# Nondestructive Tests for Detecting Discontinuities In Aluminum Alloy Arc Welds

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This paper describes an investigation conducted to evaluate radiographic and ultrasonic procedures for detecting 14 types of discontinuity in TIG or MIG arc welds in 2219-T87 aluminum alloy plate, and to determine the effects of these discontinuities on the static strength of the welded joints. The discontinuities studied were microporosity, linear porosity, scattered porosity, oxide inclusions, tungsten inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration, crater cracks, longitudinal cracks, craters, underbead folds and weld bead overlaps. The welds were examined metallographically to aid in establishing or confirming the types of discontinuity present.

Although the above work was done on 2219-T87 aluminum alloy plate, the nondestructive tests employed could also be applied to other aluminum alloys.

This investigation represents a portion of the work done on NASA Research Contract No. NAS 8-5132 on the Arc Welding of 2219 Alloy.

•WELDS of high structural integrity have been made in aluminum alloys for many years, but as in any other metal, the consistent production of such welds depends upon the use of suitable equipment and the skill and care of the welder. For these reasons, appropriate nondestructive testing procedures are necessary for determining the quality of welds in structures.

While there has been wide experience in welding and inspecting aluminum alloy weldments, there have been few data on the size and distribution of discontinuities in welds coupled with the effect on the static strength. Another area where there has been little reported work concerns the relative accuracy of radiography and ultrasonic techniques in examining aluminum alloy weld structures.

Although some data indicating relative capabilities of these nondestructive tests were obtained, no attempts were made to establish inspection standards or to develop specifications. These data should be helpful in this connection, but additional research and development is necessary before realistic inspection standards and specifications can be established.

Aluminum alloy 2219 is used extensively in welded missile structures because it exhibits good welding characteristics, uniformity of weld strength, resistance to stress corrosion cracking, and high strength at ordinary, elevated, and cryogenic temperatures. This investigation was undertaken in conjunction with a NASA research contract on the arc welding of 2219 alloy to obtain data that would be of use in establishing nondestructive testing procedures for welded joints in 2219 alloy plate. Although the radiographic and ultrasonic testing procedures discussed were employed to evaluate welds in 2219 alloy plate, the same procedures also can be applied to other aluminum alloys that might be used in highway applications.

Fourteen different types of discontinuities were deliberately introduced into a group of welded plate samples, which also included relatively sound welds (for controls).

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TABLE 1

WELD CONDITIONS CONSIDERED IN INVESTIGATION

| General Type | Specific Condition |
|---|---|
| Relatively Sound | Relatively Sound |
| Porosity | Microporosity<br>Linear Porosity<br>Scattered Porosity |
| Inclusions | Oxide Inclusions<br>Tungsten Inclusions |
| Lack of Fusion or Penetration | Lack of Interpass Fusion<br>Lack of Root Fusion<br>Lack of Side Fusion<br>Incomplete Root Penetration |
| Cracks | Crater Cracks<br>Transverse Cracks*<br>Longitudinal Cracks† |
| Miscellaneous | Craters<br>Underbead Fold<br>Weld Bead Overlap |

* *Transverse cracks were eliminated from the investigation after a number of attempts to produce such cracks failed.*

† *Investigated to only a very limited extent because of difficulty in producing such cracks.*

TABLE 2

TENSILE PROPERTIES OF 2219-T87 PLATE USED FOR WELDED PANELS*

| Designation | Plate Thickness | T.S. psi | Y.S. psi | Red. of Area-% | Elong. % |
|---|---|---|---|---|---|
| Lot A | 1/2" | 71100 | 59400 | 20 | 10† |
| Lot B | 1/2" | 67750 | 55200 | 22 | 10† |
| Lot C | 1" | 68850 | 56800 | 20 | 9** |

* *Properties are averages for two tests. Specimens from 1/2" plate had nominal diameter of 1/4"; those from 1" plate had nominal diameter of 1/2". All specimens were taken in the transverse direction.*

† *Elongation in 1" gage length.*

***Elongation in 2" gage length.*

The weld in each sample was subjected to radiographic examinations and ultrasonic tests employing conventional and some experimental procedures. The two series of tests were performed to determine which of the test methods is the more suitable in each instance. Reduced section tensile and guided bend tests on specimens containing portions of the various welds finally were conducted to determine the effect of the weld conditions on joint strength and ductility. Auxiliary phases of the work included metallographic studies to verify the types of discontinuity or to explain their effects on the properties of the joints, and fracture studies for the same purposes.

The weld conditions considered in the investigation are given in Table 1.

## PREPARATION OF WELDED PANELS

Plate of 2219 alloy and filler wire of 2319 alloy were used for the welded panels prepared for this investigation. The tensile properties of the unwelded plate are given in Table 2. One series of panels was fabricated from ½-in. plate and a second from 1-in. plate. The panels were 18 × 24 in. and were made by joining two 12 × 18 in. pieces of plate by a weld running along an 18-in. edge. In general, single-V butt joints were used in the ½-in. panels and double-V butt joints in the 1-in. panels. However, additional ½- × 18- × 24-in. panels were prepared with square butt joints welded in two passes (one on each side) with various degrees of weld penetration.

All welds were made by tungsten or consumable electrode inert-gas shielded arc welding (TIG or MIG). These procedures eliminate the need for flux and are used extensively for the welding of aluminum alloys. Joint preparation and welding procedures were varied to achieve the desired weld conditions. For example, the degree of penetration was controlled by varying such factors as root spacing, welding current and welding speed. Lack of fusion was achieved by the use of relatively cold passes at appropriate stages in the welding operation. Oxide inclusions were introduced by reducing the flow of inert gas to the point where shielding was no longer sufficient to prevent oxidation. An oiled liner in the electrode hose was used in some instances to produce porous welds. Tungsten inclusions were produced with the TIG procedure by jogging the arc on and off. Craters and crater cracks were produced by a backstepping procedure that interrupted the continuity of the welding operation.

In several instances it was necessary to produce "synthetic" defects by procedures that would not be encountered in ordinary welding operations. For example, longitudinal porosity was simulated in one instance by drilling small holes in the root pass and then covering them with a cold pass. These simulated defects were useful for checking the capabilities of the nondestructive testing procedures but such defects were not included in the mechanical property tests because the results would be misleading.

TABLE 3

IDENTIFICATION OF PANELS EXEMPLIFYING VARIOUS WELD CONDITIONS

| Nominal Weld Condition | Plate Thickness | Type of Joint | Type of Weld | Identification of Panel | |
|---|---|---|---|---|---|
| | | | | ARL S No. | APDL No. |
| Relatively Sound | 1/2" | Single-V Butt | TIG | 278454 | 1 |
| Relatively Sound | 1" | Double-V Butt | MIG | 278515 | 9B2 |
| Microporosity | 1/2" | Single-V Butt | MIG | 278491 | 9A1 |
| Microporosity | 1/2" | Single-V Butt | MIG | 278490 | 9A2 |
| Microporosity with Some Scattered Porosity | 1/2" | Single-V Butt | TIG | 278462 | 6A |
| Linear Porosity | 1/2" | Single-V Butt | MIG | 278492 | 10A1 |
| Linear Porosity (Artificial) | 1" | Double-V Butt | MIG | 278501 | 10B2 |
| Scattered Porosity | 1/2" | Single-V Butt | MIG | 278496 | 11A2 |
| Light Randomly Scattered Porosity | 1" | Double-V Butt | MIG | 278509 | 11B2 |
| Scattered Porosity | 1" | Double-V Butt | MIG | 278596 | 11B3 |
| Oxide Inclusions | 1/2" | Single-V Butt | MIG | 278598 | 12A5 |
| Oxide Film | 1" | Double-V Butt | TIG | 278549 | A5 |
| Tungsten Inclusions | 1/2" | Single-V Butt | TIG | 278456 | 53 |
| Tungsten Inclusions | 1/2" | Single-V Butt | TIG | 278486 | 53A |
| Lack of Interpass Fusion | 1/2" | Single-V Butt | MIG | 278493 | 5A1 |
| Lack of Interpass Fusion | 1" | Double-V Butt | MIG | 278516 | 5B1 |
| Lack of Root Fusion | 1/2" | Single-V Butt | TIG | 278459 | 26B |
| Lack of Root Fusion | 1" | Double-V Butt | MIG | 278511 | 6B2 |
| Lack of Side Fusion | 1/2" | Single-V Butt | MIG | 278597 | 7A4 |
| Lack of Side Fusion | 1" | Double-V Butt | MIG | 278518 | 7B1 |
| Incomplete Root Penetration | 1/2" | Single-V Butt | MIG | 278488 | 8A1 |
| Incomplete Root Penetration | 1" | Double-V Butt | MIG | 278504 | 8B2 |
| Internal Longitudinal Crack | 1" | Double-V Butt | MIG | 278495 | 3B2 |
| Craters (Face Pass) | 1/2" | Single-V Butt | MIG | 278522 | 2A1 |
| Craters (Face Pass) | 1" | Double-V Butt | MIG | 278514 | 2B2 |
| Craters (Root Pass) | 1/2" | Single-V Butt | TIG | 278461 | 46 |
| Underbead Fold | 1/2" | Single-V Butt | MIG | 278502 | 13A1 |
| Underbead Fold | 1" | Single-V Butt | MIG | 278505 | 13B1 |
| Weld Bead Overlap | 1/2" | Single-V Butt | MIG | 278519 | 14A1 |
| Weld Bead Overlap | 1" | Single-V Butt | MIG | 278512 | 14B1 |
| Reasonably Sound (Used for Reheat Treating Tests) | 1" | Double-V Butt | TIG | 278548 | A4 |
| Complete Penetration with Roots of Weld Beads Inter-penetrating about 1/8" | 1/2" | Square Butt | TIG | 285185 | – |
| Same as Preceding | 1/2" | Square Butt | TIG | 285321 | – |
| Penetration Barely Complete with Roots of Weld Beads Just Touching | 1/2" | Square Butt | TIG | 285322 | – |
| Incomplete Penetration with Separation of about 1/64" Between Roots of Weld Beads | 1/2" | Square Butt | TIG | 285323 | – |
| Incomplete Penetration with Separation of about 3/64" Between Roots of Weld Beads | 1/2" | Square Butt | TIG | 285324 | – |
| Incomplete Penetration with Separation of about 1/16" Between Roots of Weld Beads | 1/2" | Square Butt | TIG | 285187 | – |
| Same as Preceding | 1/2" | Square Butt | TIG | 285326 | – |
| Incomplete Penetration with Separation of about 1/8" Between Roots of Weld Beads | 1/2" | Square Butt | TIG | 285221 | – |
| Penetration Varying from Complete to Incomplete (Sample from NASA) | 1" | Square Butt | TIG | 278550 | – |

After a number of unsuccessful attempts to produce welds containing transverse cracks, it was concluded that the occurrence of this type of defect was extremely unlikely in inert gas shielded welds made in 2219 alloy plate with 2319 alloy filler, so further attempts were abandoned. It was likewise not possible to produce longitudinal cracks in any actual welding operation although a number of restraining schemes were used. This experience indicates that the occurrence of longitudinal cracks also is unlikely with the above welding procedure and alloys. A synthetic internal longitudinal crack was finally made by bending the panel after one or two passes had been laid down and then applying a cold pass over the resulting crack.

Table 3 gives the identification of the panels exemplifying the various weld conditions, the plate thickness, the type of joint and the welding procedure.

If the subsequent radiographic examination indicated that the desired weld condition had not been achieved, the panel was discarded, and an additional panel was welded with appropriate alterations in joint preparation and welding practice. In some instances sections were cut from the joints and examined to confirm the weld conditions.

A further check on the weld conditions was obtained from the ultrasonic, metallographic and tensile tests and from the examination of fractures in the tensile specimens. Some additional panels were made during the final stages of the test program when it became apparent that certain of the welds did not represent the desired weld conditions or the desired degrees of severity of those conditions.

The welded panels prepared by Alcoa for this investigation were supplemented by five panels with square butt welded joints received from the George C. Marshall Space Flight Center at Huntsville, Ala. (ARL S Nos. 290963 to S290967, inclusive). These panels were submitted primarily for a further evaluation of ultrasonic tests for detecting slight amounts of incomplete penetration which are discussed in a subsequent portion of this paper.

## RADIOGRAPHIC EXAMINATION

In the initial examination of each panel, practically the entire length of the weld was radiographed. These radiographs are subsequently referred to as the "full-length" radiographs. When the ultrasonic tests were completed, a 24- × 5-in. section containing a 5-in. length of weld was cut from each panel and retained as a reference sample. The welds in these radiographic panels were re-radiographed after the panels had been cut from the original weldments. These sections, which are subsequently referred to as the "radiographic panels," were reserved for the production of additional radiographs if required.

Two General Electric Co. OX-140 radiographic units were used for the radiographic examinations. Table 4 gives the exposure conditions and types of film used.

The full-length radiographs provided a valuable basis for screening the panels to separate weld conditions suitable for use in the investigation from those that were not. In most instances, the radiographs of the panels selected for further study indicated that the desired weld conditions persisted over a significant portion of the weld length.

Table 5 lists the weld conditions that could be detected radiographically with reasonable assurance, those that could not be detected in this way, and those for which detection was questionable. The radiographic observations in Table 5 are based on three groups of radiographs: the full-length radiographs, those of the 5" radiographic sections and those of the tensile and bend specimens.

The weld conditions detected with reasonable assurance were linear porosity, scattered porosity, tungsten inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration, craters and crater cracks. Detection of incomplete root penetration in square butt welds became uncertain when the separation between the roots of the weld beads was about $1/16$ in. or less.

The conditions that were not detected radiographically were microporosity and an internal longitudinal crack. In the questionable detection category were oxide inclusions, underbead folds and weld bead overlaps. The oxide inclusions were quite apparent in the radiograph of a rather extreme example (S278596) produced by welding with a deficiency of shielding gas. However, an oxide film condition (S278549) was not observed radiographically. This undetected condition prevented proper bonding of weld metal to plate metal and seriously weakened a portion of the joint. Underbead folds and weld bead overlaps show up in radiographs as would unusually thick weld crowns or weld crowns with an unsymmetrical distribution of metal. It is difficult to determine radiographically whether the metal is actually fused into the surface of the plate or merely folded over mechanically. Ordinarily, underbead folds and weld bead overlaps can be more readily identified by a visual inspection of the weld.

TABLE 4

RADIOGRAPHIC EXPOSURE CONDITIONS AND TYPE OF FILM*

| Type of Specimen | Position in Which Radiographed | Thickness Penetrated by X-Ray | KVP | Exposure Time | Film |
|---|---|---|---|---|---|
| 24" × 18" panel of 1/2" plate (single-V groove) | normal† | 1/2"** | 70-80 | 135-150 sec. | Kodak AA |
| 24" × 18" panel of 1/2" plate (square butt joint) | normal | 1/2" | 66 | 5 min. | Ansco Superay "B" |
| 24" × 18" panel of 1" plate | normal | 1" | 105 | 3 min. | Kodak AA |
| 24" × 5" radiographic panel of 1/2" plate | normal | 1/2" | 66 | 5 min. | Ansco Superay "B" |
| 24" × 5" radiographic from 1/2" panel | normal | 1" | 94 | 5 min. | Ansco Superay "B" |
| Tensile specimen from 1/2" panel | normal | 0.45-0.47" | 66 | 5 min. | Ansco Superay "B" |
| Same as preceding | transverse† | 1-1/2" | 94 | 5 min. | Ansco Superay "B" |
| Tensile specimen from 1" panel | normal | 0.95-0.98" | 90 | 5 min. | Ansco Superay "B" |
| Same as preceding | transverse | 1" | 94 | 5 min. | Ansco Superay "B" |
| Guided bend (face and root from 1/2" and 1" panels) | normal | 3/8" | 63 | 5 min. | Ansco Superay "B" |
| Same as preceding | transverse | 1-1/2" | 94 | 5 min. | Ansco Superay "B" |

* *All exposures made on General Electric Company OX-140 Radiographic Units with a tube current of 5 ma and a source-to-film distance of 36".*

† *"Normal" indicates that X-ray beam was normal to plate surface; "transverse" indicates that specimen was radiographed in an edgewise position with the X-ray beam parallel to the axis of the weld.*

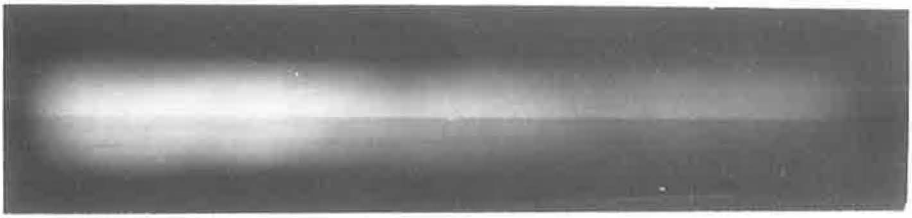
***All specimens except the machined tensile and bend specimens were radiographed with the crown on the welds so the maximum thickness penetrated by the X-ray beam is somewhat greater than the plate thickness.*

Radiographs of a number of the weld conditions under investigation are shown in Figures 1, 2 and 3. Unfortunately, it has not been possible to retain in the illustrations the degree of detail discernible in the radiographs themselves.

