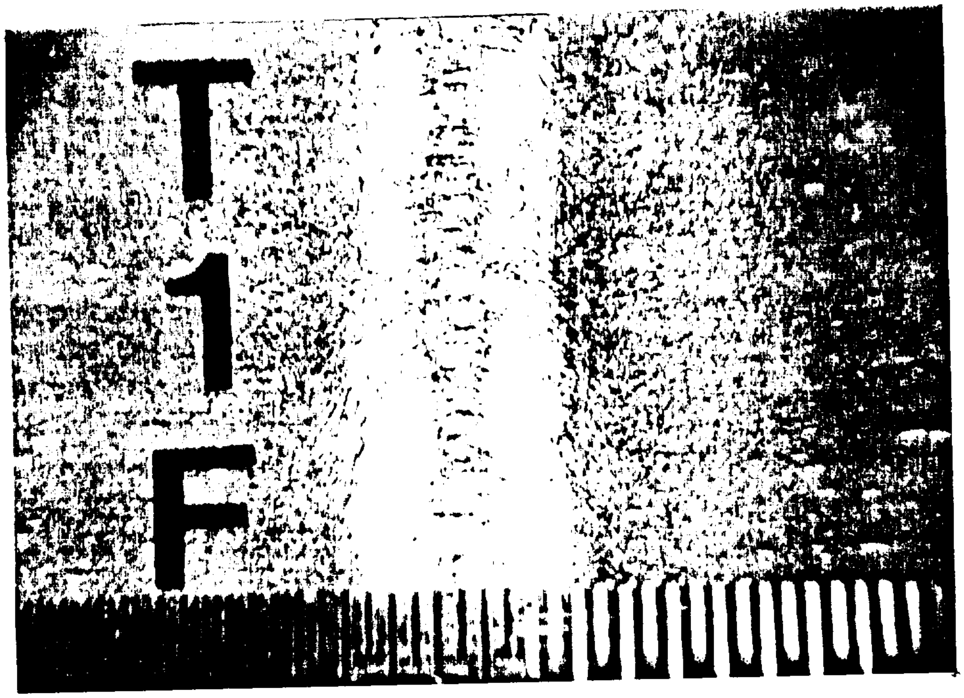


Fig. 3-21B Weld made with 50 ppm Hydrogen in shield. Cover. Back.

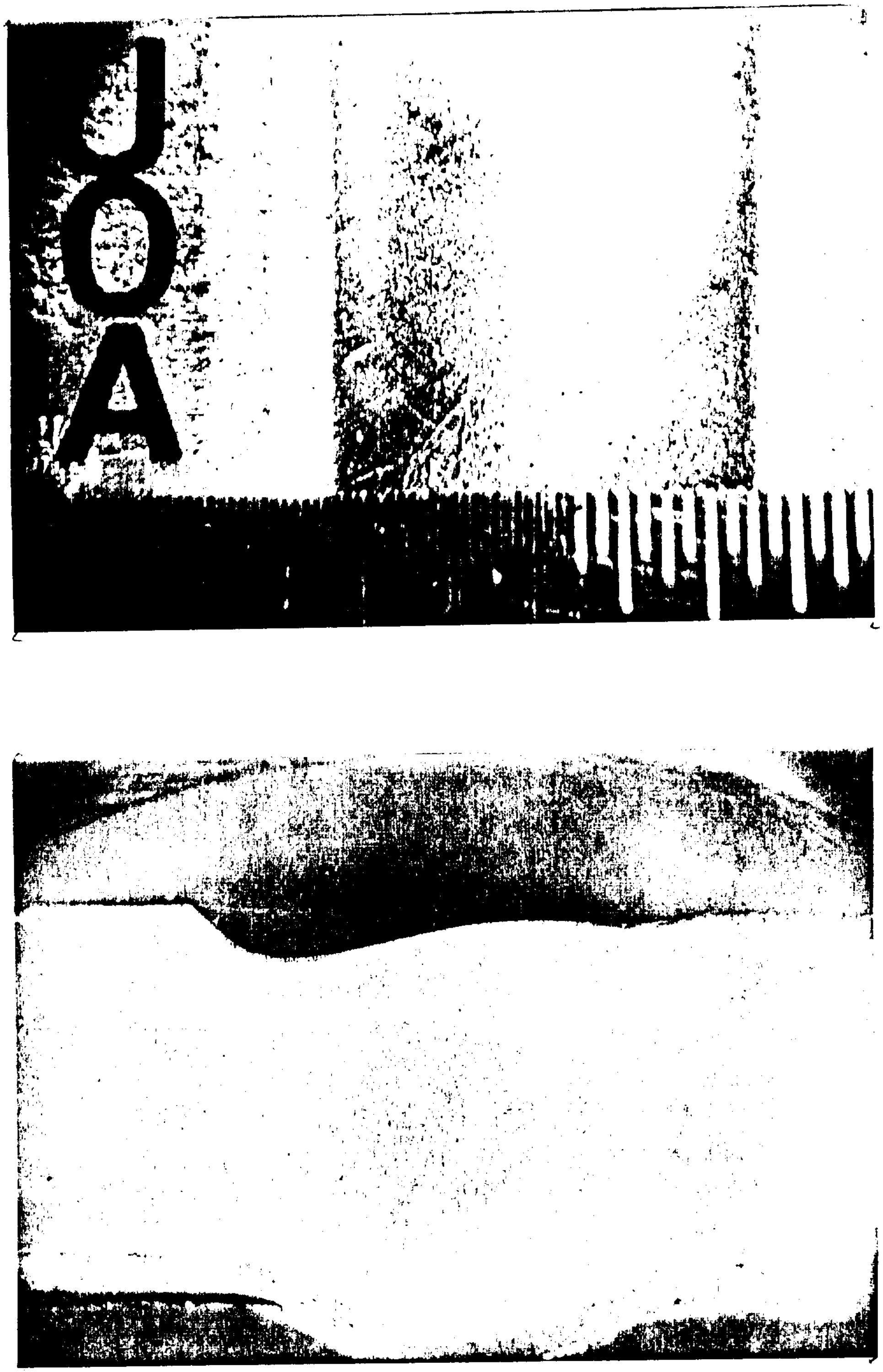


Fig. 3-21C Weld made with 25 ppm Hydrogen in shield. Keyhole. Front.

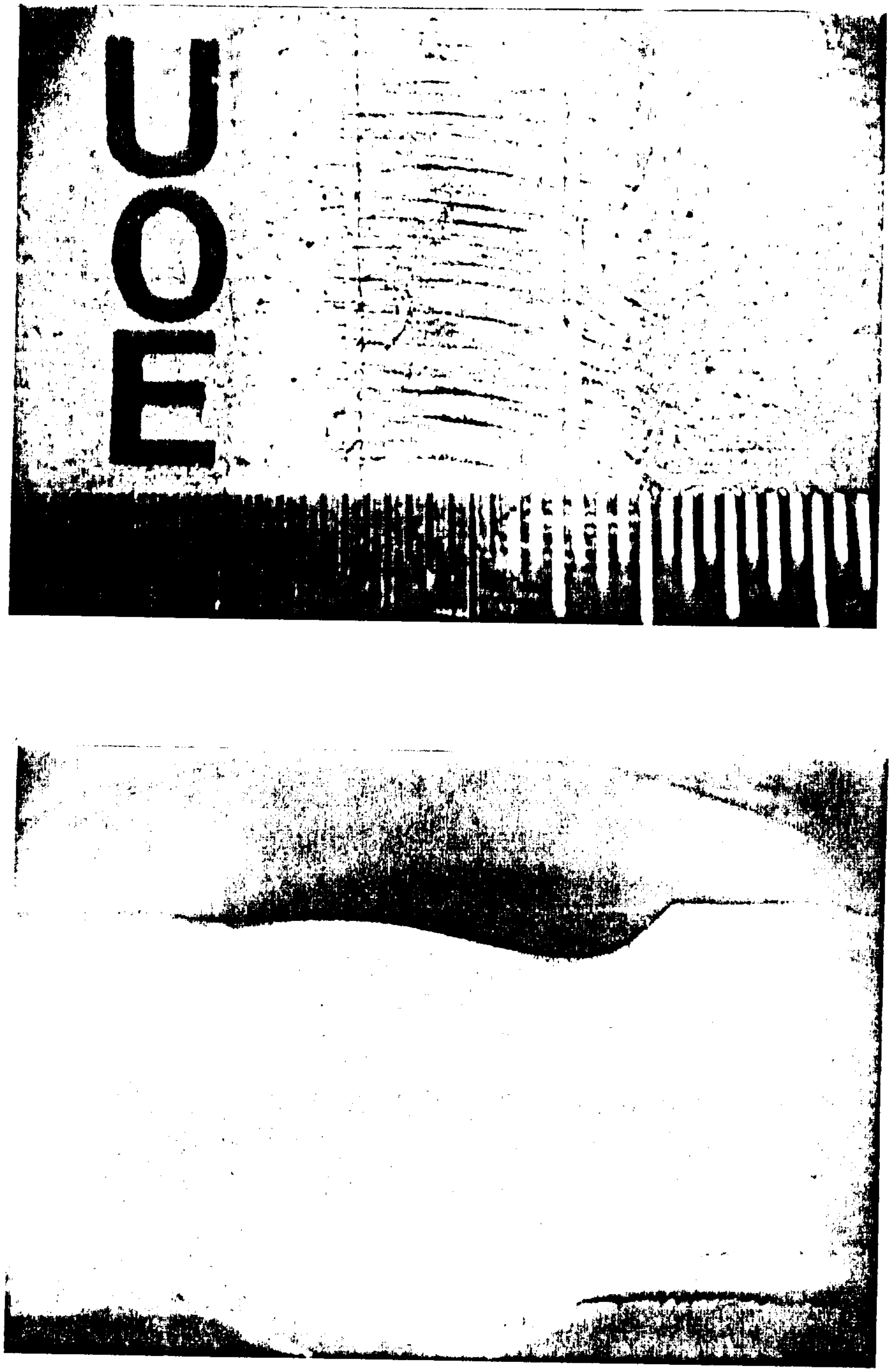


Fig. 3-21D Weld made with 25 ppm Hydrogen in shield. Keyhole. Back.

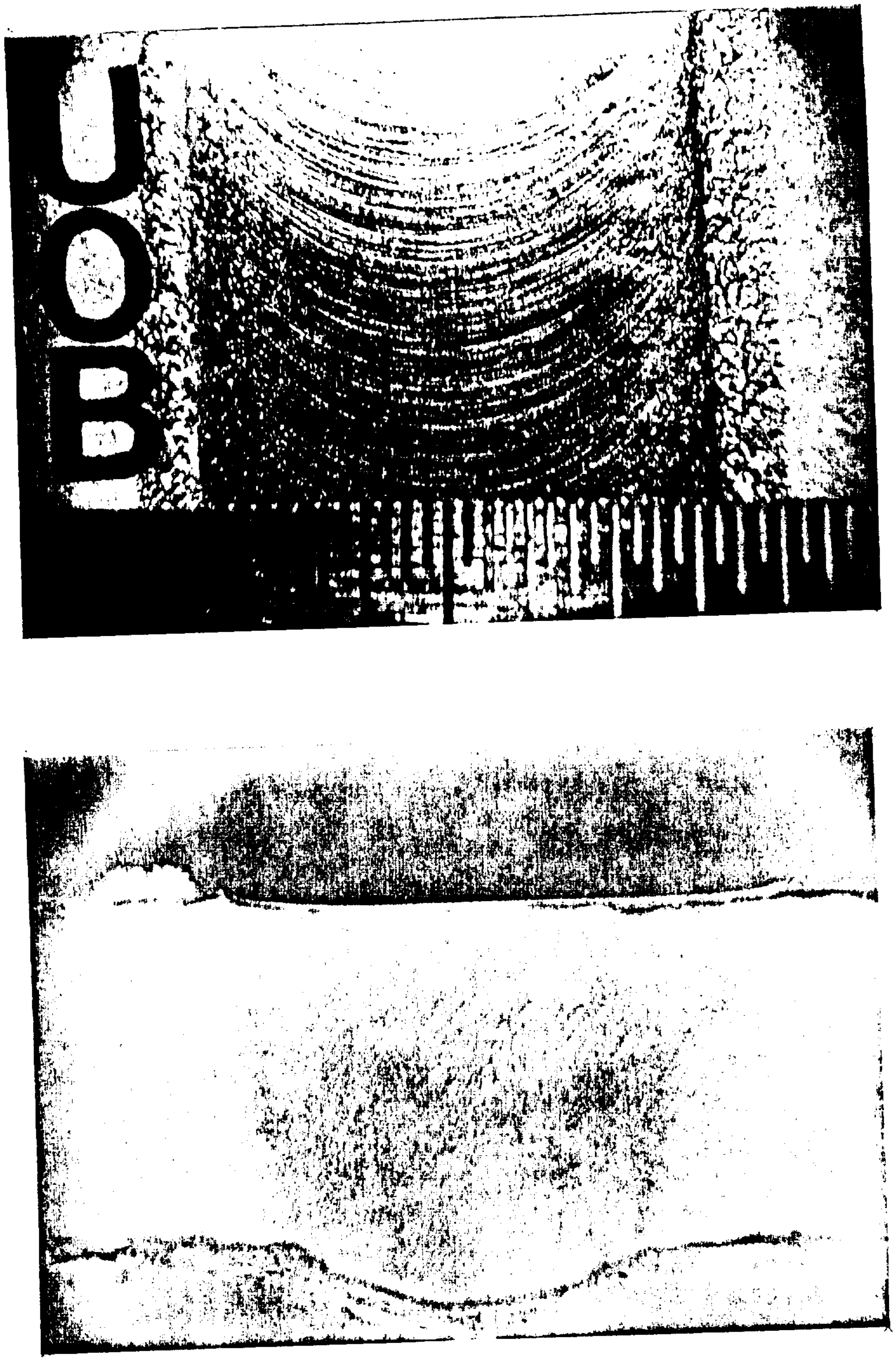


Fig. 3-21E Weld made with 25 ppm Hydrogen in shield. Cover. Front.

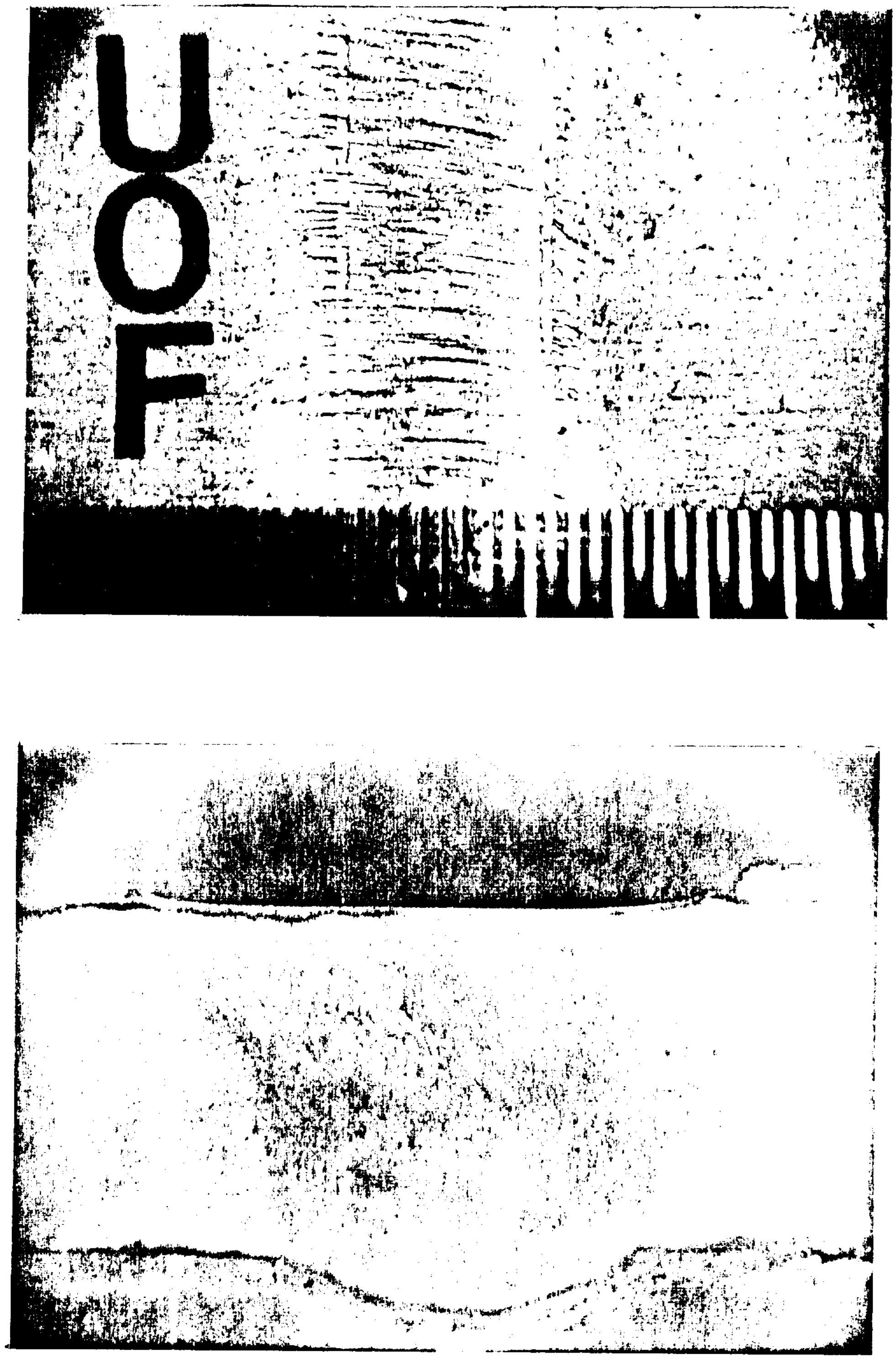
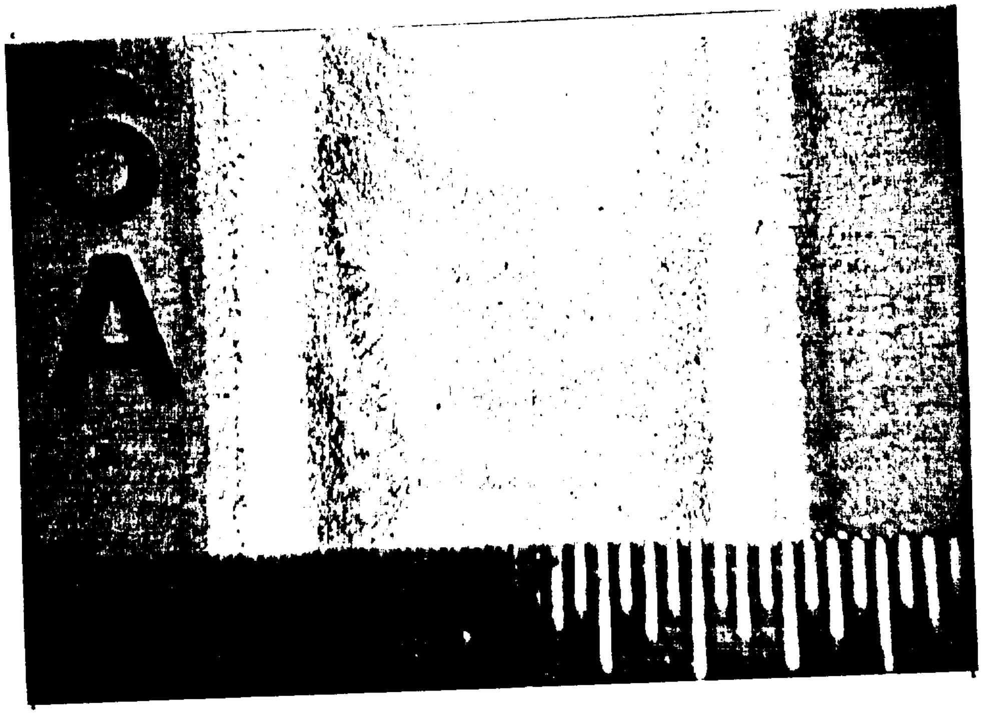


Fig. 3-21F Weld made with 25 ppm Hydrogen
in shield. Cover. Back.



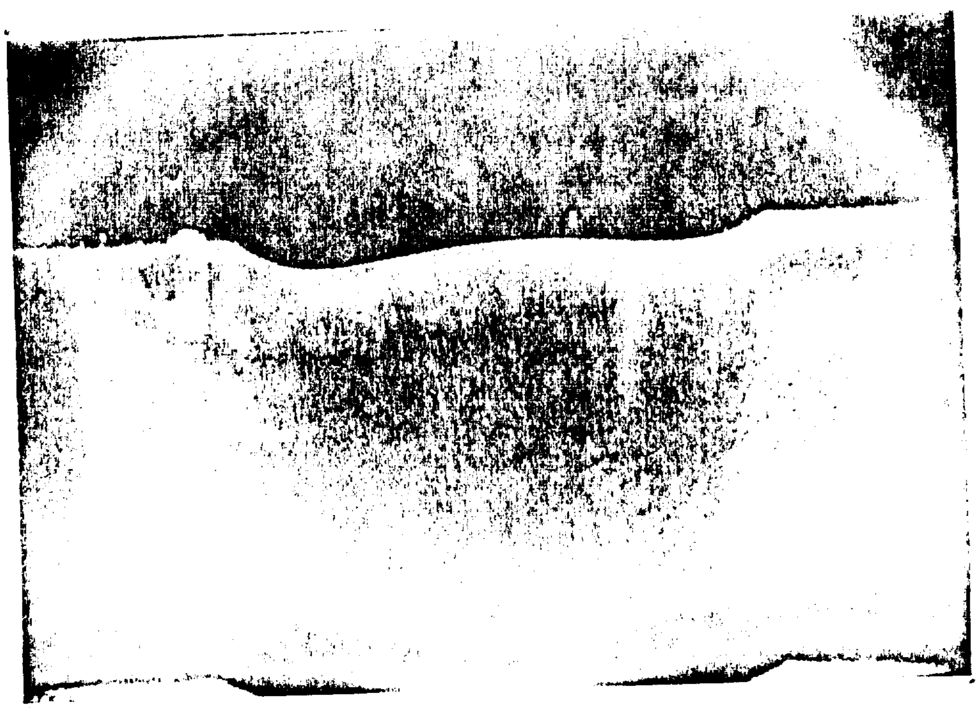


Fig. 3-22A Weld made with 600 ppm Nitrogen in arc. Keyhole. Front.
6a,6e

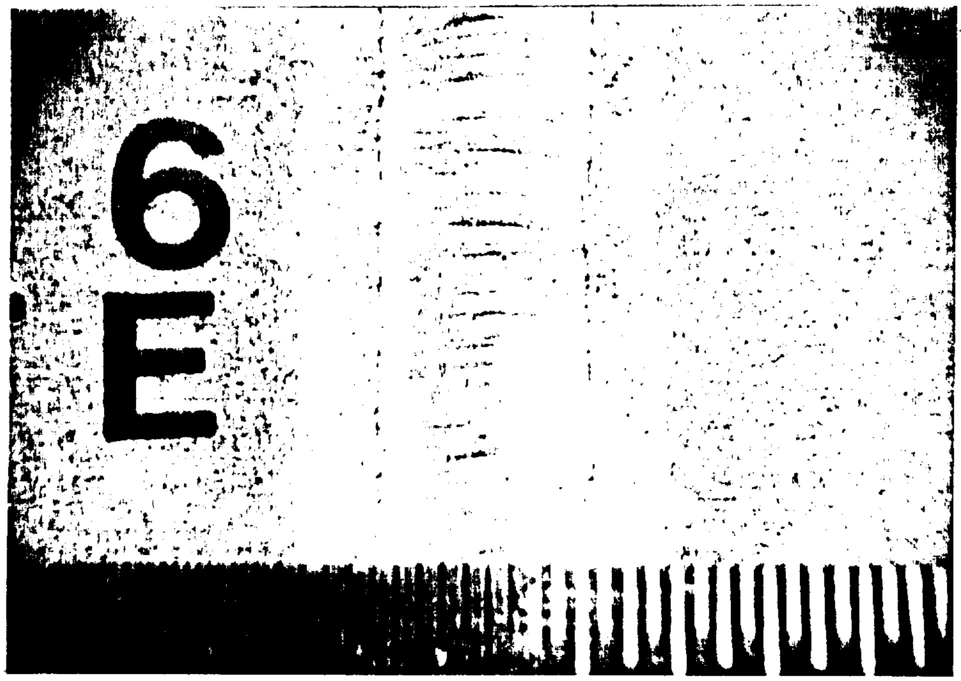


Fig. 3-22B Weld made with 600 ppm Nitrogen in arc. Keyhole. Back.

