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A SURVEY OF WELDING AND INSPECTION TECHNIQUES FOR 2219-T81 ALUMINUM ALLOY

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W. E. Witzell, M. S. Hersh, and R. T. Anderson

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

January 1967

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GENERAL DYNAMICS
Convair Division

NOTICE

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D. J. Hallman

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INTERIM REPORT

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Technical Management
NASA Lewis Research Center
Cleveland, Ohio
R. N. Johnson

GENERAL DYNAMICS
Convair Division

FOREWORD

This interim report consists of a review of current literature and of an industry survey performed by General Dynamics Convair as partial fullfillment of Contract NAS3-7951.

Areas of interest were welding and nondestructive testing of 2219-T81 aluminum alloy. The information obtained and presented in this report will be used to complete the experimental and analysis portion of the overall program under the direction of Mr. Richard N. Johnson of NASA-Lewis Research Center.

Convair personnel involved in this initial task were:

M. S. Hersh (Welding)

R. T. Anderson (Nondestructive Testing)

W. E. Witzell (Program Manager)

ABSTRACT

A literature search and industry survey were performed to determine the best techniques for the welding and subsequent inspection of type 2219-T81 aluminum alloy. Results indicated that this alloy is readily welded and no unique inspection problems are imposed by this material.

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1/SUMMARY

A literature search and industry survey were performed to determine current techniques for welding and inspection of 2219-T81 aluminum alloy (primarily for 0.063-inch-thick sheet and 1.00-inch-thick plate). Seventeen of 25 industry survey questionnaires were completed and returned. However, no strong consensus was obtained for optimum weld or weld repair techniques. Actually, the results indicated that relatively imperfection-free welds were obtained from various automatic techniques such as Gas Tungsten Arc (also known as TIG) and Gas Metal Arc (commonly called MIG).

The only consistent imperfection noted was that of porosity. More difficulties were detected for manual weld repairs, particularly if multiple repairs were made in the same area.

Detection and characterization of weld flaws are somewhat more difficult. Various techniques have some utility for specific applications, but no known single system can consistently identify and measure flaws or cracks in welded structures with sufficient accuracy as to be useful for fracture mechanics type analysis. It is probable that penetrant techniques and radiography will continue to be the primary methods of inspection of welded structure in the near future.

2/INTRODUCTION

Prior studies have indicated that 2219-T81 (and -T87) aluminum is a promising alloy for use as a cryogenic tank material.(I-1, I-2, I-3, I-4)* The properties of this alloy in both the -T81 and -T87 conditions are similar. Two differences occur during processing: 1) -T81 is heat treated and stretched by the manufacturer while -T87 is heat treated and cold worked approximately 9% by the manufacturer, and 2) -T81 is aged 18 hours at 350°F while -T87 is aged 24 hours at 325°F.(I-5)

The fracture mechanics characteristics of 2219 aluminum have been evaluated primarily in the unwelded base metal form.(I-1, I-2, I-3, I-4) However, in order to fabricate metal structures it is necessary to join the base metal. In the event that welding is used, the fracture characteristics of the welded alloy are likely to be different from the base metal characteristics.

Other than heat treat considerations, one of the causes of differences in fracture toughness is weld imperfections. To ensure favorable performance of the final structure it is necessary to weld the base metal with few or no weld flaws. Also, in order to determine the quality of the weld it is important to accurately determine the absence or presence of imperfections by some nondestructive method prior to service. Further, it is important to determine what effect an imperfection has on the strength or fracture toughness of the joint.

The current program attempts to accomplish the following:

a. Establish a sound weld technique for 2219-T81 aluminum alloy. Determination of a satisfactory weld technique was attempted by performing an industry survey and literature search. The literature was abundant with information on weld techniques and over 75% of the industry survey questionnaires were completed and returned. Unfortunately, the primary method of judging a good weld was not adequate from a fracture mechanics point of view. The usual criteria consisted of two questions: 1) "How does it look?", and 2) "Did it pass inspection?" (i.e., the appropriate specification). Some values of weld strength that were obtained are presented in this report.

b. Establish reliable inspection techniques. Again, determination of existing methods was made through a literature survey. As in welding, the reliability of these techniques is difficult to determine.

*Numbers in parenthesis indicate references. Plain numbers indicate articles pertaining to welding, while numbers following the letter "R" refer to nondestructive testing. The letter "A" indicates that an abstract is included in this report, "I" refers to general references, and "S" stands for specifications.

c. Using the techniques obtained from (a) and (b), weld and inspect 2219-T81 aluminum alloy. This will be accomplished in several ways. To isolate thickness effects, both 0.063-inch sheets and 1-inch plate will be welded and inspected. Initial acceptance of welds will be based on radiographic, ultrasonic, and penetrant inspection. After acceptable welds are obtained, a portion of the weldments will be repair welded using acceptable repair techniques. In several cases, defects will be intentionally included in the welds.

d. Determine the static fracture toughness and cyclic load flaw growth characteristics of the base metal, weldments, and weld repairs at room temperature, -320° F, and -423°F. Fracture characteristics will be compared for both sheet and plate under conditions of plane stress (sheet) and plane strain (plate). Plane stress specimens will be of the center-notched variety while plane strain tests will utilize surface crack techniques.

The results of the literature search and industry survey mentioned in (a) and (b) form the basis for this report.

3/WELDING OF 2219-T81 ALUMINUM

Task I of the Weld Flaw Enlargement Characteristics Contract (NAS3-7951) is to select the best production weld practices for butt welding 2219-T81 aluminum alloy. The two thicknesses under consideration in this program are 0.063-inch sheet and 1.00-inch plate. Because of the scope of this task, it is necessary to concentrate on procedures that are applicable to the subject thicknesses. However, data on defects, specifications, and properties developed on different gages and other 2000-series aluminum alloys are also considered. Aluminum alloy 2219-T87 differs from 2219-T81 in the amount of cold work in the sheet or plate prior to aging. The slightly higher amount of cold work in the -T87 condition increases the strength and decreases the ductility somewhat. Because the -T87 and -T81 tempers are so similar the procedures used to weld them are almost identical. All welding information developed for 2219-T87 is applicable for 2219-T81.

The parameters that are controlled during a welding process can be divided into four categories: pre-weld preparation, welding set-up, weld procedure, and post-weld treatment. The first three are considered in depth. No post-weld treatment is considered in this program, and there is no discussion of post-weld treatment in this report. The resultant weld can be evaluated on two bases: weld quality and weld properties. These are considered in some detail. Repair welding is discussed separately, both from a procedural standpoint and as it affects joint properties. The requirements of various specifications for welding and repair welding also are discussed.

Information has been accumulated through a literature search, industry survey, and from responses to a questionnaire sent to aerospace companies, research laboratories, aluminum producers, and Government installations. A complete list of references and a compilation of the questionnaire responses are included in this report.

3.1 PRE-WELD PREPARATION

Normally, certain joint design decisions are made on the basis of structural design requirements. For the purpose of this program, it is assumed that the material and thicknesses, as well as the joint configuration, have been so chosen; i.e., 2219-T81 in 0.063- and 1.00-inch thicknesses will be automatic fusion welded by an inert gas shielded process. Flat sheets or plates will be butt welded and tested in the as-welded condition.

In general, for production welding of tankage, allowable gap and mismatch are controlled to conform to a specification, but for welding in this program these two variables will be minimized. Because the flat sheets will be welded in a holddown fixture, and because flat 1.00-inch plates distort very little during welding, only negligible gap or mismatch can be expected. Excess gap or mismatch requires a larger weld to effect a joint. A larger weld means higher heat input, which lowers the joint strength. It also requires more filler wire, which in turn increases the probability of defects induced by filler wire contamination.

The joint design used to weld 0.063-inch sheet by all sources investigated is square butt; for the 1.00-inch plate a square butt joint design will also be used. Two-thirds of the responders to the questionnaire, as well as considerable data developed during the NOVA Study Program,[25] recommend this joint design. A square butt, two- or four-pass sequential weld is more economical than multi-pass groove-joint welds and has higher properties. Due to the straight sides of the weld and heat-affected zones (see Figure 1) of the square butt weld it is simpler to instrument and measure fracture properties.