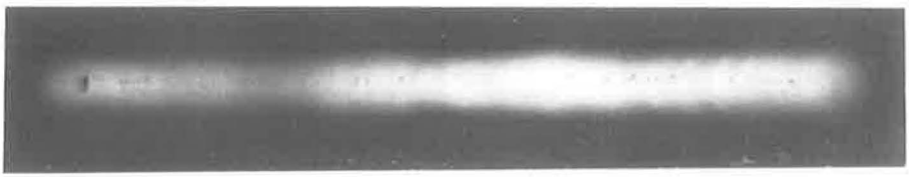
Figure 1 illustrates radiographs of a relatively sound weld, incomplete root penetration, linear and scattered porosity and lack of interpass fusion. The relatively sound weld contains some microporosity not discernible in the radiograph. Incomplete root penetration appears as a sharp line extending horizontally along the midportion of the weld bead. The linear porosity appears as an irregular scattering of faint spots along the centerline of the weld bead. The majority of the spots are in the right-hand third of the weld, but there are several just to the left of the center. Lack of interpass fusion appears as a discontinuous line of varying width and density extending along the centerline of the weld bead.

Figure 2 illustrates radiographs of welds containing tungsten inclusions, oxide inclusions and craters. Light patches associated with the high density tungsten inclusions stand out very sharply. The oxide inclusions require closer scrutiny and appear as small spots of porosity near the right-hand end of the weld bead. The craters appear as rounded zones with relatively dark centers.

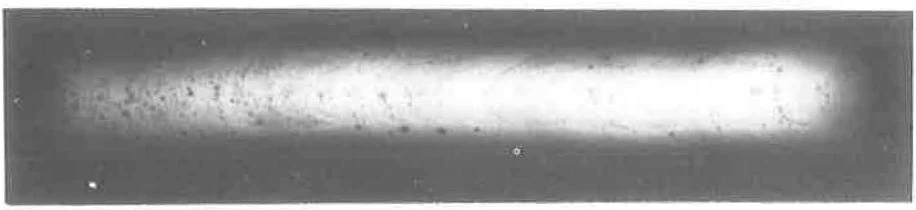
S278454 – RELATIVELY SOUND TIG WELD



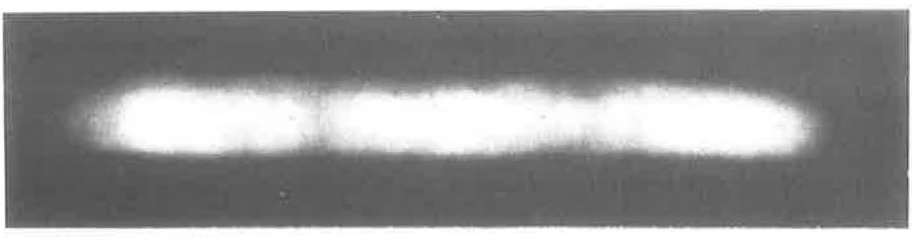
S278488 – MIG WELD WITH INCOMPLETE ROOT PENETRATION



S278492 – MIG WELD WITH LINEAR POROSITY

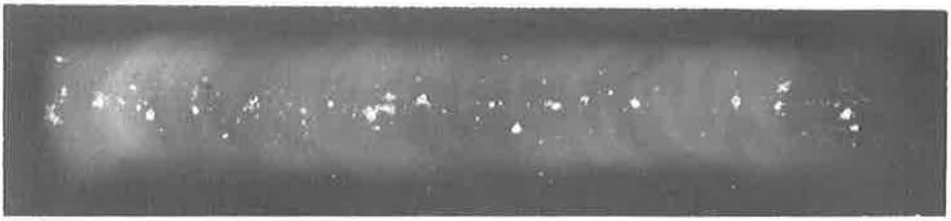


S278496 – MIG WELD WITH SCATTERED POROSITY

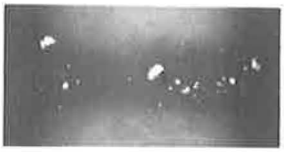


S278493 – MIG WELD WITH LACK OF INTERPASS FUSION

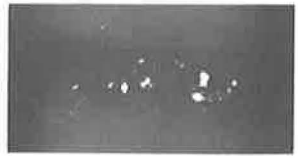
Figure 1. Radiographs of welds in $\frac{1}{2}$-in. 2219-T87 plate.



S278456 – TIG WELD WITH TUNGSTEN INCLUSIONS

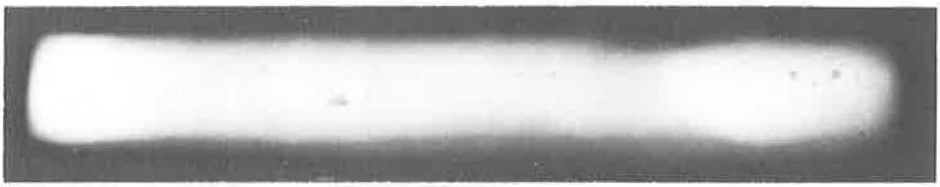


TENSILE
S278486-T2

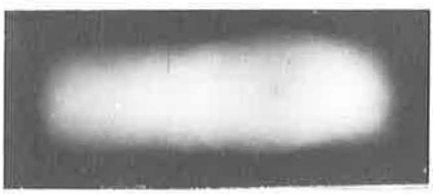


BEND
S278486-B3

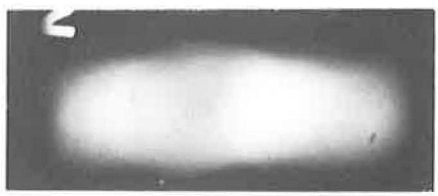
TENSILE AND BEND SPECIMENS WITH TUNGSTEN INCLUSIONS



S278598 – MIG WELD WITH OXIDE INCLUSIONS AND POROSITY

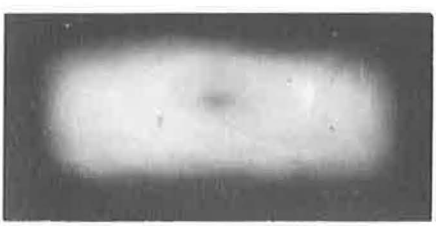


S278522-T1

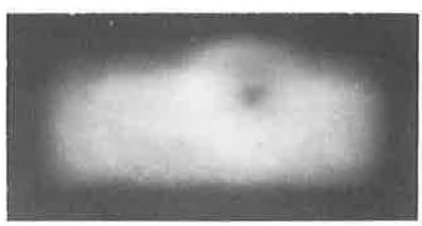


S278522-2

CRATERS IN TENSILE BLANKS
(MIG WELD – FACE PASS)



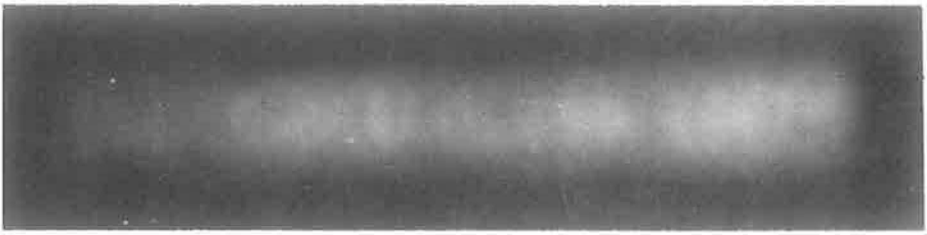
S278461-T1



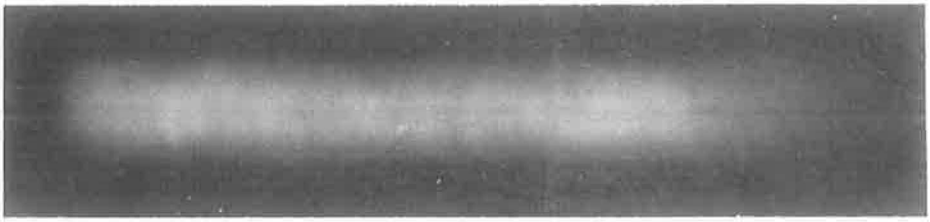
S278461-T2

CRATERS IN TENSILE BLANKS
(TIG WELD – ROOT PASS)

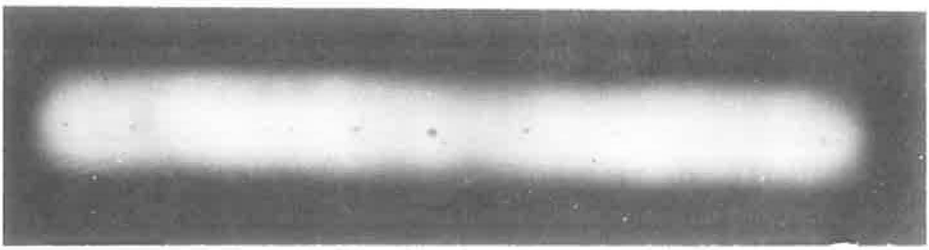
Figure 2. Radiographs of welds in $\frac{1}{2}$-in. 2219-T87 plate.



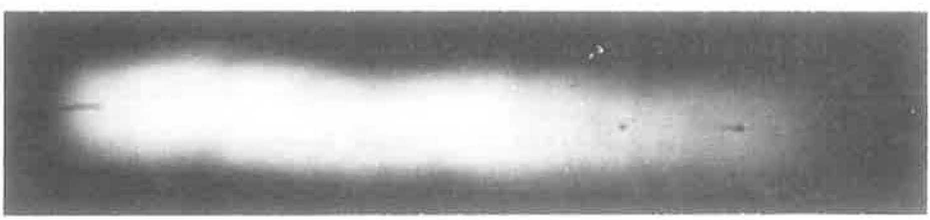
S278515 – RELATIVELY SOUND MIG WELD



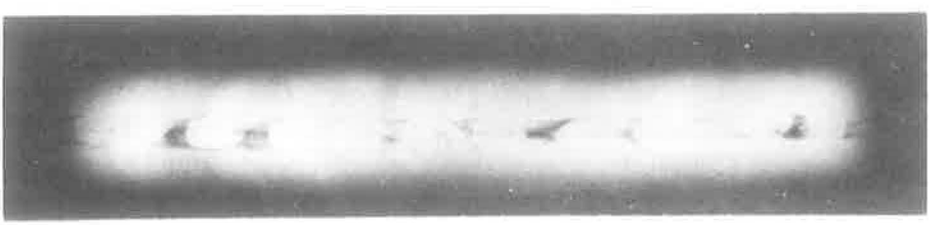
S278504 – MIG WELD WITH INCOMPLETE ROOT PENETRATION



S278501 – MIG WELD WITH LINEAR POROSITY



S278516 – MIG WELD WITH LACK OF INTERPASS FUSION



S278511 – MIG WELD WITH LACK OF ROOT FUSION

Figure 3. Radiographs of welds in 1-in. 2219-T87 plate.

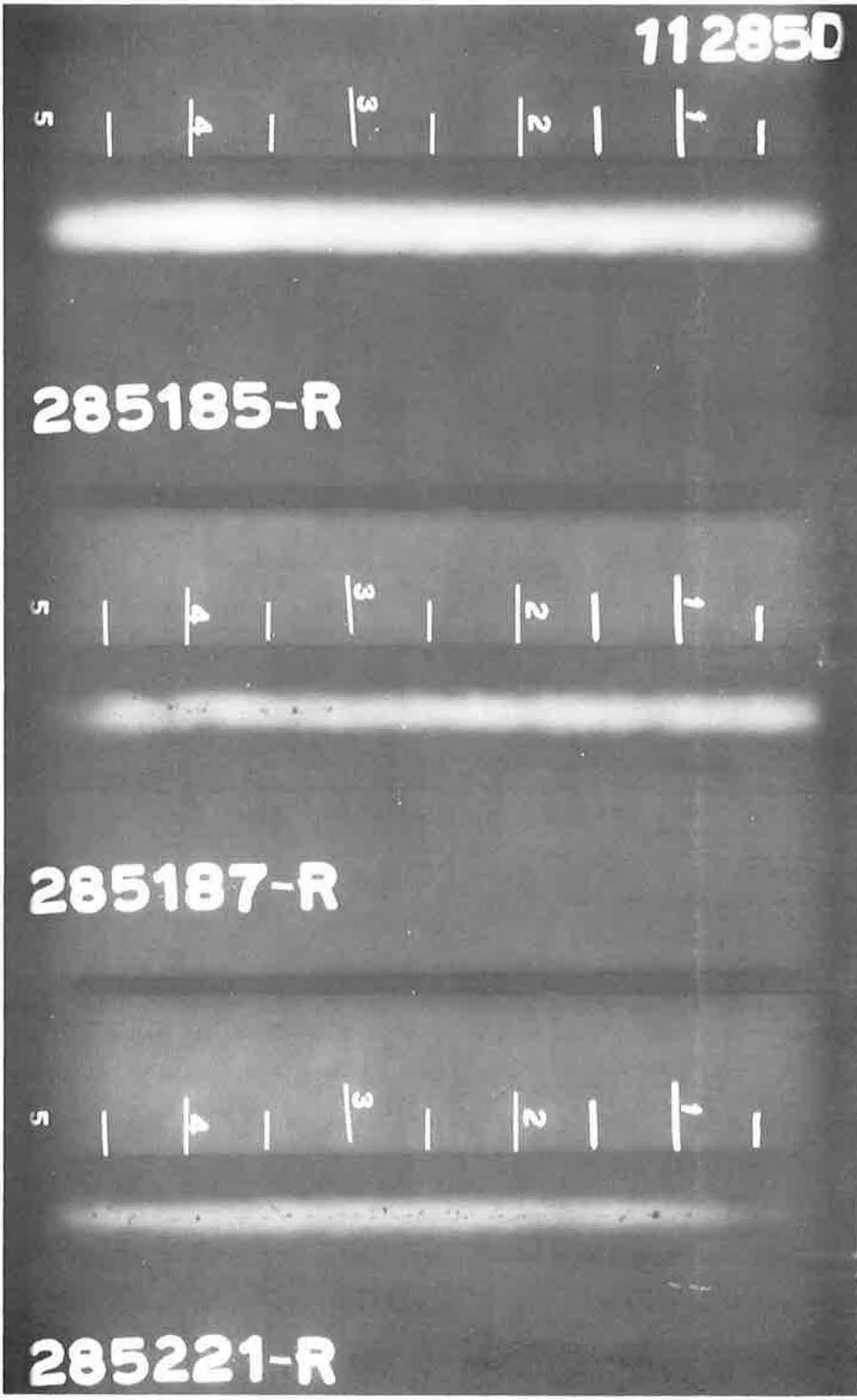
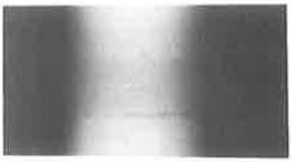
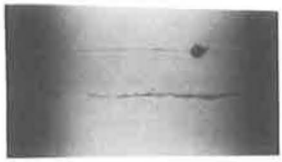



Figure 4. Radiographs of square butt welds in $\frac{1}{2}$-in. 2219-T87 plate representing various degrees of penetration: S285185-R, complete with interpenetration of weld bead roots; S285187-R, moderately incomplete; and S285221-R, markedly incomplete.