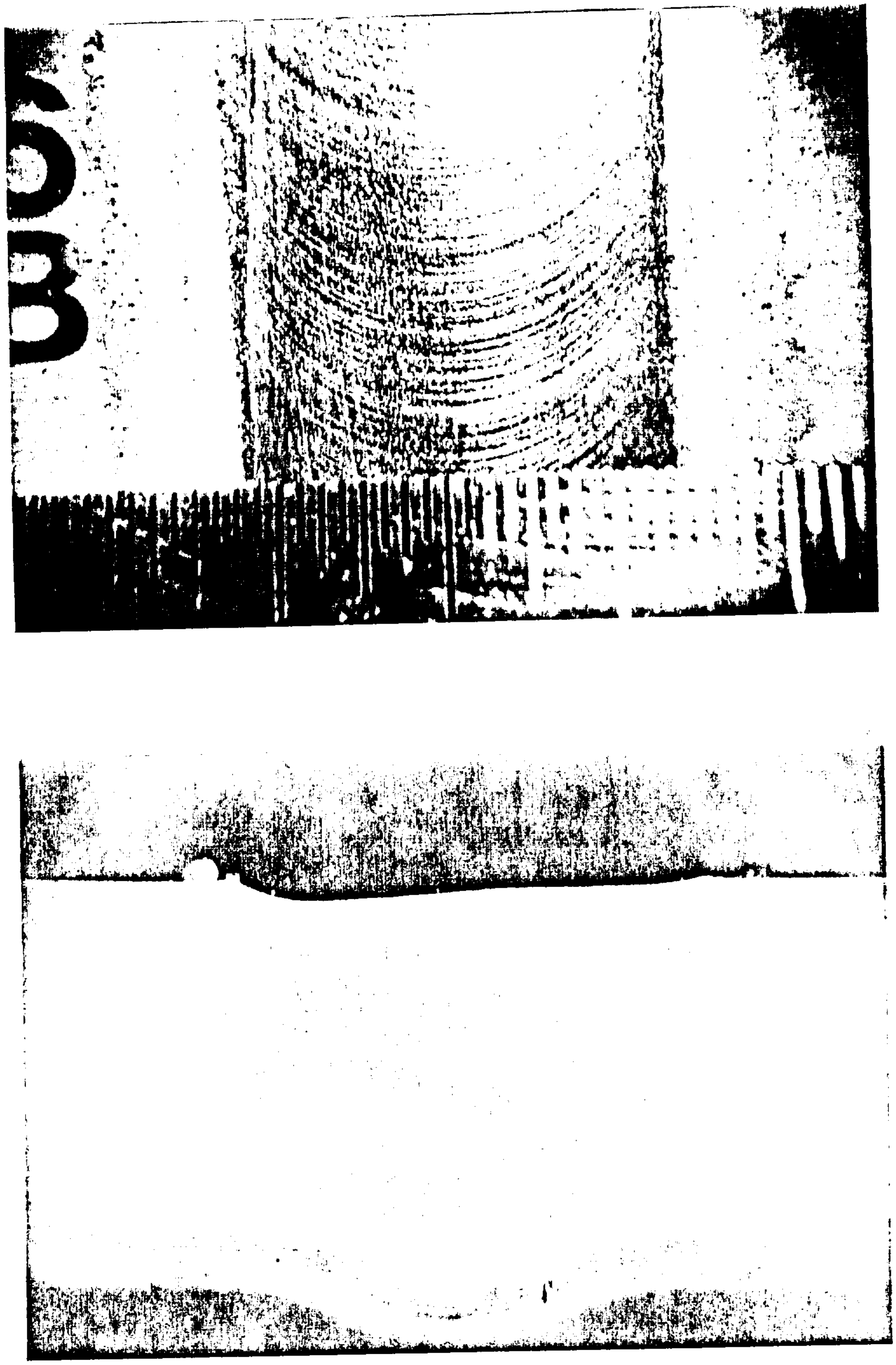
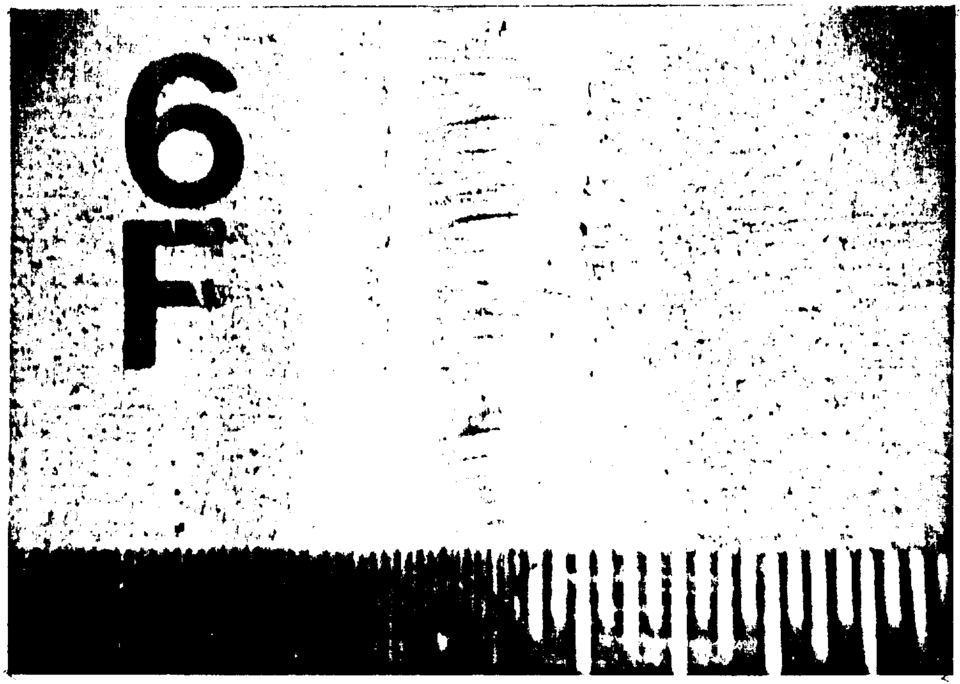


Fig. 3-23A Weld made with 600 ppm Nitrogen
in arc. Cover. Front.
6b,6f



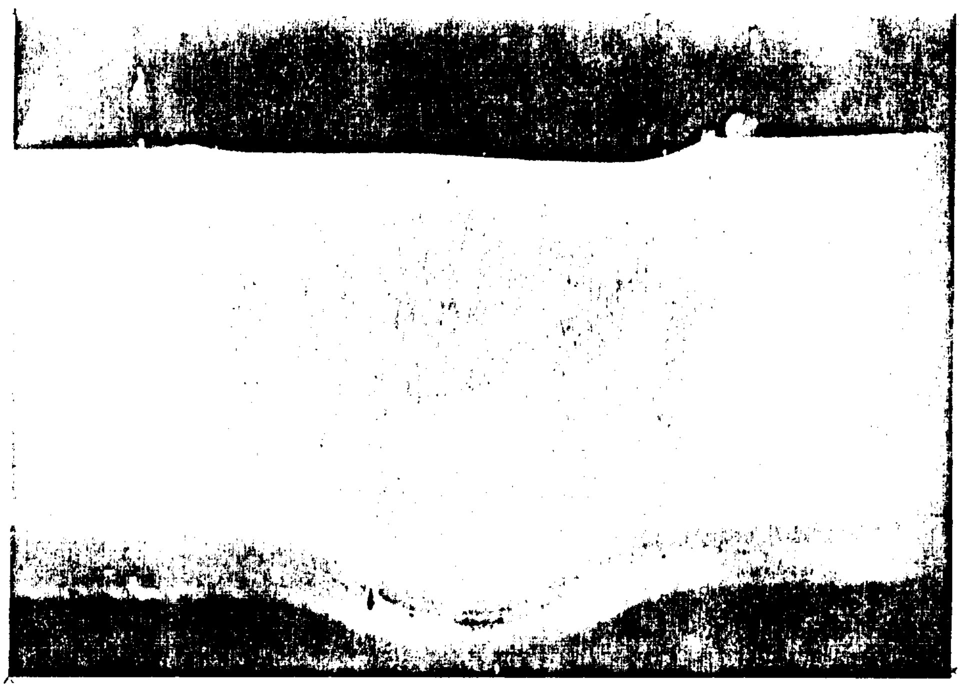
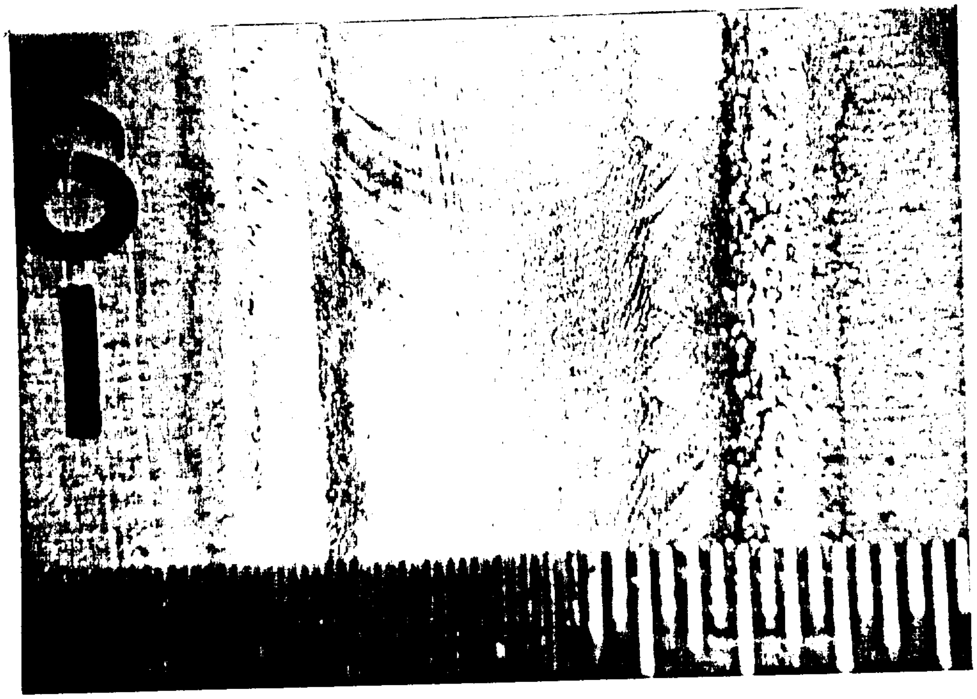


Fig. 3-23B Weld made with 600 ppm Nitrogen in arc. Cover. Back.



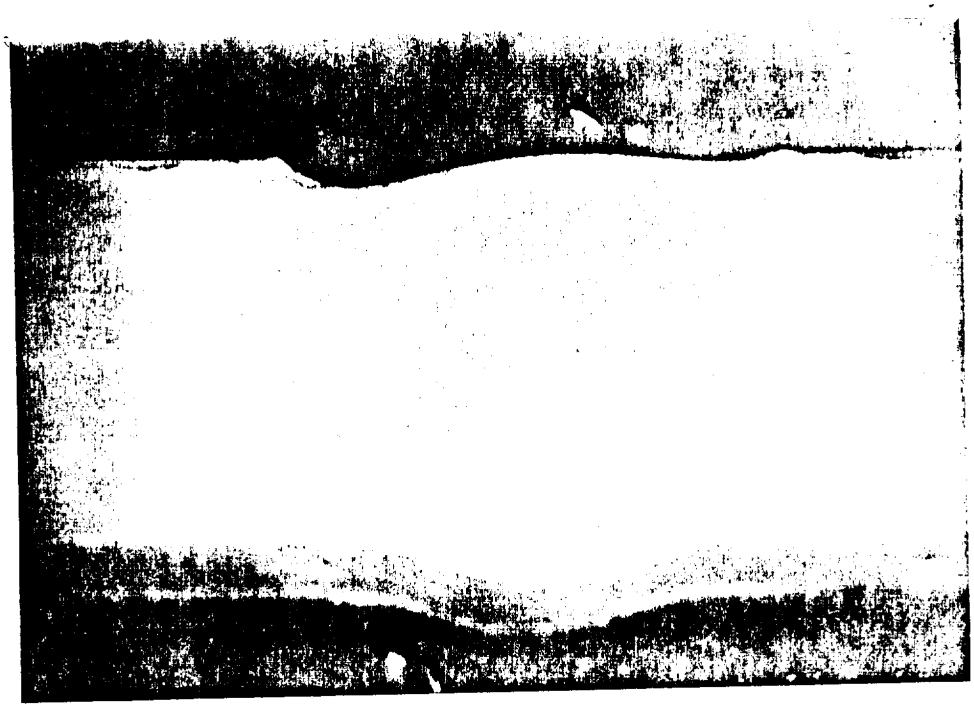


Fig. 3-24A Weld made with 300 ppm Nitrogen
in arc. Keyhole. Front.
6i,6m

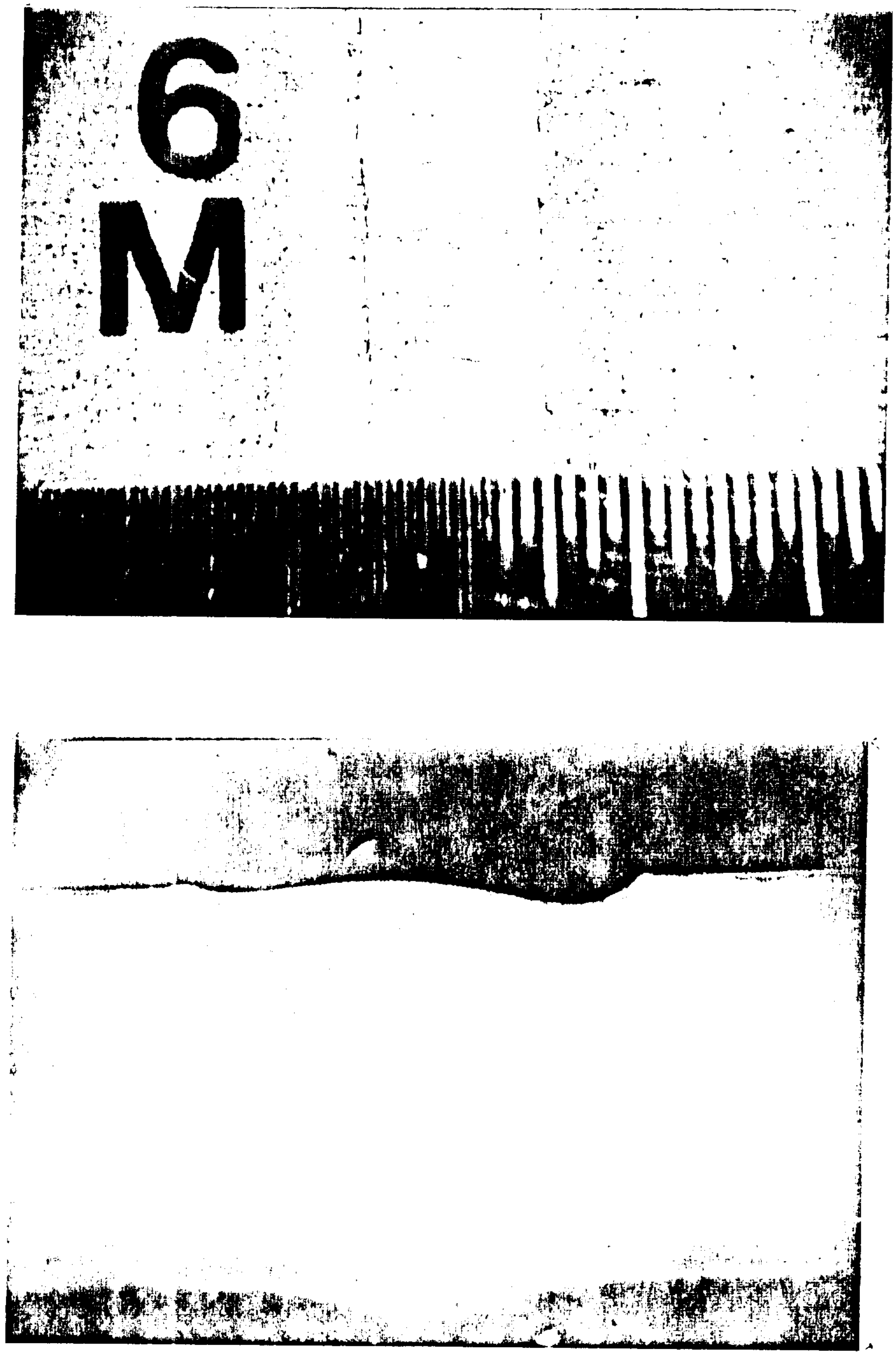


Fig. 3-24B Weld made with 300 ppm Nitrogen in arc. Keyhole. Back.

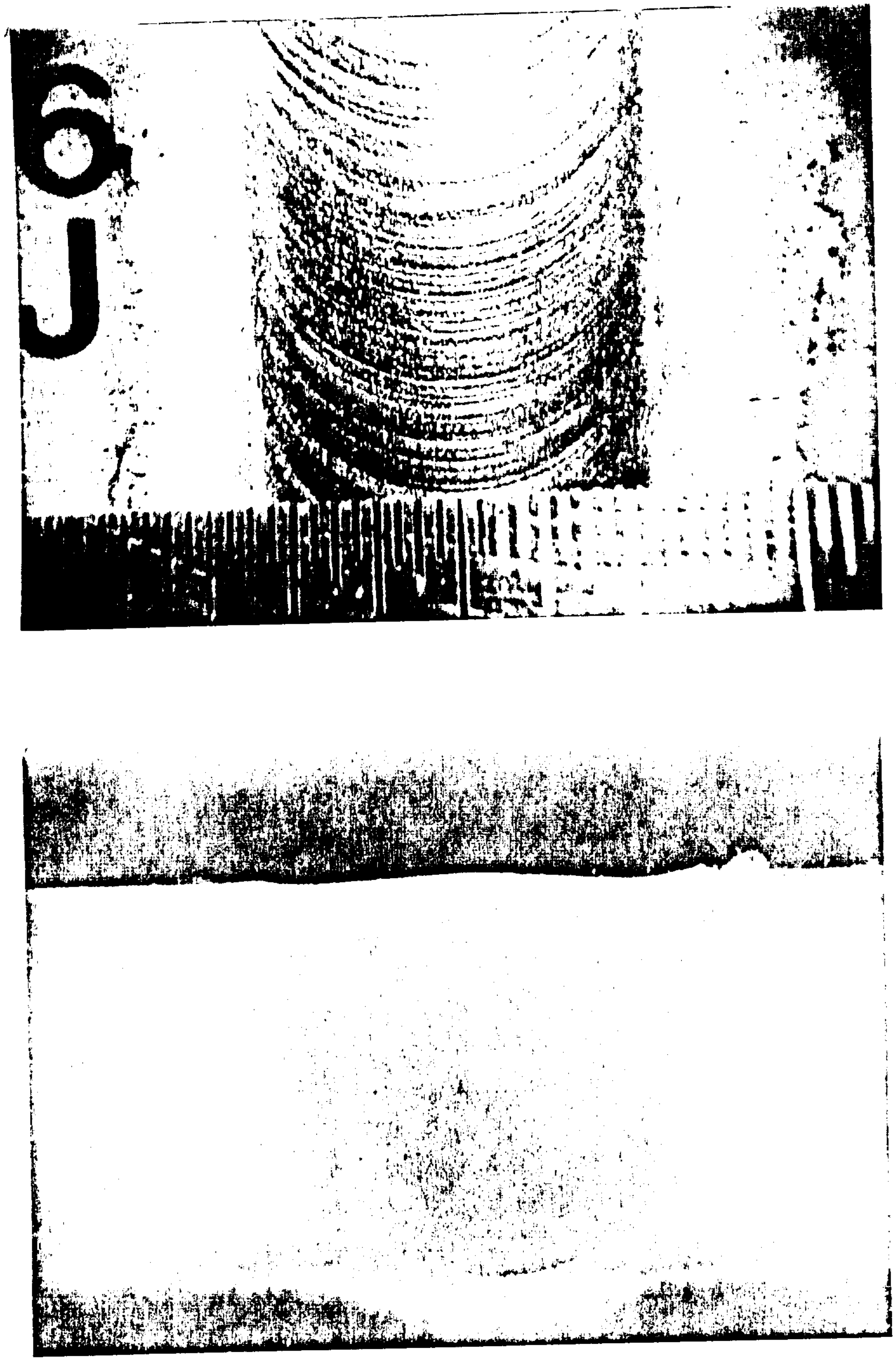


Fig. 3-25A Weld made with 300 ppm Nitrogen in arc. Cover. Front

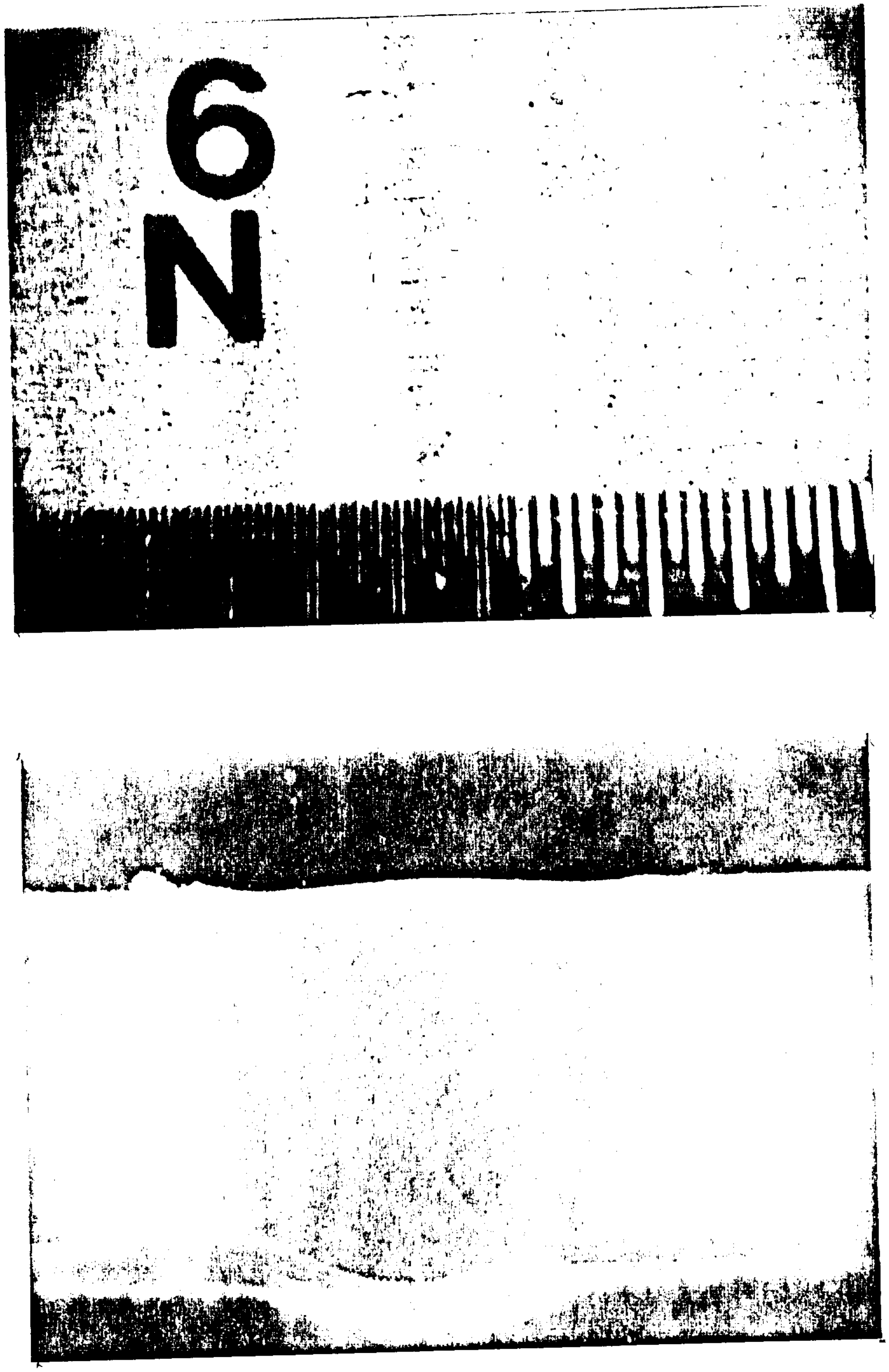


Fig. 3-25B Weld made with 300 ppm Nitrogen
in arc. Cover. Back.

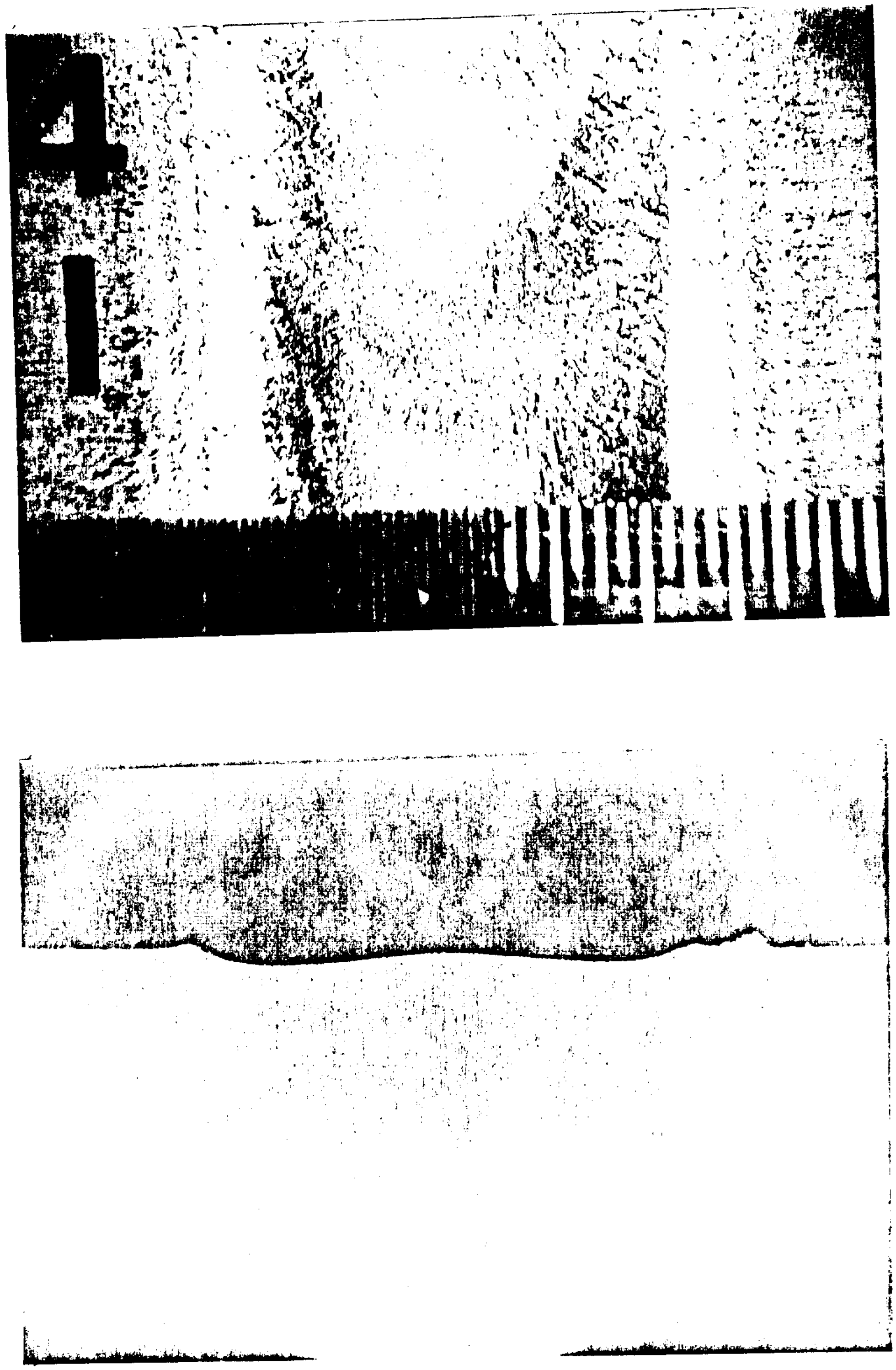


Fig. 3-26A Weld made with 500 ppm Methane in arc. Keyhole. Front.
4i,4m

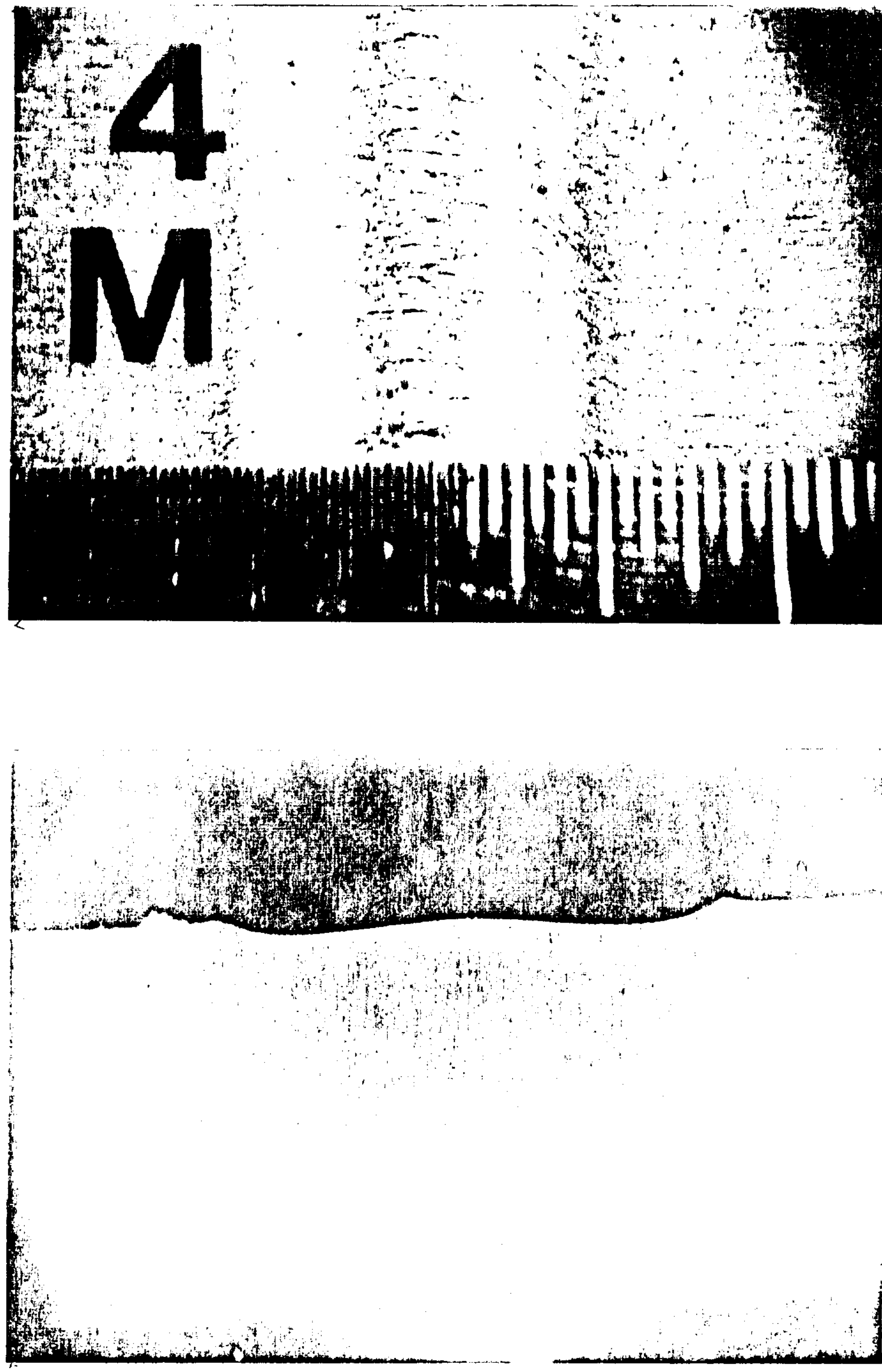
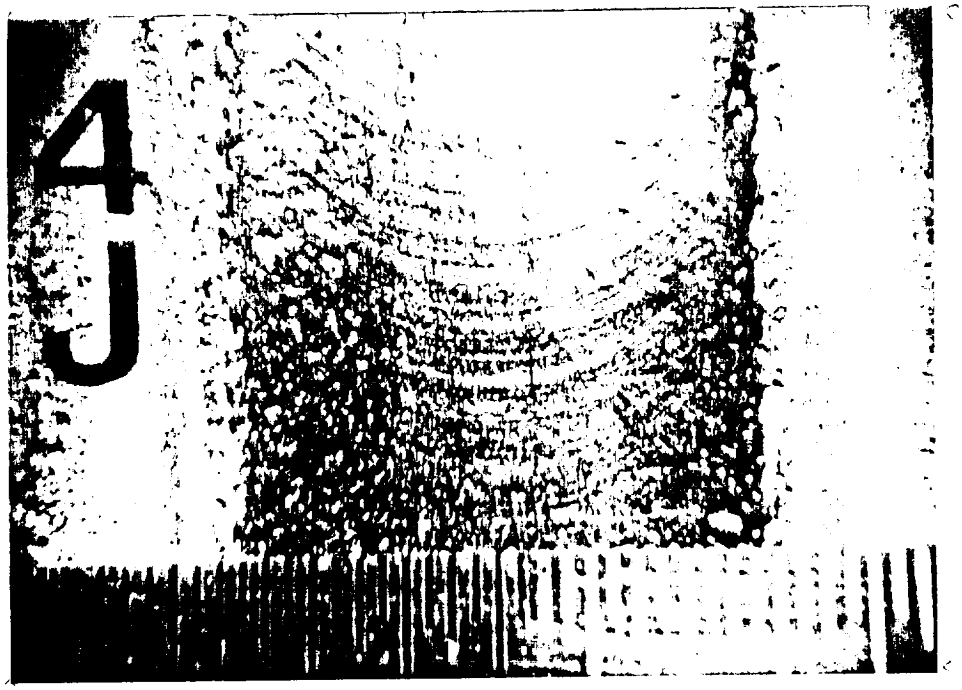


Fig. 3-26B Weld made with 500 ppm Methane in arc. Keyhole. Back.