The most critical pre-weld step is joint preparation and cleaning. In conformance with all government and most company specifications, the butting faces are to be filed and both sides of the sheets or plates are to be hand scraped. The scraping extends sufficiently back from the weld to preclude surface contamination entering the joint. Normally 1/2 inch is sufficient. Scraping welds significantly reduces the number of defects.[30] Of 40 welds properly scraped prior to welding, 33 were Class I quality and only 3 were rejectable under Class II requirements. Of 40 identical welds, not scraped, 14 were Class I and 20 were rejectable under Class II requirements. The joint is to be wiped clean with a volatile solvent such as MEK (methyl ethyl ketone). The joint preparation and cleaning must occur within four hours of welding to prevent re-contamination.

For this program the sheets and plates are to be cleaned with MEK. The surfaces are to be hand scraped and the weld edges draw filed.

3.2 WELD SET-UP

The first consideration in setting-up to weld is to determine the process to use. Gas tungsten arc (GTA, also called TIG) welding is superior to gas metal arc (GMA, also called MIG) for welding aluminum because GTA welds have better quality and higher and more consistent strength.[21] Additionally, for welding 1.00-inch plate GMA welding requires groove-joint preparation and multi-pass welding. The 1.00-inch plate must be welded by the direct-current straight polarity (DCSP) process to get sufficient penetration. There is much disagreement on the proper process for welding 0.063-inch sheet. In this report, if the process is not specified it is GTA.

Nearly half the responses to the questionnaire recommended GTA alternating current for welding the sheet. A-c welding is more forgiving to variations in process and set-up, and, in general, results in welds with slightly less porosity. However, DCSP welding will be used for the 0.063-inch sheet because of higher joint strength, a result of lower heat input, its more frequent appearance in welding literature,[56, 17, 51, 10, 58] and because it is probable that both the Boeing Company and the Lockheed

Corporation will use GTA-DCSP welding for a pair of 9-foot oblate-spheroid tanks intended for Lewis Research Center in-house research. These tanks represent the present state-of-the-art in fabrication of thin-gage aluminum vessels.

For this program, the sheet is to be welded in one pass because it is simple and efficient. The plate is to be welded in two passes sequentially(6) (one pass from each side), without filler wire if possible. Two-pass welding of butt joints in heavy plates is the practice generally used in the aerospace industry because it is both economical and minimizes the use of filler wire. Fewer passes mean fewer opportunities for the introduction of defects, and less filler means less introduction of water vapor into the weld. It may be necessary to use two additional passes with filler wire to consistently eliminate undercutting.

It is possible to weld in any standard position; flat, vertical, or horizontal. The decision to weld in the flat position is based on two considerations. First, it is the simplest, and results in the most consistent welds. Second, as can be seen in Figure 2, the tensile fracture of 1.00-inch plate specimens occurs consistently in the center of the weld. Vertically and horizontally welded specimens fracture near the edge of the weld, with the fracture moving in and out of the heat-affected zone. Thus flat-position welding simplifies both welding and testing.

Start and tail slope characteristics, which are important for production welding, have to be detailed to the particular equipment and configuration to be welded. For this program, these start and stop details will not be evaluated.

Welding fixtures and backup bar tooling for thin sheet are very different from those for thick plate. Thin sheet welding requires hard tooling to prevent distortion during welding. Backup bars can be copper or steel and of varying groove configurations. The primary concern is to control the heat distribution in order to allow gas to escape and to more uniformly cool the weld. The tooling must be chosen on the basis of the specific equipment and set-up. Thick plate welding does not require any tooling, except to align the parts, because of the stiffness of the plate. On 3/8-inch plate, it was found(11) that a wider backup bar improved the weld quality. For this program, a mild steel backup bar with a 1/8-inch deep by 3/8-inch wide groove will be used for welding the sheet. To achieve greater cooling for repair welding the sheet, a copper backup bar with a 0.040-inch deep by 0.187-inch wide groove will be used. No backup bar will be used for the plate. See Table 1.

The electrodes used for GTA welding of aluminum are almost universally two-percent thoriated tungsten. For the sheet, a 3/32-inch diameter was preferred by most surveyed, as was a 1/8-inch diameter for the plate. There exists considerable variation of opinion on the proper electrode tip configuration. In general, for automatic GTA-DCSP welding, a slightly tapered electrode is preferred over a sharp taper because it holds up longer and distorts less. For welding thick plate, the electrode is either blunt or tapered to half the diameter and then is left blunt. This increases penetration while maximizing tip life and minimizing electrode breakdown. For a-c welding, a ball tip electrode is preferred because of the heat input to the electrode during the reverse polarity cycle. For this program similar electrodes will be used. The electrodes are described in Table 1.

The filler wire diameter is generally matched to the joint design and welding process, and is generally not critical. A 1/16-inch-diameter wire can be used for almost all butt welding, though many prefer a 3/64-inch-diameter wire for sheet thicknesses, as will be used in this program. No filler wire will be used to weld the plate. For repair welding, 3/32-inch wire will be used (see Table 1).

The torch nozzle size is determined by the amount of cover gas to be used. Few data are available for selecting the proper nozzle, though most weldors have personal preferences. Aluminum welding generally requires a high volume of cover gas (50 to 100 CFH) to prevent contamination and thus relatively large torch nozzles are used.

3.3 WELD PROCEDURE

The major variables to consider when developing a weld procedure are voltage, current, travel speed, wire feed, cover gas, backup gas, and, for heavy sections, the number and sequence of passes. These factors are intimately involved with both weld quality and properties. In this section, only those decisions concerned with selecting the process variables will be considered. Table 1 contains the process variables to be used in this program. Tables 2 and 3 list the weld procedures found through the literature search and from responses to the questionnaire, as well as those used for this program, for 0.063-inch sheet and 1.00-inch plate, respectively.

The purpose of a weld procedure is to maximize mechanical properties, which generally means minimizing heat input, and to optimize weld quality, which generally means minimizing imperfections and irregularities. Although the weld parameters cannot be varied independently, each has a somewhat different function. Each will, therefore, be discussed separately and then jointly. Table 4 is a compilation of the general effects of varying the major welding variables in automatic TIG-DCSP (the process chosen for this program) welding of 2219-T81 aluminum.

Voltage, which cannot be varied independently from the electrode elevation,[40] determines the arc characteristics. Insufficient voltage will cause the weld bead to spread, and in the case of heavy plate, prevent sufficient penetration. Excess voltage increases the heat input without increasing quality, and accelerates electrode breakdown. For DCSP welding of aluminum in thicknesses up to one inch (Tables 2 and 3) the range of voltage is 11 to 15 volts, with the one exception where travel speed is unusually high. Furthermore, this variation is most probably the result of equipment characteristics. This range of voltage will be maintained throughout this program.

Current is the primary parameter used to control depth of penetration[54,40] and has the greatest effect on mechanical properties.[54] In combination with travel speed, it controls the weld cooling characteristics. The current is the variable most frequently adjusted while developing the procedure and even when making the weld. Insufficient current causes the arc to be unstable, and results in insufficient penetration. The weld bead configuration will remain constant if the current and travel speed are increased or decreased together, maintaining a constant ratio. For 0.063-inch sheet, currents from 40 to 125 amps are used, and for 1.00-inch plate, currents as high as 500 amps are used. It is the intent of this program to minimize the current, i.e., use 40 amperes for welding the sheet. For welding the plate 475 amperes will be used to ensure full penetration.

Ideally, one would wish to maximize travel speed to reduce welding time and cost and to minimize heat input. However, in order to reduce the amount of porosity, a slower travel speed is required to allow the weld to outgas. In heavy plate, reducing the travel speed increases the penetration and reduces the bead cross-section for a given heat input.[40] Typical travel speeds for 0.063-inch sheet were 8 to 20 ipm, and for 1.00-inch plate 3 to 7 ipm. For this program, 12 ipm, for the sheet, and 3.5 ipm, for the plate, will be the travel speeds used.

In developing a weld procedure, the voltage, current, and travel speed are optimized by minimizing heat input (voltage × current/travel speed), while maintaining required weld quality. All the procedures listed in Tables 2 and 3 apparently will give acceptable results on certain equipment for certain applications. Average values should give a reasonable starting point for developing a weld procedure.

The amount of filler wire required is a function of fit-up and desired bead contour. For thin sheet, filler wire is required to supply material for bead reinforcement. If the fit-up is good, a wire-feed to travel-speed ratio of 1.0 to 1.5 (based on a wire diameter equal to the sheet thickness) is sufficient. A ratio of 1.2 will be maintained in this program. A poorer fit-up requires more filler wire to maintain proper bead contour. Poor fit-up also results in a larger weld and requires a higher heat input. This lowers the weld properties. Because of the expansion of the weld metal, 1.00-inch plate may be welded without any filler wire. However, this requires very accurate fit-up. If there is a gap between the two plates to be welded, a good joint configuration may be obtained by two additional surface passes using a small amount of filler wire made at relatively high welding speeds. These additional passes are primarily to eliminate undercutting and smooth the bead contour. In general, it is more economical to machine the joint accurately and eliminate the two additional weld passes, which is what is intended in this program.