278518-T2†



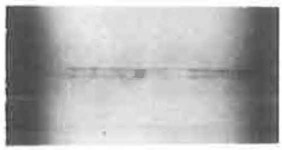
278597-T2

LACK OF SIDE FUSION

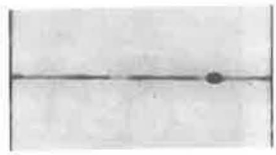
278596-T1†

SCATTERED POROSITY

278511-T2†



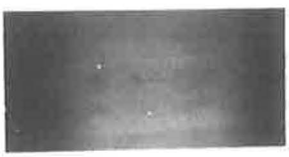
278459-T2



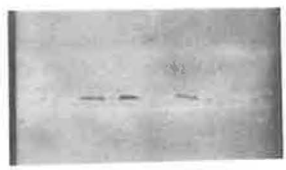
278459-B2

LACK OF ROOT FUSION

†From 1" panels; all others from 1/2" panels.

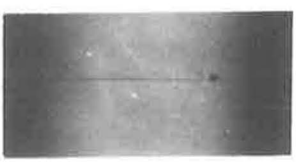


278493-T2

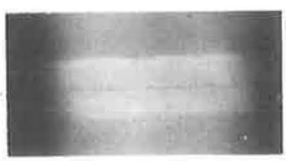


278493-B2

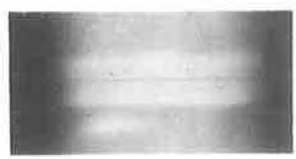
LACK OF INTERPASS FUSION



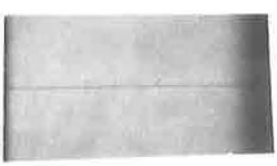
278488-T2



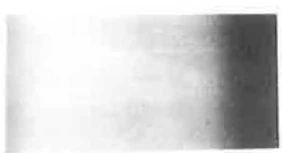
285187-T2*



285221-T2*



278488-B4



285187-B1*

285221-B4*

INCOMPLETE PENETRATION

*Square butt joints; all others V-groove.

Figure 5. Radiographs of welds in some tensile specimens (-T) and bend specimens (-B).

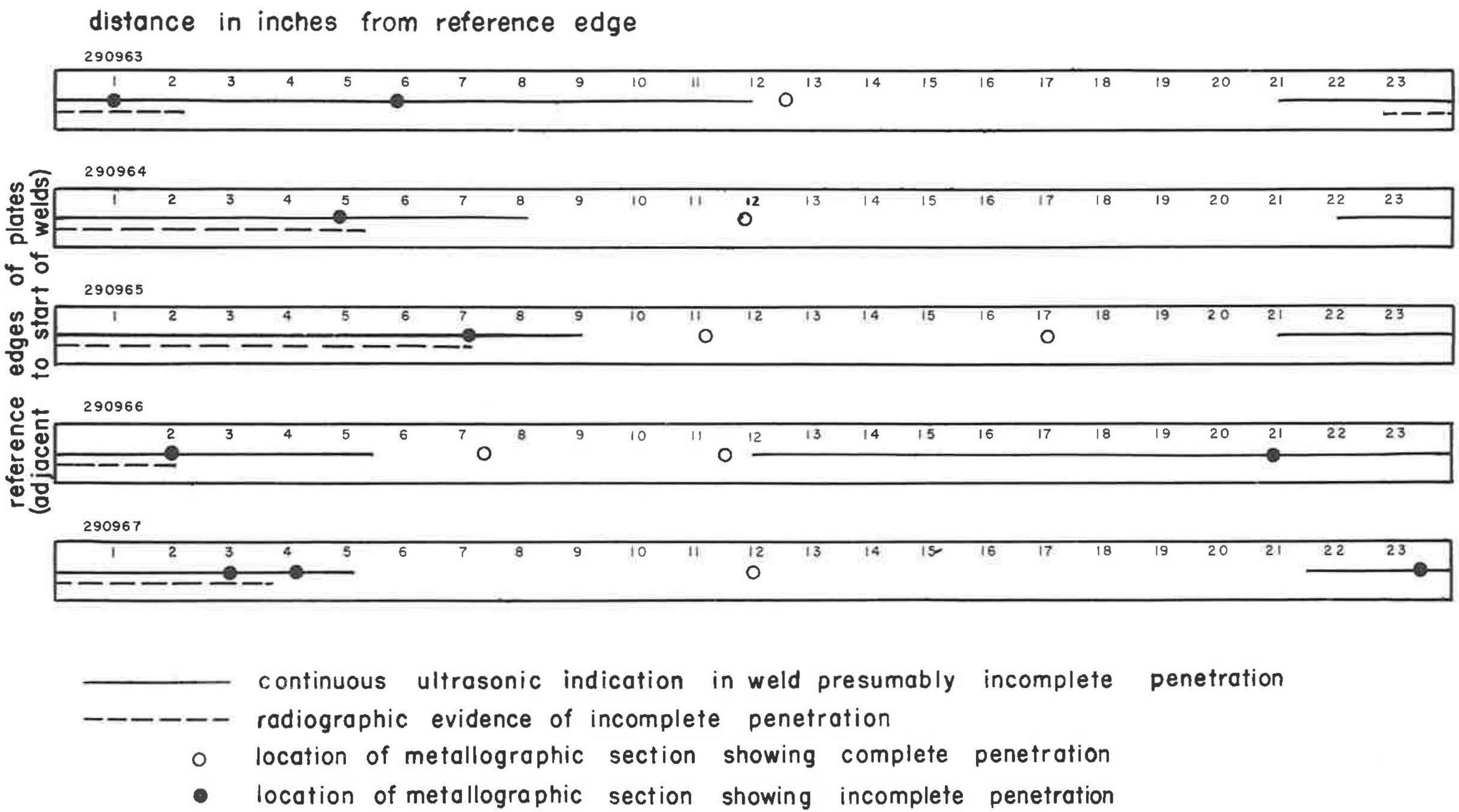



Figure 6. Results obtained from the ultrasonic, radiographic and metallographic tests for incomplete penetration.

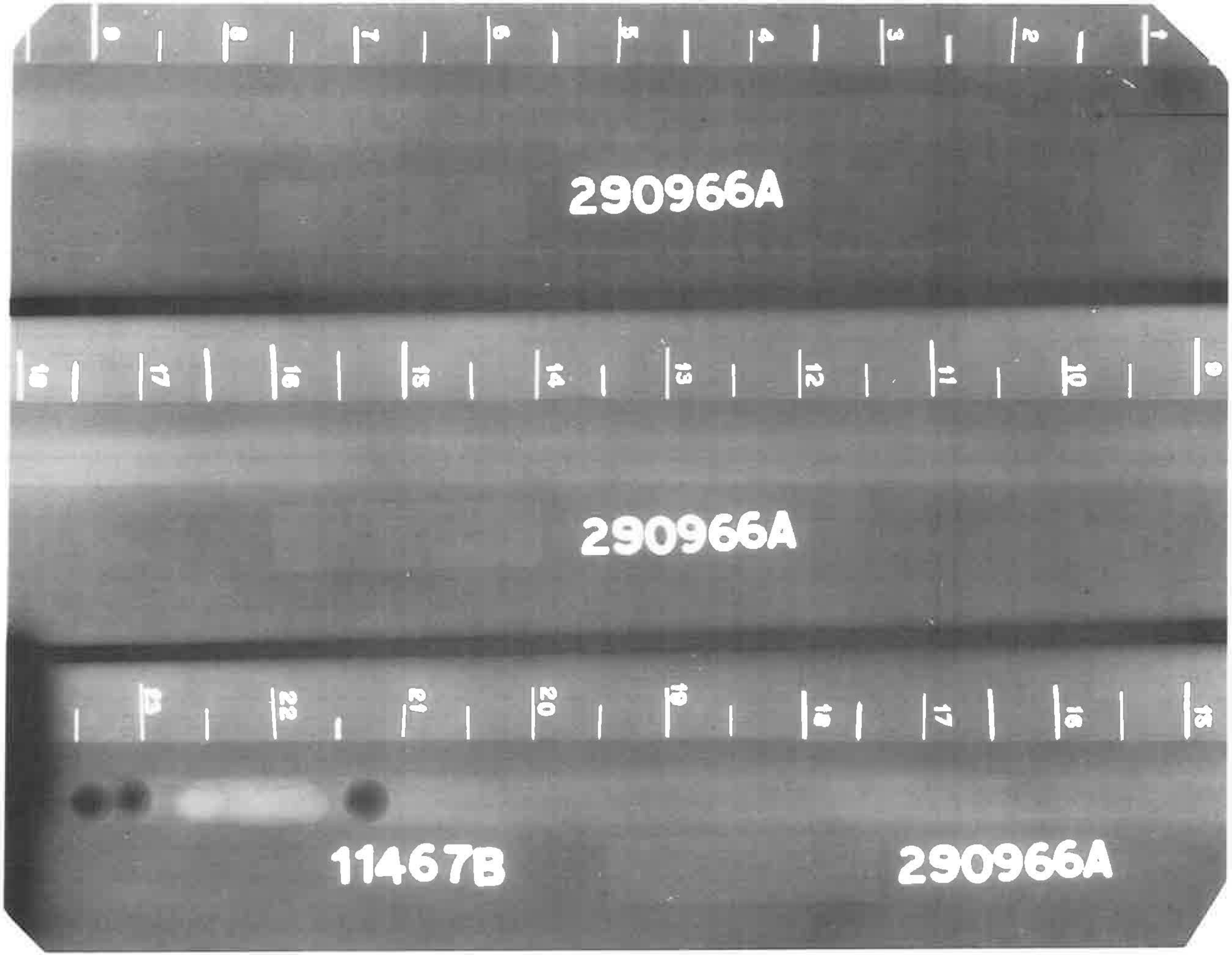



Figure 7. Radiograph of weld in panel S290966 after scarfing (about two-thirds original size). Weld starts about $1\frac{1}{4}$ in. from "reference" end of plate (upper right); incomplete penetration is evident for a distance of about three-fourths in. at beginning of weld; circular indentations (dark spots) may be associated with weld setup or attachment of equipment.

The radiographs in Figure 3 include a relatively sound weld containing some microporosity not discernible in the radiograph and welds with incomplete root penetration, linear porosity, lack of interpass fusion and lack of root fusion. The line of incomplete root penetration is broader and more diffuse than that in Figure 1. The lack of interpass fusion is evident as a few dark spots along a very faint, diffuse and discontinuous horizontal line through the mid-portion of the weld. The conspicuous dark spots in the bottom radiograph indicate voids of significant size along unfused portions of the weld root.

Figure 4 shows radiographs of square butt welds in ½-in. plate with several degrees of penetration and fusion. The marked incomplete penetration in panel S285221-R (roots of two weld beads about ⅛ in. apart) is plainly discernible and is associated with linear porosity. Panel S285187-R in which the roots of the weld beads are about ¹⁄₁₆ in. apart, shows radiographic evidence of the incomplete penetration along only a portion of the weld length.

Radiographs of the welded joints in a number of machined tensile and bend specimens are reproduced in Figure 5. The weld conditions represented are lack of side, root and interpass fusion, incomplete penetration and scattered porosity.

Figure 6 shows the extent of incomplete penetration detected radiographically in the square butt welds from the George C. Marshall Space Flight Center. Figure 7 is a radiograph of one of these welds (S290966).

## ULTRASONIC TESTS

All welds were inspected by an angle-beam shear-wave ultrasonic procedure in which the ultrasonic beam was directed through the plate and into the weld as shown in Figure 8. Four traverses of the search unit were made along lines roughly parallel to the weld and extending over its full length. These scans were made along each side of the weld and on each surface of the plate. Maximum response from discontinuities was obtained by slightly rotating the search unit about an axis normal to the plate surface and varying its distance from the weld.

A 2.25-mc lithium sulfate angle-beam shear-wave contact search unit and a Sperry Type UR Reflectoscope were used for most of the ultrasonic tests. The angle-beam search unit produced a shear-wave beam refracted to approximately 48 deg in the plate (angles of incidence and refraction are given with respect to a normal to the plate surface). Standardization was attained by adjusting the equipment for a 2.5-in. peak-to-peak indication from a ⅛ in. diameter hole drilled through the ½ in. dimension and normal to the surface of a ½ × 2½ × 14 in. aluminum alloy angle beam reference plate.

A variable angle 2.25-mc lithium sulfate contact search unit was also employed for a limited number of tests. Other tests were conducted with experimental immersion testing apparatus employing higher test frequencies. A special lucite holder in which search units of the immersion type could be mounted was constructed for the latter tests. This holder contained a water column to provide coupling between the search unit and the part

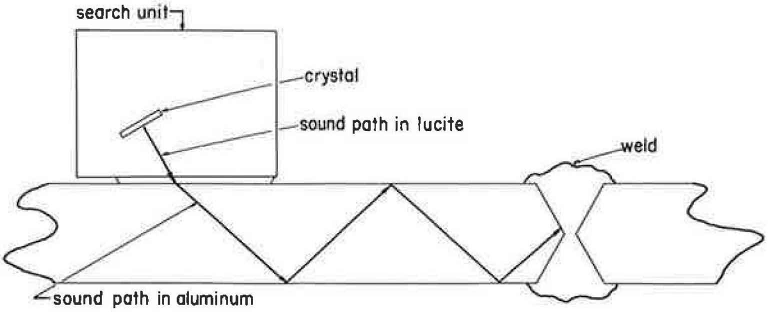



Figure 8. Shear wave search unit in position for an ultrasonic examination of 2219-T87 weldments.

Figure 9. Angle-beam search units used for ultrasonic weld inspection; unit in upper right is contact unit transmitting a shear wave into aluminum at a refracted angle of 48°, other unit is a liquid filled, variable angle unit.

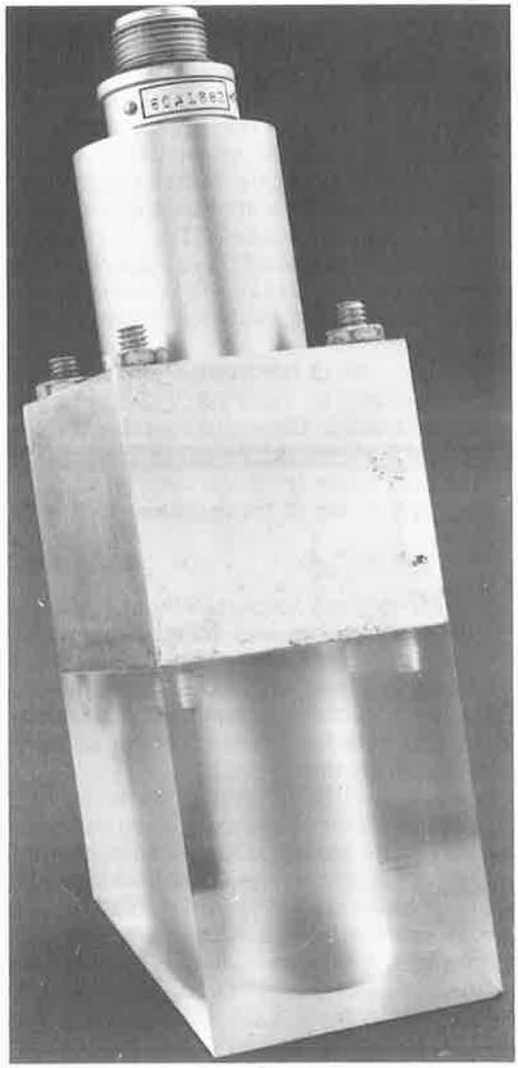


Figure 10. Special holder for immersion type search units.

being inspected. It was designed so that a shear-wave beam could be directed into the part at an optimum refraction angle of 45 deg. Tests were made with this unit at frequencies of 5 and 10 megacycles using lithium sulfate transducers of both the focusing and nonfocusing types. The three ultrasonic search units are shown in Figures 9 and 10.

After the initial ultrasonic inspections were concluded, weld beads on a number of samples were machined or ground flush with the plate surface and re-examined to determine whether extraneous ultrasonic indications were obtained from bead geometry or discontinuities in the crown of the welds. Samples containing weld crowns that appeared to be causing extraneous indications with the fixed-angle contact search unit were re-examined with the variable-angle search unit. These comparison tests were performed to establish a possible refraction angle other than 48 deg that might eliminate or minimize the extraneous indications.

The ultrasonic tests were not limited to the inspection of the as-welded panels. The tensile and bend specimens machined from the panels were also examined ultrasonically. The examination of the latter provided a further means of determining the effect of the weld crowns on ultrasonic response. The square butt welds previously referred to were examined with particular regard for incomplete root penetration.

The results of the ultrasonic tests on joints of the V-groove type are summarized in Table 5. The conditions readily detected ultrasonically include oxide inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration and internal longitudinal cracking.