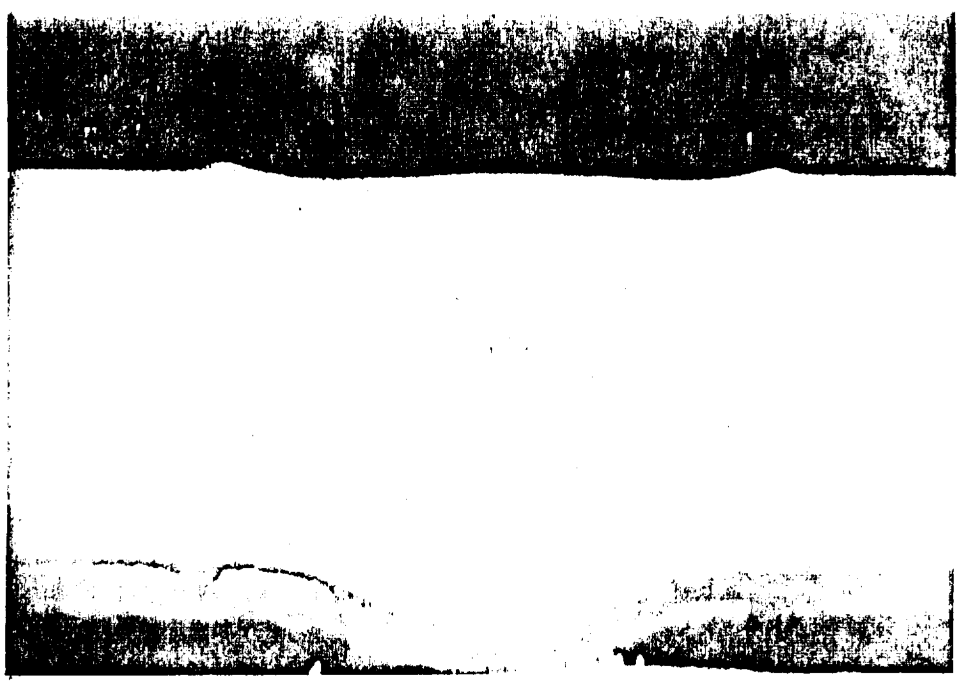


Fig. 3-27A Weld made with 500 ppm Methane
in arc. Cover. Front.
4j,4n

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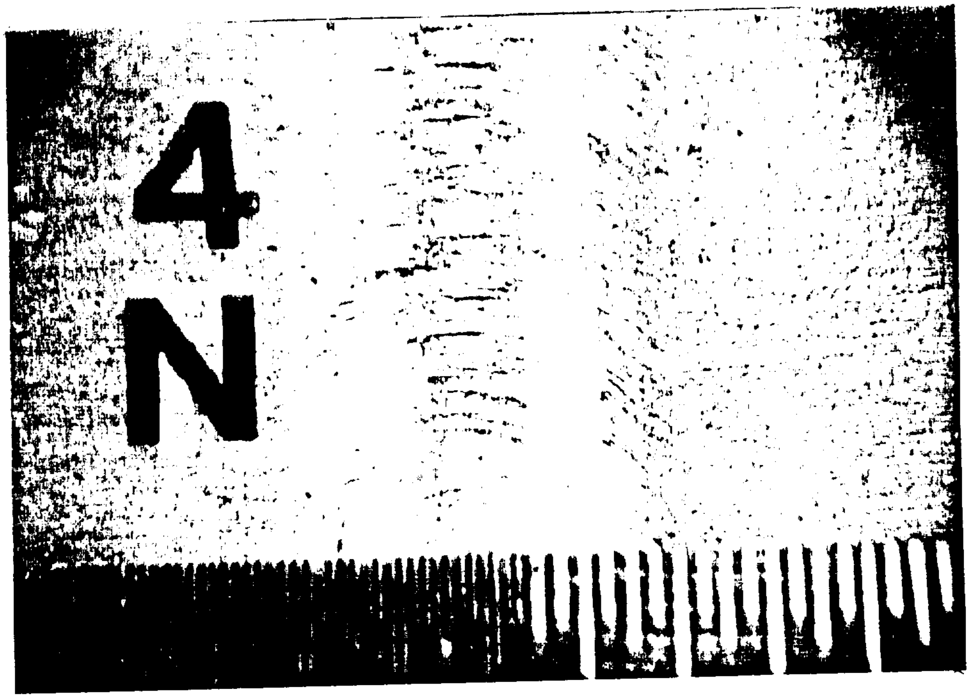


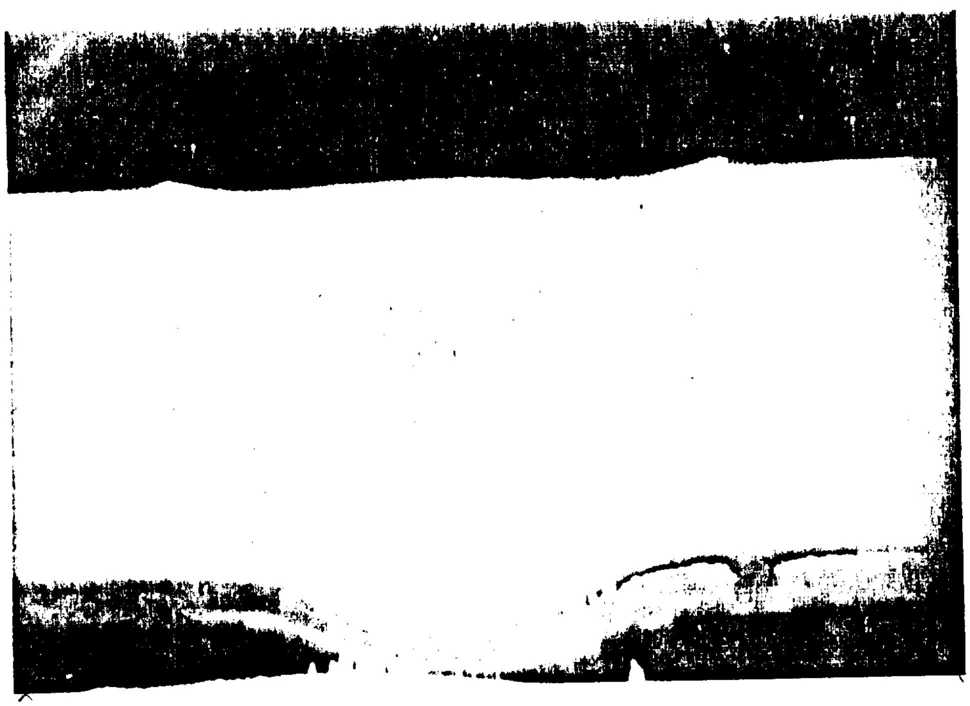
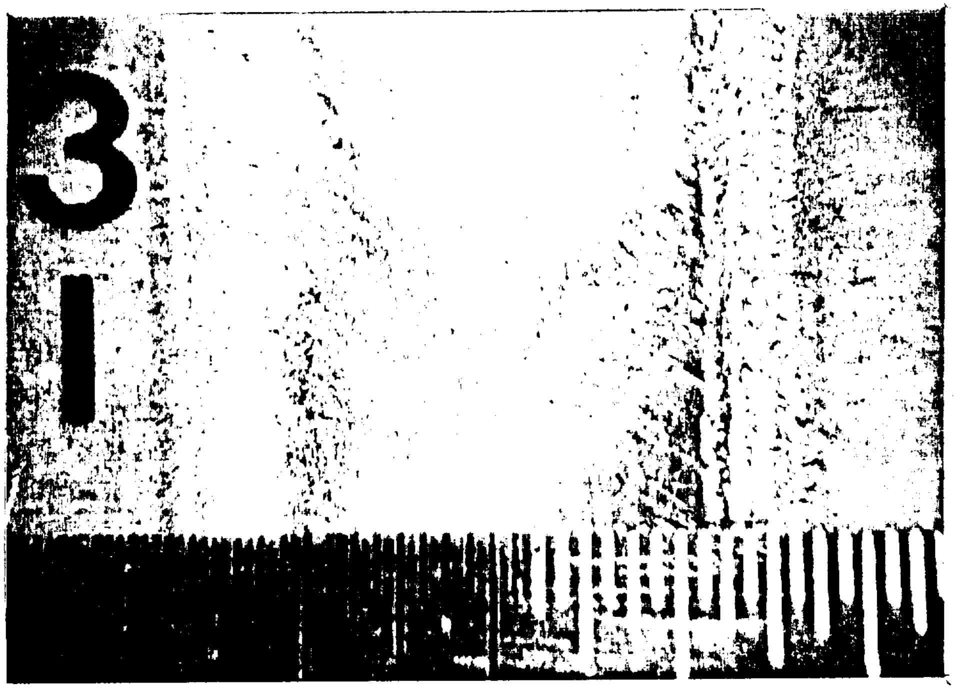


Fig. 3-27B Weld made with 500 ppm Methane in arc. Cover. Back.



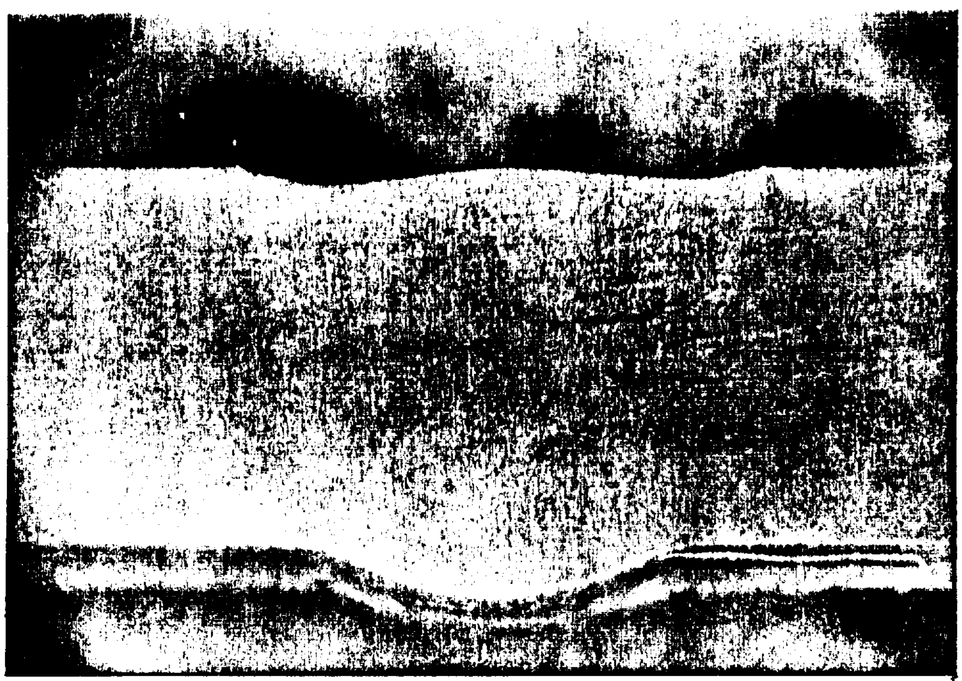


Fig. 3-28A Weld made with 250 ppm Methane in arc. Keyhole. Front.
3i,3m

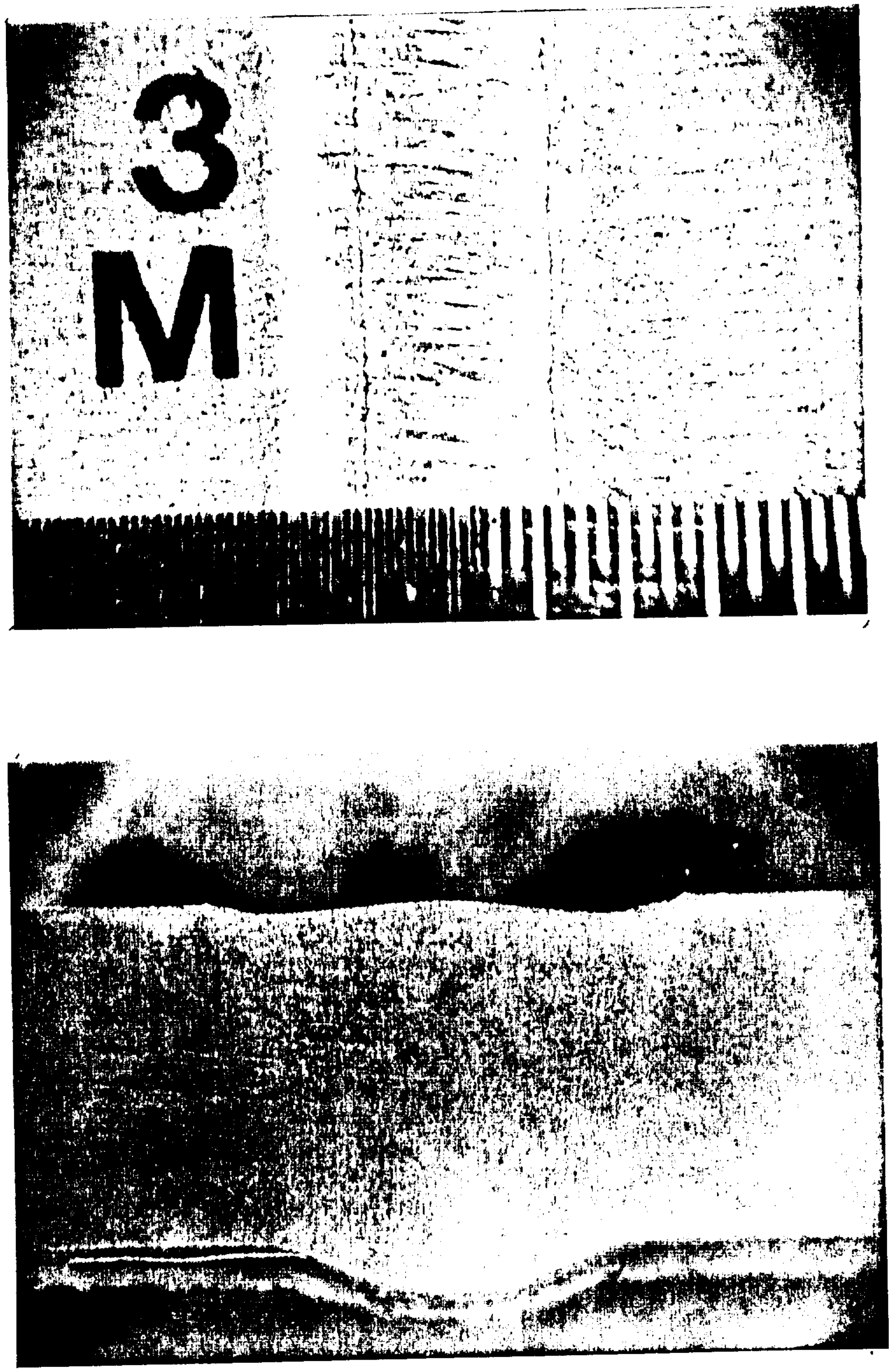
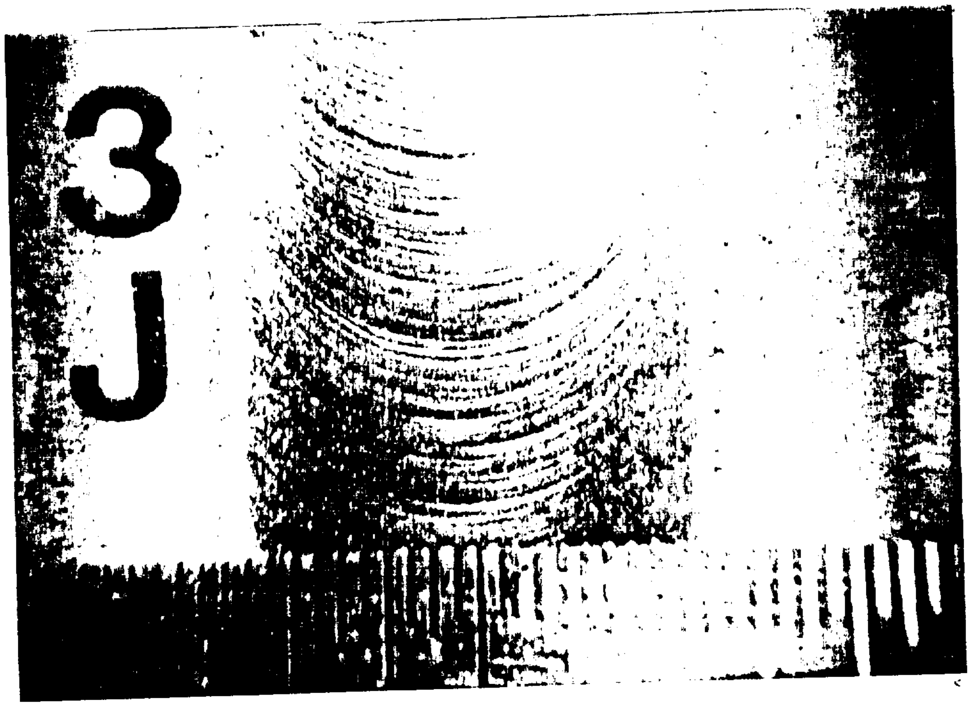


Fig. 3-28B Weld made with 250 ppm Methane in arc. Keyhole. Back.



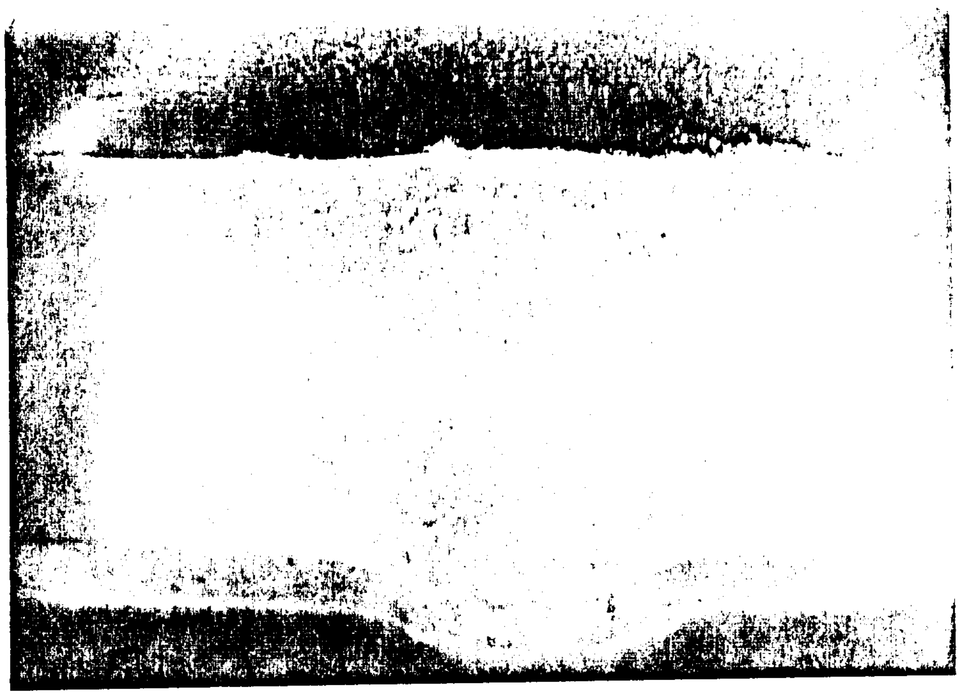
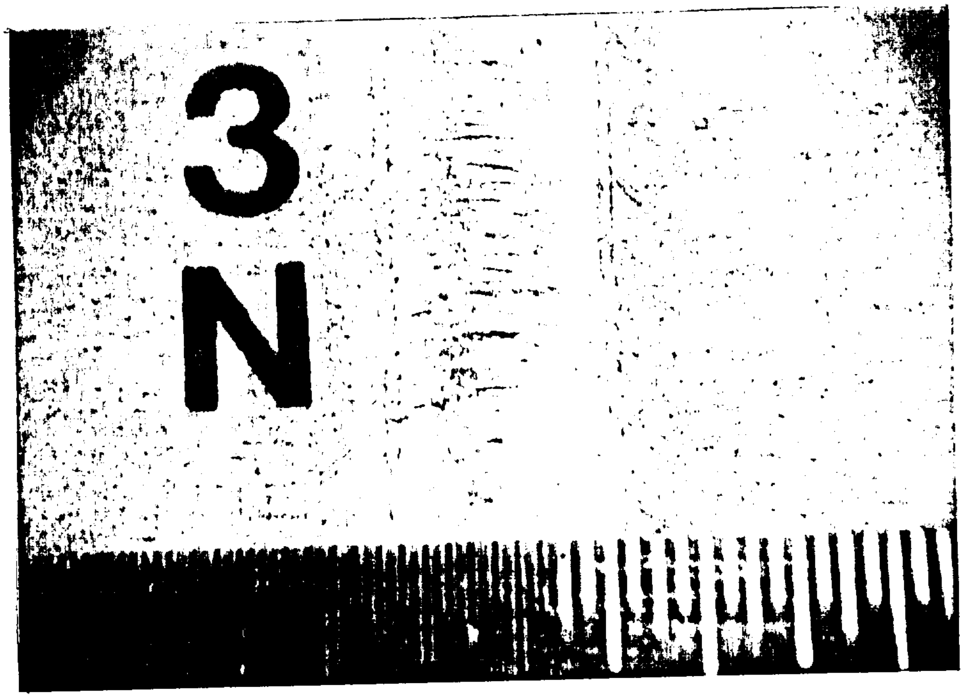


Fig. 3-29A Weld made with 250 ppm Methane in arc. Cover. Front.
3j,3n



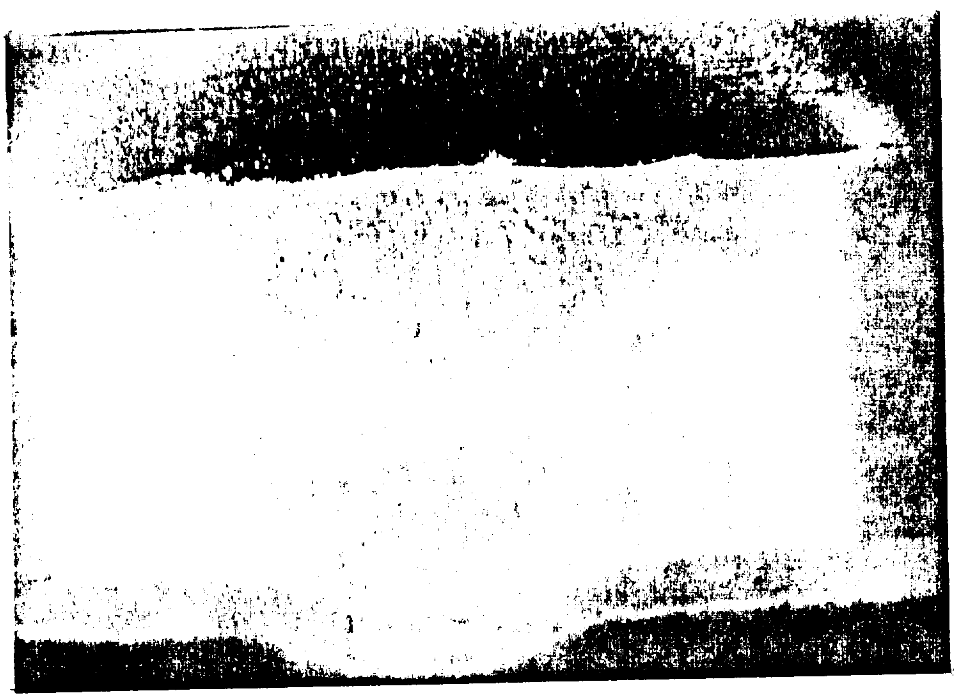


Fig. 3-29B Weld made with 250 ppm Methane in arc. Cover. Back.