The proper cover gas to use for aluminum welding depends on the welding process. For a-c welding, argon is preferred, though some responses to the questionnaire indicated helium could also be used. For DCSP welding, helium is used almost exclusively. A few sources, however, recommend a mixture of 75% helium and 25% argon. Helium is a hotter gas; that is, for given settings it produces a higher arc voltage. It gives deeper penetration, but 2-1/2 to 3 times the volume of helium is required to give the equivalent gas coverage of a given volume of argon. Argon produces a more stable arc and reduces splatter, but this is only critical with a-c welding where the current flow reverses. With DCSP welding using helium gas, a better bead geometry is obtained but the arc length must be more carefully controlled. Excess helium at low amperage increases arc sensitivity and reduces arc stability; therefore, for welding thin sheet it must be carefully controlled. For 0.063-inch sheet, 50 to 60 CFH of helium is generally used, and for 1.00-inch plate, 85 to 100 CFH is used, as will be used in this program. Because no backup tooling is used to weld heavy plate, no backup gas is used. In a two-pass sequential weld, there is no penetration pass and backup shielding is not required. For one-pass welding of sheet, backup gas can help protect the weld bead drop-through from oxidation. Most responses to the questionnaire indicate that backup gas is not used. This is most probably because the weld bead is ground flush after welding and the surface oxides are thus removed. For this program, however, 12 CFH of argon will be used as backup gas to minimize root porosity.

3.4 WELD QUALITY

The literature abounds with information on the effects of various weld defects on the resultant weld properties and on methods of producing and controlling defects. It is important to realize that the validity of using data developed on artificial defects to represent the effect of real defects has never been substantiated. Because of this, care must be exercised in interpreting this literature.

In welding 2219 aluminum, the imperfection which is most difficult to eliminate, and which accounts for almost all the indications on weld radiographs, is porosity. Porosity is the result of gases, primarily hydrogen, trapped in the solidifying weld metal. It has been shown that moisture produces significantly more porosity than hydrogen gas. The shielding gas impurity[7,54] is, by far, the most significant cause of porosity. Control of metal chemical content and residual metallic impurities are far less important. Hydrogen additions to the shielding gas can cause porosity only when the hydrogen is added in extremely large amounts,[7] which would not be possible under normal welding conditions. It was learned at Lockheed, during the industry survey, that porosity has resulted with gas flows of 12 to 150 CFH and travel speeds of 8 to 75 ipm. It was stated that proper shielding during outgassing is the key to preventing porosity. Filler wire cleanliness must be maintained to prevent oxides from causing weld porosity. NASA-MSFC has put out a specification[48] governing acceptance of filler wire. Proper travel speed[32] is the normal means of controlling porosity.

The effect of tungsten inclusions on weld effectiveness is not clear. Artificially induced tungsten,[57,29] where the inclusions have no sharp edges, do not reduce joint strength or fatigue properties, even in large sizes. Tungsten inclusions occurring as the result of welding can have sharp edges and act as cracks.

Mismatch, though not very critical in amounts that are not difficult to guarantee, does increase due to uneven heat input[30] as welding proceeds. In this program, mismatch can be easily controlled and is no problem.

Cracks are the most serious defect in reducing all desired properties, and all efforts should be made to prevent weld cracking. The 2219 aluminum is extremely insensitive to cracking, and there appears to be little difficulty in preventing the occurrence of cracks.

Limits of weld imperfections will be discussed in the section on specifications. It should be noted that in many cases no specification exists that will guarantee sufficient quality, and not reject many joints that will adequately perform the task for which they were designed.

3.5 WELD PROPERTIES

The properties of welds that are of concern fall into three general categories: strength, ductility (ability to deform plastically), and toughness. Very few toughness data are available for 2219 aluminum welds. That, in fact, is the prime concern of this program. Pfluger[49] claims that, "Because of the low as-welded yield strength, measurement of fracture toughness of welds in 2219 aluminum is subject to error. However, the fracture toughness of the weld and heat-affected-zone is greater than that of the parent metal." Tables 5 and 6 list some typical mechanical properties of welded 2219-T81. Table 6 includes some repair weld data discussed in the section on repair welding.

Joint efficiencies of 65 to 70% are typical. The apparently low elongation in sheet tensiles, with a weld that is significantly softer than the base metal, is not a true measure of weld ductility. The tensile strength of the weld metal is lower than the base metal yield strength, and though the elongation in 2 inches may be 2%, the elongation in the weld may be as high as 16%. Marshall Space Flight Center has been able to establish a 35 KSI allowable tensile strength for GTA-DCSP welded 1.00-inch 2219 plate with 99% confidence and 99.3% conformity.[21]

The heat input, measured in joules per inch of weld per inch of thickness, has been considered the controlling factor in maintaining joint properties. Increasing the heat input decreases the weld tensile strength and increases the elongation.[32] Recent work[6,15,16,31,47] has indicated that the properties of welds are, more accurately, a function of the weld time-temperature characteristics. The temperature is the maximum temperature reached during the welding cycle, and the time is the time during which the weld is above some critical temperature. For aluminum this temperature is 450°F. Weld strength increases with higher maximum temperatures (up to 1500°F) and shorter times, while ductility, measured by tensile elongation, increases with higher maximum temperatures and longer times above 450°F. The short welding times needed to maximize strength are not practical for normal welding procedures;

however, rapid quench rates can be obtained under certain restricted conditions. Obtaining a peak weld temperature of near 1500°F is an obtainable goal, which in fact improves both strength and ductility. Longer weld cycles not only improve ductility, but allow gas to escape from the weld, reducing the porosity levels. With the current state-of-the-art capabilities, significant improvement in development of weld procedures to produce desired joint properties is possible. However, it appears that production welding personnel require considerable updating to achieve these goals.

3.6 WELD REPAIR

The repair of welds is, perhaps, the most controversial and certainly the most difficult-to-control part of making a production joint. The problem is best divided into three topics: what to repair, how to repair, and repair weld properties. For ease of presentation, these are discussed in reverse order.

Because of the divergence of controls in the few repair weld studies conducted, it is difficult to ascertain the effect of repair welds on production joints. Though R. A. Davis(21) found no loss of tensile strength with three successive automatic repairs, others(25,34) find a degradation of strength with each successive weld repair. As shown in Table 6, the ductility decreases with repair welding. The impairment to local properties produced by a short repair is a complete unknown. Certainly, manual repairs degrade both the strength and ductility because of the extremely slow welding speeds employed.

The repair welding requirements which can be generalized are discussed under specifications. Tables 7 and 8 list the questionnaire responses plus the procedures to be used in this program for the manual weld repairing of 0.063-inch and 1.00-inch 2219-T81 aluminum, respectively. The responders were almost equally divided on a-c versus DCSP repair, with a majority favoring a-c for the sheet and DCSP for the plate. Automatic repair welding would normally repeat the original weld procedure. The number of repairs allowed, at a given location, before the joint is sent to review varies from one to three. The difficulty is that in most companies, as with Convair and Lockheed (personal communication), there are no specific weld repair procedures. Welds are repaired to "best shop practice."

Since there are no good generalized procedures on how to repair welds, improperly made repairs can introduce more serious defects than were originally in the weld. Additionally, since repairs generally degrade the mechanical properties of the joint,(25) it becomes critically important to know when to repair. It is evidenced by examining weld specifications (to be discussed later) that many feel the effect of even minor imperfections such as porosity can be more degrading to the joint than the loss of mechanical properties inherent in repair. The general tenor of the Symposium on Weld Imperfections held in Palo Alto, California, 19-21 September 1966, was that even gross defects or cracks, up to given lengths, can be tolerated by design requirements, whereas repair welds could not be so tolerated without lowering reliability.

For this program, the sheet will be manually repaired in one pass after the previous weld is milled out to a depth of 0.040 inch. The procedure is given in Table 1. Three repairs will be made. The plate repairs will be short, 1 to 2 inches long, located in the center of the test specimens. The weld in this area will be ground out to a depth of 1/2 inch with a rotary file. Three repairs will be made using the procedure outlined in Table 1.