## TABLE 5

### EFFECTIVENESS OF RADIOGRAPHY AND ULTRASONIC INSPECTION FOR DETECTING VARIOUS WELD CONDITIONS

| Weld Condition | Condition Detected by Radiographic Examination | | | Condition Detected by Ultrasonic Examination* | | |
|---|---|---|---|---|---|---|
| | Yes | Questionable† | No | Yes | Questionable† | No |
| Microporosity | | | X | | | X |
| Linear Porosity | X | | | | X | |
| Scattered Porosity | X | | | | X | |
| Oxide Inclusions | | X | | X | | |
| Tungsten Inclusions | X | | | | X | |
| Lack of Interpass Fusion | X | | | X | | |
| Lack of Root Fusion | X | | | X | | |
| Lack of Side Fusion | X | | | X | | |
| Incomplete Root Penetration** | X° | | | X°° | | |
| Crater Cracks | X | | | | X | |
| Internal Longitudinal Crack | | | X | X | | |
| Craters | X | | | | X | |
| Underbead Fold | | X†† | | | | X |
| Weld Bead Overlap | | X†† | | | | X |

* *With a few exceptions, ultrasonic tests were made with a 2.25 mc lithium sulfate contact angle-beam search unit producing a shear wave beam refracted at an angle of 48° to the normal in the aluminum. In most cases it was necessary to grind or machine the weld flush with the plate surface to avoid extraneous indications from the weld crown. A few tests made during the latter part of the investigation with a liquid-filled variable-angle search unit indicated that the extraneous indications might also be eliminated or minimized by introducing the sound beam at a suitable angle.*

† *This category includes instances where the condition was not detected with certainty or where it was detected in one sample but not in another.*

** *This condition was investigated in square butt joints as well as in the single-V and double-V groove joints used for all other phases of the investigation.*

° *Detection became uncertain when separation between roots of weld beads was about 1/16" or less.*

°° *Ultrasonic method appears superior to radiographic method for detecting slight incomplete penetration in square butt welds but exact limit of detection has not yet been determined.*

†† *Weld crown malformations are usually apparent in a radiograph but it might be difficult to relate them to a specific defect.*

The reflectograms reproduced in Figures 11 through 15 show the screen presentations obtained with relatively sound welds and welds containing a number of the discontinuities. The weld conditions reliably detected by ultrasonic testing usually gave well-defined indications. An ultrasonic noise level (hash) like that in Figure 11 was noted in testing most welds.

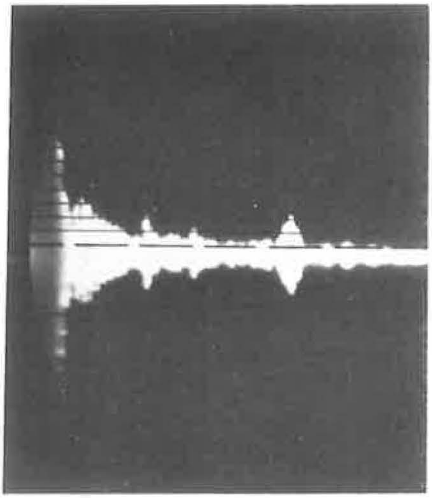
The weld conditions that were not detected consistently or with assurance in the ultrasonic tests include scattered porosity, linear porosity, craters and tungsten inclusions. In general, weld bead overlaps, underbead folds and microporosity were not detected by the ultrasonic tests.

Table 6 gives the ultrasonic response obtained from discontinuities in the square butt welds with various degrees of penetration. Figure 16 contains reflectograms corresponding to 3 of the square butt welds (S285221, S285107 and S285105) representing various degrees of incomplete penetration. Detection of incomplete penetration in welds of this type becomes uncertain when the separation of the two weld bead roots is less than about $\frac{1}{16}$ inch.

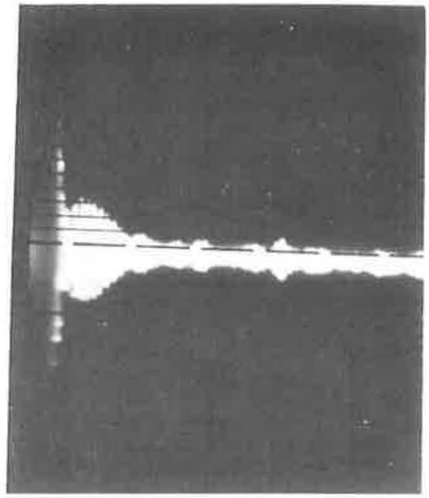
The five square butt welds obtained from the George C. Marshall Space Flight Center were examined ultrasonically with the conventional 2.25-mc angle-beam shear-wave

1/2" THICK PLATE

1" THICK PLATE

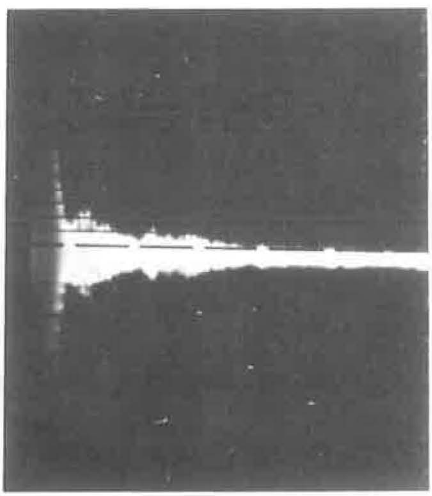


278454-T1

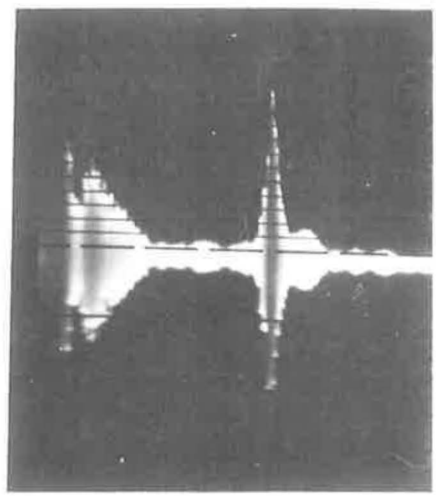


278515-T1

relatively sound and some microporosity



278522-T2



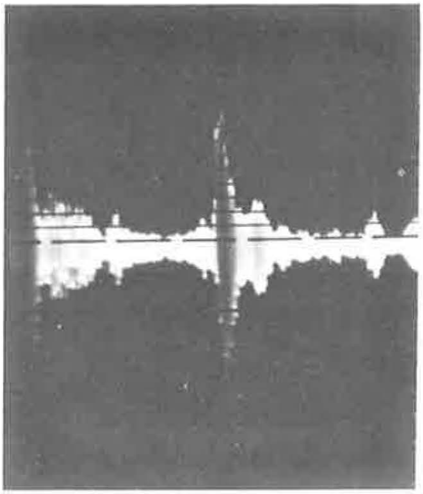
278514-T1

craters

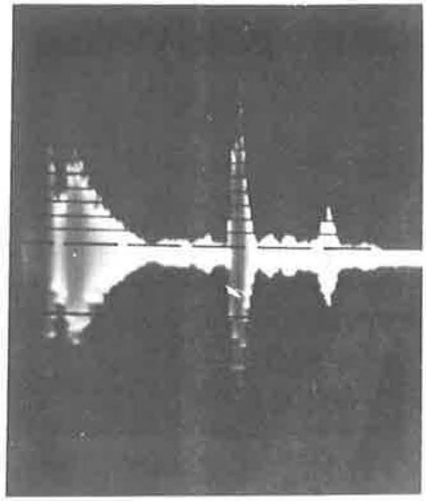
Figure 11. Reflectograms showing ultrasonic indications corresponding to various weld conditions.

1/2" THICK PLATE

1" THICK PLATE

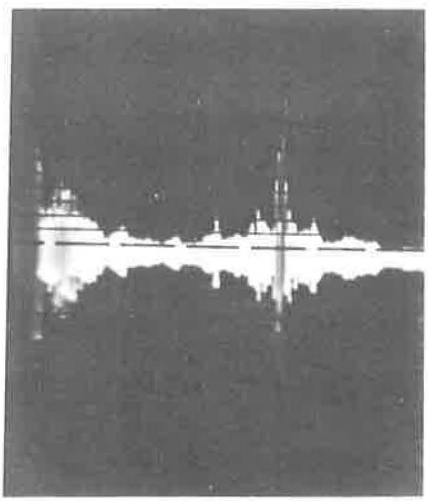


278493-T1

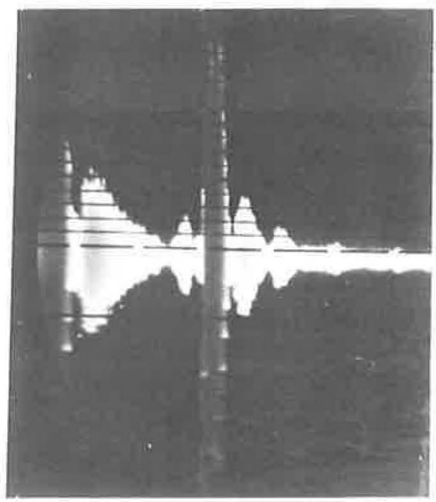


278516-T2

lack of interpass fusion



278459-T2



278511-T2

lack of root fusion

Figure 12. Reflectograms showing ultrasonic indications corresponding to various weld conditions.

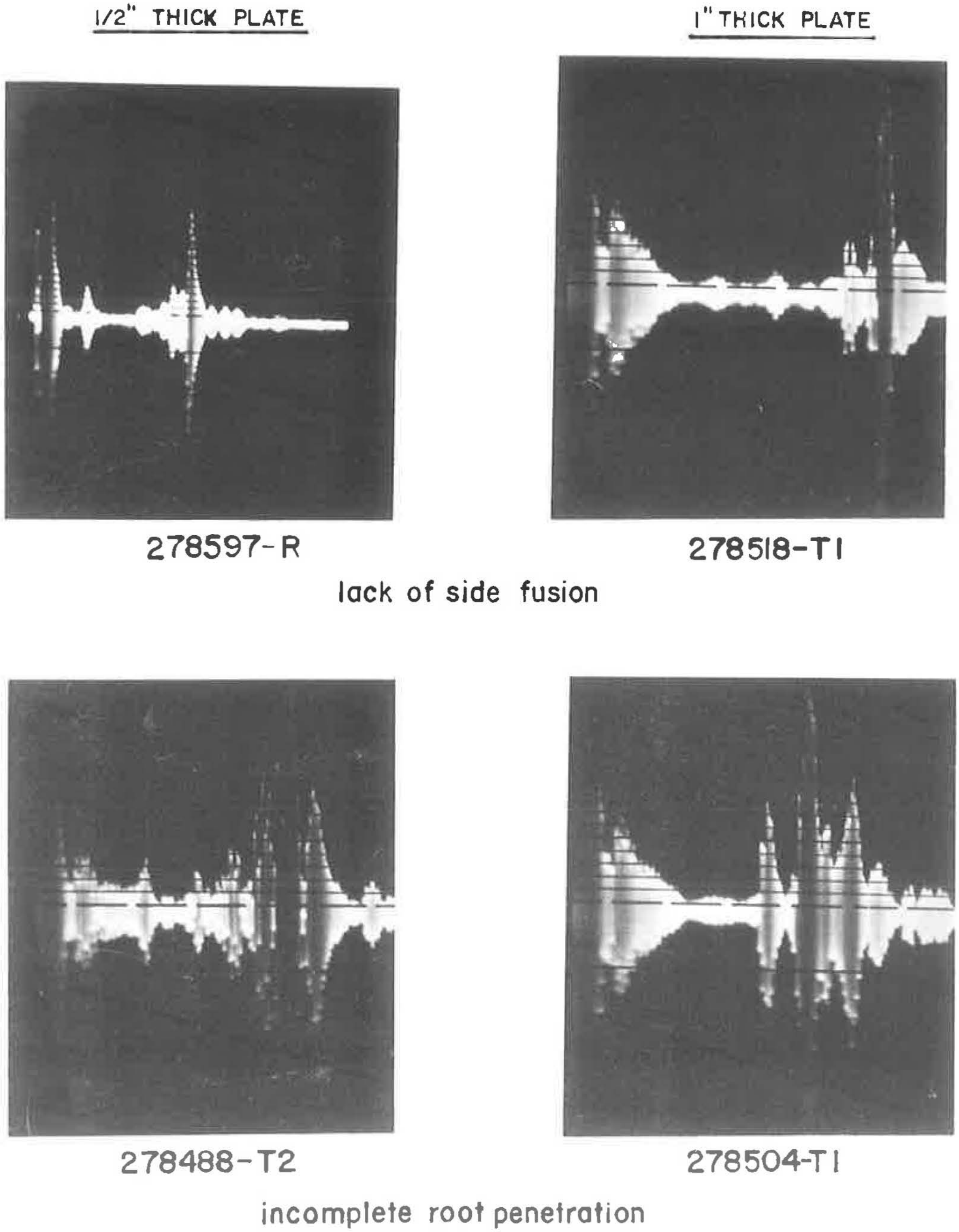



Figure 13. Reflectograms showing ultrasonic indications corresponding to various weld conditions.

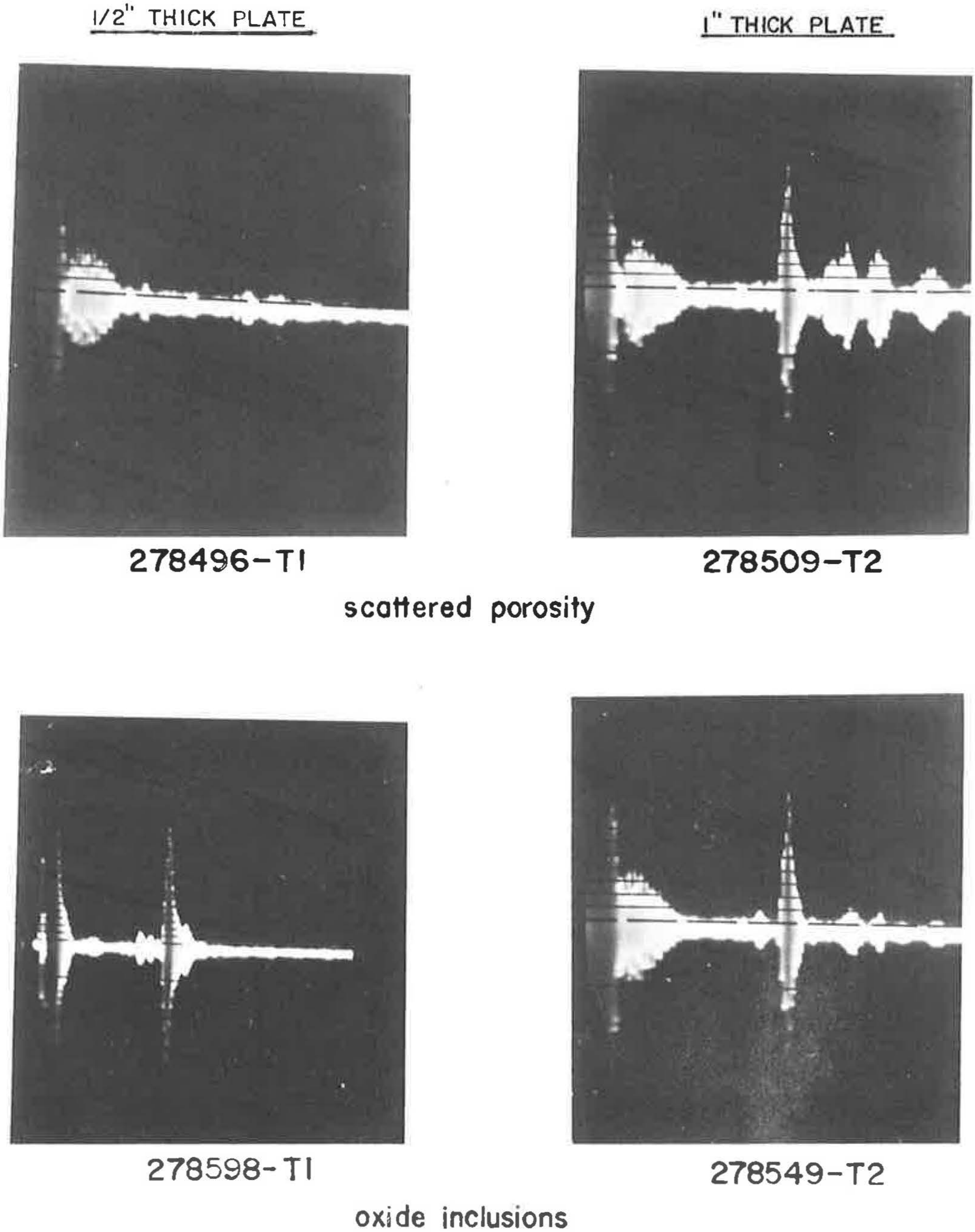
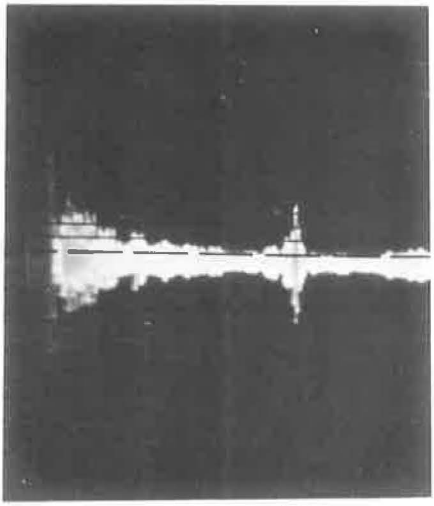


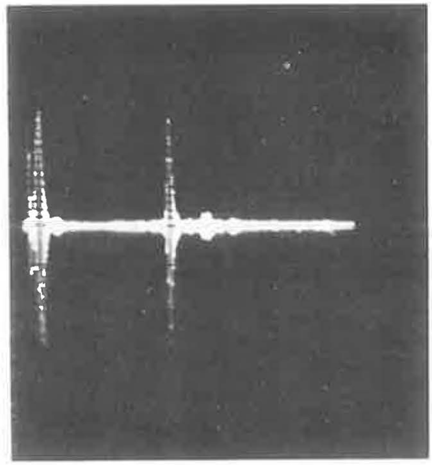

Figure 14. Reflectograms showing ultrasonic indications corresponding to various weld conditions.