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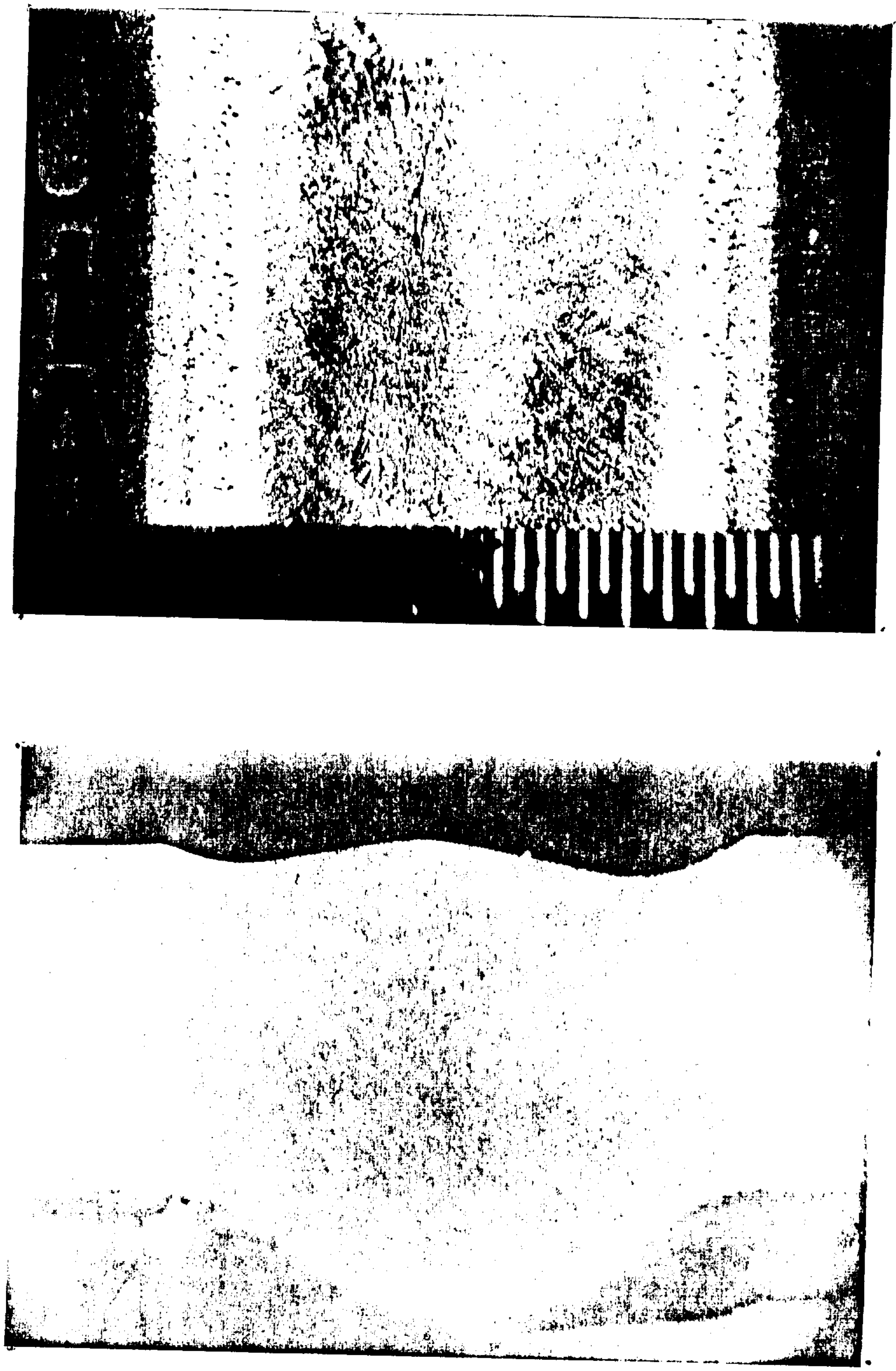
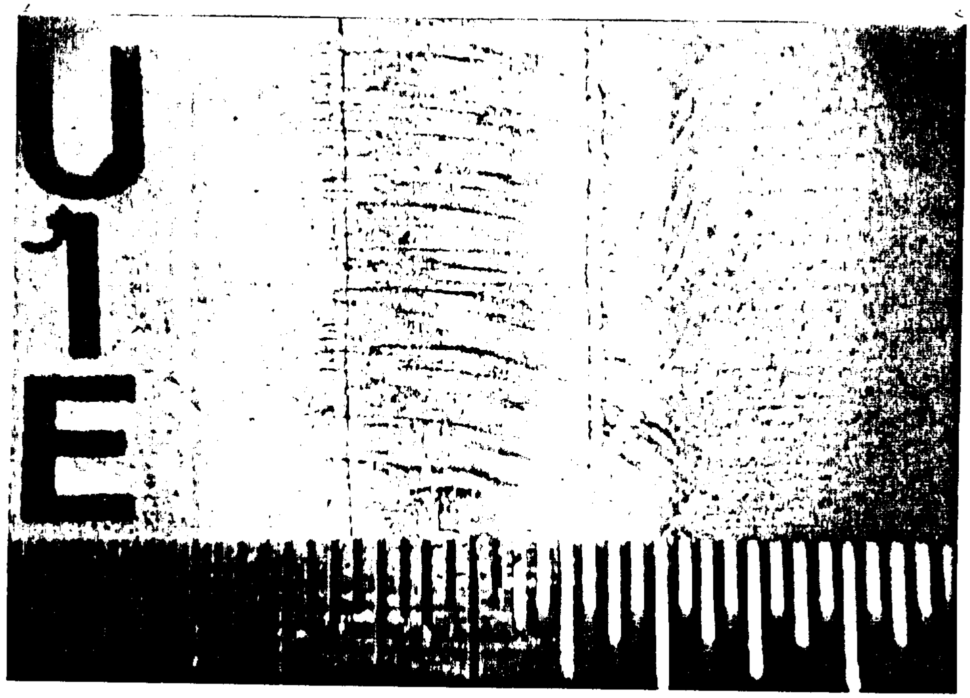


Fig. 3-30A Weld made with 100 ppm Methane
in arc. Keyhole. Front.
ula,ule



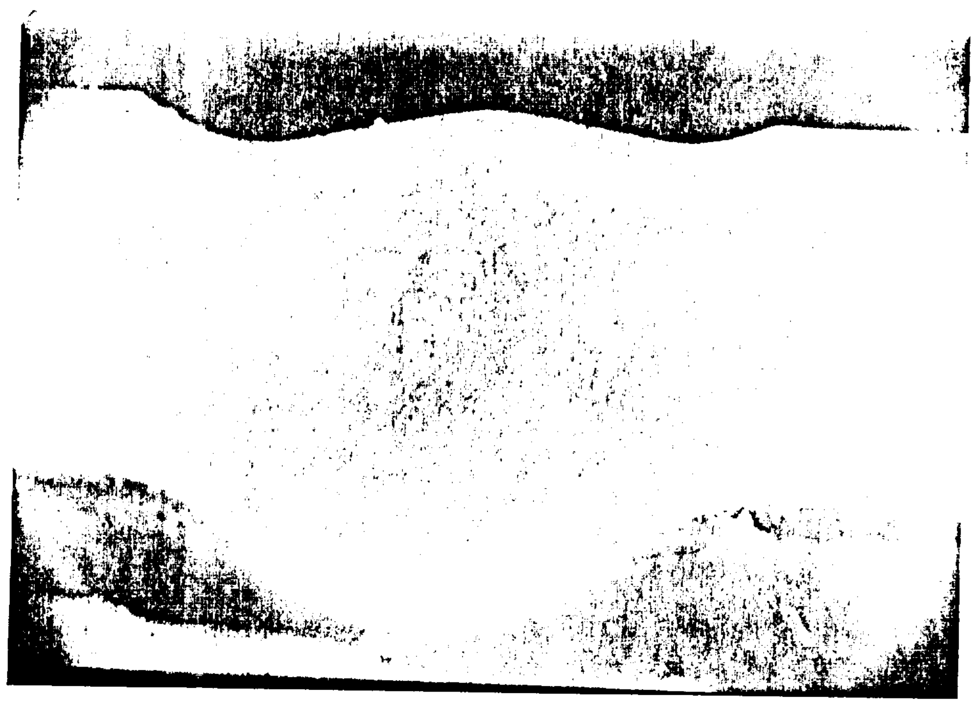


Fig. 3-30B Weld made with 100 ppm Methane
in arc. Keyhole. Back.

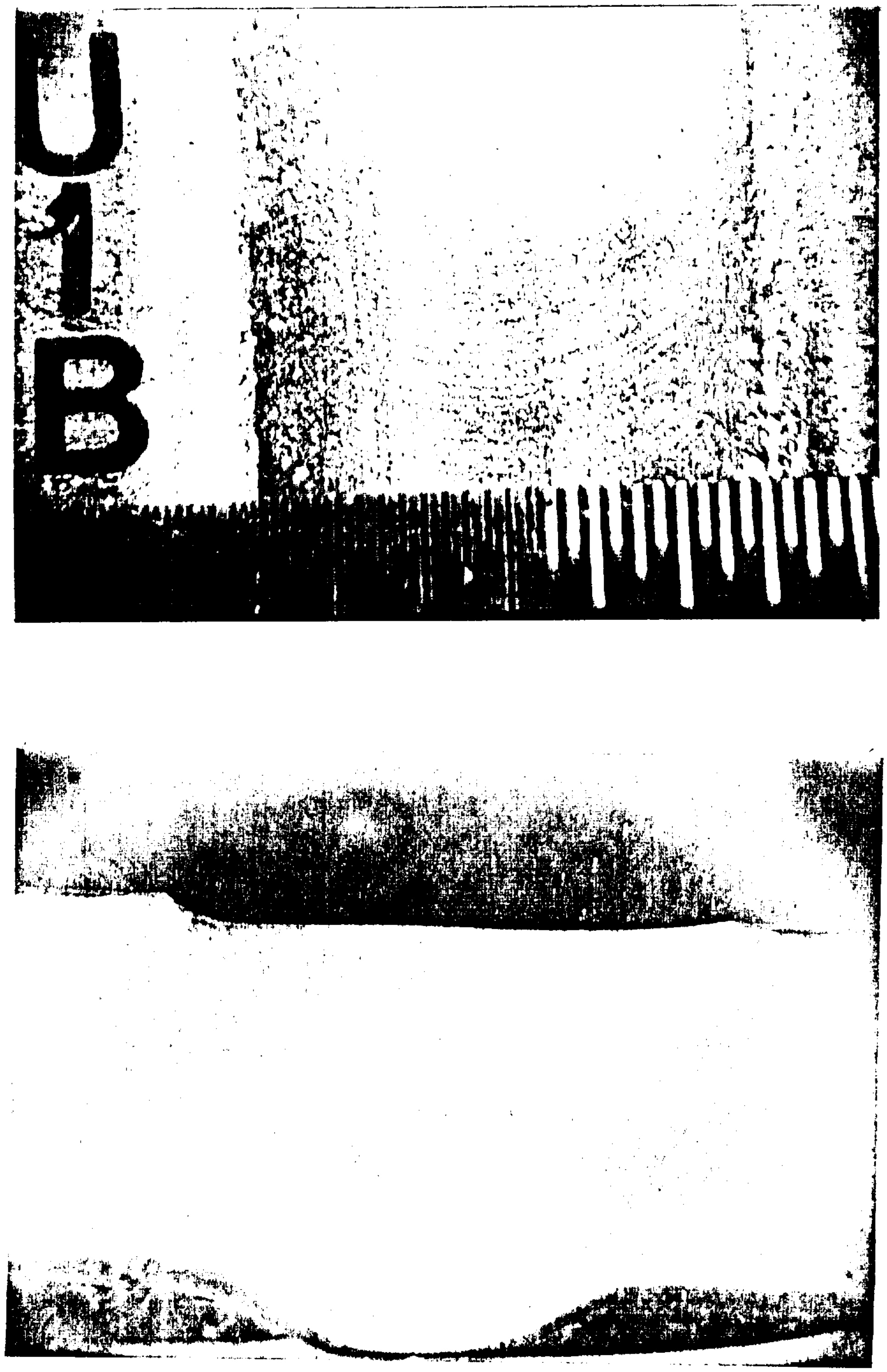


Fig. 3-31A Weld made with 100 ppm Methane in arc. Cover. Front.
u1b,u1f

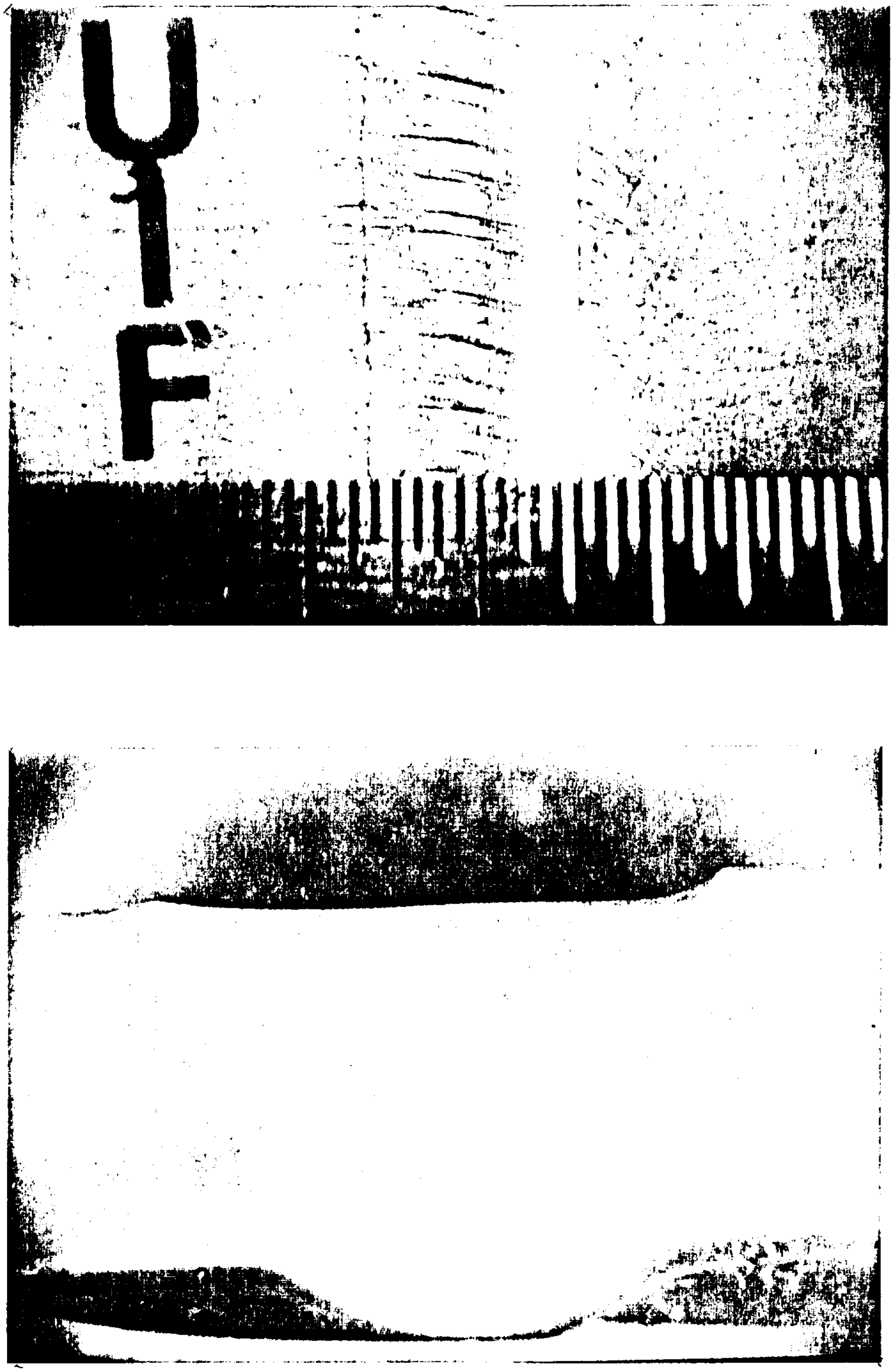


Fig. 3-31B Weld made with 100 ppm Methane
in arc. Cover. Back.

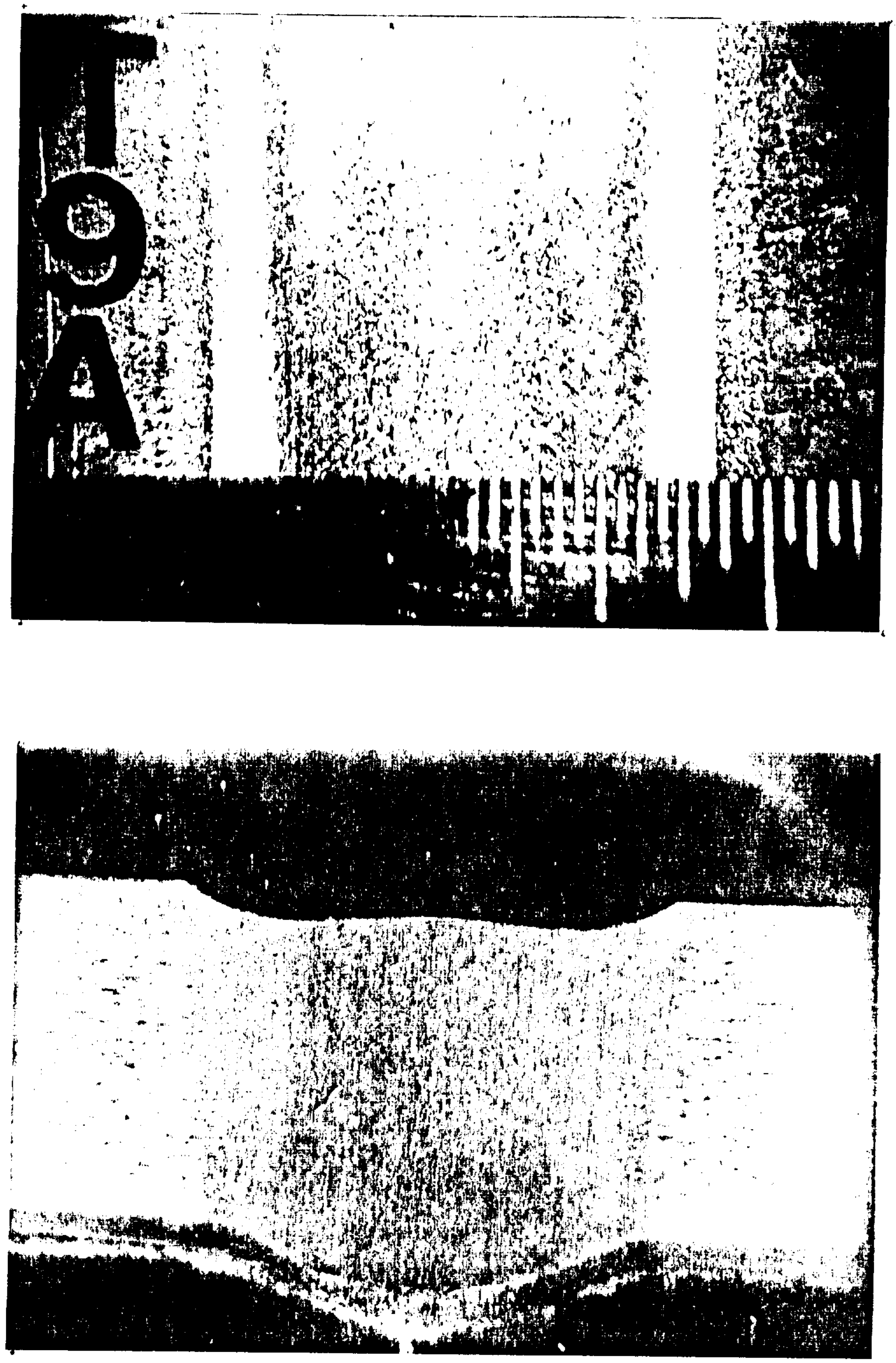


Fig. 3-32A Weld made with 515 ppm Oxygen in arc. Keyhole. Front.
t9a,t9e

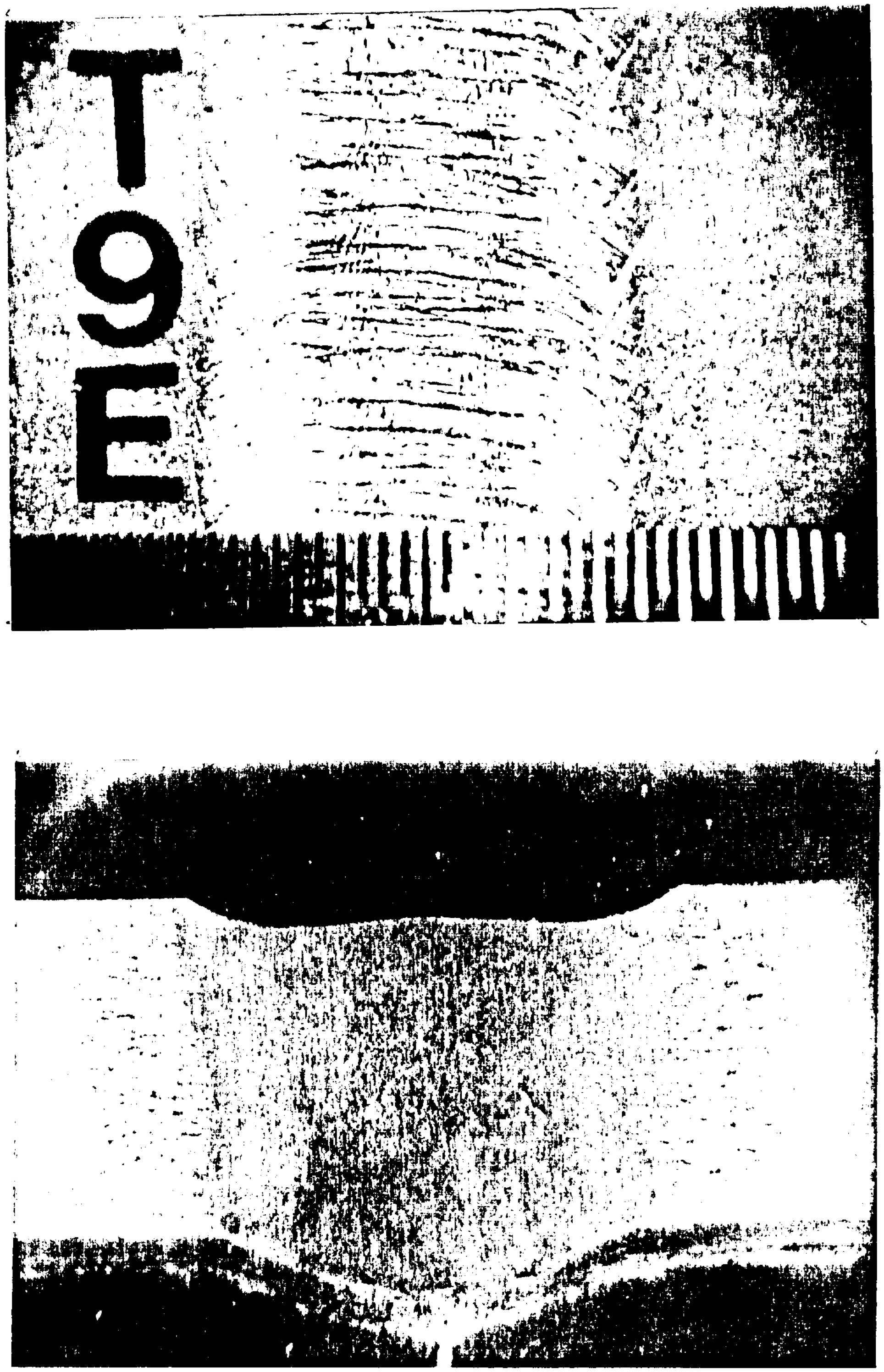


Fig. 3-32B Weld made with 515 ppm Oxygen in arc. Keyhole. Back.

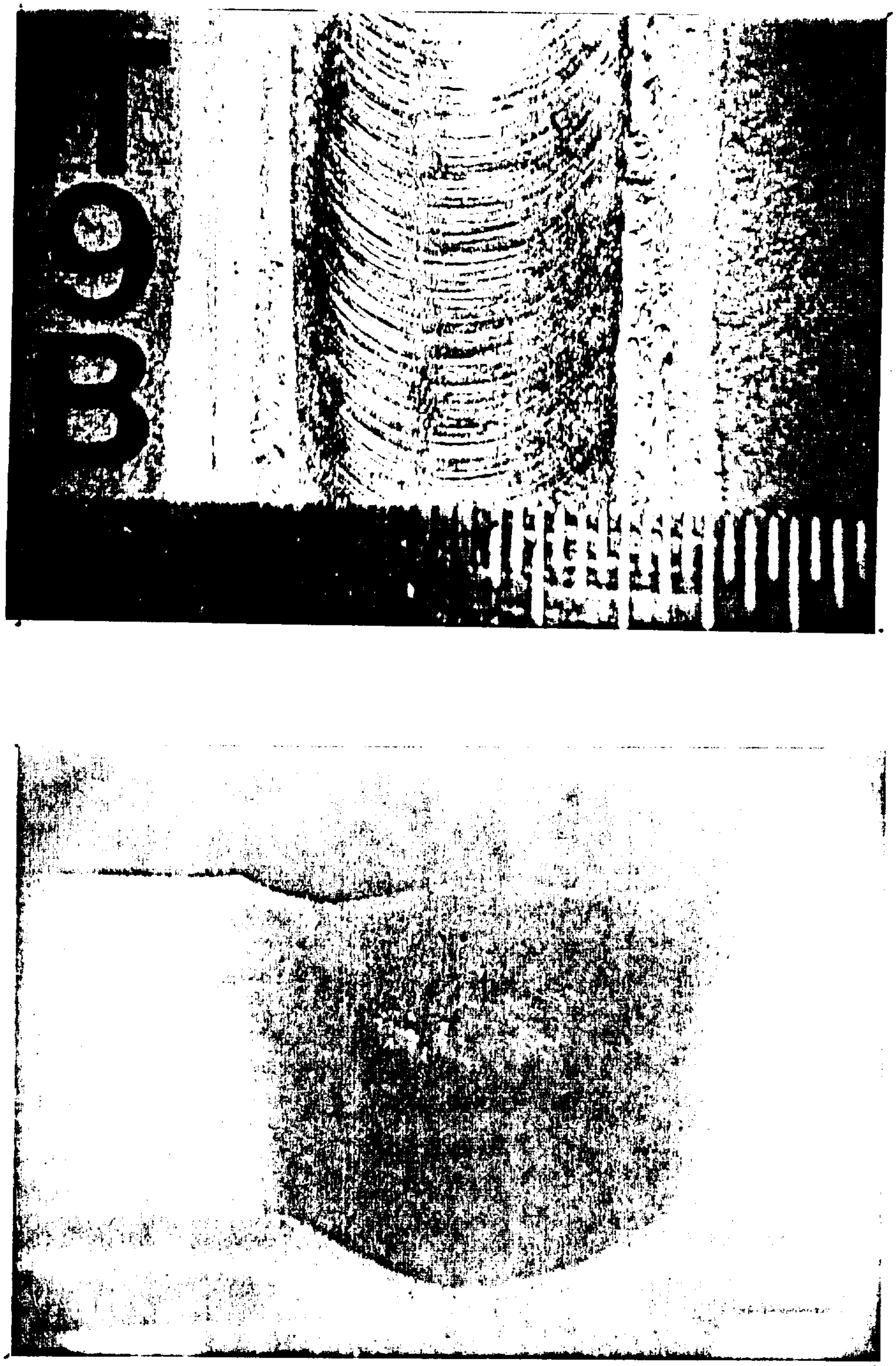


Fig. 3-33A Weld made with 515 ppm Oxygen
in arc. Cover. Front
t9b,t9f

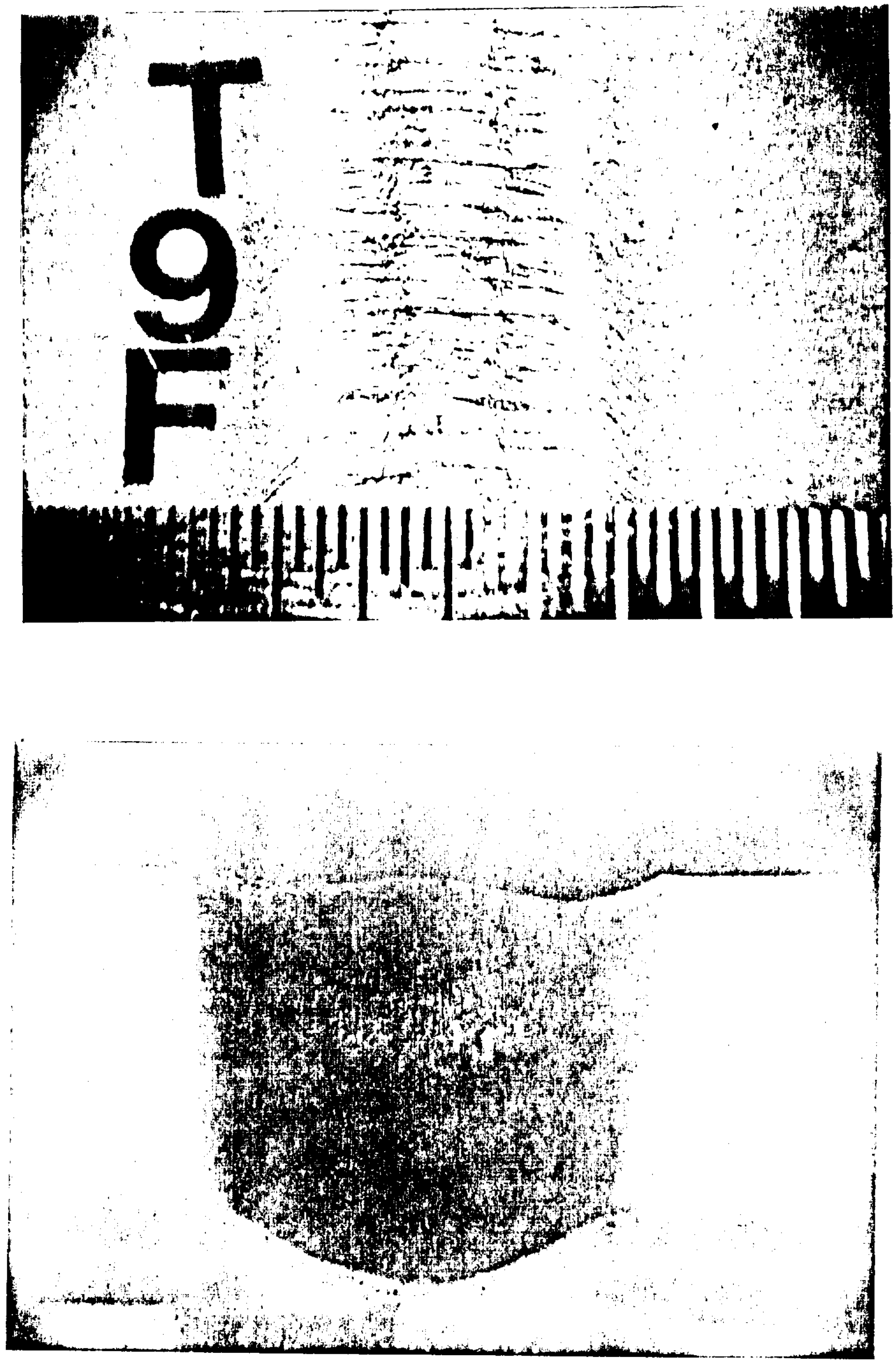


Fig. 3-33B Weld made with 515 ppm Oxygen in arc. Cover. Back.