3.7 SPECIFICATIONS

All major manufacturers have welding specifications and/or use government specifications to control the welding of aluminum. All these specifications require documentation; chemistry control of wire, gas, etc. For butt welds, all the specifications examined require 100% penetration and complete fusion; these specifications allow no cracks, cold laps, or tailed porosity. In reality, of course, no cracks means no cracks detectable by radiography or dye penetrant. In the following discussion of specifications, "t" refers to the thickness of the thinnest member being joined. The requirements of a few specifications are compared. The reference number is underlined.

1. Weld Bead Reinforcement (see Figure 3a)

   <u>42</u>: For GTA-DC, 0.010 inch minimum; for GTA-AC and GMA, 0.15t minimum; not less than 0.032 inch on top side.

   <u>45</u>: For thicknesses up to 1/8 inch, approximately (1/3)t total; for thicknesses over 1/8 inch, (1/8)t each side, not to exceed 1/8 inch.

   <u>26</u>: For automatic welds:

GAUGE (inch)	TOP REINFORCEMENT	DROP-THRU
0 - 0.040	1t maximum	1t maximum
0.041 - 0.100	(1/2)t maximum	(1/2)t maximum
0.101 - 0.500	(1/5)t maximum	(1/5)t maximum
0.500 and over	3/32 inch maximum	3/32 inch maximum

2. Weld Bead Width (Figure 3b)

   <u>42</u>: For t up to 0.100, 0.500 inch maximum; for t over 0.100 inch, 0.450 inch + (1/2)t maximum.

   <u>45</u>: For t up to 1/8 inch, minimum feasible; for t from 1/8 to 1/2 inch, 1.5t maximum; for t over 1/2 inch, 1.3t maximum.

3. Weld Bead Undercut (Figure 3b)

42: On the underside, 0.10t maximum; on the topside, 0.05t maximum. No undercut to extend over 1.00 inch.

45: No undercutting allowed.

26 and 27: On each side, 0.05t maximum.

4. Dross (oxides)

42: "Eyebrow" dross (appears as an eyebrow on a radiograph) is not allowed. Dross lines, not open to the surface, are allowed up to 1.00 inch long.

The other specifications do not mention dross.

5. Inclusions and Porosity (Figure 3c)

42: Linear and scattered tungsten inclusions and scattered porosity is rejectable if the number and size of imperfections exceeds the limits of graphs. There are different graphs for Class I and Class II welds.

For Class I welds in 0.060-inch sheet, three 1/32-inch or five 1/64-inch voids are permissible; in 1.00-inch plate three 3/64-inch, seven 1/32-inch, or thirty 1/64-inch voids are permissible per inch of weld. For Class II welds in 0.060-inch sheet, twenty-seven 1/32-inch, or forty 1/64-inch voids are permissible; in 1.00-inch plate, four 1/8-inch, fifteen 1/16-inch, or sixty 1/32-inch voids are permissible per inch of weld.

Isolated tungsten inclusions and isolated porosity is rejectable if the sum of the diameters of the voids exceeds 0.5t in one inch for Class I and 0.7t in one inch for Class II welds. All linear porosity is rejectable. Graphs and definitions of isolated, scattered, and linear are included in the specification.

26: For some applications, MIL-R-45774, Std. III, applies. This allows linear and scattered voids not in excess of standard radiographs contained in the document. The requirements are generally equivalent to Class II welds of Reference 42. The requirement for isolated voids is identical to Reference 47, Class I. For other applications, GD/A 0-77008 applies. This rejects all linear inclusions and linear porosity. Scattered and isolated inclusions and porosity may not exceed (1/3)t, or 0.060 inches, whichever is smaller. The minimum pore separation must be three times the maximum pore diameter. The number of pores may not exceed 8 in 4 inches, of which no more than 5 may be in 1 inch. Pores smaller than t/10 separated by 3t/10 shall not be considered in rejection.

6. Mismatch (Figure 3d)

42: Per a graph. For 0.060-inch sheet, 0.040-inch mismatch is allowed; for 1.00-inch plate, 0.060-inch mismatch is allowed.

45: For Class I welds, mismatch may not exceed 0.05t, for Class II it may not exceed 0.10t.

26: The maximum allowable mismatch is 0.5t.

27: The maximum allowable mismatch is 0.10t.

Comparing these specifications for allowable mismatch results in an interesting comparison:

	ALLOWABLE MISMATCH				
THICKNESS (inches)	REF. 42	REF. 45 CLASS I	REF. 45 CLASS II	REF. 26	REF. 27
0.060	0.040	0.012	0.024	0.030	0.006
1.00	0.060	0.050	0.100	0.500	0.100

It is obvious that many of these values are unrealistic and that considerable work is needed in the area of weld specifications.

The only weld repair specifications the authors could find were from NASA-Marshall Space Flight Center.(46,55) The rest of this section refers to the requirements of these specifications, which require certification of weldor and equipment, numerous cleanliness requirements, and use of radiography and dye penetrant tests. They list all the repairable defects. These are a repeat of the welding specification lists.

For a-c welding argon shielding gas is required. For d-c welding helium is recommended, but 75% helium, 25% argon can be used as shield gas. When a-c welding, a ball tip electrode is required. When d-c welding, the electrode is to be ground to a 4 to 1 taper, with the final tip diameter being at least 1/3 the electrode diameter.

The repair procedure for all internal defects is to grind the reinforcement flush on both sides, and then grind or machine a groove sufficiently deep to remove the defect. If $t \leq 5/32$ inch, a square groove joint is ground or machined. If $t > 5/32$ inch, a 60-degree included angle vee-groove with a 60-degree taper at each end is ground or machined into the plate. The allowable depth of grinding is a function of the material thickness. For each thickness of material there is a maximum allowable depth that may be ground or machined to remove a defect. If the defect is not removed by machining to the maximum allowable depth, the weld is repaired and a groove is machined from the other side.

There is no repair procedure for mismatch or tears, as each must be considered individually. Overlap is to be ground out and radiographed prior to repair.

The importance of minimizing heat input to the material during repair is reflected in the requirement of using a stringer bead repair technique. No bead is allowed to exceed 1/8 inch in height. Three repairs are allowed, and after the final repair the weld must be shaved to within 1/64 inch of the base metal.

3.8 WELDING SUMMARY

A compilation of the questionnaire responses is included as Table 9. It is apparent that little agreement can be reached about the proper welding procedure for 0.063-inch sheet. Even for 1.00-inch plate, where it was generally agreed to use GTA-DCSP and helium shielding gas, there is considerable divergence of opinion on groove preparation, number of passes, and welding variables. There are two basic reasons for this divergence of opinion. First, 2219 aluminum is readily weldable and reasonably "forgiving" with respect to weld procedures. This makes it possible to produce adequate joints, especially in sheet, with a wide variety of procedures. Secondly, each source has developed their procedure with a different application or design requirement in mind. Different procedures for different applications is the general rule in welding, and 2219 is no exception.

4/NONDESTRUCTIVE TESTING

The objective of this report is to present findings of a survey of technical literature relating to nondestructive testing of welds in aluminum alloys, particularly 2219. Furthermore, critical technical evaluation of these findings is intended to provide definition of the general inspection problems likely to be encountered when weldments of 2219 are adopted for use as cryogenic tankage.

4.1 DISCUSSION

Basically, the various nondestructive tests commonly applied to flaw detection are not sensitive to alloy differences within a particular basis metal. However, the application of these tests are dependent upon certain restrictions. As a specific example for this particular alloy, inspection of a weld deposit may differ significantly from the technique necessary for plate inspection.

Nondestructive testing (NDT) is particularly influenced by geometry, both with respect to the overall test object goemetry as well as the expected defect geometry. These geometries are principally dictated by the processes and designs involved rather than the materials per se. Of course, it would be absurd to neglect material characteristics; magnetic particle tests are excellent for ferromagnetic alloys, but totally inapplicable for aluminum or titanium.

The point is that the area of investigatory interest should not be restricted to NDT of the particular aluminum alloy, nor for that matter restricted to aluminum. Most of the NDT problems related to weld inspection are a result of the fact that welding has been done. Hence literature searching was directed toward the general area of NDT of welds rather than just NDT of 2219 aluminum alloy welds.

Large numbers of references can be found dating as far back as the late 1930's. Radiographic and penetrant tests of welds were performed even earlier. Following early work of the late 1930's and through the World War II years, no appreciable advances were made. However, with the advent of the advanced technology associated with aerospace developments, the current decade has provided an abundance of technical literature on NDT. The 1955 to 1960 era produced many fine works, which today, only six years later, are, as referred to in one technical periodical, "old-hat." Most of the basic radiographic, penetrant, eddy current, magnetic field, and ultrasonic techniques and equipment were well developed by 1960. The so-called "infrared" or thermal tests were only just begun by that time. Microwave nondestructive test developments were begun after 1960, but these tests are only applicable to nonconductive materials when internal flaws are to be detected.