1/2" THICK PLATE



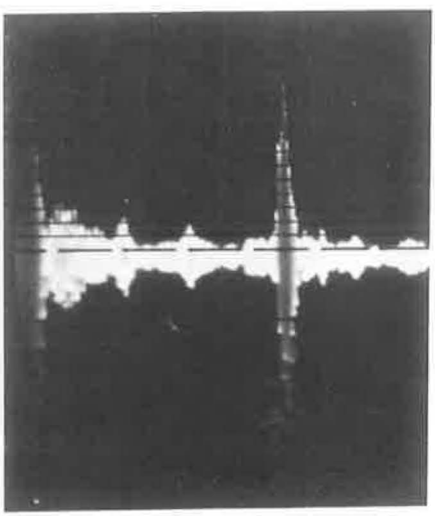
278492-T1

1" THICK PLATE



278501-R

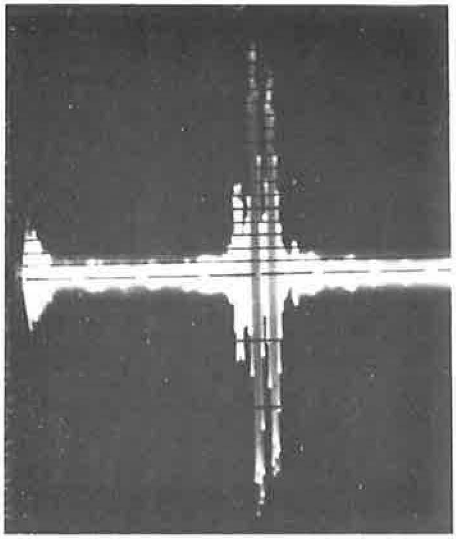
linear porosity



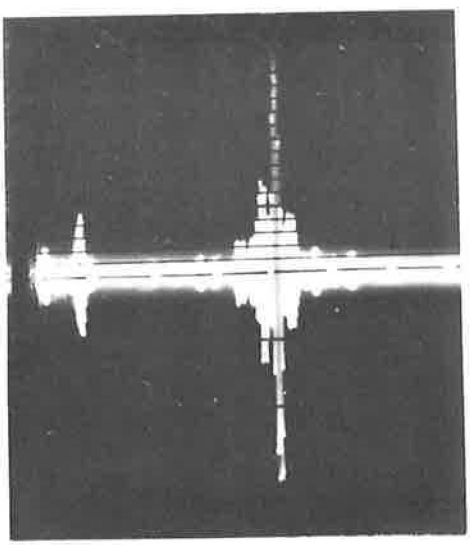
278486-T2

tungsten inclusions

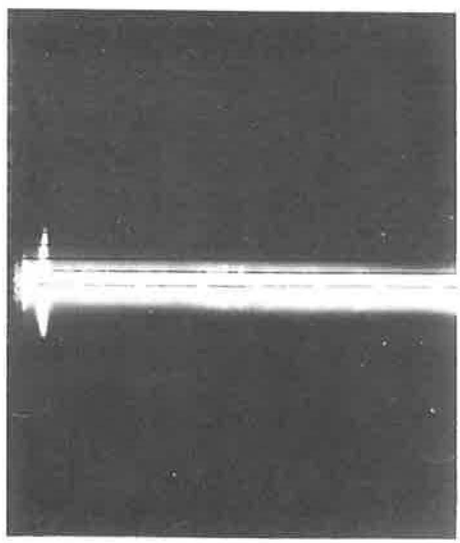
Figure 15. Reflectograms showing ultrasonic indications corresponding to various weld conditions.



A- indication from incomplete penetration
S- 285221



B- indication from incomplete penetration
S- 285187



C- screen presentation from complete
penetration S-285185

Figure 16. Reflectograms showing ultrasonic indications from varying degrees of penetration.

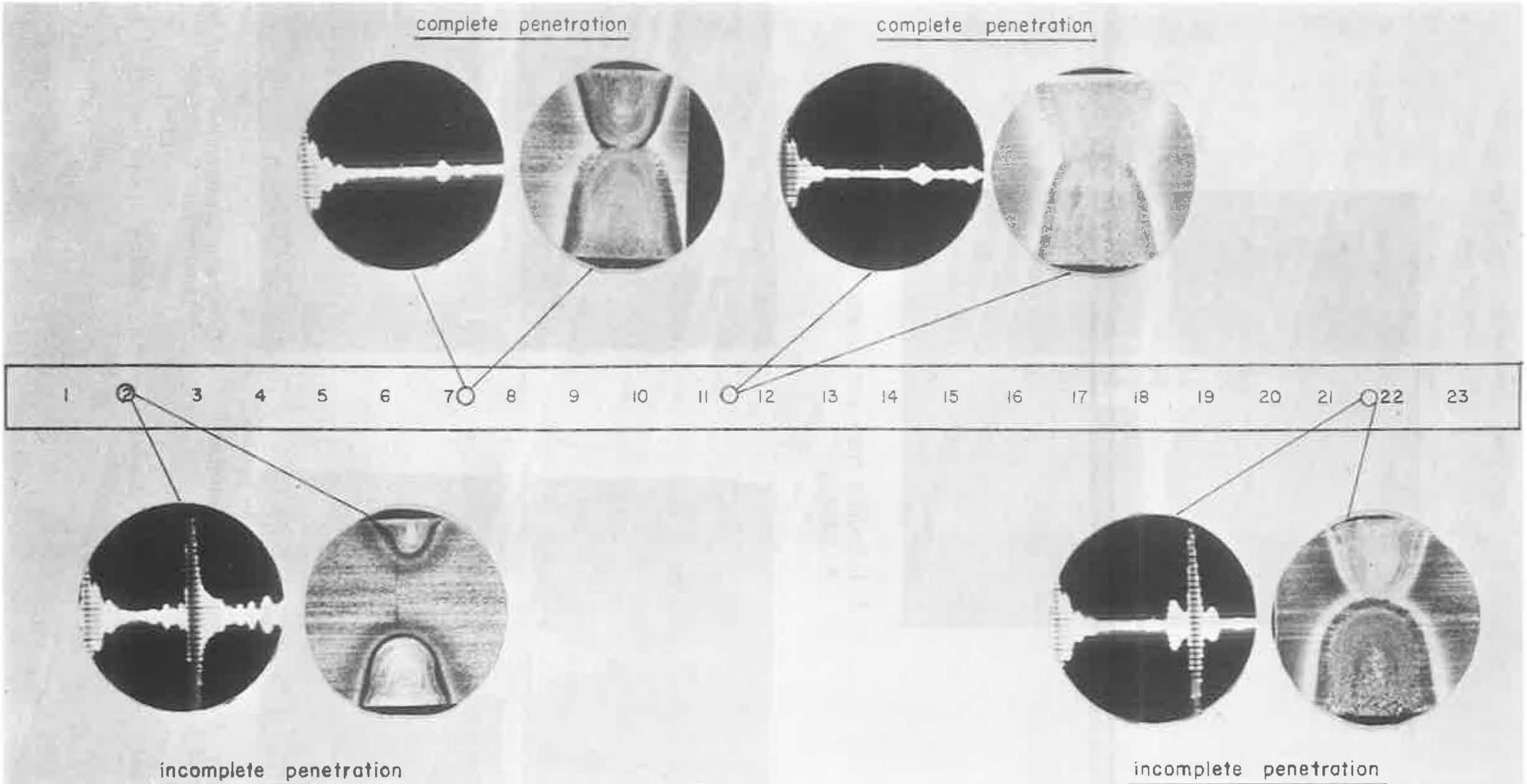



Figure 17. Reflectograms and macrographs from corresponding locations in weldment numbered 290966.

**TABLE 6**

**ULTRASONIC INDICATIONS FROM VARIOUS DEGREES OF PENETRATION IN SQUARE BUTT WELDS.**

| S No. | Penetration Sought | Measured Bead Separation or Interpenetration | Ultrasonic Indication Height |
|---|---|---|---|
| 285185 | Complete with some interpenetration | Int. Approx. 3/32" | 0.3" p-p† |
| 285187 | Incomplete with a small root separation | Sep. Approx. 1/16" | 2.4" p-p |
| 285221 | Incomplete with substantial root separation | Sep. Approx. 1/8" | 3.2" p-p |
| 285321 | Complete with roots interpenetrating about 1/8" | Int. 5/32"* | 0.2"p-p† |
| 285322 | Barely complete with roots just touching | Sep. 0.046"* | 0.7" p-p |
| 285323 | Incomplete with root separation of about 1/64" | Int. 1/32"* | 0.4" p-p |
| 285324 | Incomplete with root separation of about 3/64" | Sep. 0.066"* | 1.0" p-p |
| 285326 | Incomplete with root separation of about 1/16" | Sep. 0.060"* | 2.2" p-p |

** Average of two measurements on metallographic sections: other values are for one section.*

*† Normal hash level; no isolated indications.*

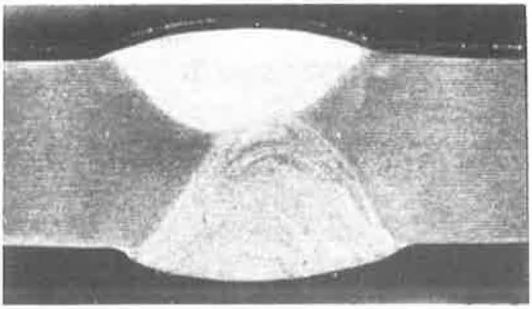
test and with the special immersion test using 5- or 10-mc lithium sulfate search units in a lucite holder. The results of the conventional tests were shown graphically in Figure 6, which also shows the results of the radiographic examinations previously described. Figure 17 shows reflectograms and corresponding macrosections representing several locations along one of these welds (S290966). In one instance, incomplete penetration that escaped detection in the ordinary ultrasonic test was detected in the special test using higher frequencies.

## METALLOGRAPHIC EXAMINATIONS

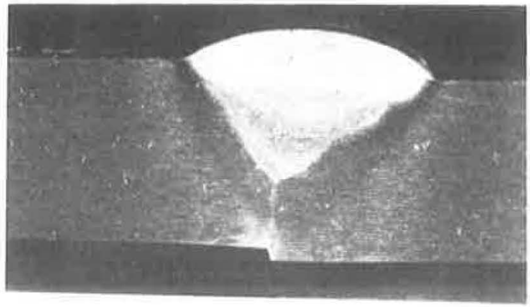
Following the ultrasonic examination of the original 18- × 24-in. panels, transverse sections through the welds were removed for metallographic examination. In the majority of the welds, this examination was limited to a macroscopic study at low magnification but in some instances, it was necessary to make examinations at higher magnification to check on specific conditions.

Closely related to the metallographic studies was examination of the fractures in the specimens subjected to the tensile and bend tests. These examinations were made to obtain further information on weld structure and soundness.

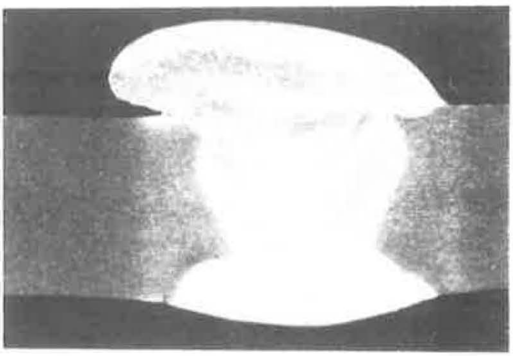
The macroscopic examinations and fracture studies helped to confirm the weld conditions sought, most of which had previously been identified by radiographic examination. Metallographic examinations also showed the presence and extent of conditions such as microporosity, oxide inclusions and incomplete penetration. (In this paper



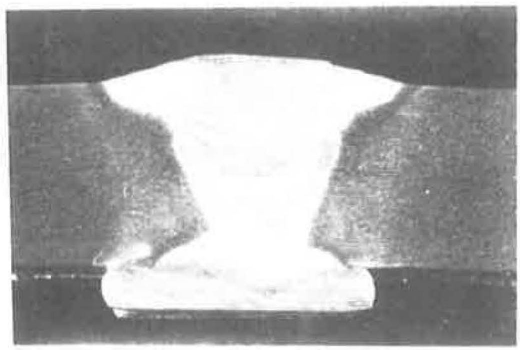
S278454 – RELATIVELY SOUND WELD
(Etch 10% NaOH)



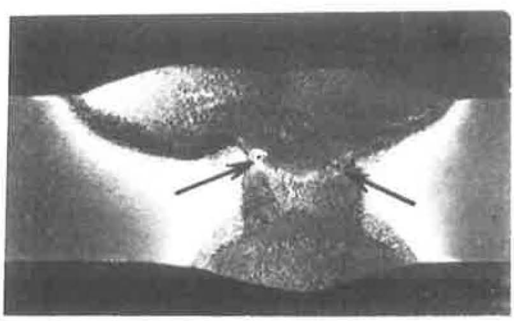
S278488 – INCOMPLETE ROOT PENETRATION (Etch 10% NaOH)



S278519 – WELD BEAD OVERLAP
(Etch 10% NaOH)

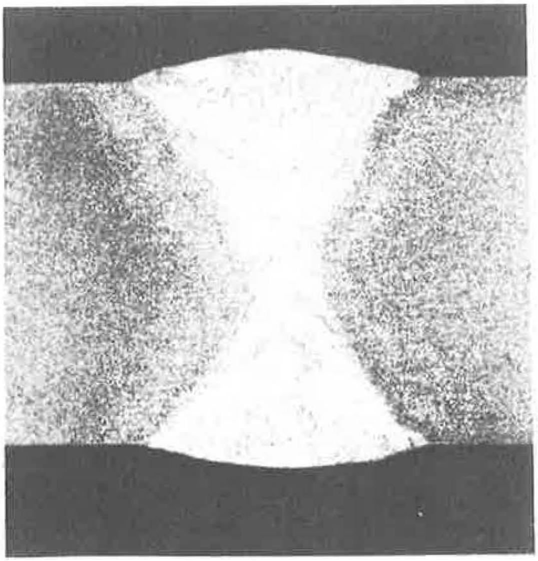


S278502 – UNDERBEAD FOLD
(Etch 10% NaOH)

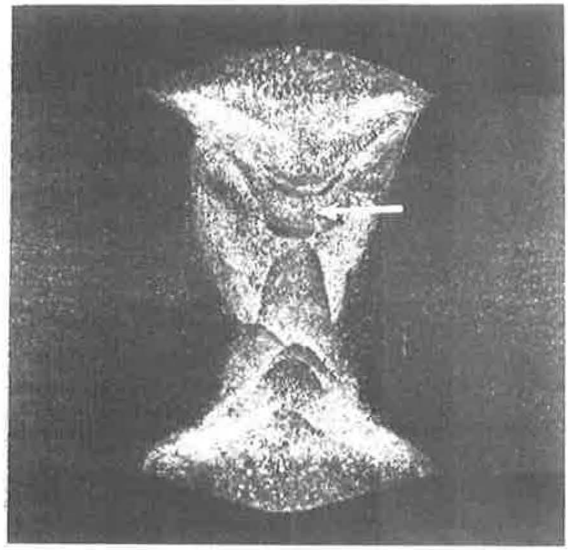


S278597 – LACK OF SIDE FUSION
(Etch Keller's)

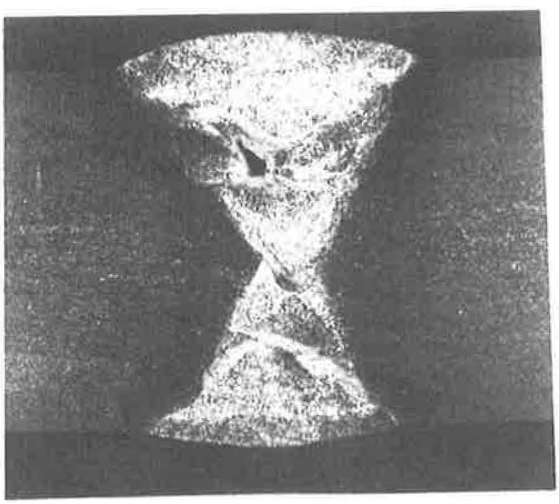
Figure 18. Macrographs of sections through butt welds in ½-in. 2219-T87 plate (mag. 2X).