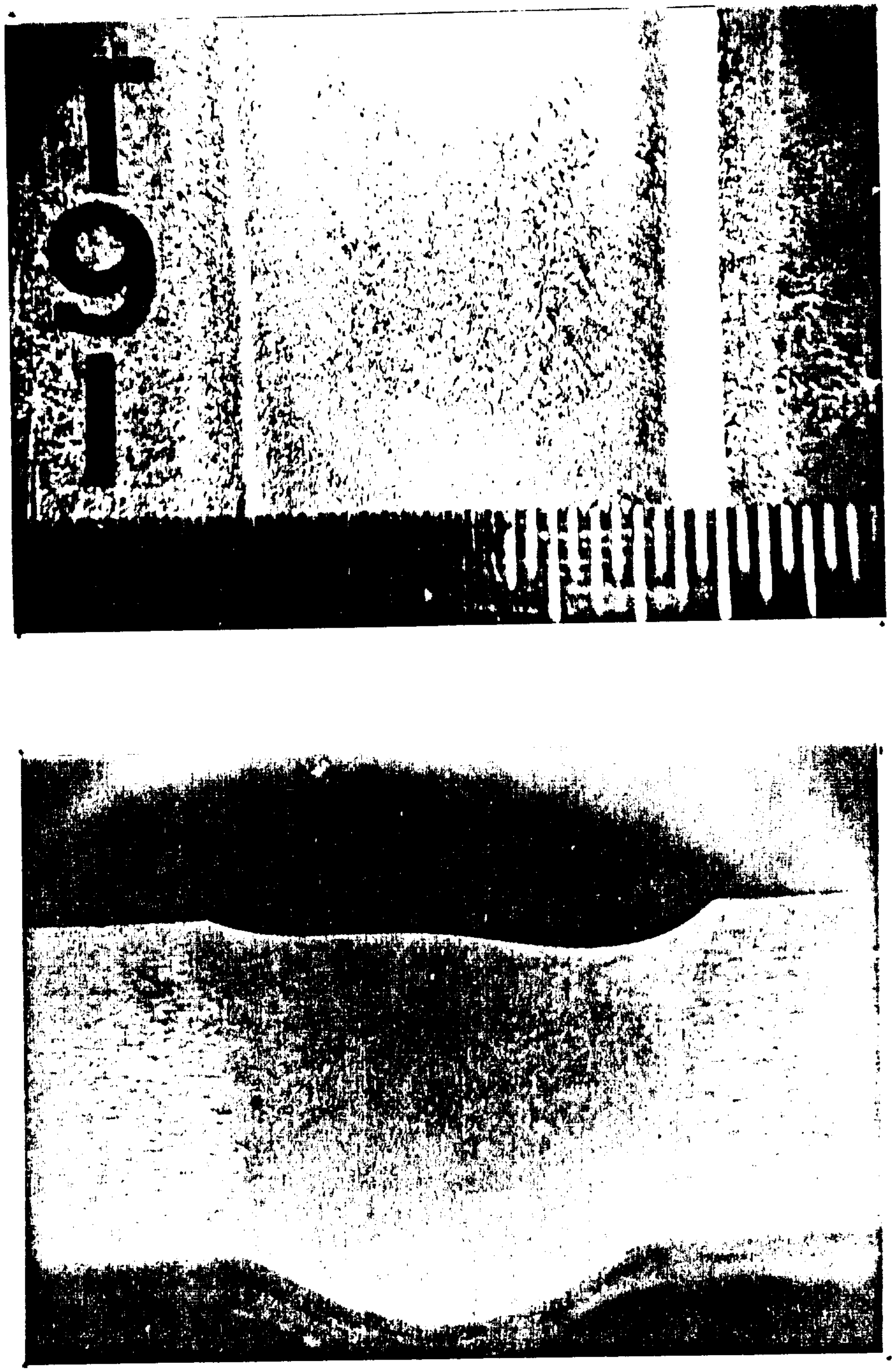


Fig. 3-34A Weld made with 400 ppm Oxygen
in arc. Keyhole. Front.
t9i,t9m

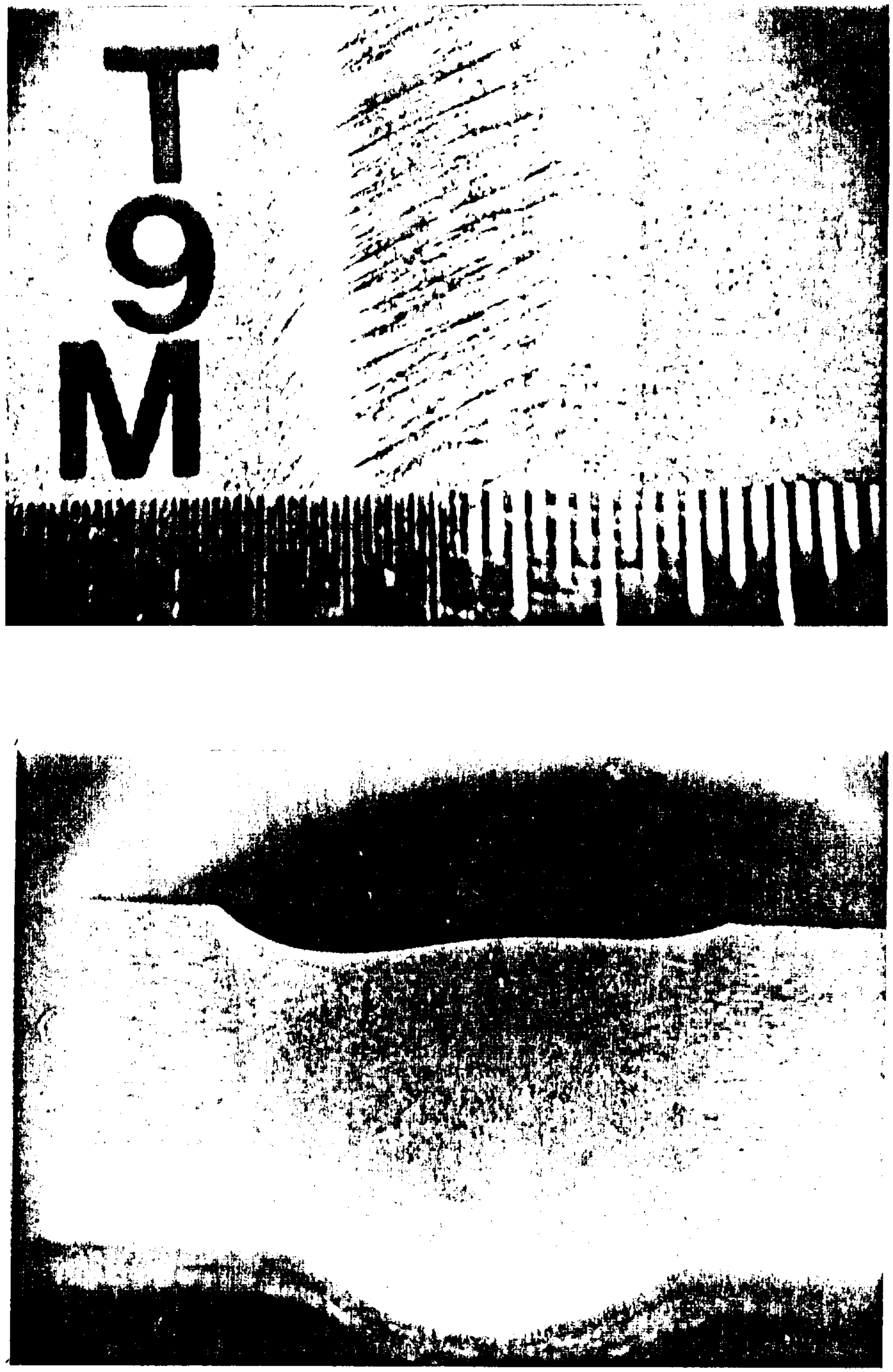
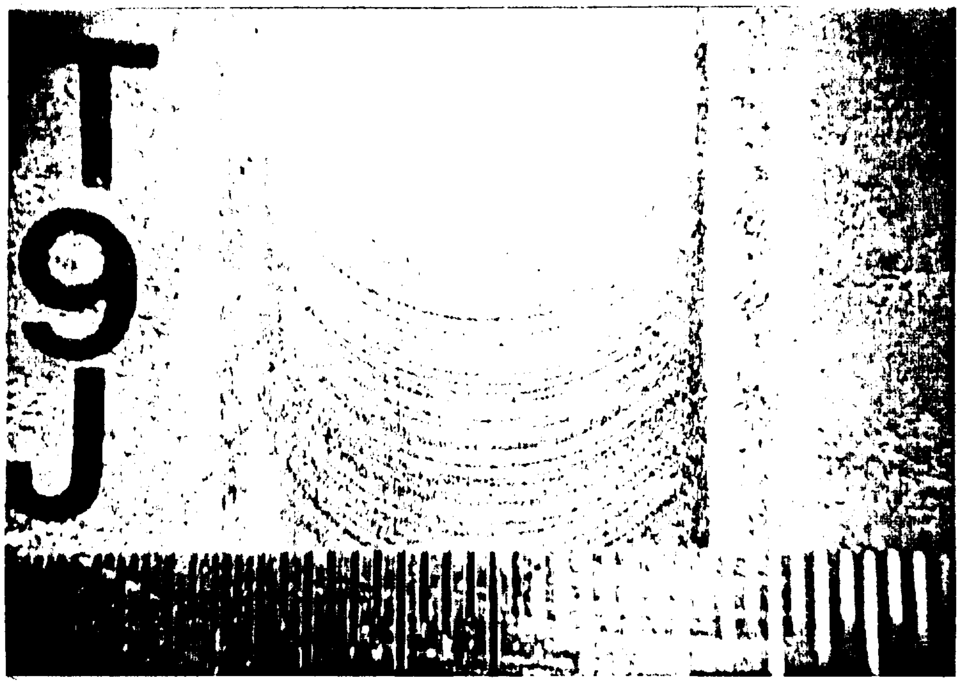


Fig. 3-34B Weld made with 400 ppm Oxygen in arc. Keyhole. Back.



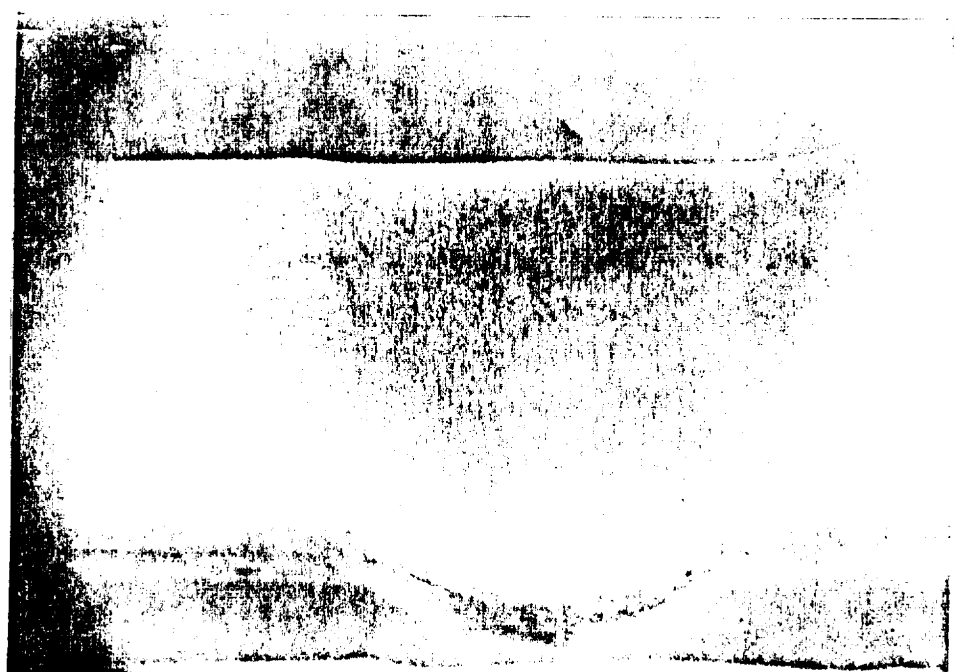
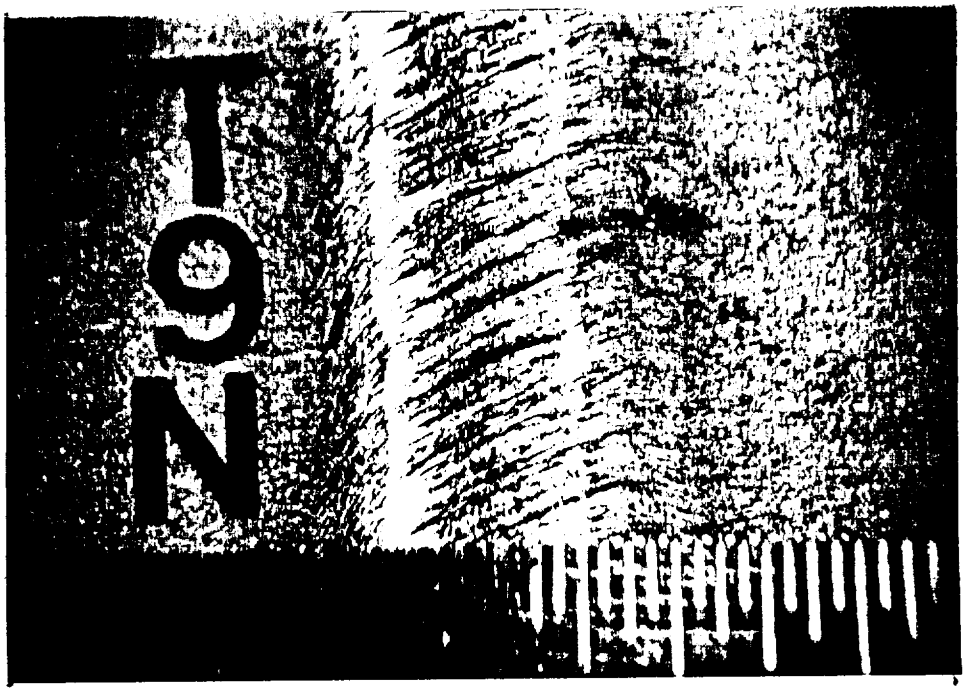


Fig. 3-35A Weld made with 400 ppm Oxygen in arc. Cover. Front.
t9j,t9n



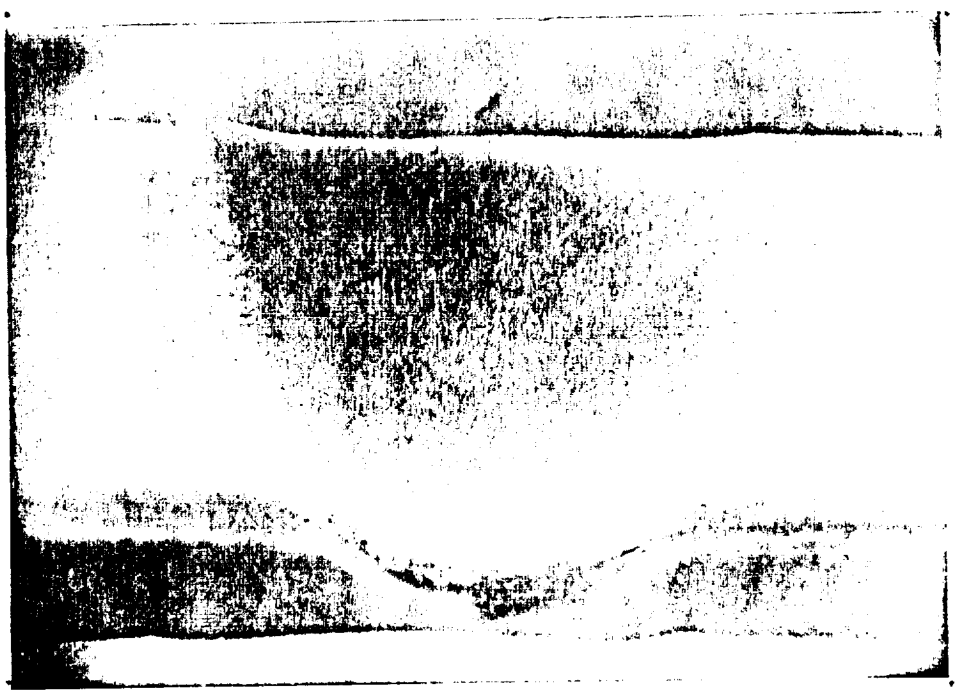
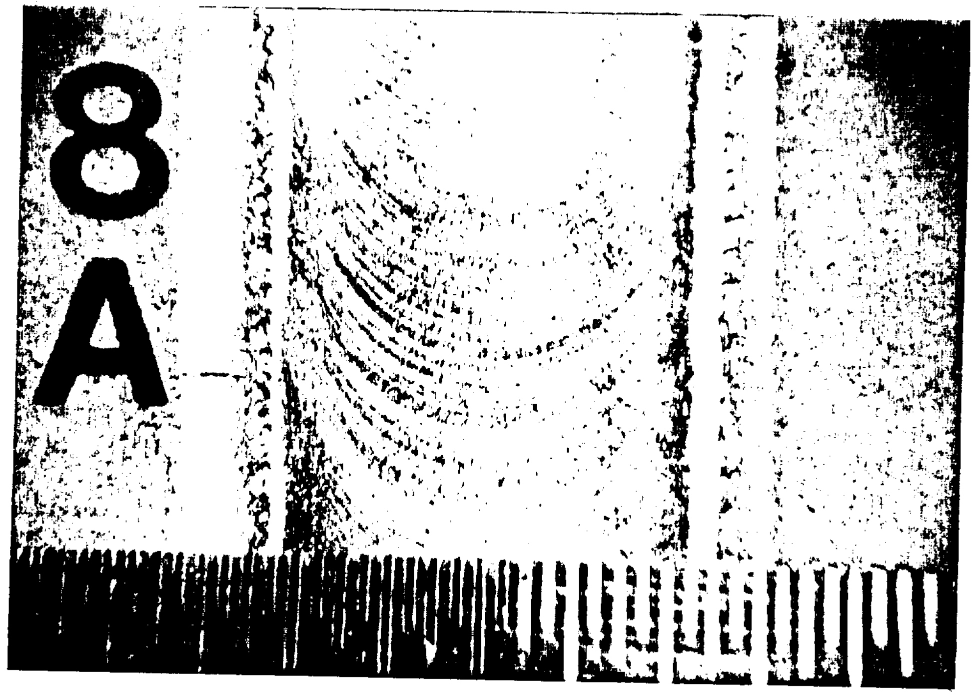


Fig. 3-35B Weld made with 400 ppm Oxygen
in arc. Cover. Back.



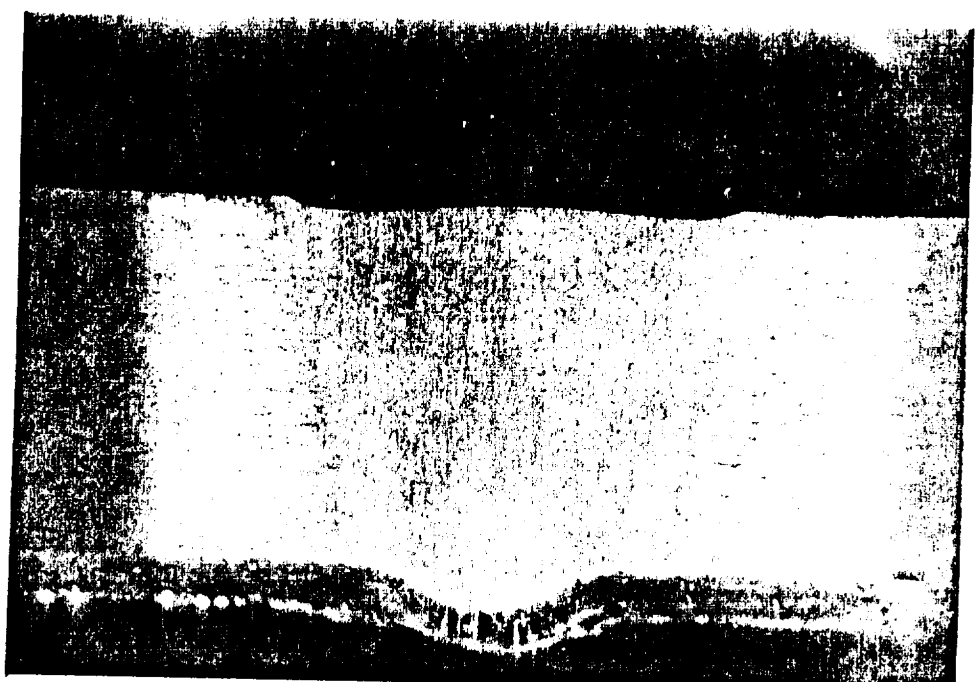


Fig. 3-36A Weld made with 250 ppm Oxygen in arc. Keyhole. Front.
8a,8e

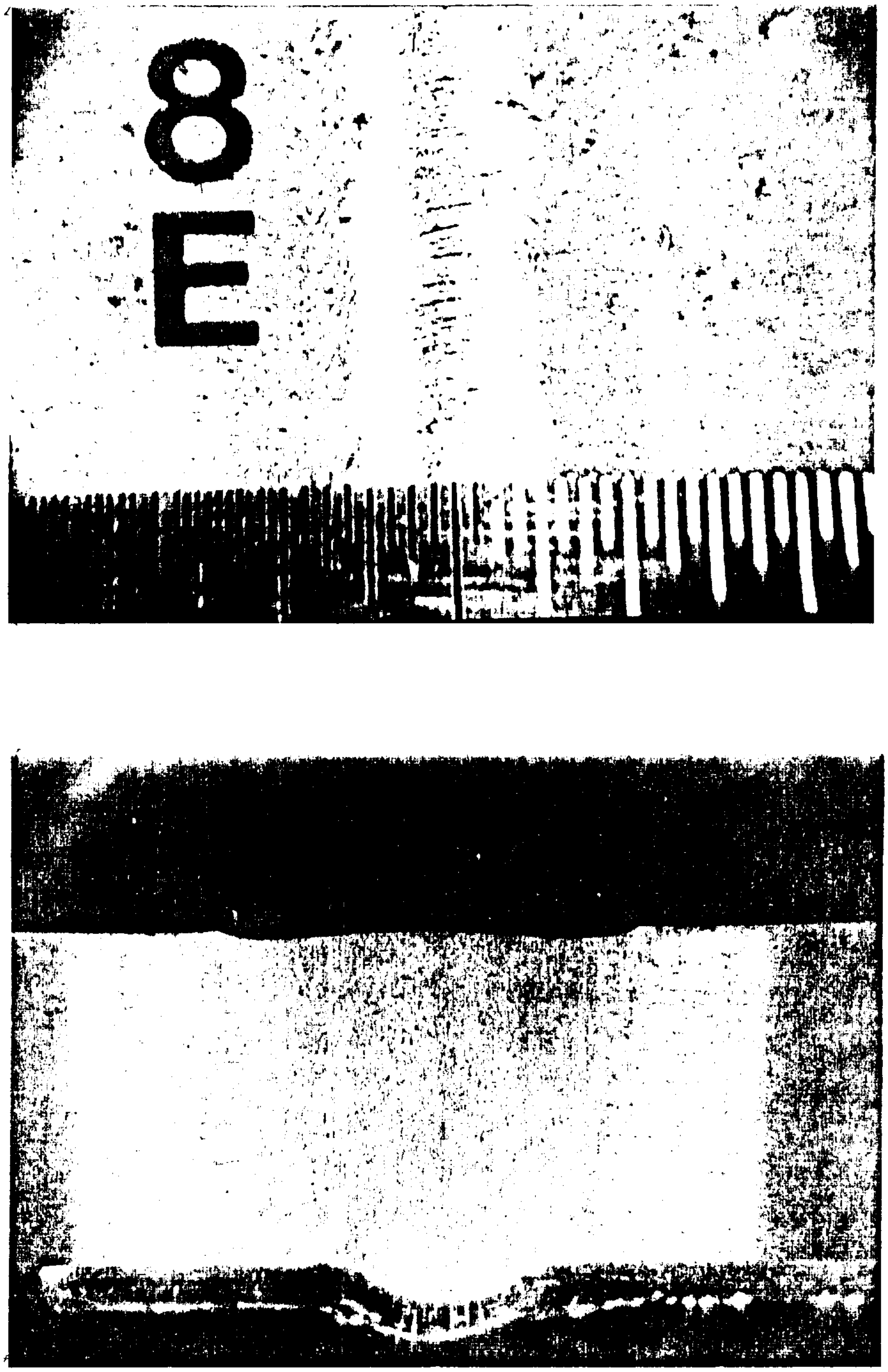


Fig. 3-36B Weld made with 250 ppm Oxygen in arc. Keyhole. Back.