4.2 CURRENT RESEARCH AND DEVELOPMENT

A review of the literature from 1960 to the present reveals that much energy has been expended in tooling or automating the "old-hat" methods and adapting them to very specific applications. Another area of prime interest has been in improvement of equipment by the basic equipment manufacturers or modification of available equipment by the users. Still another facet is in the refinement of technique development; that is, the basic test method is not new, but the applications of particular tests have been expanded through technique refinement. The remaining area of interest, development of completely new methods, is the least exploited at present.

These four broad areas should now be discussed with reference to the literature and as they relate to this contract. Summarizing, the current research and development effort is being devoted to:

a. Automating state-of-the-art methods for specific applications.

b. Instrument and equipment improvements or modifications.

c. Technique refinement and application.

d. New technology, new test methods.

4.2.1 AUTOMATING STATE-OF-THE-ART METHODS FOR SPECIFIC APPLICATIONS.

The automation or systems approach utilizes existing technology in test methods with emphasis on minimizing the human element and decreasing the time required for testing. One such approach is cited in Reference A-3. Here the attempt was to integrate several complementary nondestructive tests into a single device that would automatically scan a weld and provide recorded data. Another approach (Reference A-1) involves a single basic test method where elaborate tooling and positioning devices were developed to automate the testing. Still another approach (Reference R-3) involves elaborate data processing in the attempt to eliminate human interpretation of radiographic data. A further example of the systems approach involves acoustic spectrometry for weld defect characterization. Although no literature reference can be cited, a system was recently installed at Marshall Space Flight Center. Significant systems have been developed for purposes other than weld inspection. For example, automated infrared, ultrasonic, and radiographic systems are used on large solid rocket motors to assess propellant and propellant bond integrity. A complex ultrasonic system is used by North American Aviation, Inc., to determine honeycomb integrity in various Apollo structures.

4.2.2 INSTRUMENT AND EQUIPMENT IMPROVEMENTS OR MODIFICATIONS.

Standard nondestructive testing equipment commerically available in the United States is technically advanced, reasonably inexpensive, reliable, and flexible in scope of application. However, for the equipment to provide flexibility some essential design compromises have been made by the manufacturers. Of course, special purpose equipment is available, but it often costs more to obtain and use than it does to obtain standard equipment and add components or modify it for special purposes. Examples of current and recent past work done and reported are found in References A-7, A-13, A-20, and R-21. For the nondestructive evaluation of fusion welds, practically no instrument or equipment improvement has been made which is significant. The acoustic spectrometer at Marshall Space Flight Center may prove the exception; however, the device is reported still undergoing evaluation and information concerning it is sparse.

4.2.3 TECHNIQUE REFINEMENT AND APPLICATION. By far the most effort is expended in refinement of basic technique and application to specific problems. Conventional equipment is applied to specific problems or configurations. Technique refinement is the first step in systems development. Much of the work done by Boeing on the Saturn S-IC welds was of this nature (Reference A-3). The nondestructive testing effort on this contract is also of this type.

The accomplishments in technique development are many and varied. Examples are cited in References A-1, A-3, A-6, A-9, A-11, A-12, A-14, A-19, A-20, A-25, R-1, R-10, R-11, R-12, R-15, R-17, R-19, and R-25.

4.2.4 NEW TECHNOLOGY, NEW TEST METHODS. Since the introduction of microwave and infrared detection tests, no really new test methods have evolved. This fact is not particularly surprising, nor is it necessarily detrimental. For the nondestructive tests that depend on transmission of energy into or through the test object, it can be seen that the energy forms used ranges (without any gap) completely throughout the electromagnetic spectrum. The wavelengths range from meters to fractions of an angstrom and completely cover the usable portion of the spectrum, particularly since the IR and microwave bands have been incorporated into nondestructive tests. This fact almost precludes any further introduction of new energy forms. However, to the extent that the LASER is a "new" development, even though that portion of the spectrum has been exhaustively investigated for many years, "new" nondestructive test methods have yet to be discovered.

From the literature surveyed and through contacts within industry and NDT equipment vendors, it does not appear that any new significant technology is imminent.

4.3 WELD INSPECTION

The basic nondestructive test for weld quality remains to be film radiography. With proper attention to technique, most defects are readily revealed. The defect most difficult to detect is lack of fusion, particularly on multipass welds where the lack of fusion lies in planes other than normal to the principal surfaces. Porosity, common to aluminum weldments, is readily visualized, and measurements of its size and extent can be made with fair accuracy. However, radiography of thin sections, say 1/8 inch or less, must be done with care. Some process specifications do not require that penetrameters or other technique indicators have geometric relationship to the part being inspected if it is less than 1/4-inch thick. For example, one of the most commonly applied process standards, MIL-STD-453, Reference S-6, requires that, "4.2.2.1.1.1 - The penetrameter thickness shall not be greater than 2 percent of the thickness of the section to be radiographed, except for sections less than 1/4 inch in thickness where a penetrameter 0.005 inch thick shall be used." The impact of this allowance is that for a section thickness substantially below 1/4 inch, a penetrameter 0.005-inch thick can easily be shown with inadequate technique. For example, with a section about 0.08-inch thick, 50 kilovolts can be selected as the x-ray tube potential and provide a radiograph that clearly shows the specified quality level. However, small defects, even cracks, can go undetected in this thickness at 50 kilovolts. Proper technique requires perhaps 20 to 30 kilovolts, a capability not routinely available in many x-ray labs.

It is strongly recommended that the prevalent radiographic process standards be supplemented with additional requirements for a section thickness below 1/4 inch.

Many attempts have been made to use ultrasonic techniques for weld inspection. For some materials and in some applications, ultrasonic inspection has been used in conjunction with film radiography. However, no applications in aerospace components are evidenced where ultrasonic testing has been used alone and as the basis for quality assurance acceptance. The difficulties associated with ultrasonic testing of welds are several:

a. The inherent roughness of external weld surfaces precludes longitudinal mode inspection. Treatment of the surfaces improves the acoustic coupling problem, but increases cost and, in some cases, reduces joint strength.

b. The cast grain structure associated with welding usually results in acoustic attenuation in the weld zone. Some grains formed during welding are so large that their boundaries reflect the ultrasonic energy much the same as a defect would. In order to eliminate grain boundary "noise," a lower frequency can be selected; however, lower frequency usually results in reduced defect detection sensitivity.

c. The orientation of defects in a weld is unpredictable. Some defects such as lack of penetration, longitudinal or transverse cracking, or undercut assume predictable orientation, but in most cases these defects are more readily detected by some other means; for example, visual inspection or penetrants. Internal weld defects, on the other hand, assume a multiplicity of probable orientations. Ultrasonic tests (as is the case with most nondestructive tests) are highly directional in sensitivity. The incident sound wave must be directed normal or nearly normal to the largest reflecting area of the defect. For some processes that produce predictably oriented defects, the incident beam can be directed in one or more angles such that all significant defects are revealed. Wrought metal forgings and rolled or drawn products, for example, are readily tested with ultrasound where that test method is often the sole basis for acceptance.

For these reasons and others, castings are seldom inspected ultrasonically. Welding bears some similarity to casting; hence the problems are similar. However desirable, ultrasonic inspection has not enjoyed prominence as a reliable, economic means of weld inspection. There are some indications that satisfactory techniques may be forthcoming which will be more reliable. However, it is almost certain that they will involve a systems-type device limited to very specific applications.

Penetrant testing also remains an important technique for inspection of welds for surface-connected defects. Most notably, penetrants are capable of revealing very small, tight surface cracks. There is some objection to the use of penetrants in that, in multipass welds or repairs, the penetrant can contaminate the weld. Care must be taken to clean the part thoroughly if welding does follow penetrant inspection.

Eddy current techniques have been tried, with very limited success, for inspection of aluminum welds. The Boeing Company (Reference A-3) has outlined an approach that just begins to overcome inherent problems. Eddy current tests are extremely sensitive to material compositional changes resulting from heat input or any other process that affects the electrical conductivity or magnetic permeability of any region of the part. In fact, as cited in Reference A-9, eddy current tests for conductivity were related to hardness and strength variations in the heat-affected zone of 2014-T6 aluminum. Surface irregularities also present a problem in eddy current testing of welds. Eddy current testing is also limited in depth of penetration versus sensitivity considerations. In order to obtain adequate depth, it is often necessary to sacrifice sensitivity. As with ultrasonic testing, there is no known application where eddy current tests are used as the sole basis for acceptance of a weld, except for welded thin wall tubing.