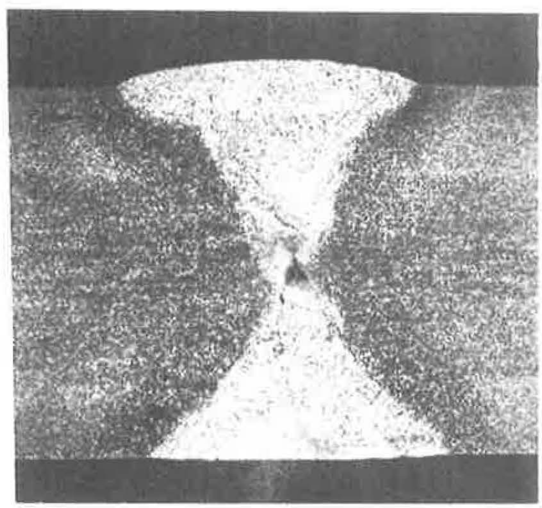
**278515 – RELATIVELY SOUND WELD**



**S278495 – INTERNAL LONGITUDINAL CRACK**

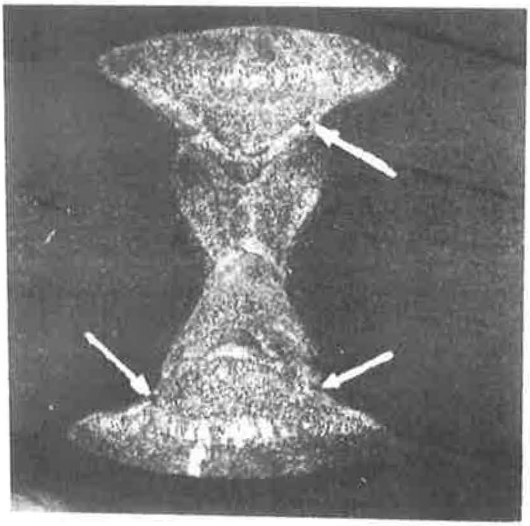


**S278516 – LACK OF INTERPASS FUSION**

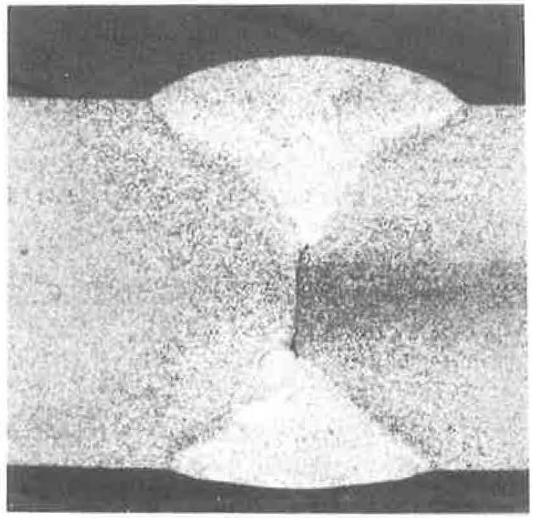


**S278511 – LACK OF ROOT FUSION**

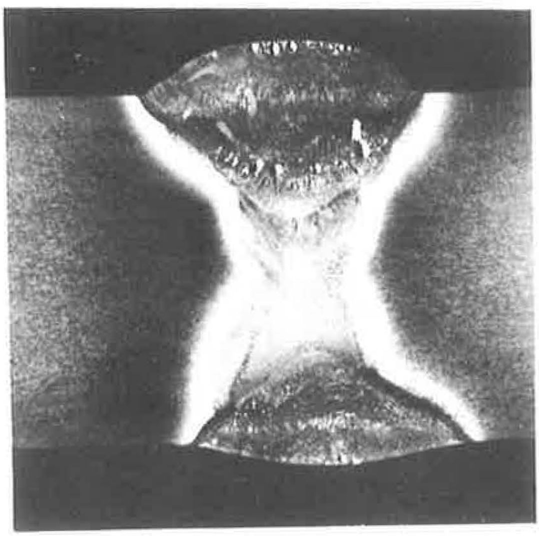
Figure 19. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X, etch 10% NaOH).



S278518 – LACK OF SIDE FUSION
(Etch 10% NaOH)

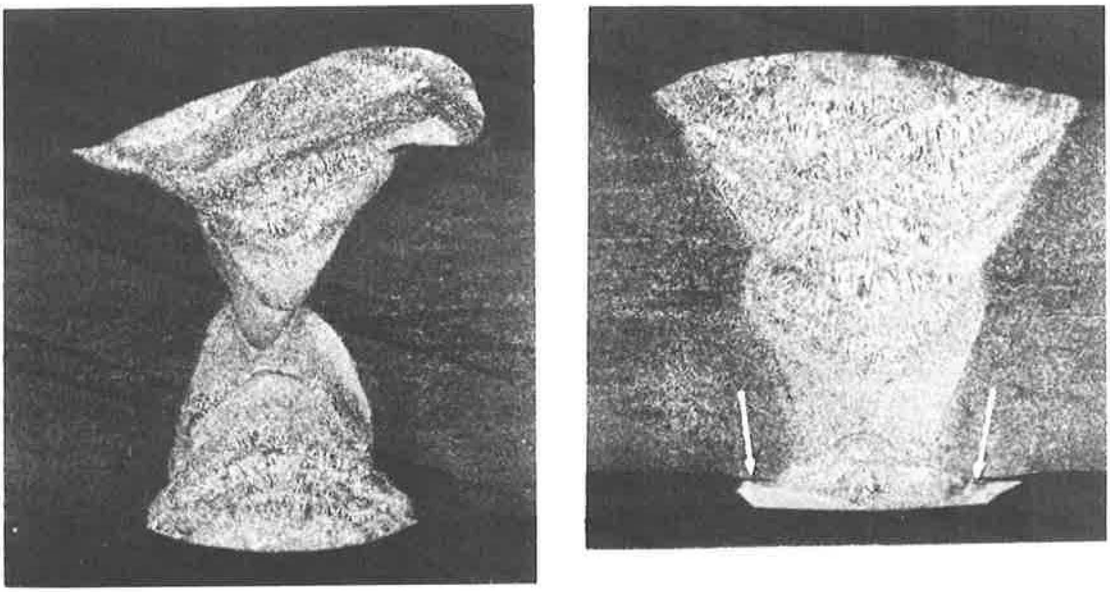


S278504 – INCOMPLETE ROOT PENETRATION (Etch 10% NaOH)



S278596 – SCATTERED POROSITY
(Etch Keller's)

Figure 20. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X).



**S278512 – WELD BEAD OVERLAP** | **S278505 – UNDERBEAD FOLD**

Figure 21. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X, etch 10% NaOH).

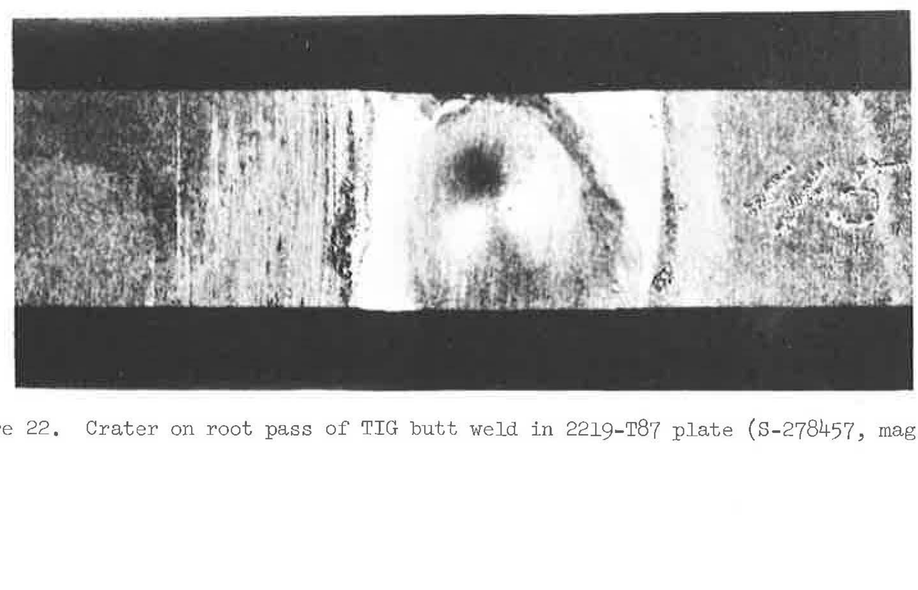


Figure 22. Crater on root pass of TIG butt weld in 2219-T87 plate (S-278457, mag. 2X).

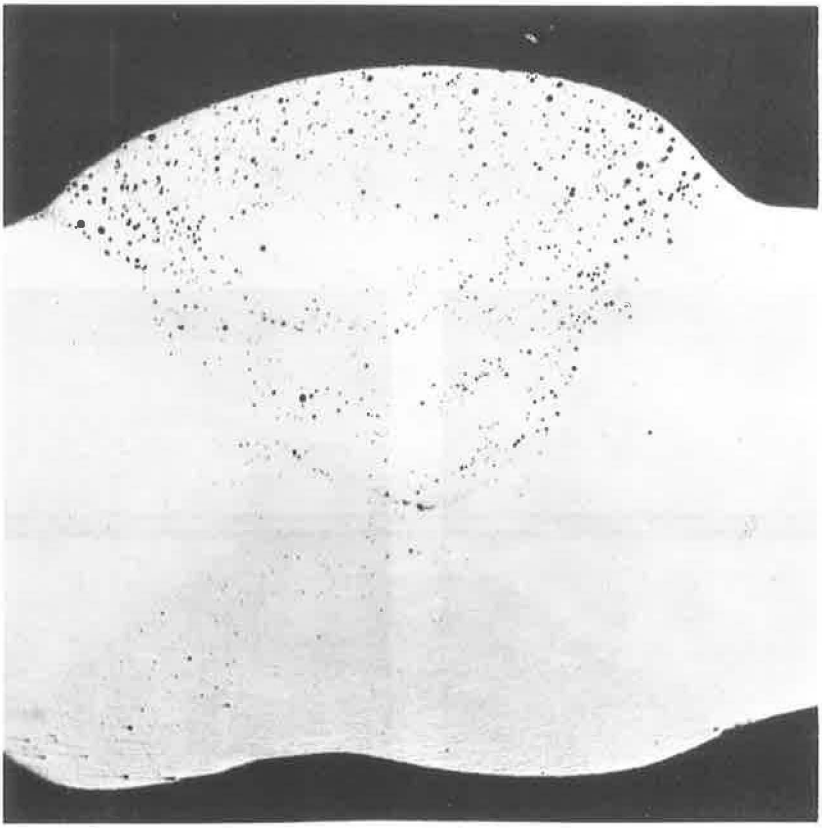


Figure 23. Macrograph of section through weld and crater (max. 5X, as-polished).

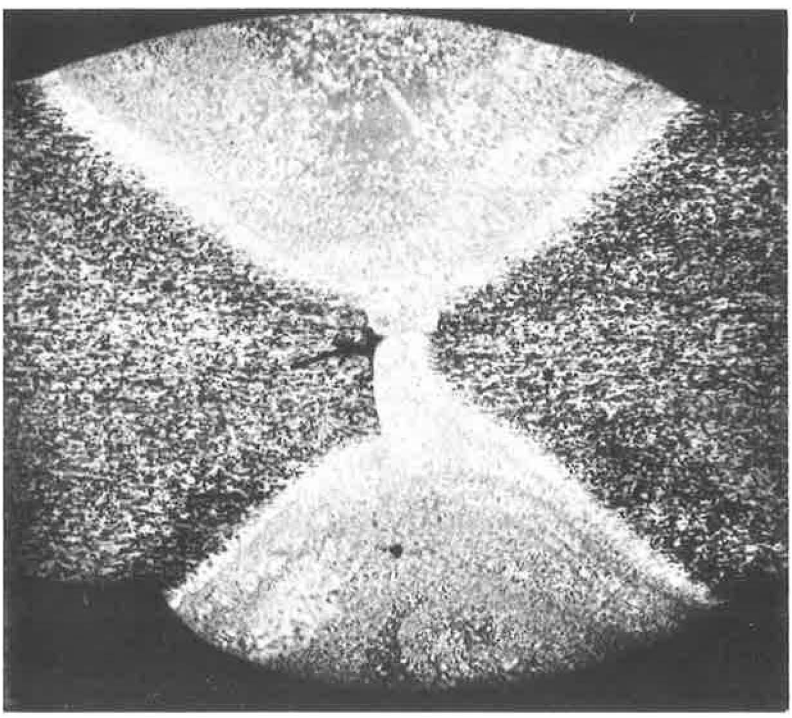


Figure 24. Macrograph of section through TIG weld in $\frac{1}{2}$-in. 2219-T87 plate; arrow indicates lack of root fusion (S-278459, mag. 5X, etch Keller's).

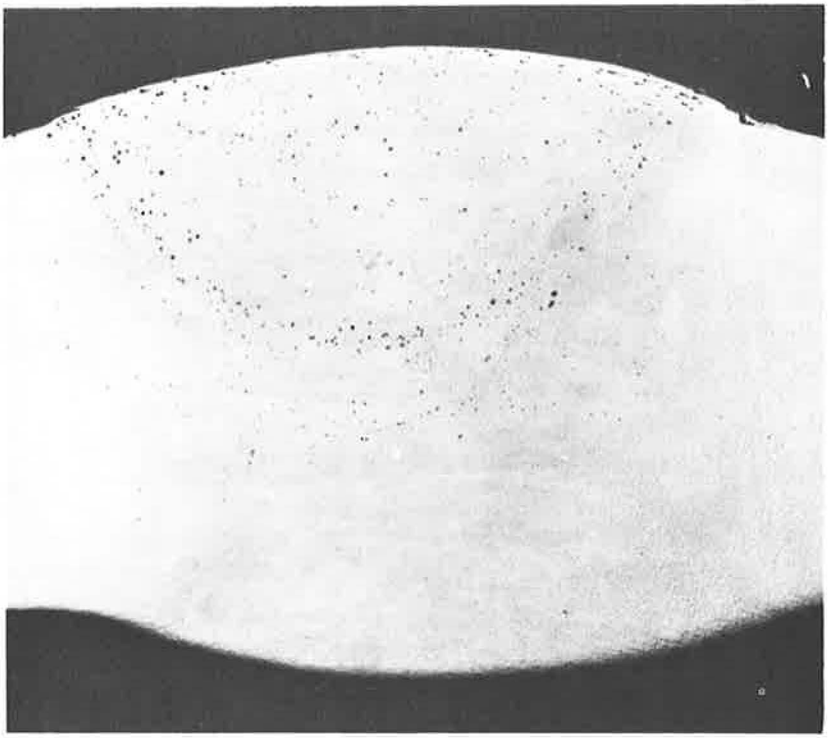


Figure 25. Macrograph showing microporosity in an otherwise sound TIG weld in ½-in. 2219-T87 plate (S-278454, mag. 5X, as-polished).