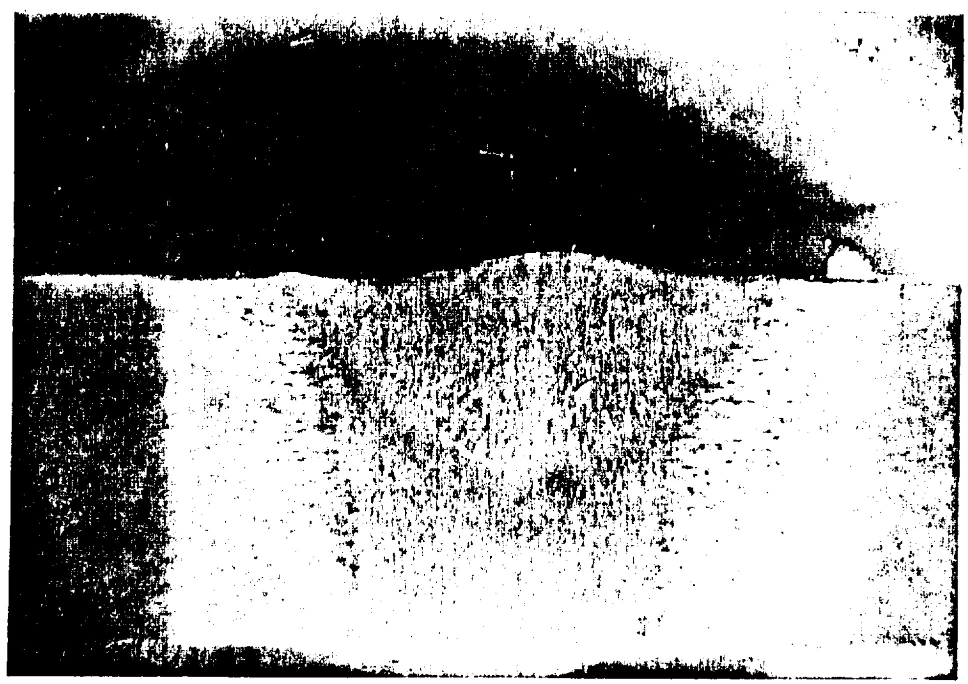


Fig. 3-37A Weld made with 250 ppm Oxygen in arc. Cover. Front.
8b,8f

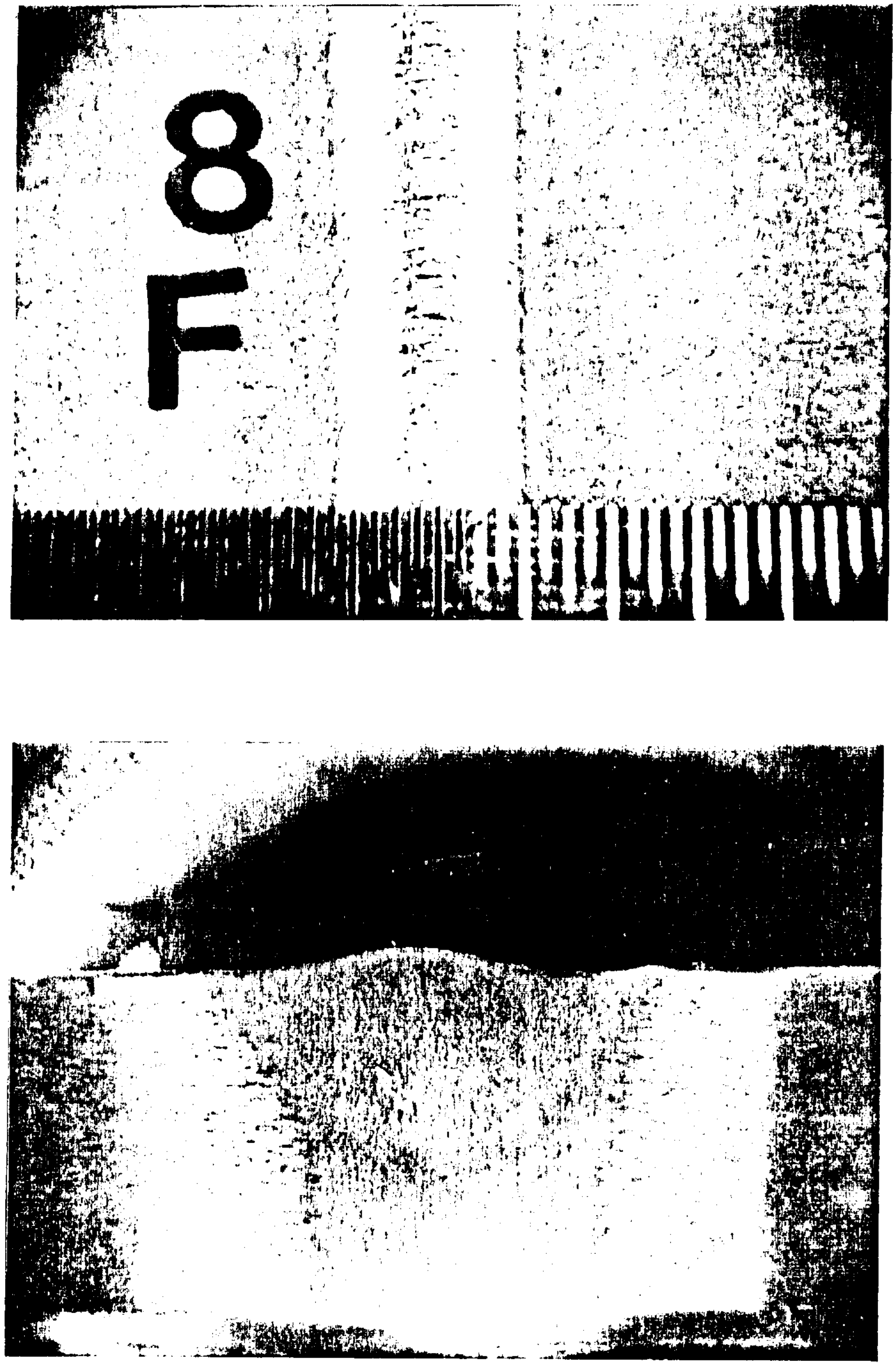


Fig. 3-37B Weld made with 250 ppm Oxygen in arc. Cover. Back.

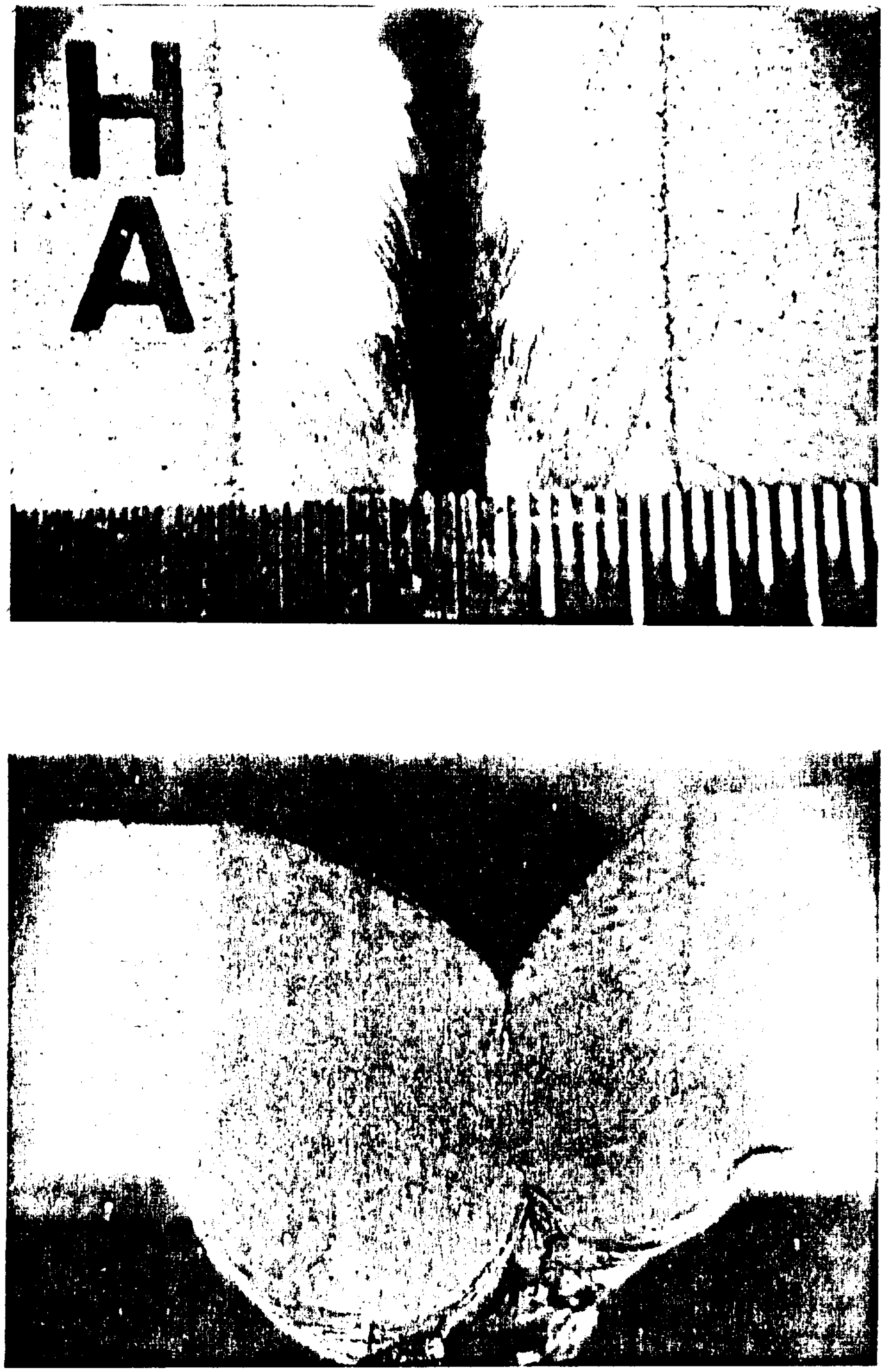
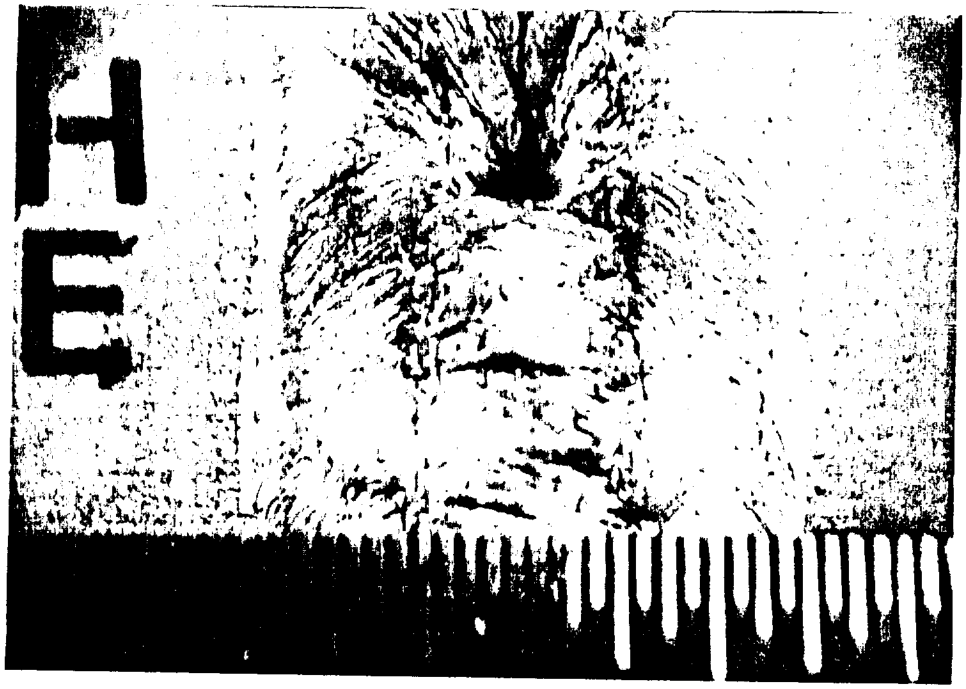


Fig. 3-38A Weld made with 250 ppm Hydrogen in arc. Keyhole. Front.
ha,he



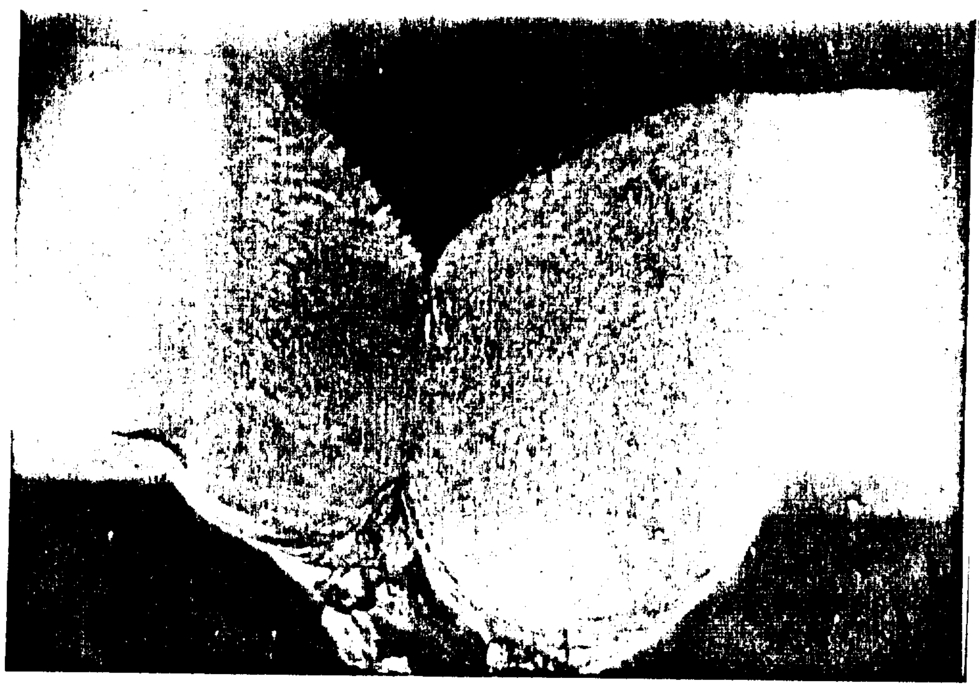


Fig. 3-38B Weld made with 250 ppm Hydrogen in arc. Keyhole. Back.

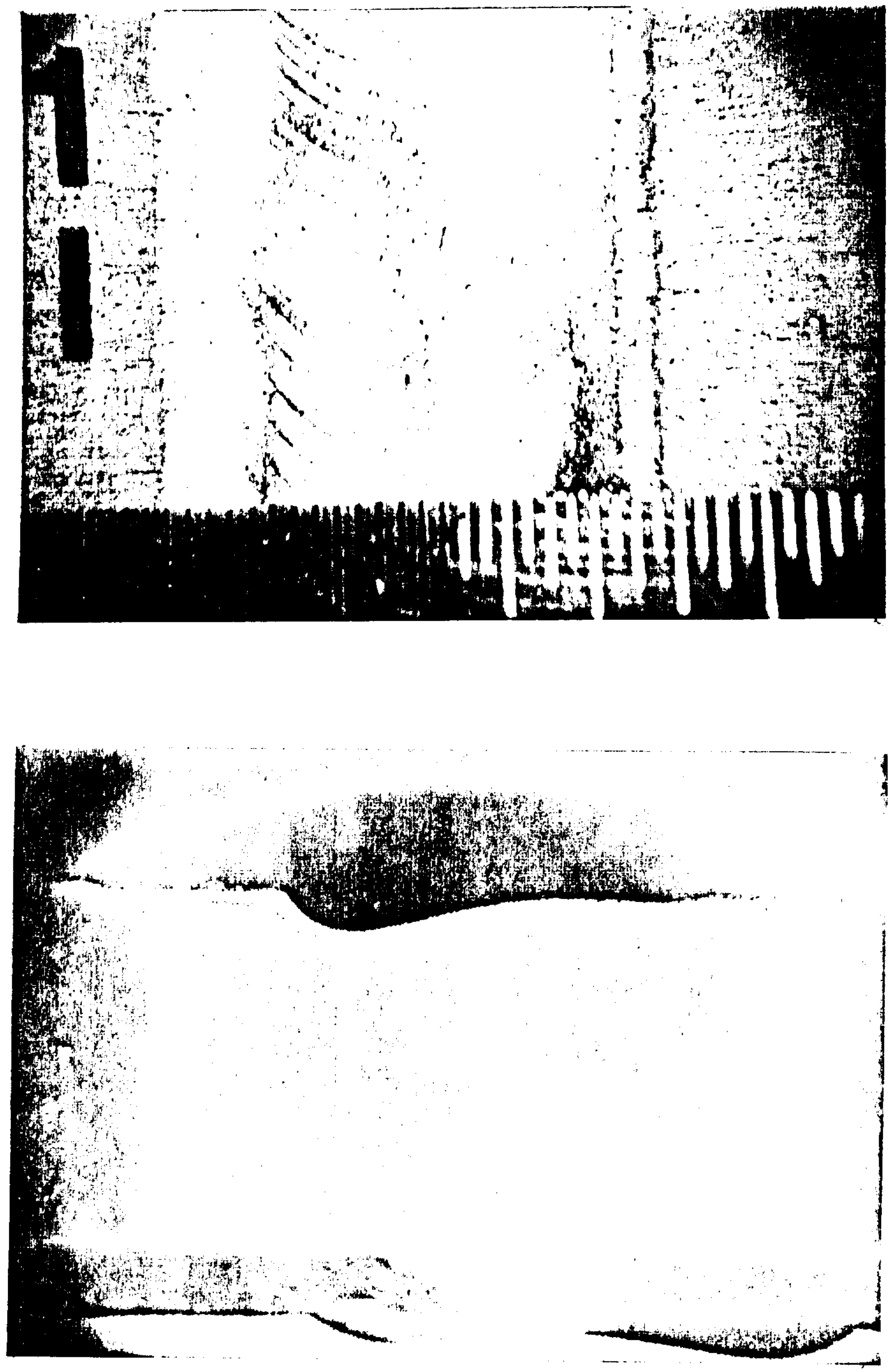
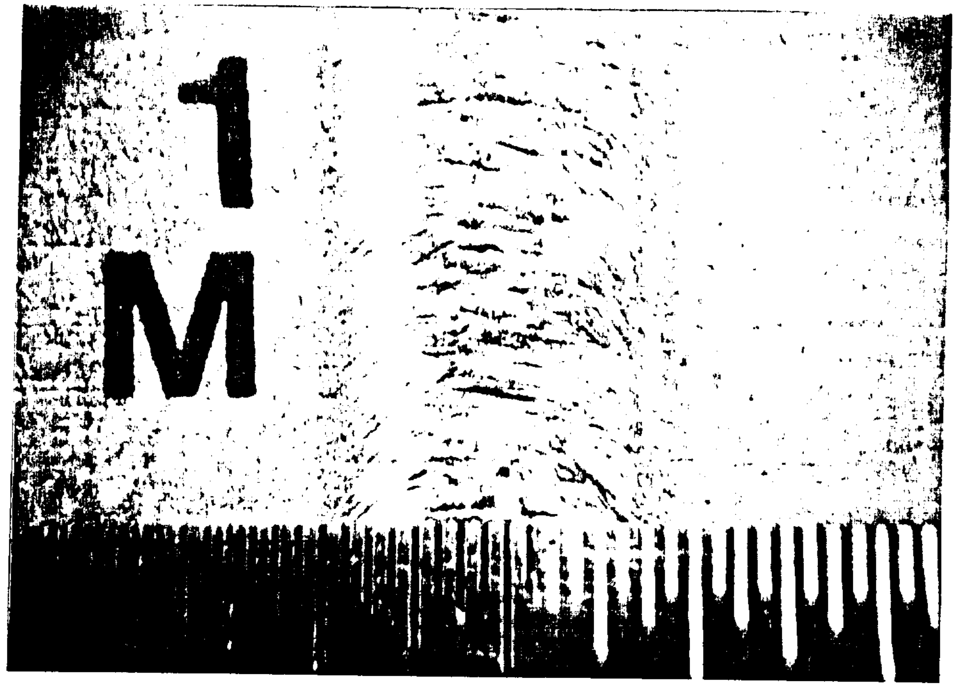


Fig. 3-39A Weld made with 100 ppm Hydrogen in arc. Keyhole. Front.
1i,1m



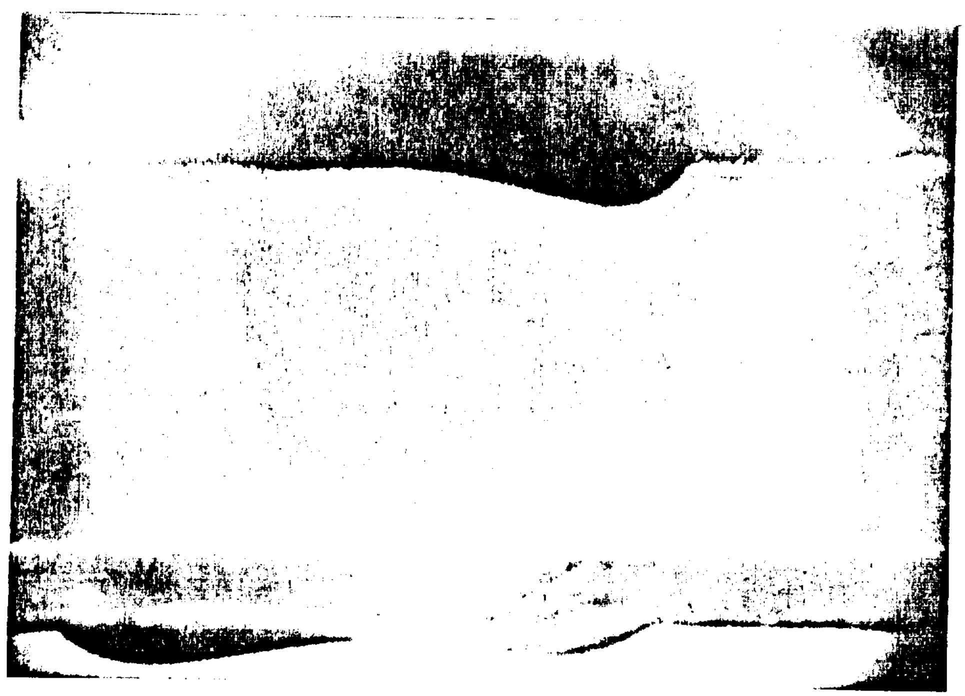
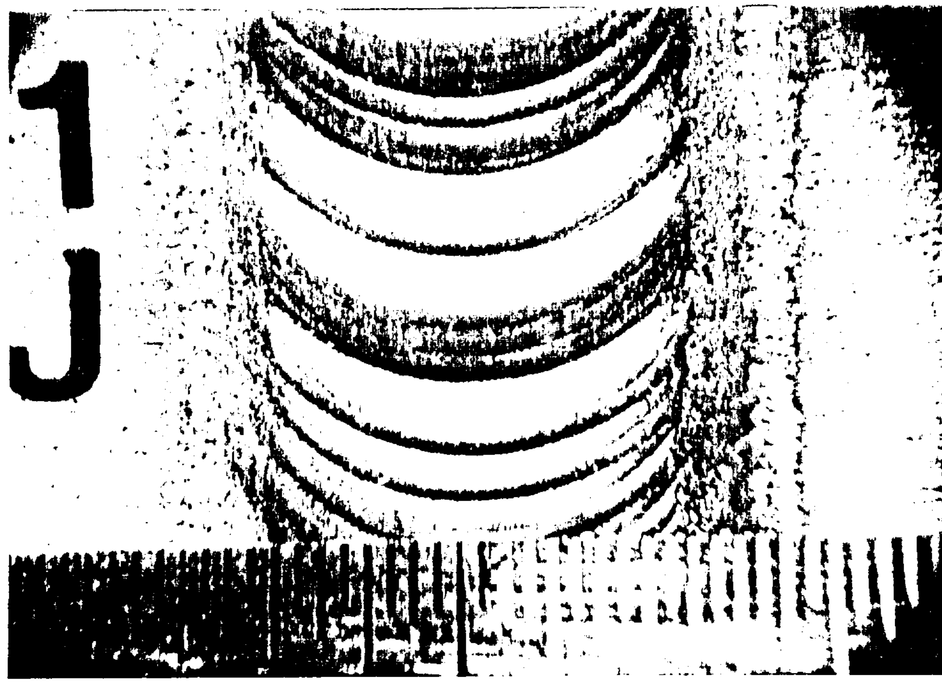


Fig. 3-39B Weld made with 100 ppm Hydrogen
in arc. Keyhole. Back.



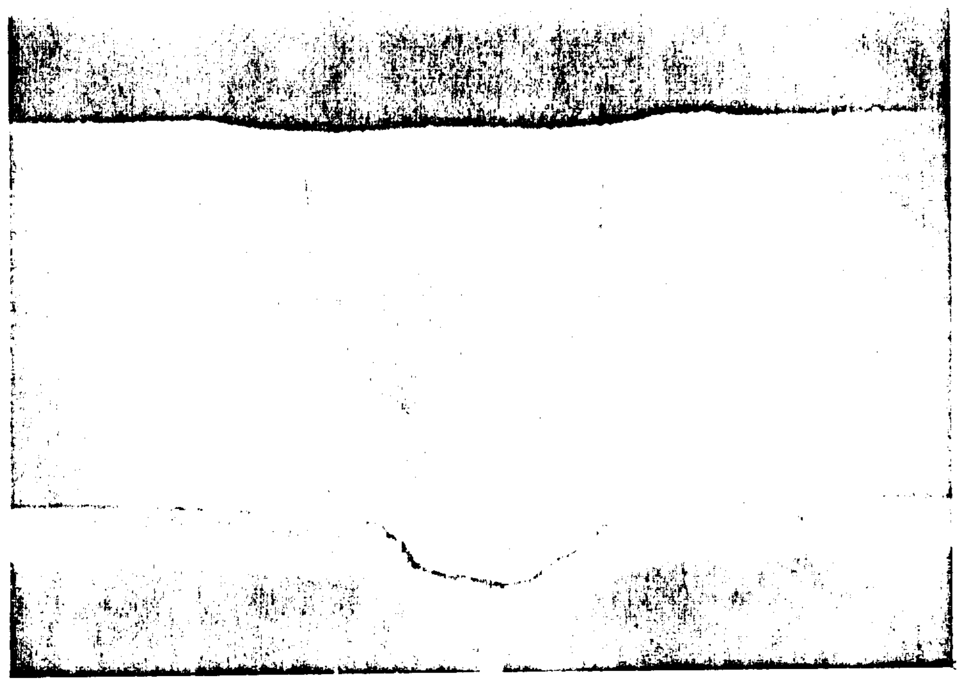


Fig. 3-40A Weld made with 100 ppm Hydrogen in arc. Cover. Front.
1j,1n

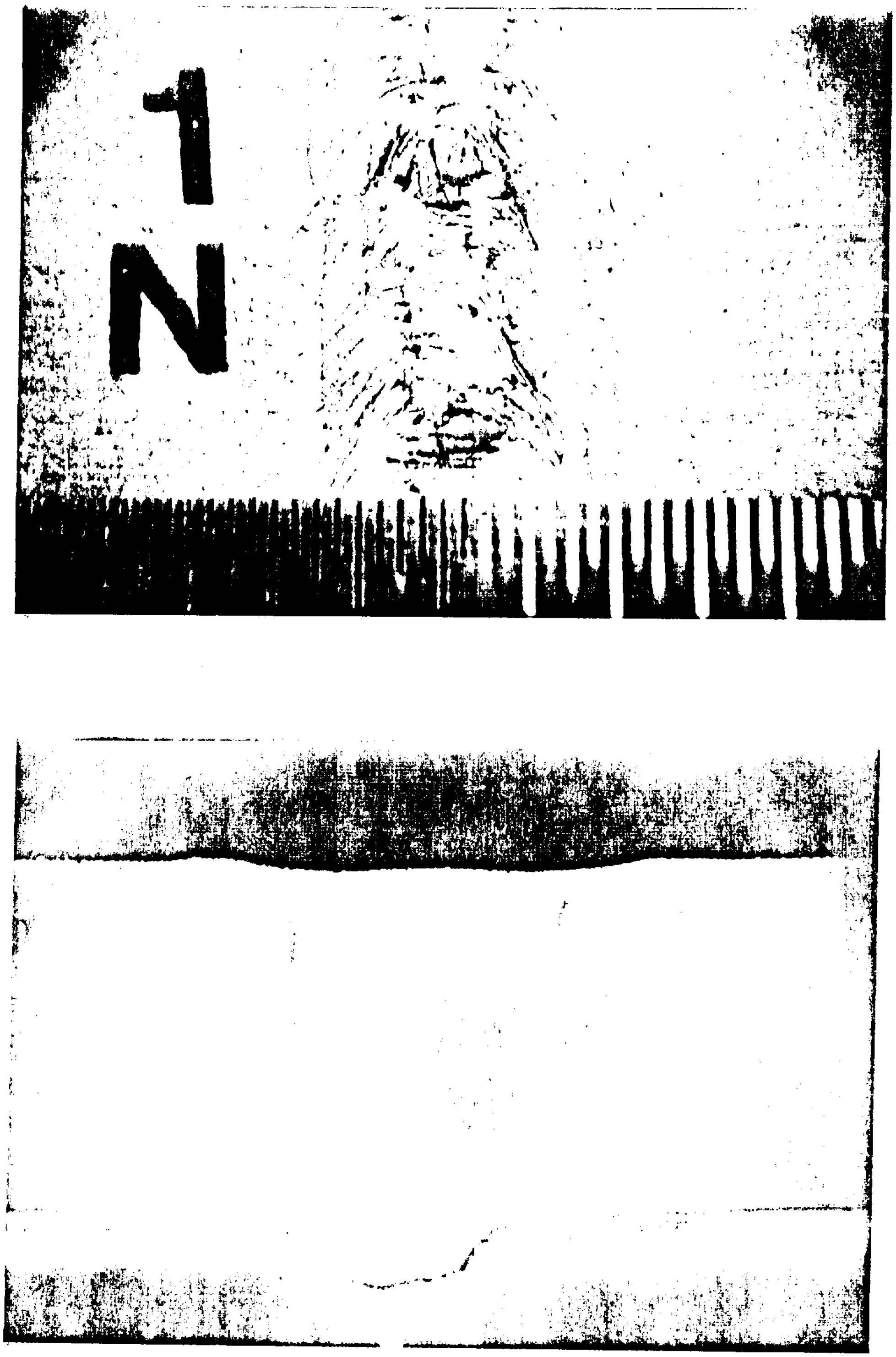


Fig. 3-40B Weld made with 100 ppm Hydrogen
in arc. Cover. Back.