The articles that best identify the state-of-art of inspection applications as they relate to welding are References A-16, R-2, R-5, R-6, R-8, R-10, R-16, R-18, R-20, R-26, and R-27.

4.4 ANALYTIC METHODS AND STANDARDIZATION

Nondestructive testing has been utilized as an analytic tool and aid in various basic studies. As in this program, various techniques have been developed to both collect data and evaluate quality of new materials and processes. The literature is fairly abundant with examples. As they relate to some of the test methods proposed in this contract, the references are:

a. For ultrasonic methods of defect evaluation, A-6, A-10, A-11, A-12, A-19, A-24, A-25, R-1, R-15, R-24, and R-25.

b. Radiographic estimation of the third dimension of defects, A-5, A-15, A-17, A-26, R-3, and R-14.

An associated effort is standardization of various nondestructive tests. Artificial flaws are most often the basis for quantitative relationships expressed in NDT specifications. Artificial flaws are a barely adequate basis for technique comparisons. Too often these standards are mistaken for bearing a direct quantitative relationship to actual flaws. For example, in ultrasonic inspection the reference standard is typically a flat-bottomed hole of specified diameter, drilled a specified depth into a block of specified thickness. Defects in the test object are accepted or rejected on the basis of reflection amplitude from the defect as related to the reflection amplitude from the flat-bottomed hole in the reference block. The flat-bottomed hole presents a controlled geometry reflective surface (two-dimensional) under ideal, known conditions. A like reflection from a defect within a test object does not infer that the part contains a similar size flat-bottomed hole. Since naturally occurring defects assume a variety of shapes, sizes, and orientations, they can seldom be "illuminated" by the incident sound wave in the idealized manner of flaw standard illumination. Except in the case of some laminar defects in parts of simple geometry, actual defects revealed by ultrasonic tests are nearly always larger than the artificial defect to which they are compared.

Problems of standardization similar to the above example exist with nearly all nondestructive tests. Nondestructive detection of defects has become secondary to the effort expended in characterizing the defects found. Several references relate to this effort: A-10, A-23, and R-9. Many other articles contain more limited discussions of standardization problems: A-3, A-5, A-11, A-12, A-13, A-20, R-3, R-5, R-10, R-11, R-16, R-18, R-19, R-20, and R-27.

4.5 ALUMINUM WELD DEFECTS

Aside from the nondestructive testing aspects of aluminum weldments, some selected references are included which discuss the various types of defects encountered and their effect. These articles are included here since it is apparent that a basic understanding of defects likely to occur is a prerequisite to the development or selection of NDT methods. These references include: A-2, A-4, A-21, A-22, R-4, R-7, R-13, and R-26.

4.6 ABSTRACT LISTS AND OTHER REFERENCES

During the literature survey, several lists of abstracts and other literature sources were uncovered. These lists contain many articles not directly related to this contract, but are included for the record. Other articles found were of general interest, some containing surveys but with no significant technical content. These are: A-8, A-16, A-18, R-17, R-22, R-23, R-26, and R-27.

4.7 SPECIFICATIONS

Quite commonly, acceptance criteria for fusion welding are totally based upon the outcome of nondestructive tests. As previously mentioned, radiographic inspection is the mainstay nondestructive test for welding. Nearly every major contractor and subcontractor in the aerospace industry has its own specification governing welding. Most welding specifications contain the nondestructive testing requirements, although in some instances process-type specifications govern welding and refer to acceptance specifications that contain the NDT requirements.

Wherever possible, for critical aerospace applications, radiographic inspection of welds is called for. Radiography is sometimes supplemented with penetrant, magnetic particle, ultrasonic, eddy current, and visual inspection. Invariably, where NDT is required, propagating-type defects are not permitted. Cracks, lack of fusion, incomplete penetration, elongated porosity or inclusions, and linearly disposed porosity are defects considered propagating. Undercut, most often revealed visually, is also unacceptable. Scattered porosity and other rounded inclusions are acceptable in various degrees of individual size and proximity, depending on the intended application of the part and individual philosophies of the various manufacturers. The most commonly applied process-type specification governing radiographic inspection technique is MIL-STD-453, Reference S-6. Several specifications are listed here which represent a sampling of aerospace specifications containing various forms of acceptance criteria: S-1, S-2, S-3, S-5, and S-7.

Several ultrasonic specifications for weld inspection are known. However, these were unobtainable on the basis that they are tentative and the authors are unwilling to circulate them without further correlation.

One specification (Reference S-8) indicates separate requirements for weld filler wire quality.

Reference S-4 is a recent compilation of the most commonly used NDT specifications.

4.8 SUMMARY OF NONDESTRUCTIVE TESTING FOR THIS PROGRAM

The nondestructive testing effort to support this program is mostly basic technique application with some technique development required for later tasks. Integration of nondestructive tests throughout the program will benefit the development of test data by: 1) assuring that raw materials are sound, 2) defining the extent of unintentional defects in welds, 3) monitoring flaw growth, and 4) characterizing intentional defects.

For both the 0.063-inch and 1.00-inch-thick material, ultrasonic and penetrant testing will be performed. Samples of the weld filler wire will be penetrant tested. All welds will be radiographed and penetrant tested; additionally, the 0.063-inch-thick welds will be eddy current tested and the 1.00-inch-thick welds ultrasonically tested.

Flaw growth in both thicknesses will be monitored radiographically and ultrasonically. Eddy current tests will be applied to the 0.063-inch thickness to monitor flaw growth.

For the repair welds, ultrasonic and radiographic tests will be employed to characterize intentional flaws and to monitor flaw growth. An attempt will be made to correlate radiographic film density measurements with defect dimensions.

4.9 SUMMARY OF NONDESTRUCTIVE TESTING (GENERAL)

Current technical literature reveals that NDT on welds has not been greatly refined in the current decade. Radiography in various forms remains as the basis of internal evaluation for even the most critical application welds; penetrant and magnetic particle tests are used for surface defects. Metallurgical structure changes through the fusion and heat-affected zones often limit the validity of ultrasonic and eddy current tests.

Some advances are evident in equipment, technique development, and automated systems which have benefitted specific product inspection needs. However, the basic problem seems to lie in the failure to provide an NDT "package" which not only detects all weld defects but which also completely characterizes them.

Almost without exception, designers, materials and process engineers, and manufacturing, welding, and quality assurance engineers conclude that improved NDT for welds is necessary. However, basic studies are required to more adequately define the effect of defects on functional integrity of welds. In conjunction with these studies and improved NDT techniques, the current literature also leads to the conclusion that increased effort should be expended upon improvements in welding process controls.

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40. Liptak, J. A., "Gas Tungsten Arc Welding Heavy Aluminum Plate," Welding Journal, June 1965.

41. "Development of Stress Relief Treatments for High Strength Aluminum Alloys," Contract NASA-11091, Quarterly Progress Report No. 5, Manlabs, Inc., March 1965.

42. "Fusion Welding of Aluminum Alloys-Process Spec. EPS55406," Code Ident. No. 38597, Martin Company-Denver, 7 March 1966.

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44. Musil, L. M., "Develop Weld Techniques-2219 Shear Form Program," Lockheed LMSC-MRI 222.08, April 1963.

45. "Welding Fusion Specification For," MSFC-Spec.-135, 16 January 1963.

46. "Manufacturing Specification for Repairing Defective Welds in Aluminum Alloys," Mfg. Spec. MS200.4, MSFC, 21 September 1961.

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48. "The Acceptance of Spooled Type 2319 Aluminum Weld Filler Wire for the S-1C Vehicle," M-ME-MPROC-700.1, MSFC, 4 December 1962.

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50. Rieppel, P. J., "Weld Defects in Aluminum Versus Base Plate and Filler Wire Composition," Paper, Weld Symposium, NASA MSFC, July 1964.

51. Robinson, I. B., Collina, F. R., and Dowd, J. D., "Welding High Strength Aluminum Alloys," Welding Journal, May 1962.

52. Rupert, E. J., and Rudy, J. F., "Analytical and Statistical Study on the Effect of Porosity Level on Weld Joint Performance," Contract NAS8-11335, Martin CR-66-15, March 1966.

53. Sears, S. L., and Crial, R. S., "Welding 2219 Aluminum for Bomarc Fuel Tanks," Metals Progress, November 1961.

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57. Warren, L., "Weld Defect Evaluation of 2219-T81 Aluminum Alloy," Lockheed LMSC-MRI 222.01, 16 July 1962.