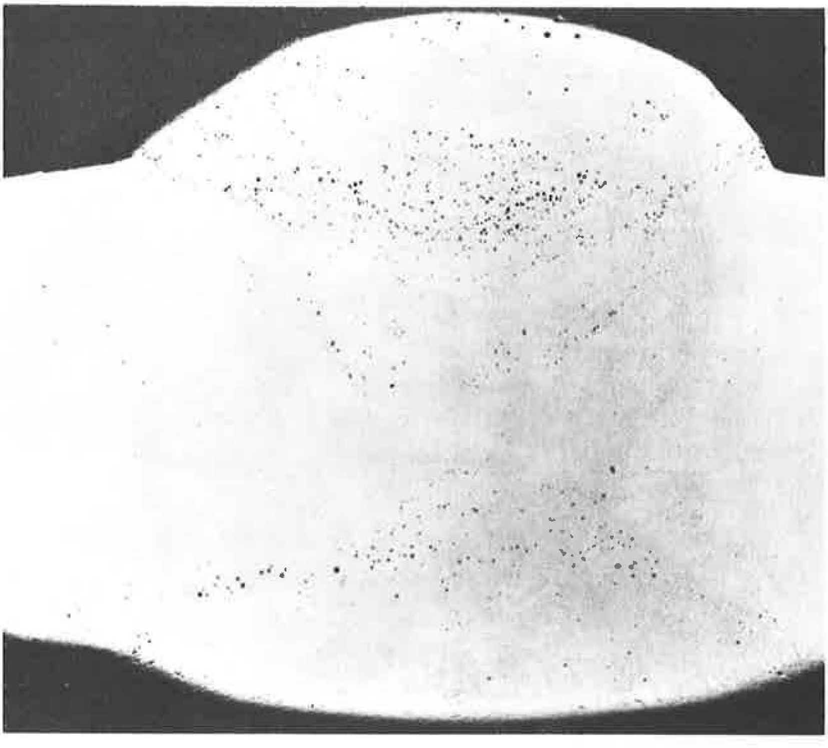


Figure 26. Macrograph showing microporosity in a MIG weld in ½-in. 2219-T87 plate (S-278490, mag. 5X, as-polished).

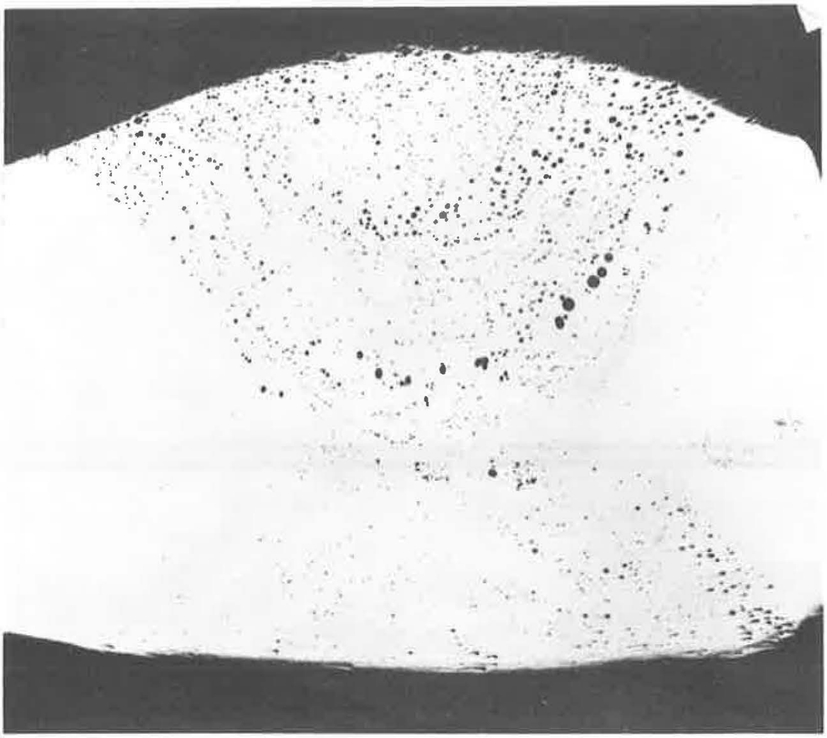
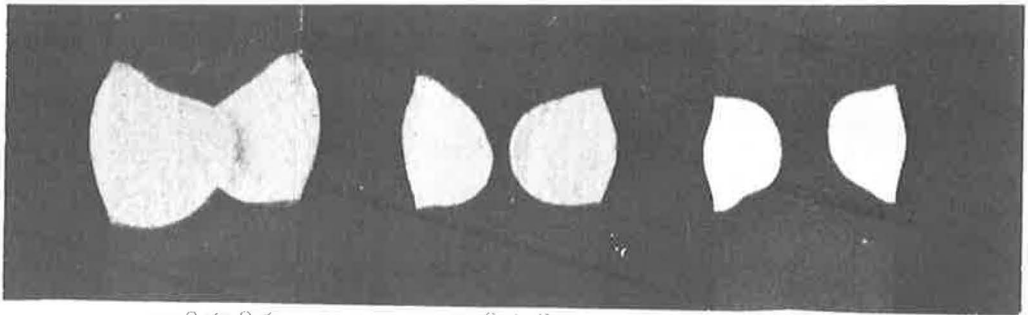
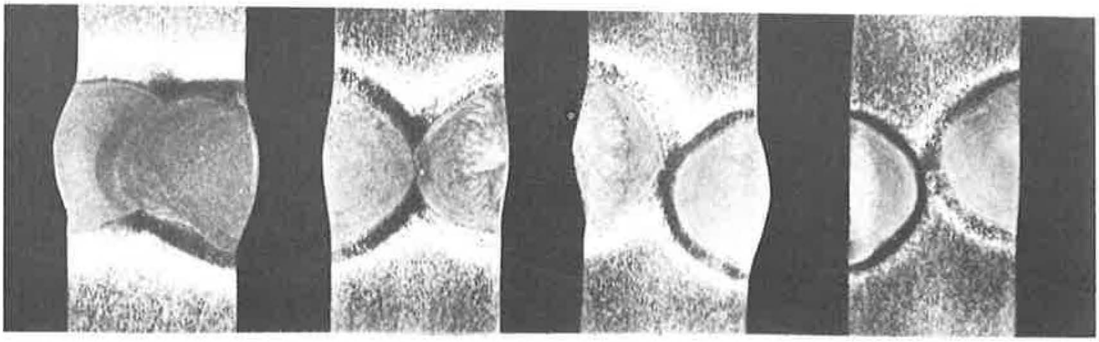


Figure 27. Macrograph showing porosity in a TIG weld in $\frac{1}{2}$-in. 2219-T87 plate (S-278462, mag. 5X, as-polished).

Figure 28. Micrographs showing oxide inclusions in MIG weld in $\frac{1}{2}$-in. 2219-T87 plate (S-278598, mag. 500X, etch Keller's).



S285185 S285187 S285221



S285321-M1 S285323-M1 S285322-M1 S285324-M1

Figure 29. Macrographs of sections through square butt TIG welds in 2219-T87 plate showing various degrees of penetration (mag. 2X, etch: top row 10% NaOH, bottom row Keller's).

microporosity is arbitrarily defined as porosity in which the voids have diameters less than about 0.01 in. which is approximately the smallest void discernible to the unaided eye.) Various weld conditions are shown in the macrosections included in Figures 18, 19, 20 and 21.

Figure 22 is a 2× photograph of a crater on the root pass of a TIG butt weld in ½-in. plate. A macrosection through the weld and crater appears in Figure 23. Fine porosity is rather generally distributed through the weld bead on the face side but the root side bead is comparatively sound. A more detailed metallographic examination of the section failed to reveal any significant effect of the crater on the structure of the surrounding weld metal.

Figure 24 shows a macrograph of a section through a TIG weld in ½-in. plate. An arrow indicates lack of root fusion. Figures 25 and 26 illustrate microporosity in otherwise sound welds in ½-in. plate. Figure 27 shows rather generally distributed porosity in a TIG weld in ½-in. plate. The larger pores are in the macro range and the finer ones in the micro range. Figure 28 shows oxide inclusions in a MIG weld in ½-in. plate. The weld was made with a reduced flow of shielding gas to favor oxide formation. The macrographs in Figure 29 illustrate various degrees of penetration in the square butt welds previously referred to.

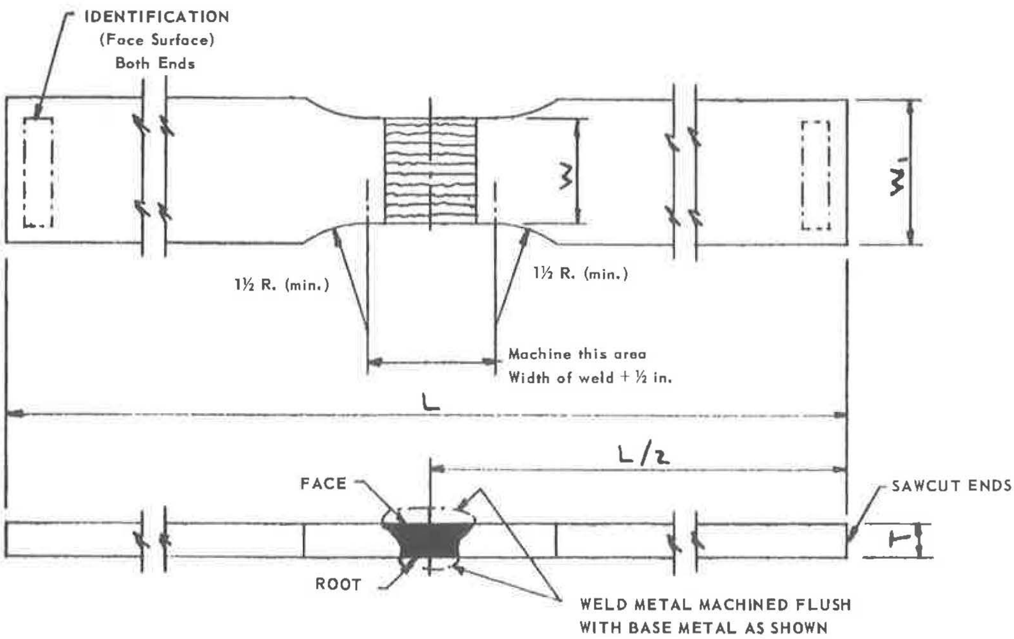
Metallographic measurements of the extent of interpenetration or separation of the weld bead roots in the square butt welds were summarized in Table 6, previously referred to in conjunction with the ultrasonic tests.

## DISCUSSION OF NONDESTRUCTIVE TESTS

As previously pointed out (see Table 5) a substantial fraction of the weld discontinuities can be detected both radiographically and ultrasonically. Radiographic examination provides more information on the exact nature of the weld conditions but the ultrasonic procedure would be faster for large-scale commercial inspection and more amenable to automation.

One shortcoming of the ultrasonic method that probably can be overcome is associated with extraneous indications originating from the crowns on the welds. In some instances it is necessary to scarf the weld to determine whether an ultrasonic indication is associated with an actual defect. A few preliminary tests with the variable-angle liquid-filled search unit suggested that a search unit angulating technique could be developed for minimizing the extraneous indications originating from the weld bead. Extraneous ultrasonic indications were also consistently reduced by merely smoothing the weld crowns before testing.

Substantial incomplete penetration in the square butt welds (root separations in excess of about $^1/_{16}$ in.) could be detected by both the radiographic and the ultrasonic procedures. However, the ultrasonic procedure was much more effective for detecting this condition when the weld bead roots were separated by the smaller distances associated with only slight amounts of incomplete penetration.




**SPECIMEN DIMENSIONS**

NOTE: Specimen thickness greater than decimal dimension (last No. 1st Col.) shall be machined in accordance with the dimension shown for the next higher specimen thickness range.

NOTE: For specimen layout allow 3/16 in. for sawcut and finish of edges.

| Nominal Thickness, in. (T) | Total Width, in. (Wi) | Width at Weld, in. (W) | Minimum Length, in. (L) |
|---|---|---|---|
| 1/4 to 0.356 | 2 | 1½ | 18 |
| 3/8 to 0.475 | 2 | 1½ | 20 |
| 1/2 to 0.720 | 2 | 1½ | 22 |
| 3/4 to 0.963 | 2 | 1½ | 24 |
| 1" to 1.455 | 1½ | 1" | 28 |
| Greater than 1-1/2 | 1½ | 1" | 30 |

Figure 30. Reduced-section tensile specimen.

## TABLE 7

## TENSILE STRENGTHS OF ARC WELDED 2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS*

| S No. | APDL No. | Type of Weld | Plate Thickness | Nominal Weld Condition | Tensile Test Spec. No. | Tensile Test T.S.+ psi |
|---|---|---|---|---|---|---|
| 278454 | 1 | TIG | 1/2" | Relatively sound but some microporosity | T1 | 36200(a) |
| | | | | | T2 | 39000(a) |
| | | | | | Av. | 37600 |
| 278515 | 9B2 | MIG | 1" | Relatively sound but some microporosity | T1 | 41900(c) |
| | | | | | T2 | 41900(c) |
| | | | | | Av. | 41900 |
| 278491 | 9A1 | MIG | 1/2" | Microporosity | T1 | 38400(a) |
| | | | | | T2 | 38600(a) |
| | | | | | Av. | 38500 |
| 278490 | 9A2 | MIG | 1/2" | Microporosity | T1 | 38900(a) |
| | | | | | T2 | 39100(a) |
| | | | | | Av. | 39000 |
| 278462 | 6A | TIG | 1/2" | Microporosity with some scattered macroporosity | T1 | 32500(c) |
| | | | | | T2 | 35700(c) |
| | | | | | Av. | 34100 |
| 278492 | 10A1 | MIG | 1/2" | Linear porosity | T1 | 34300(a) |
| | | | | | T2 | 34900(a) |
| | | | | | Av. | 34600 |
| 278496 | 11A2 | MIG | 1/2" | Scattered porosity | T1 | 34800(c) |
| | | | | | T2 | 33600(c) |
| | | | | | Av. | 34200 |
| 278509 | 11B2 | MIG | 1" | Light randomly scattered porosity | T1 | 29300(c) |
| | | | | | T2 | 29800(a) |
| | | | | | Av. | 29550 |
| 278596 | 11B3 | MIG | 1" | Scattered porosity | T1 | 32800(a) |
| | | | | | T2 | 37700(a) |
| | | | | | Av. | 35250 |
| 278598 | 12A5 | MIG | 1/2" | Oxide inclusions | T1 | 16500(a) |
| | | | | | T2 | 18000(a) |
| | | | | | Av. | 17250 |
| 278549 | A5 | TIG | 1" | Oxide film | T1 | 25200(c) |
| | | | | | T2 | 19600(c) |
| | | | | | Av. | 22400 |
| 278486 | 53A | TIG | 1/2" | Tungsten inclusions | T1 | 34700(b) |
| | | | | | T2 | 29600(a) |
| | | | | | Av. | 32150 |

(Continued)

TABLE 7 (Continued)