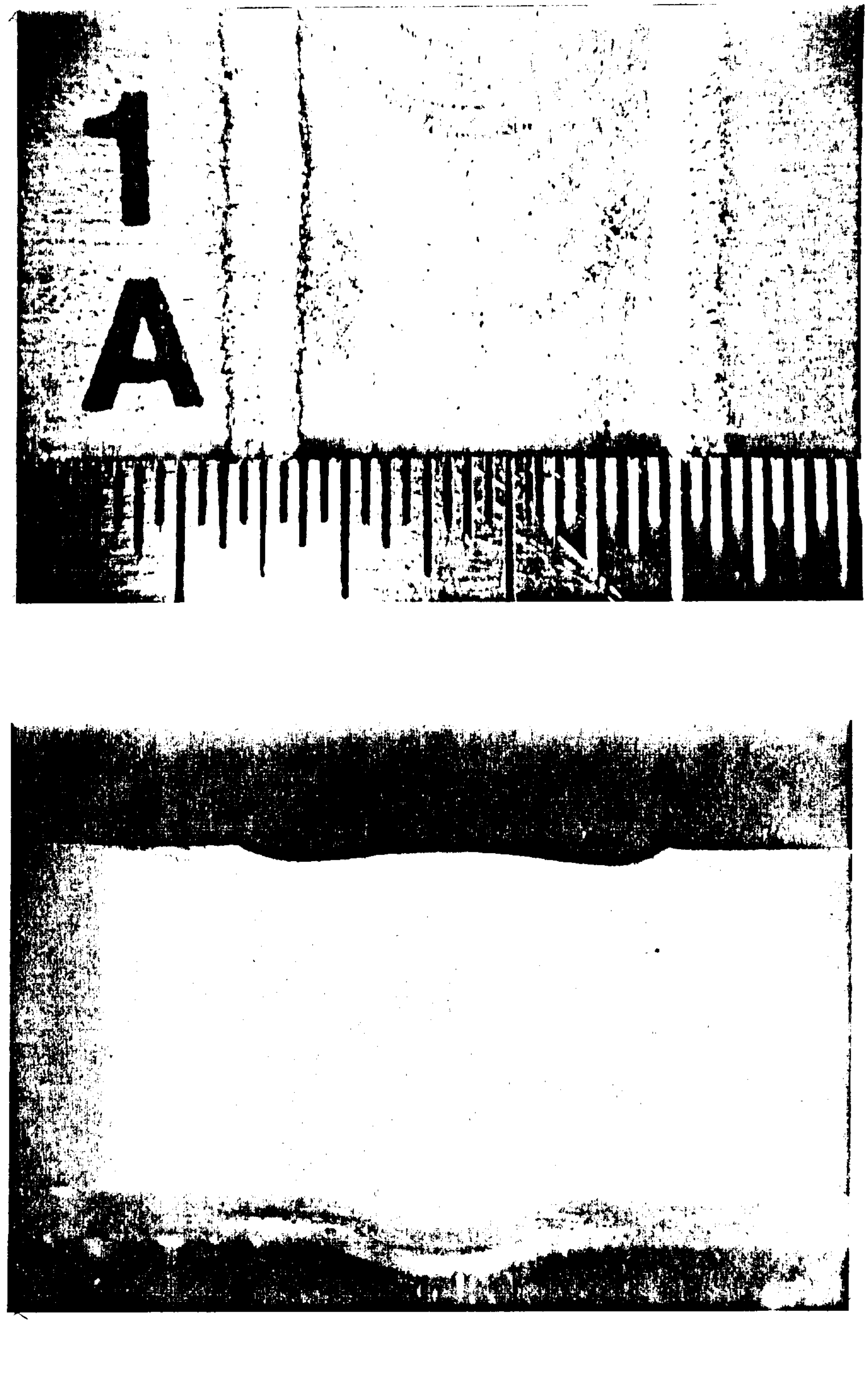


Fig. 3-41A Weld made with 25 ppm Hydrogen in arc. Keyhole. Front.
1a,1e

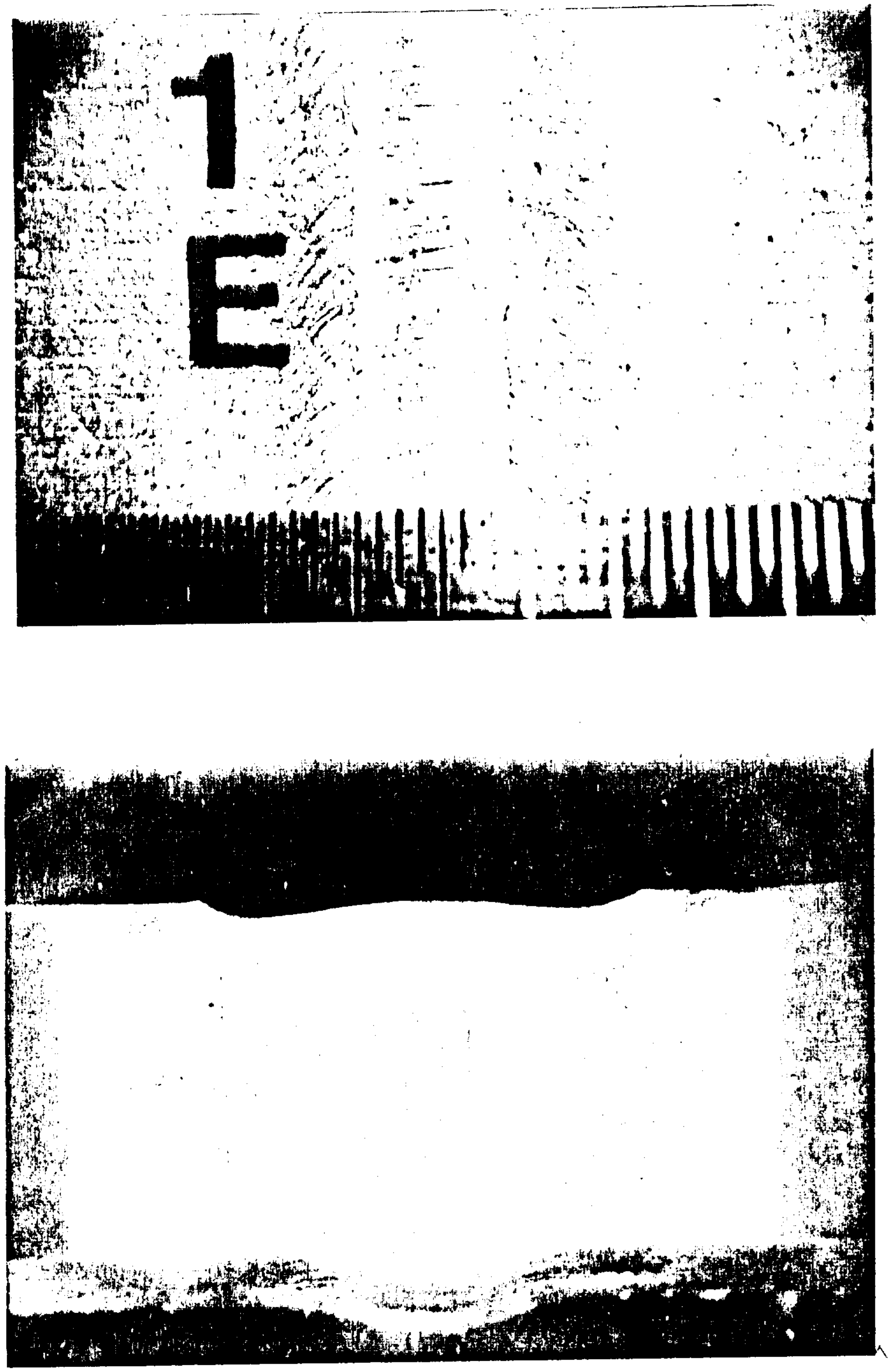
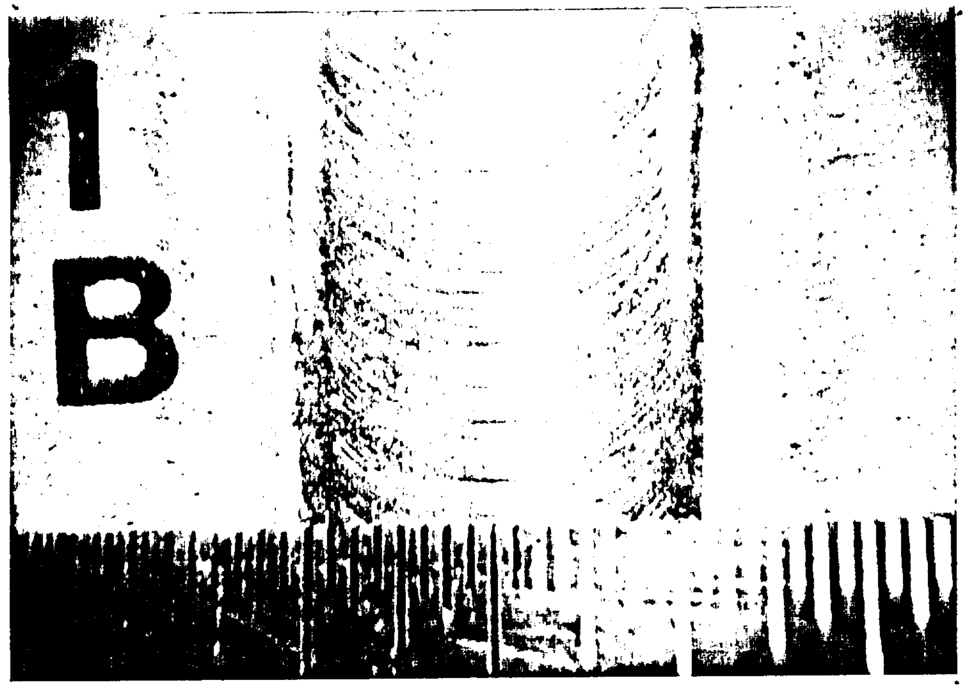


Fig. 3-41B Weld made with 25 ppm Hydrogen in arc. Keyhole. Back.



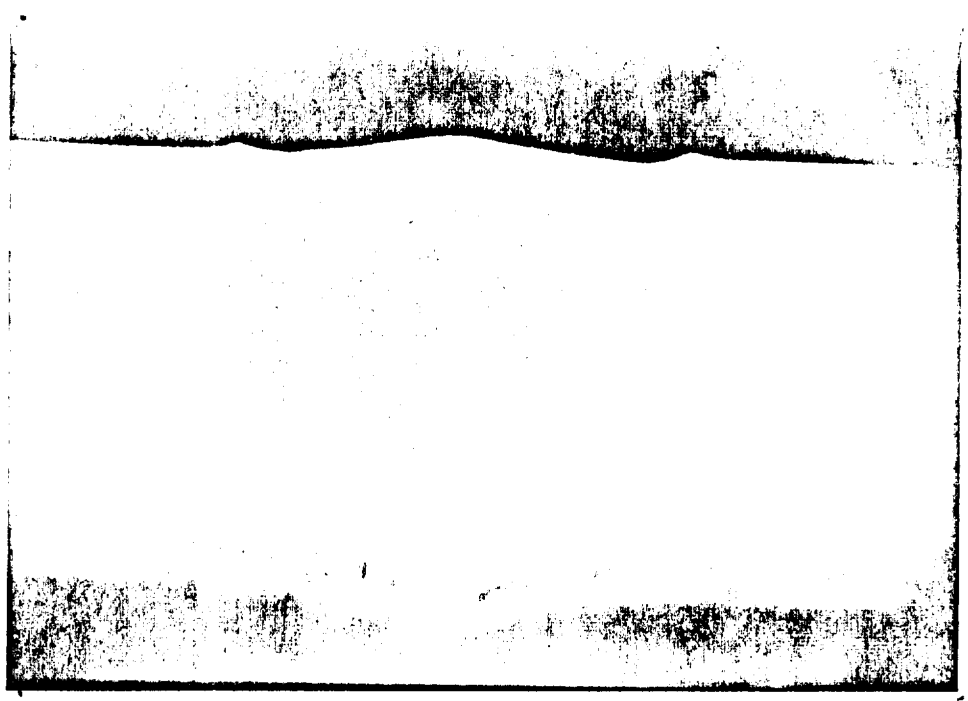


Fig. 3-42A Weld made with 25 ppm Hydrogen
in arc. Cover. Front.
1b,1f

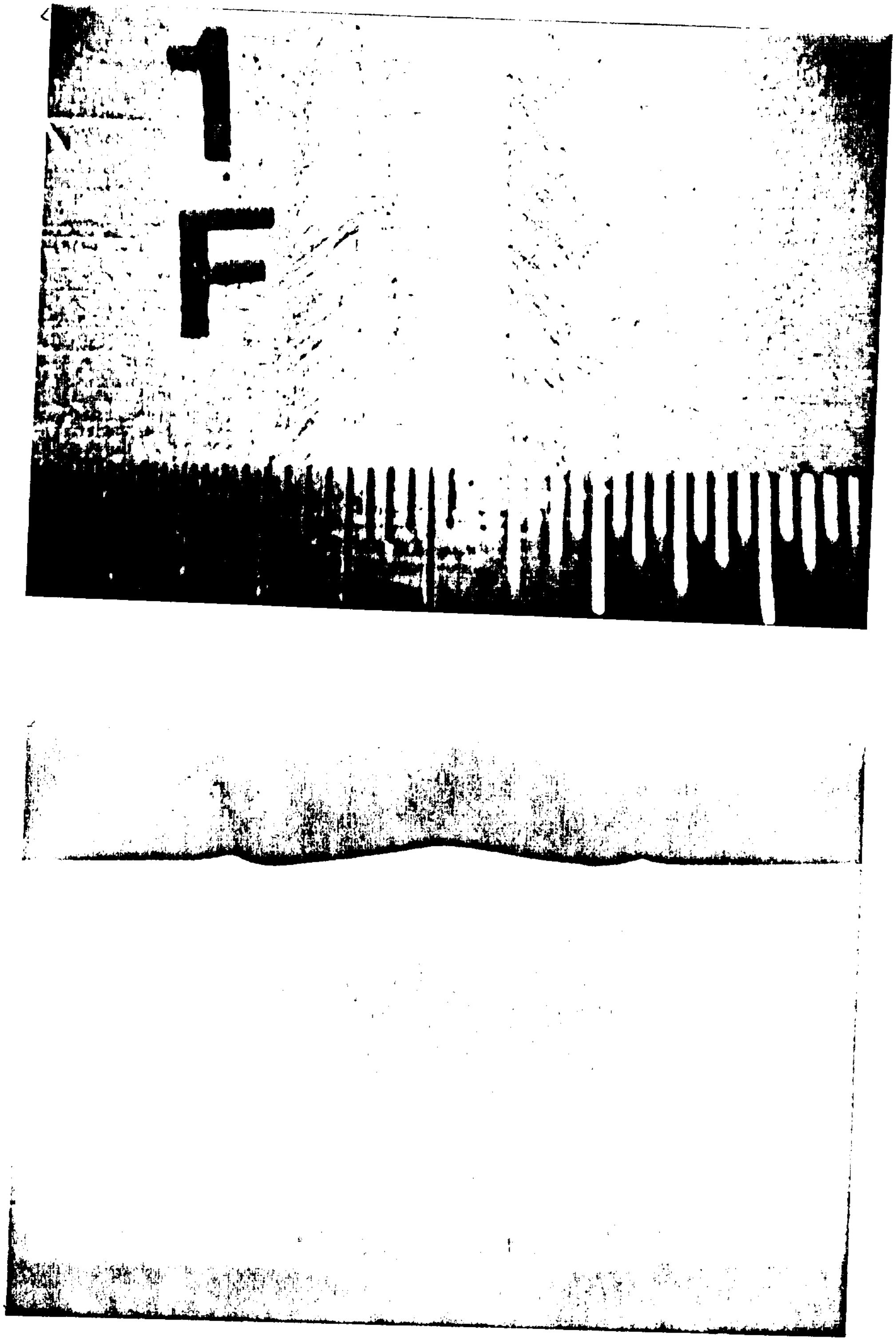


Fig. 3-42B Weld made with 25 ppm Hydrogen in arc. Cover. Back.

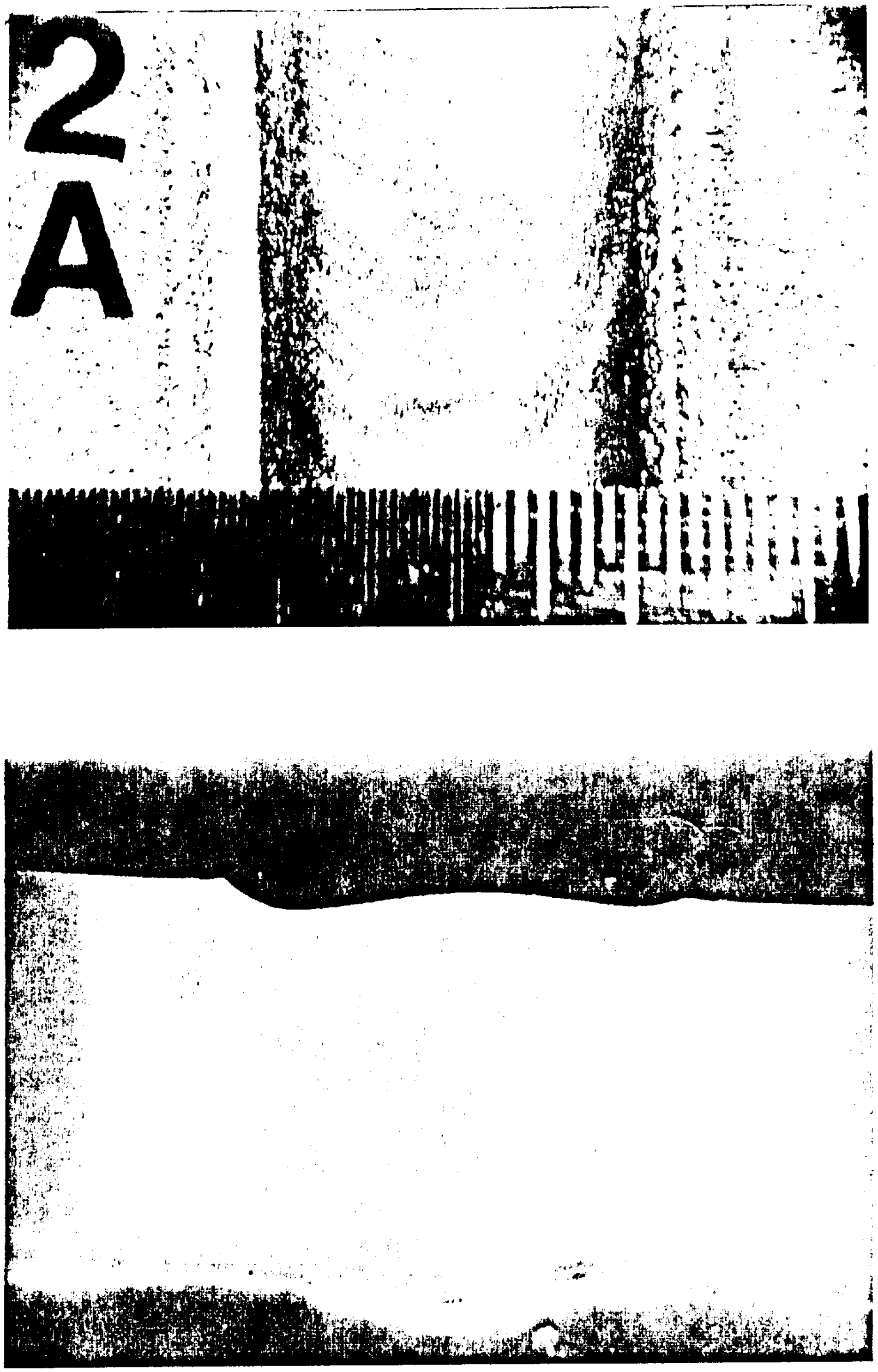
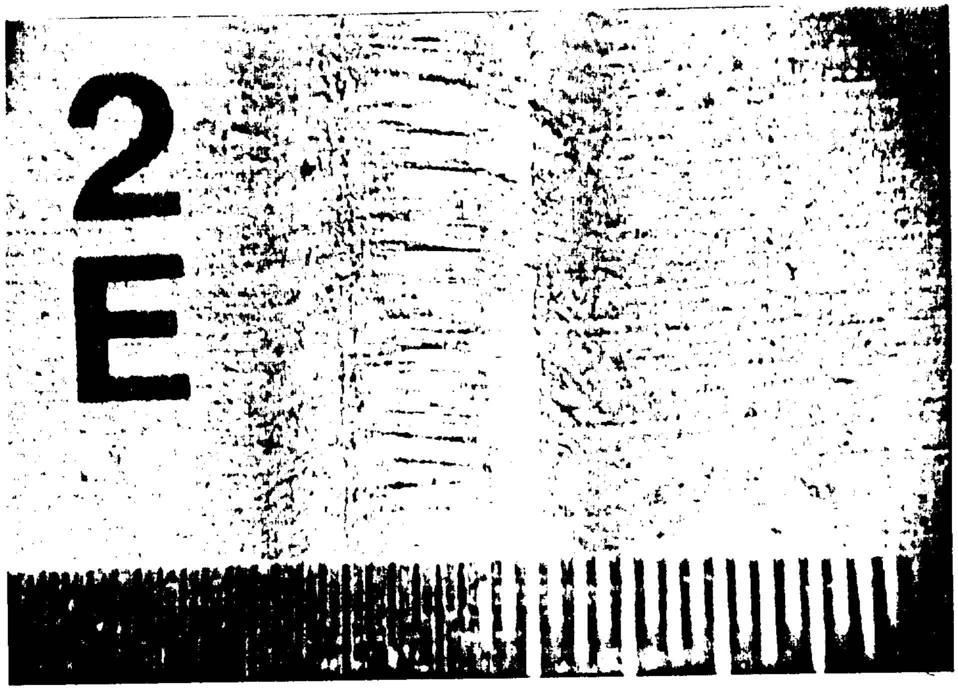


Fig. 3-43A Weld made with 10 ppm Hydrogen in arc. Keyhole. Front.
2a,2e



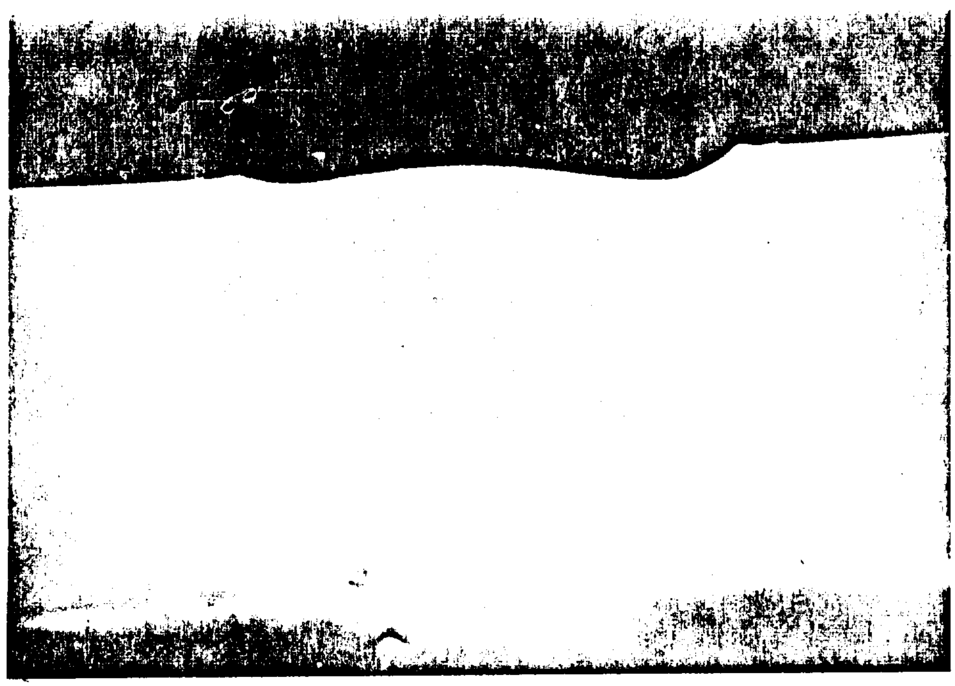


Fig. 3-43B Weld made with 10 ppm Hydrogen in arc. Keyhole. Back.