58. Whitfield, C., and Manary, R. C., "A Weld Schedule Developed at GD/A," General Dynamics Convair, 11 May 1964.

59. Wylie, R. D., "Development of Welding Techniques and Filler Metals for High Strength Aluminum Alloys," Contract No. NAS8-1529, Annual Summary Report Project 07-1063, SRI, 11 October 1965.

5.3 NONDESTRUCTIVE TESTING

R-1. Ando, Y., and Noboru, N., "On the Measurement of the Velocity of Propagation of Brittle Cracks in Steel Plates by Ultrasonic Methods," Proceedings 3rd International Conference for NDT, Tokyo, p. 667-670, March 1960.

R-2. "Ultrasonic Testing is a Fast, Economical Means of Discovering Weldment Flaws," Welding Engineer, Vol. 45, p. 40, June 1960.

R-3. "Computer Unveils Weld Defects," Iron Age, Vol. 195, No. 4, p. 85, 28 January 1965.

R-4. "What Martin Thinks of Weld Porosity," Steel, Vol. 153, No. 10, p. 68, 2 September 1963.

R-5. "Eddy-Currents Test Aluminum Rod Quality," Steel, Vol. 153, No. 5, p. 85, 29 July 1963.

R-6. Banks, B., "Advances in Non-Destructive Metal Testing," Metal Industry, Vol. 103, No. 12, p. 390, 19 September 1963.

R-7. Blankard, Milton H., and Pincus, Irving, "What to Look for when Welding 2014 Aluminum," Metal Progress, Vol. 88, No. 6, p. 74-76, December 1965.

R-8. Bobbin, J. E., "Ultrasonic Weld Inspection at Work in Industry Has Resulted in the Development of Efficient and Reliable Quality Control Techniques," Welding Journal, Vol. 39, p. 34, January 1960.

R-9. Bowman, H. J., "A Standard for Eddy-Current Tests," Metal Progress, Vol. 82, No. 1, p. 78-79, July 1962.

R-10. "Ultrasonic Inspection of Welds in Thin-Walled Tube," Henry Brutcher Translation, No. 6485, 13 pp., Altandena, California.

R-11. Burd, B. B., "New Eddy-Current Test for Tubing," Metal Progress, Vol. 77, No. 4, p. 101, April 1960.

R-12. Hagemaier, D., and Kleint, R., "Evaluating Aluminum Alloys by Nondestructive Tests," Metals Progress, November 1964.

R-13. Kammer, P. A., et al., "The Relations of Filler Wire Hydrogen to Aluminum Weld Porosity," Welding Journal, Vol. 42, p. 433-s, October 1963.

R-14. Klein, E., "The Properties of Photographic Emmulsions," Journal of Physical Chemistry, Vol. 66, p. 2407, December 1962.

R-15. Kusenberger, F. N., Barton, J. R., and Donaldson, W. L., "Nondestructive Evaluation of Metal Fatigue," Southwest Research Institute Final Report, Contract AF 49(638)-1147, 13 March 1964.

R-16. Libby, H. L., "Introduction to Eddy-Current Methods and Techniques," ASTM Special Publication, No. 223, p. 13, April 1957.

R-17. McSkimin, J., and Chambers, R. P., "Methods of Measuring Mechanical Properties of Plastics with High Frequency Ultrasound," IEEE Transactions on Sonics and Ultrasonics, Vol. SU-11, No. 2, p. 74-84, November 1964.

R-18. Ostrofsky, B., "Ultrasonic Inspection of Welds," Welding Journal, Vol. 44, p. 97, March 1965.

R-19. Page, G. G., "Recent Developments in Pipe and Tube Inspection Techniques," Metallurgist, Vol. 3, No. 10, p. 218, London, August 1965.

R-20. Quinn, C. E., "Quality Control with Eddy-Current Techniques," Metal Progress, Vol. 76, No. 3, p. 70, September 1959.

R-21. Ruff, E., "An Eddy-Current Flaw Detector," Electronic Engineering, Vol. 32, No. 390, p. 480, August 1960.

R-22. Schall, W. E., "Eddy-Current Testing," Industrial Electronics, Vol. 1, p. 309, March 1963.

R-23. Seidel, R. A., "Eddy-Current Testing ··· Fast and Versatile," Metal Progress, Vol. 83, p. 87-90, May 1963.

R-24. Suzuki, H., and Nakamura, H., "A Study of Weld Cracking of Aluminum and Its Alloys," National Research Institute for Metals, Transactions, Vol. 5, No. 1, p. 31, 1963.

R-25. Truell, R., et al., "Ultrasonic Methods in the Study of Fatigue and Deformation in Single Crystals," ASD-TDR-62-186, Brown University, February 1962.

R-26. Young, J. G., "Quality Control in Aluminum Welding," Welding and Metal Fabrication, Vol. 32, p. 62, February 1964.

R-27. Young, J. G., "Inspection and Testing of Aluminum Welds," Light Metals, Vol. 23, p. 248, September 1960.

5.4 NONDESTRUCTIVE TESTING, ABSTRACTS

A-1. "Advanced Radiographic Procedures for the XB-70A Air Vehicle," NA-66-188, North American Aviation, Inc., Los Angeles Division.

ABSTRACT

Radiography was widely used by the Los Angeles Division of North American Aviation, Inc., for the XB-70A Air Vehicle. Limitations in applying conventional radiographic procedures were overcome by developing advanced in-motion, radioisotope, and in-tooling procedures for inspecting brazed honeycomb structures, brazed tubular joints, and fusion welds. The development of these procedures was founded on the active variables affecting contrast, distortion, unsharpness, and image size. These advanced procedures demonstrate the versatility of radiography as an inspection tool.

A-2. Baysinger, F. R., "Observations on Porosity in Aluminum Weldments," Minutes, Aluminum Welding Symposium, George C. Marshall Space Flight Center, p. 121, 7-9 July 1964.

ABSTRACT

Among other things, a major contributor to weld porosity is said to be defective filler wire. The wire surface should be free of chips, nicks, gouges, and cold laps. Cold laps are particularly bad since they can entrap drawing compounds and other contaminants. Laminations in the base material are cited as another contributor to porosity.

A-3. Berryman, L., "Nondestructive Test Program for S-1C Tank Weldments," Contract NAS8-5608, The Boeing Company, Number D5-10031, Code Ident. No. 81205.

ABSTRACT

An extensive report outlining the development of an equipment which demonstrates the feasibility of combining several nondestructive test methods into an automated system for testing various welds in S-1C tanks.

A-4. Cline, C. L., "Porosity in 2219 Aluminum Alloy Weldments," RIFT Development Manufacturing Report, Lockheed Missiles and Space Company, September 1963.

ABSTRACT

Porosity, which was causing radiographically unacceptable welds, was determined to be caused from filler wire contamination. Suspected were particles of plastic from the wire spools. Measures were taken to exclude these particles from passing through the wire feed port, with the result that acceptable welds were obtained. Other observations revealed pits and laps or seams in the weld wire.

A-5. Criscuolo, E. L., "Slit Detection by Radiography," Materials Evaluation, Vol. XXIV, No. 4, p. 201-205.

ABSTRACT

Listed are parameters of slit detection and their interactions. Shown is the effect of slit width and image unsharpness. The use of the Joyce-Loebl microdensitometer is described in order to obtain density profiles of slits. The scan operature was 0.0012-inch with instrument sensitivity set at 0.04 density/cm. Film density on Eastman Kodak Type M and Type AA was maintained between density 2.0 and 3.0.

A-6. Daniel, J. A. Jr., and Lowery, R. L., "The Production of Microscopic Fatigue Cracks in Compressor Blades," Materials Evaluation, Vol. XXIII, No. 12, p. 583.

ABSTRACT

Stainless steel compressor blades subject to high-stress fatigue tests were checked by ultrasonic methods at 5 mc with surface waves. It is claimed that slip planes could be detected before the cracks could be seen under a metallurgical microscope.

A-7. Grubinskas, R. C., "Development of Eddy-Current Inspection Equipment," U. S. Army Materials Research Agency, AMRA TR 63-24, November 1963.

ABSTRACT

This report details probe coil design and commerical instrument evaluation and selection for eddy-current testing of aluminum, brass, copper, magnesium, and titanium.

A-8. Grubinskas, R. C., and Merhib, C. P., "A Report Guide to Literature in the Field of Electromagnetic Testing," U. S. Army Materials Research Agency, AMRA MS 65-03, April 1965.