TENSILE STRENGTHS OF ARC WELDED
2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS*

| S No. | APDL No. | Type of Weld | Plate Thickness | Nominal Weld Condition | Tensile Test Spec. No. | Tensile Test T.S.+ psi |
|---|---|---|---|---|---|---|
| 278493 | 5A1 | MIG | 1/2" | Lack of interpass fusion | T1 | 32300(a) |
| | | | | | T2 | 31800(a) |
| | | | | | Av. | 32050 |
| 278516 | 5B1 | MIG | 1" | Lack of interpass fusion | T1 | 33300(a) |
| | | | | | T2 | 32500(a) |
| | | | | | Av. | 32900 |
| 278459 | 26B | TIG | 1/2" | Lack of root fusion | T1 | 16500(a) |
| | | | | | T2 | 17900(a) |
| | | | | | Av. | 17200 |
| 278511 | 6B2 | MIG | 1" | Lack of root fusion | T1 | 27300(a) |
| | | | | | T2 | 27300(b) |
| | | | | | Av. | 27300 |
| 278597 | 7A4 | MIG | 1/2" | Lack of side fusion | T1 | 27700(a) |
| | | | | | T2 | 27200(a) |
| | | | | | Av. | 27450 |
| 278518 | 7B1 | MIG | 1" | Lack of side fusion | T1 | 33100(b) |
| | | | | | T2 | 32700(a) |
| | | | | | Av. | 32900 |
| 278488 | 8A1 | MIG | 1/2" | Incomplete root penetration | T1 | 9800(a) |
| | | | | | T2 | 10100(a) |
| | | | | | Av. | 9950 |
| 278504 | 8B2 | MIG | 1" | Incomplete root penetration | T1 | 21500(a) |
| | | | | | T2 | 21100(a) |
| | | | | | Av. | 21300 |
| 278522 | 2A1 | MIG | 1/2" | Craters (face pass) | T1 | 33700(a) |
| | | | | (Specs. T1 and T2 include | T2 | 30300(a) |
| | | | | craters; T3 and T4 do not) | Av. | 32000 |
| | | | | | T3 | 37700(a) |
| | | | | | T4 | 38500(a) |
| | | | | | Av. | 38100 |
| 278514 | 2B2 | MIG | 1" | Craters (face pass) | T1 | 32500(a) |
| | | | | (Specs. T1 and T2 include | T2 | 34500(a) |
| | | | | craters; T3 and T4 do not) | Av. | 33500 |
| | | | | | T3 | 40000(c) |
| | | | | | T4 | 42500(b) |
| | | | | | Av. | 41250 |
| 278461 | 46 | TIG | 1/2" | Craters (root pass) | T1 | 24700(c) |
| | | | | (Specs. T1 and T2 include | T2 | 24800(c) |
| | | | | craters; T3 and T4 do not) | Av. | 24750 |
| | | | | | T3 | 34100(c) |
| | | | | | T4 | 32800(c) |
| | | | | | Av. | 33450 |

(continued)

**TABLE 7 (Continued)**

**TENSILE STRENGTHS OF ARC WELDED 2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS***

| S No. | APDL No. | Type of Weld | Plate Thickness | Nominal Weld Condition | Tensile Test Spec. No. | Tensile Test T.S.+ psi |
|---|---|---|---|---|---|---|
| 278548 | A4 | TIG | 1" | Reasonably sound--(Specs. T1 and T3 tested in as-welded condition; T2 and T4 reheat-treated and aged to -T62 temper before testing.) | T1 | 29900(a) (As welded) |
| | | | | | T3 | 25500(a) (As welded) |
| | | | | | Av. | 27700 (As welded) |
| | | | | | T2 | 46400(a) (Reheat treated) |
| | | | | | T4 | 47100(a) (Reheat treated) |
| | | | | | Av. | 46750 (Reheat treated) |

*Reduced-section specimens used for all tensile tests. Single-V butt joints used for all 1/2" plates and double-V butt joints for all 1" plates. All specimens tested in as welded condition.*

*+Letters in parentheses after tensile values indicate path of fracture: (a) through weld, (b) at edge of weld and (c) partly through and partly at edge of weld.*

## TENSILE TESTS

In order to determine the effect of various weld conditions on joint strength and ductility, reduced-section tensile tests and face and root guided bend tests were made on specimens representing all but a few of the weld conditions included in the investigation. These tests were omitted in the case of a few welds containing the synthetic defects previously mentioned. Because the significance of the bend tests was questionable, their results also have been omitted.

With one exception, the joints were tested without reheat treatment although it was recognized that joint properties could be influenced by the heat of welding as well as by the weld condition. To obtain some indication of this heat effect, four reduced section

**TABLE 8**

**EFFECT OF DEGREE OF PENETRATION ON TENSILE STRENGTH OF SQUARE BUTT WELDED SPECIMENS OF 2219-T87 PLATE***

| S No. | Penetration | Tensile† Strength psi |
|---|---|---|
| 285185 | Complete. Roots of two weld beads interpenetrate one another to depth of about 1/8". | 42,600 |
| 285187 | Moderately incomplete. About 1/16" separation between roots of two weld beads. | 30,000 |
| 285221 | Markedly incomplete. About 1/8" separation between roots of two weld beads. | 26,400 |

**Welds made in 1/2" plate by TIG-DCSP procedure using 2319 filler wire and one pass on each side of joint. Test specimens conform with Section IX of ASME Boiler and Pressure Vessel Code, 1962 Edition. Values are averages for two tests.*

*† Reduced-section specimens.*

tensile specimens were machined from a 1-in. TIG welded plate of 2219-T87 alloy. Two of these specimens were reheat treated and aged to the -T62 temper (heat-treated 1½ hr at 1,000° F, quenched in cold water and aged 36 hours at 375° F) before testing while the remaining two were tested in the as-welded condition. It was not feasible to restore the original -T87 temper as this requires a strain-hardening step between solution heat treatment and aging.

In the case of several panels containing weld craters, some of the tensile blanks were cut to include craters, and others were cut from portions of the same welds that were free from craters. The type of reduced-section specimen employed for the tensile tests is shown in Figure 30.

The results of the tensile tests on specimens from the panels with single-V and double-V joints are given in Table 7. With two exceptions (S278548-T2 and -T4) these specimens were tested in the as-welded condition.

It appears unlikely that microporosity has had any significant adverse effect on weld strength although a completely sound weld was not available for comparison. However, in certain instances the coarser forms of porosity appeared to affect the strength of the weld adversely. Weld strength also appears to have been adversely affected by oxide inclusions and film, tungsten inclusions (particularly in the case of specimen S278486-T2), lack of interpass, root and side fusion, and incomplete root penetration.

Craters appeared to exhibit an adverse effect on tensile strength in spite of the fact that the actual crater cavities were removed in machining the specimens. The average reduced section tensile strengths for specimens with and without craters from 2 welded panels are as follows:

| Panel S No. | Tensile Strength, psi | |
|---|---|---|
| | With Craters | Without Craters |
| 278461 | 24750 | 33450 |
| 278514 | 14250 | 33500 |
| 278522 | 32000 | 38100 |

The data for the last group (S278548) of specimens listed in Table 7 give a rough indication of the extent to which joint strengths have been influenced by the heat of welding. The average tensile strength of 27,700 psi for the as-welded specimens was increased to 46,750 psi by reheat treatment and aging to the -T62 temper.

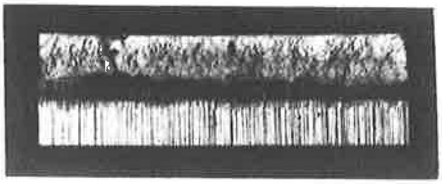
Table 8 gives reduced section tensile test data for some of the TIG welded square butt joints in ½-in. plate. It is evident that even moderately incomplete penetration with a root separation of about 1/16-in. has had a marked effect in reducing the tensile properties of this type of joint.

## EXAMINATION OF FRACTURES

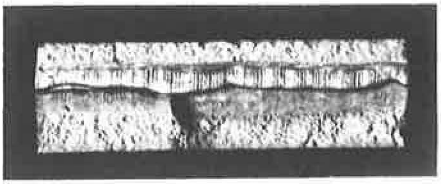
Examination of the fractures in the tensile specimens helped to confirm the following weld conditions: incomplete root penetration; lack of root, interpass and side fusion; linear and scattered porosity and oxide inclusions and film. Photographs of tensile fractures associated with these conditions are shown in Figures 31 and 32. The fractures shown in Figure 31 are from ½-in. panels and those in Figure 32 from 1-in. panels.

In fracture S278488 (incomplete root penetration) the sawed surface of the unpenetrated land is plainly evident. Fracture S278459 (lack of root fusion) shows the wavy lower edge of weld metal that has not fused into the plate. This metal has taken the imprint of saw marks on the groove. A fissure extends in from the left side for about half of the specimen width.

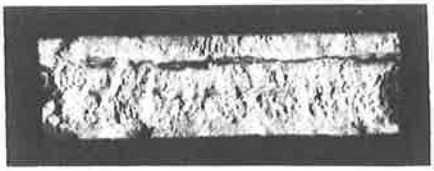
The lack of interpass fusion in S278493 appears as a dark line or shallow fissure extending almost completely across the fracture about ⅛ in. below the top surface.



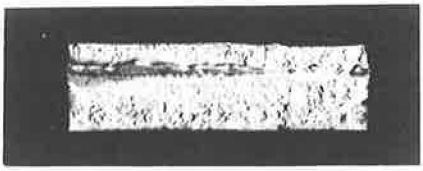
S278488
INCOMPLETE ROOT PENETRATION



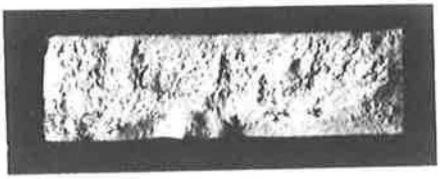
S278459
LACK OF ROOT FUSION



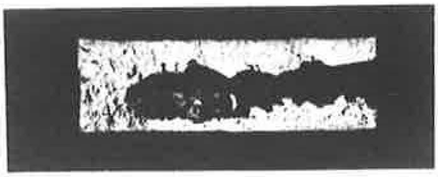
S278493
LACK OF INTERPASS FUSION



S278597
LACK OF SIDE FUSION



S278492
LINEAR POROSITY



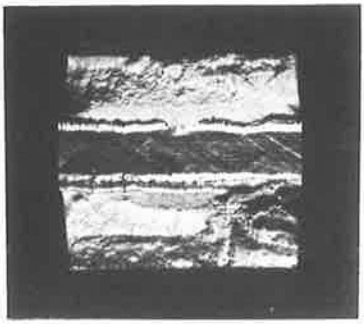
S278598
OXIDE

Figure 31. Tensile fractures in specimens from welded $\frac{1}{2}$-in. 2219-T87 plates (natural size or slightly enlarged).

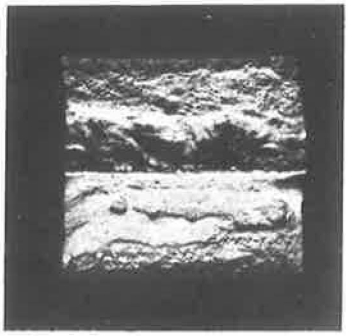
Lack of side fusion in S278597 appears as a shallow tapering cavity extending from the left edge about two-thirds across the fracture. There are two isolated cavities near the right side. A few small cavities associated with the linear porosity appear in the lower part of fracture S278492. The dark surface that covers over one-third of the fracture in S278598 had a carbon-like appearance which is probably associated with finely dispersed oxide.

The first fracture in Figure 32 is associated with incomplete root penetration. The surface of the unpenetrated land in S278504 forms a conspicuous band about $\frac{1}{4}$-in. wide extending completely across the fracture. The dark areas just above the horizontal centerline in fracture S278511 are cavities associated with the lack of root fusion that this specimen exemplifies.

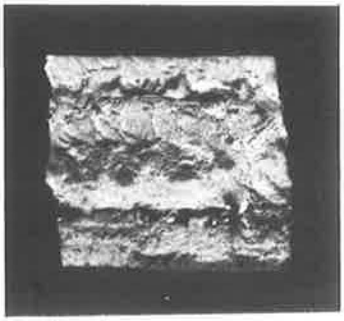
In the fracture of S278516 (lack of interpass fusion) a narrow band that is generally dark but which contains some small white spots extends horizontally across the fracture about $\frac{5}{16}$-in. above the lower edge. This band represents an unsound region associated with the lack of interpass fusion. Fracture S278518 (lack of side fusion) exhibits a narrow band that is generally dark but which contains small light spots and patches. This band extends across the greater part of the fracture about $\frac{3}{16}$ in. above the lower edge. It represents an unsound portion of the joint associated with the lack of side fusion. The scattered porosity in fracture S278596 is conspicuously evident in a zone about $\frac{3}{16}$-in. extending horizontally across the fracture a short distance below the top edge.



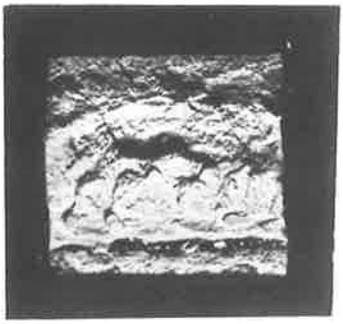
S278504
INCOMPLETE
ROOT PENETRATION



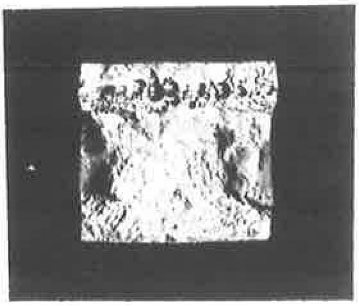
S278511
LACK OF ROOT FUSION



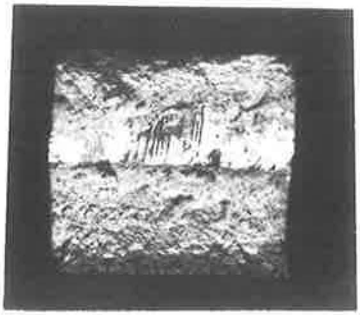
S278516
LACK OF
INTERPASS FUSION



S278518
LACK OF SIDE FUSION



S278596
SCATTERED POROSITY



S278549
OXIDE FILM

Figure 32. Tensile fractures in specimens from welded 1-in. 2219-T87 plates (natural size or slightly enlarged).

The white areas just above the horizontal centerline in fracture S278549 (oxide film) represent portions of the fracture where an oxide film is believed to have prevented bonding between the weld metal and the metal of the plate. The weld metal has actually taken the imprint of saw marks on the groove but did not fuse to it.

Fracture studies and a metallographic examination indicated that the lower strength of the specimens with craters might be related to a concentric ring pattern of coarse and fine grains apparent in the fracture and thought to be connected with the crater formation, but further work would be necessary to adequately explain the effect of the craters on weld strength.

## CONCLUSION

Radiographic examinations and ultrasonic tests are valuable and effective procedures for determining the structural integrity of welds in aluminum alloy structures. The former procedure gives a more definitive picture of the actual weld condition. Nevertheless, it is probable that ultrasonic examination will gradually replace radiography for the inspection of long lengths of weld because this method is faster and more readily automated.

Certain of the discontinuities deliberately introduced into the welds for this investigation significantly impaired strength. It is important to note, however, that a number of the specimens were extreme examples of the conditions they represented. Welds containing limited amounts of certain of the discontinuities might be entirely suitable for many applications. In setting up rejection limits for radiographic or ultrasonic inspection of welds, consideration must be given to the requirements for the application in which the welds are to be used. Otherwise, the unwarranted rejection of usable assemblies may result in a substantial financial loss.

## ACKNOWLEDGMENT

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## *Discussion*

SIMON A. GREENBERG, Industrial Consultant, Flushing, N.Y.—This paper presents an interesting initial investigation of the defects which might be encountered in inert gas welding of aluminum. It also offers a first attempt at the evaluation of the feasibility of defect detection by nondestructive methods and an evaluation of the effects of such defects on structural integrity.

Being a beginning, the work reported in this paper does not cover any aspect it treats in depth. The greatest benefit to be derived from this paper will be from the prompting it gives to further work in exploring each of the subjects covered separately and in greater depth.

A separate study of the different techniques of radiography and ultrasonics as applied to aluminum welds would be most beneficial.

As the authors point out, their study of the effects of weld defects was done with welds containing unusually large amounts of defects. If a study were made to establish the margin of acceptance of each type of defect, it should lead to reasonable, valid specification acceptance standards. This would permit fullest use of aluminum, yet allow for screening out those welds which are structurally unsound.

Although the authors surely did not intend it, this paper would serve the structural field very well indeed if it prompted a study of the effects of weld defects in steel on their structural behavior.

Our present requirements are probably safe, but they are born of opinion and subjective experience. In some instances they are vague for lack of valid data on which to base more specific requirements.

A study of weld defects in steel might permit relaxation of some of the requirements and answer the clamor of many that this be done—which we cannot do at present for lack of data on which to base such relaxations. It might even be found that acceptance standards for some defects should be more stringent for some combinations of service conditions.

Most important, such studies, for whatever materials they are made, will permit more efficient use of the material and a closer approach to its full utilization in structural design and fabrication. Thus, we can closer approach the economic design of structures, something that is too often overlooked by our designers today.