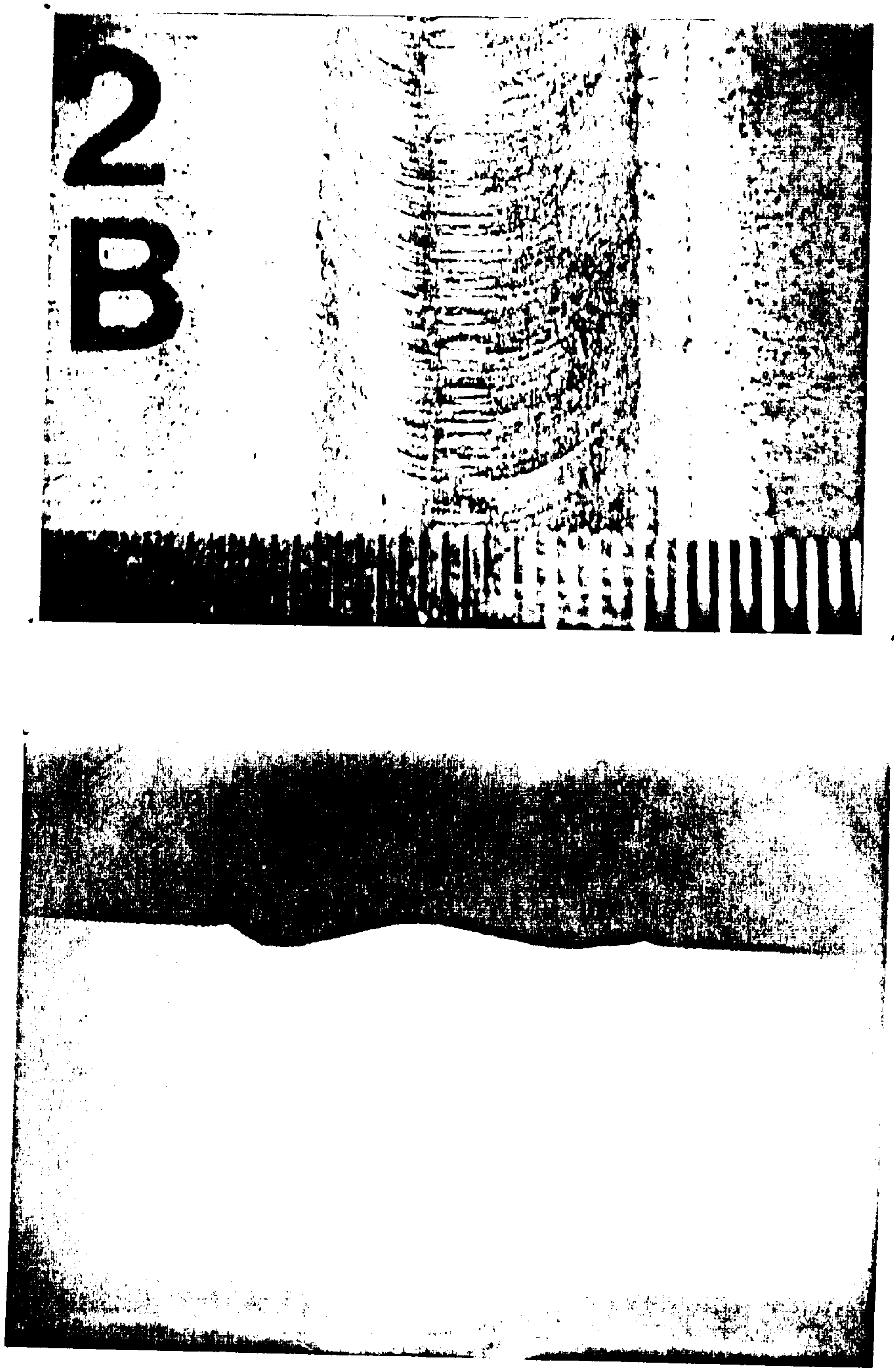
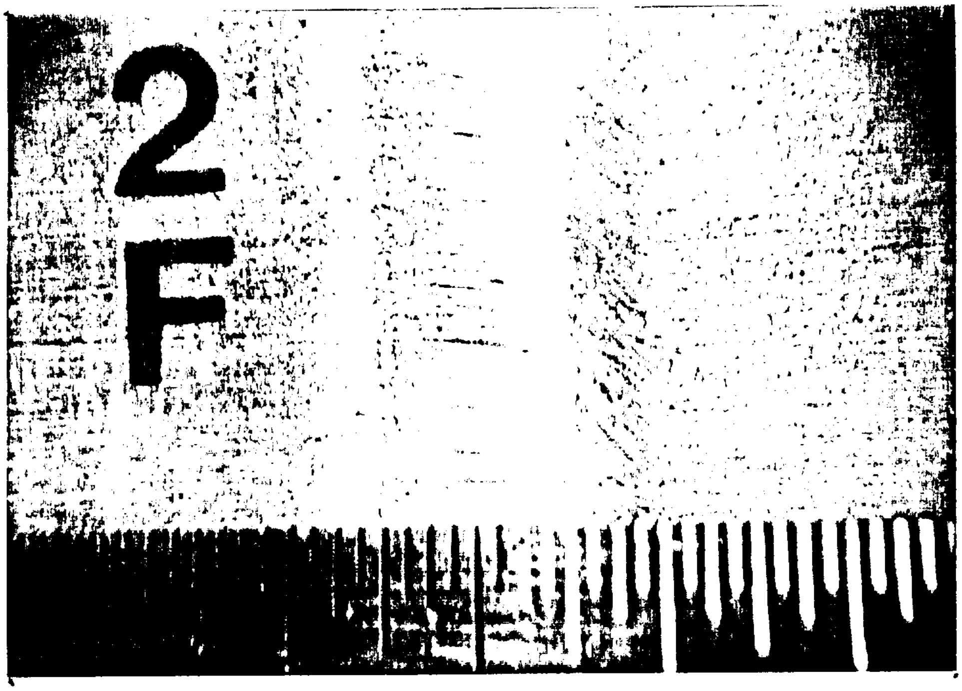


Fig. 3-44A Weld made with 10 ppm Hydrogen in arc. Cover. Front.
2b,2f



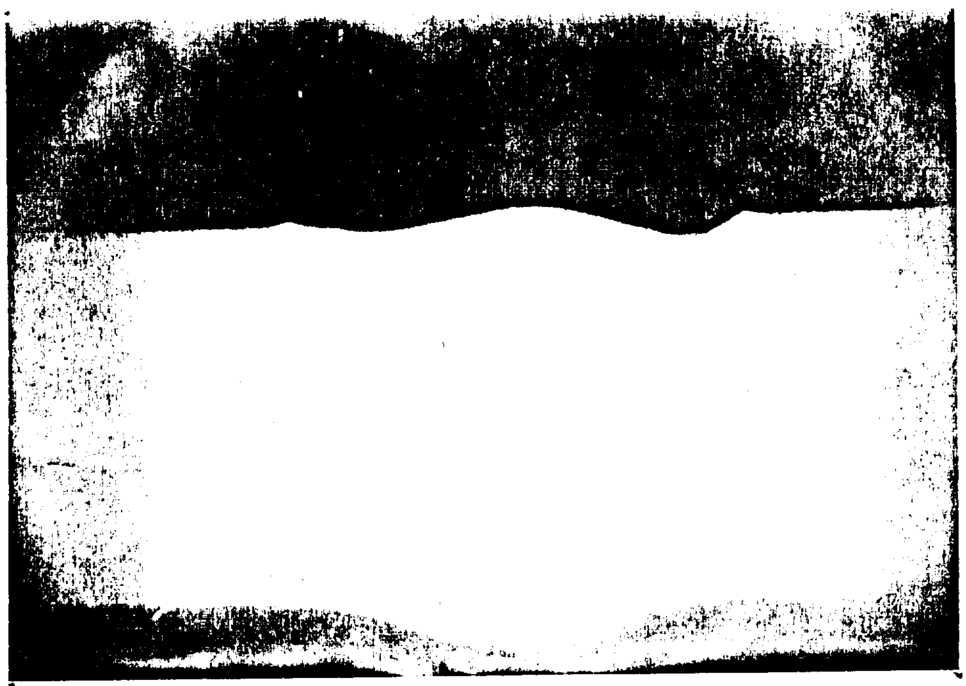


Fig. 3-44B Weld made with 10 ppm Hydrogen in arc. Cover. Back.

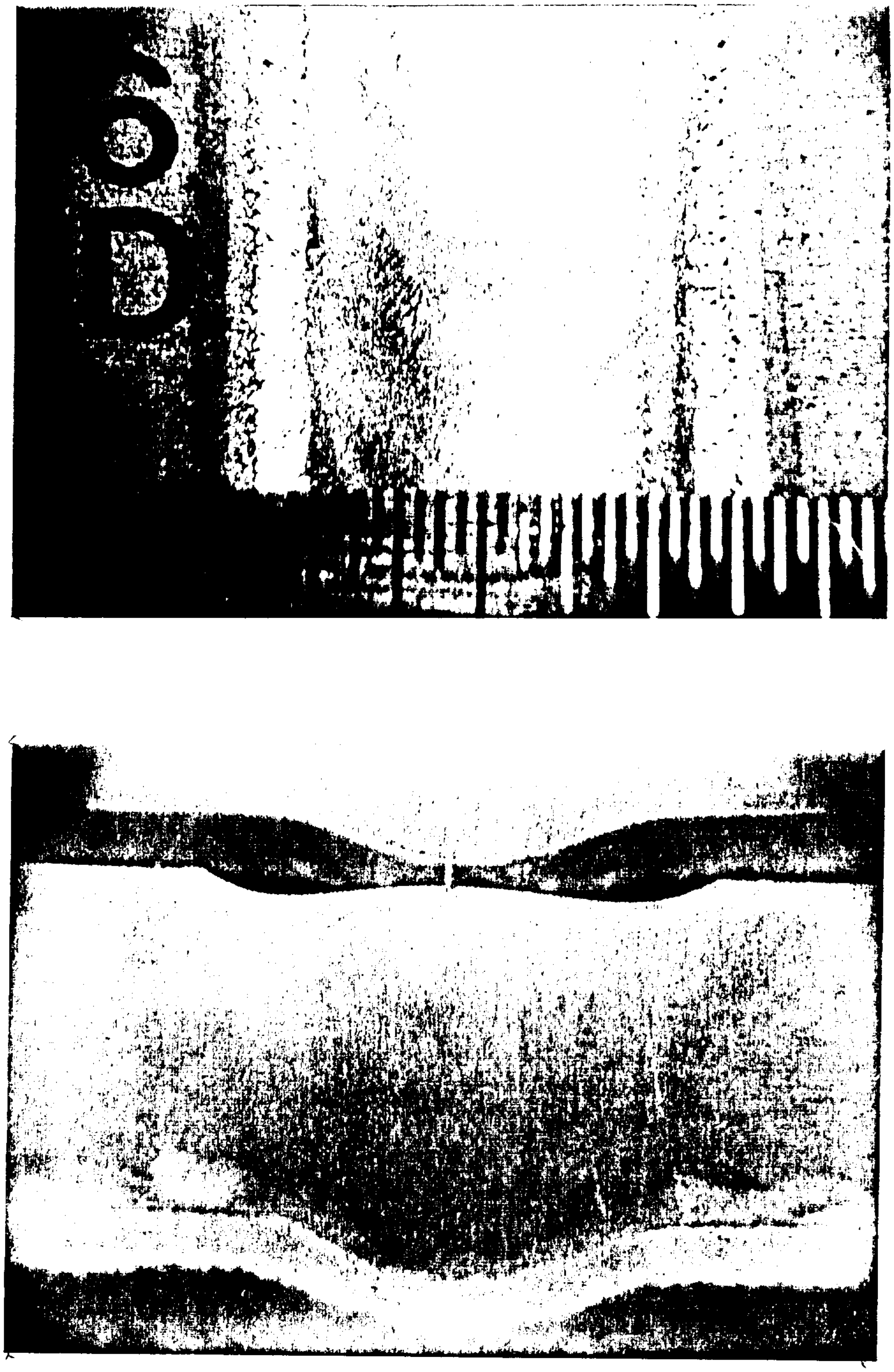


Fig. 3-45A Pure gas weld.
Keyhole. Front

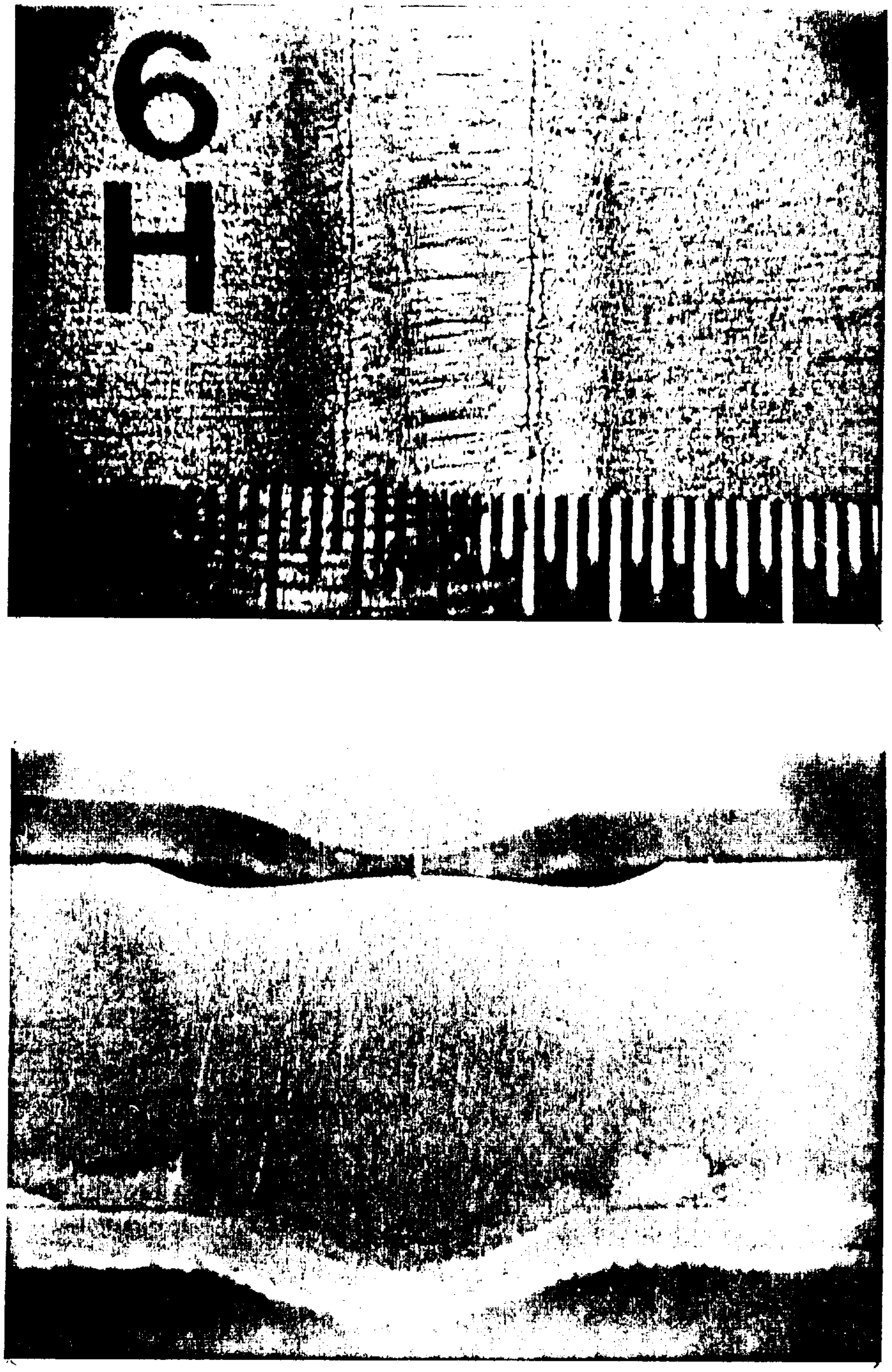
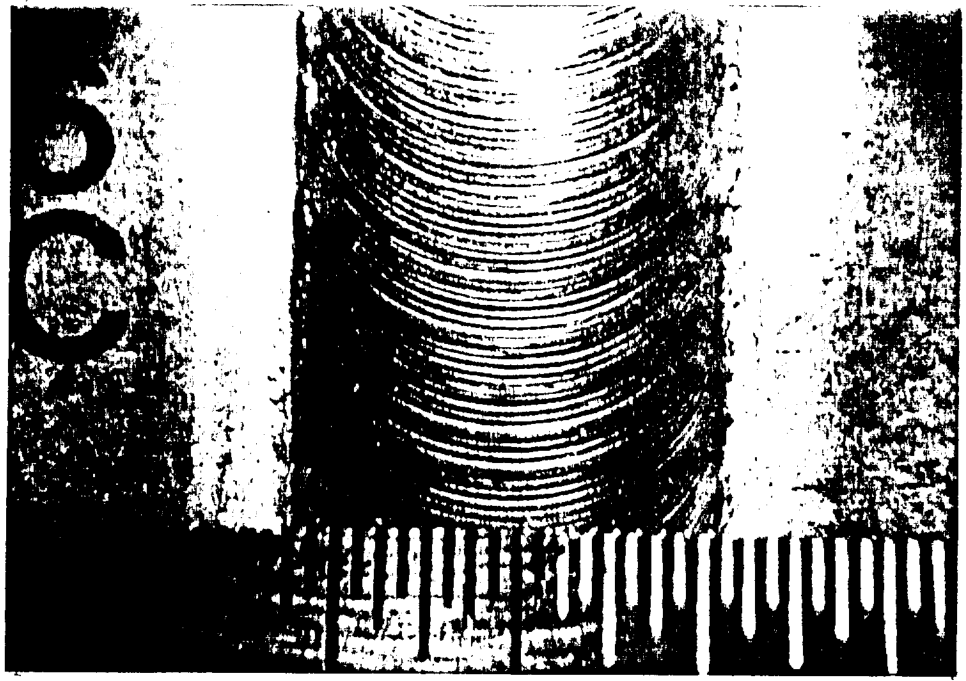


Fig. 3-45B Weld made with pure gas.
Keyhole. Back.



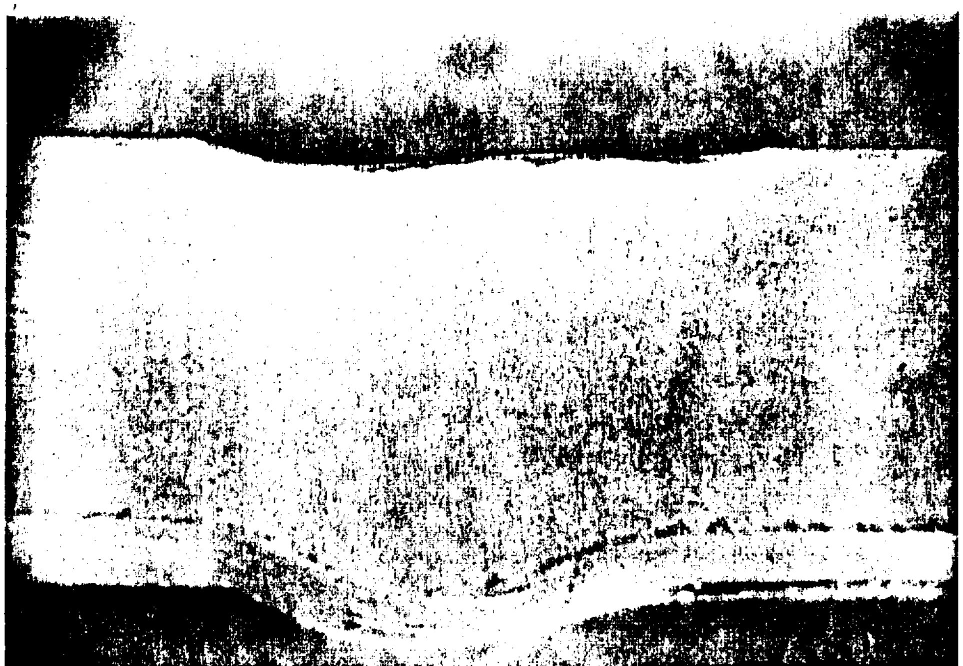


Fig. 3-46A Weld made with pure gas.
Cover. Front.

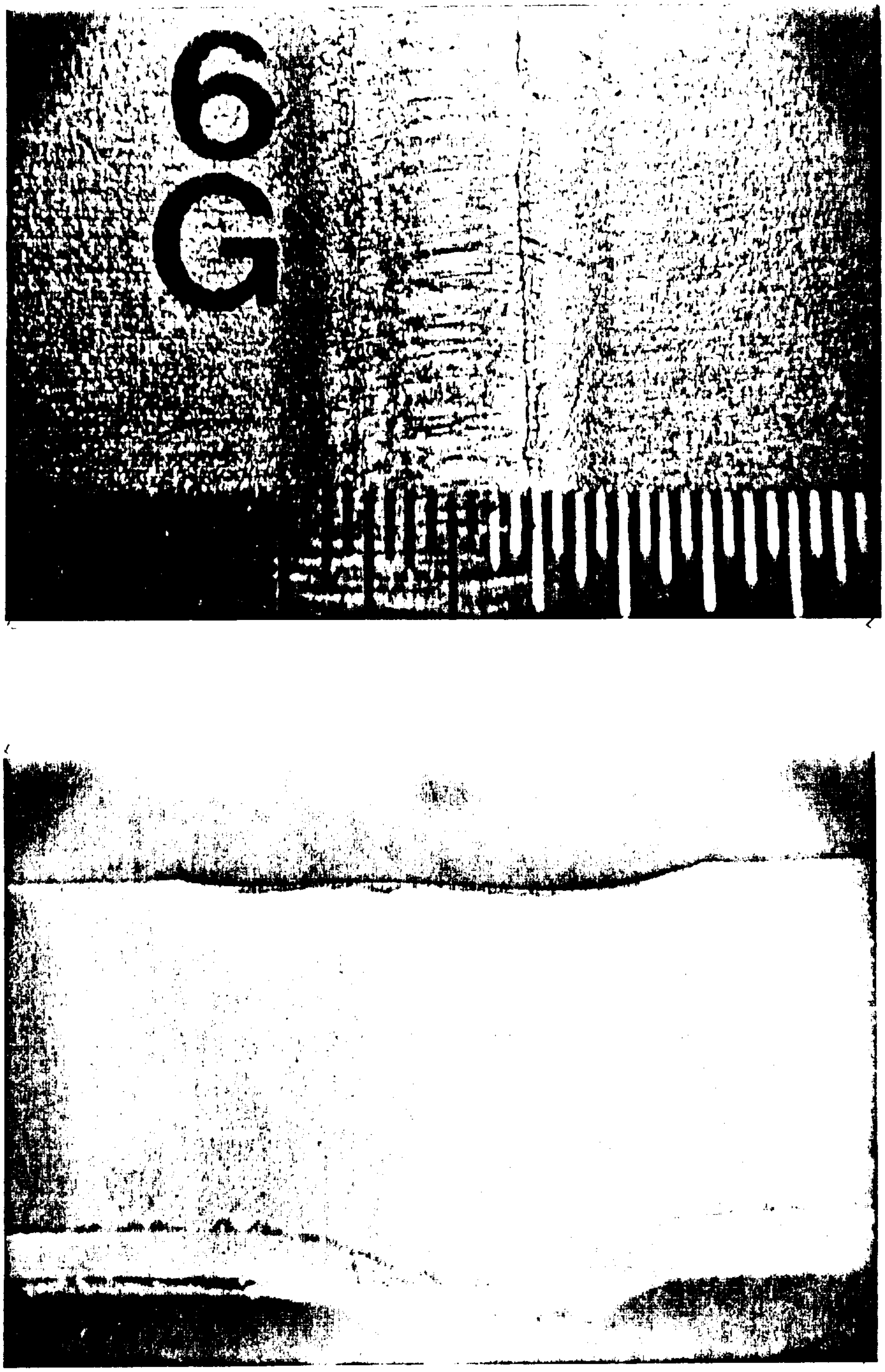


Fig. 3-46B Weld made with pure gas.
Cover. Back.

FRONT SURFACE IN COVER PASS SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
very slight ripples	650 ppm-very fine regular ripples	400 ppm-no cover possible	520 ppm-fine ripples	500 ppm-heavy ripple
	325 ppm-fine ripples	250 ppm-no cover possible	260 ppm-smooth ripples	250 ppm-moderate ripples
		100 ppm-moderate ripples		50 ppm-moderate ripples
				20 ppm-very slight ripples

FRONT SURFACE TEXTURE OF KEYHOLE PASS
SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
smooth	650 ppm-smooth; undercut	400 ppm-extremely disturbed, poor metal flow	520 ppm-smooth	500 ppm-well ripples
	325 ppm-slight ripples undercut	250 ppm-extreme ripples, border-line major flow disturbance	260 ppm-smooth	250 ppm-slight ripples
				50 ppm-slight ripples
	100 ppm-slight ripple	100 ppm-slight ripple		20 ppm-smooth

GRANULAR EXTRUSIONS IN KEYHOLE PASS
SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
slight	650 ppm-none	400 ppm-moderate on nonundercut side	520 ppm-none	500 ppm-very heavy large
	325 ppm-none	250 ppm-moderate	260 ppm-none	250 ppm-heavy
	100 ppm-slight	100 ppm-moderate some are inside weld bead		50 ppm-moderate
				20 ppm-slight

BACK SURFACE TEXTURE
SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
fine smooth ridges evenly spaced	650 ppm-slight ridges angled toward undercut side	400 ppm-dull patches appear black, very coarse ridges	520 ppm-fine ridges	500 ppm-very rough irregular
	325 ppm-slight ridges angled toward undercut side	250 ppm-coarse ridges	260 ppm-fine ridges	250 ppm-moderate ridging
				50 ppm-moderate ridging
	100 ppm-slight ridges	100 ppm-moderate ridges		20 ppm-slight ridging

GRANULAR EXTRUSIONS IN COVER PASS
SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
slight	650 ppm-moderate+ on undercut side	400 ppm-no cover possible	520 ppm-moderate (+) some inside weld	500 ppm-heavy some inside weld bead
	325 ppm-moderate	250 ppm-borderline unweldable no cover	260 ppm-moderate only on edges	250 ppm-heavy some inside weld bead
		100 ppm-moderate		50 ppm-moderate
				20 ppm-moderate

REFLECTIVITY OF COVER PASS SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
1	650 ppm-1	400 ppm-no cover	520 ppm-1+	500 ppm-1
	325 ppm-2	250 ppm-no cover	260 ppm-1	250 ppm-1
				50 ppm-1
		100 ppm-2		20 ppm-1

1=dull
2=shiny

REFLECTIVITY OF KEYHOLE PASS
SHIELD CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
1	650 ppm-1	400 ppm-none	520 ppm-1	
				500 ppm-2
	325 ppm-1	250 ppm-2	260 ppm-1	
				250 ppm-1+
	100 ppm-1	100 ppm-2		50 ppm-1
				20 ppm-1

1=dull, 2=shiny

FRONT SURFACE TEXTURE OF KEYHOLE PASS
ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
smooth	600 ppm-slight ripples, smooth	500 ppm-slight ripples	515 ppm-smooth	250 ppm-cut through sheet
			400 ppm-smooth	100 ppm-slight ripling, under cutting
	300 ppm-slight ripples, smooth	250 ppm-slight ripples	250 ppm-smooth	
		100 ppm-smooth no ripples		25 ppm-free ripples
				10 ppm-smooth

FRONT SURFACE TEXTURE IN COVER PASS
ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
very slight ripples, smoothest	600 ppm-fine smooth ripples	500 ppm-moderate ripples	515 ppm-no ripples, very smooth	250 ppm-unweldable
	300 ppm-fine smooth ripples	250 ppm-moderate ripples	400 ppm-slight ripples, smooth	100 ppm-severe ripples
		100 ppm-slight ripples		25 ppm-moderate ripples
			250 ppm-slight ripples	10 ppm-slight ripples

BACK SURFACE TEXTURE
ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
small smooth evenly spaced ridges	600 ppm-smooth ridges	500 ppm-moderate (+) ridging	515 ppm-very rough (+)	250 ppm-extremely poor metal flow
	300 ppm-smooth ridges	250 ppm-moderate ridging	400 ppm-very rough, slanted toward undercut	100 ppm-irregular poor metal flow
		100 ppm-moderate ridging	250 ppm-moderate ridges	25 ppm-moderate ridges
				10 ppm-slight ridges

GRANULAR EXTRUSIONS IN COVER PASS
ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
Slight	600 ppm-slight	500 ppm-very heavy present in weld bead	515 ppm-slight present in weld bead	250 ppm-nonweldable
	300 ppm-slight	250 ppm-moderate	400 ppm-slight present in weld bead	100 ppm-none
		100 ppm-moderate few in weld bead	250 ppm-slight	25 ppm-slight
				10 ppm-slight

GRANULAR EXTRUSIONS IN KEYHOLE PASS
ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
slight	600 ppm-very slight	500 ppm-moderate many in weld bead	515 ppm-none	250 ppm-unweldable
			400 ppm-none	100 ppm-none
	300 ppm-slight	250 ppm-moderate many in weld bead	250 ppm-slight	
		100 ppm-slight		25 ppm-slight
				10 ppm-slight

REFLECTIVITY COVER ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
1	600 ppm-1	500 ppm-1	515 ppm-2	250 ppm-unweld-able
	300 ppm-1	250 ppm-1	400 ppm-2	100 ppm-2
				25 ppm-1
		100 ppm-1	250 ppm-1	10 ppm-1

1=dull
2=shiny

REFLECTIVITY OF KEYHOLE PASS ARC CONTAMINANTS

PURE	NITROGEN	METHANE	OXYGEN	HYDROGEN
1	600 ppm-1	500 ppm-1	515 ppm-1	250 ppm-unweld-able
	300 ppm-1	250 ppm-1	400 ppm-1	100 ppm-1
			250 ppm-1	25 ppm-1
				10 ppm-1

1=dull
2=shiny