ABSTRACT

This monograph contains numerous abstracts of current literature relating to nondestructive testing, particularly eddy-current methods. Approximately 300 articles have been abstracted and listed with subject and author headings.

A-9. Hagemaier, D., and Basl, G. J., "Analysis of the Heat Affected Zone in 2014-T6 Weldments by Nondestructive (Eddy-Current)Methods," Rocketdyne Technical Information Presentation Paper Presented at Spring Convention of SNT, March 1966.

ABSTRACT

Eddy-current, conductivity, and hardness plots were taken across fusion welds in 2014-T6 material. Tensile strength data were correlated with conductivity and hardness. Variations in conductivity and hardness were noticed across the heat-affected zone of weldments fabricated with and without chill bars.

An analysis of the conductivity-hardness-strength relationship for 2014-T6 material overaged during welding was accomplished by controlled overaging of 2014-T6 sheet and plate stock. The mechanical property degradation due to overaging at 400 to 1100°F were correlated with hardness and conductivity. Also investigated was the effect of quench delay on CHS relationship of properly aged 2014-T6 material.

Test results indicate that mechanical property degradation of 2014-T6 material due to overaging or improper quench delay can be determined by the hardness-conductivity relationship.

A-10. Howl, D. A., "The Correlation of Defect Size and Reflected Ultrasonic Signal in Extruded Bar Stock," Ultrasonics, Vol. 2, p. 186, October - December 1964.

ABSTRACT

There is a significant correlation between the size of a defect in extruded bar stock and the reflected ultrasonic signal from the defect. A regression relationship, significant at the 1% level, predicts the defect width in bar stock from the ultrasonic signal.

A-11. Klima, S. J., Lesco, D. J., and Freche, J. C., "Ultrasonic Technique for Detection and Measurement of Fatigue Cracks," NASA Technical Note TN D-3007, Lewis Research Center.

ABSTRACT

An ultrasonic system was developed and used to observe the formation of fatigue cracks in center-notched sheet specimens of unalloyed aluminum, two aluminum alloys, a mild steel, and a nickel-base alloy. The reflection technique was used to detect minute fatigue cracks. The through-transmission technique was used to a limited extent to measure relatively long cracks. Actual lengths of detected cracks were determined by microscopic examination.

A-12. Lautzenheiser, C. E., Whiting, A. R., and Wylie, R. E., "Crack Evaluation and Growth During Low-Cycle Plastic Fatigue - Nondestructive Techniques for Detection," Materials Evaluation, Vol. XXIV, No. 5, p. 241-248.

ABSTRACT

Describes ultrasonic monitoring of defects during fatigue testing of pressure vessels. Details two transducer testing techniques and methods for bonding transducers to test object. Standardization of electronic instrument drift is accomplished by bonding a transducer to a reference standard. An appendix describes the procedure for transducer bonding with Eastman 910 adhesive.

A-13. Libby, H. L., "An Improved Eddy-Current Tubing Test," Materials Evaluation, Vol. XXIII, No. 4, p. 181.

ABSTRACT

A description of equipment and probe coils is included. Equipment was operated at 200 Kc and had an internal test coil assembly. Coils were about 0.5-inch diameter with differential windings and were spaced 1/16-inch apart. Each coil had 130 turns of #44 copper wire.

A-14. Lyst, J. O., and Babilon, C. F., "Detecting Fatigue Cracks in Notched Fatigue Specimens by Changes in Electrical Resistance," Materials Research and Standards, Vol. 2, p. 485-489, June 1962.

ABSTRACT

This paper describes a method of detecting cracks in a fatigue specimen by measuring the changes in the electrical resistance of the surface by direct-current conduction. Both resistance and crack length were observed to increase as fatigue life was consumed. In rotating-beam fatigue tests, cracks propagated slowly until the crack covered about 5% of the cross-sectional area, after which the rate of propagation increased rapidly to failure. Fatigue cracks as small as 0.005-inches deep could be detected in the 0.330-inch diameter specimens by this method and cracks could be detected when the change in resistance was as small as 2.5%.

A-15. Magnusson, E. J., "Estimating the Third Dimension of Propellant Defects by Radiographic Density Measurements," Thiokol Chemical Corporation, Redstone Division, Huntsville, Alabama, 4 January 1961.

ABSTRACT

Empirical radiographic data was collected such that the third dimension of solid propellant defects could be established through measurement of photographic density of radiographs. Curves relating the change in photographic density versus the change in propellant thickness due to a void were developed.

A-16. Maring, H. E., "Inspection Methods for Aluminum Alloy Weldments," Paper presented at Aluminum Welding Seminar, Chicago, Illinois, 23-25 February 1966.

ABSTRACT

Nondestrictive Testing methods discussed are:

1. Visual
2. Sectioning and Trepanning
3. Liquid Penetrants
4. Leak Detection
5. Radiographic
6. Ultrasonic

Visual inspection, aided by up to 10X magnification and good lighting, is performed for cleanliness, smoothness, welder's technique and joint fit.

Quality specifications relating to electrodes are MIL-E-16053, AWS A5.10, ASTM B-285 and QQ-R-566.

Visual and spot radiographic examination are recommended during the process welding particularly after the root pass. Sectioning and trepanning with visual inspection is suggested where applicable.

Visible dye penetrants are recommended for as-welded surfaces, while fluorescent penetrants should be used for machined weld surfaces.

Leak detection is often performed on closed-container weldments. Air pressure testing, hydrostatic pressure testing, liquid penetrants, halogen leak detectors and mass spectrometer helium leak detectors are all methods for leak testing and are utilized in accordance with the sensitivity required.

X- and gamma-radiography are widely accepted methods of evaluating weld quality. A table is presented which shows that the exposure factor for 2219 alloy is 2.3 times that for 3003 alloy. Discussed on the requirements of

ASME Boiler and Pressure Vessel Code, Paragraphs UW-51 and VW-52 and Appendix IV in Section VIII; MIL-R-45774; AWS D2, 0-63, Paragraph 409.

An ultrasonic weld testing procedure is presented. Data is presented relating to the types and sizes of defects detected.

A-17. Mascis, R. J., "Theoretical Density Ratios as a Standard for Interpretation of Cobalt 60, 1000-Curie Gammagraphs," Aerojet-General Corp., Report No. SRP 202 (Special), 25 March 1960.

ABSTRACT

A numerical standard has been established for the interpretation of cobalt-60, 1000-curie gammagraphs of Polaris production motors. The numerical value is obtained from a comparison of two film density readings taken with a densitometer in the area of the gammagraph containing the suspected defect. The resulting density ratio may be used successfully as a standard to differentiate between a normal and a defective area. The ratios presented in this report are adaptable to radiographs of Polaris motors inspected with a 2-Mev X-ray unit. Furthermore, the general method of the film density ratio can be adapted to include radiographic and gammagraphic inspections at all energy levels and with all film types.

A-18. McClurg, G. O., "Index, Materials Evaluation (Formerly, Nondestructive Testing, Volumes XII through XXIII)," Materials Evaluation, Vol. XXIII, No. 12, p. 590.

ABSTRACT

Listing by subject and author of articles appearing from January 1954 through December 1965.

A-19. Rasmussen, J. G., "Prediction of Fatigue Failure Using Ultrasonic Surface Waves," Nondestructive Testing, Vol. XX, No. 2, p. 103, March - April 1962.

ABSTRACT

Experiments were made on detection of fatigue damage in electro-polished 2024-ST3 aluminum alloy. Surface waves at 4 megacycles were propagated from a barium titanate transducer cemented to the fatigue test specimen with Kerr Green Impression Compound No. 2. Response of the ultrasonic instrument was compared under conditions of static loads, no loads and dynamic loads at various numbers of cycles. Curves were prepared from the data collected from which early detection of fatigue damage could be used to predict ultimate failure.

A-20. Renken, C. J., and Selner, R. H., "Refractory Metal Tubing Inspection Using Ultrasonic and Pulsed Eddy-Current Methods (AEC Contract)," Materials Evaluation, Vol. XXIV, No. 5, p. 257-262.

ABSTRACT

Aperatures for eddy-current fields are described. Sizes range from 0.04 to 0.065-inch diameter. The probe coil is placed inside a copper cylinder with the aperature cut in the side or end of the cylinder.

A-21. Rieppel, P. J., "Weld Defects in Aluminum Versus Base-Plate and Filler Wire Composition," Minutes, Aluminum Welding Symposium, George C. Marshall Space Flight Center, p. 63, 7-9 July 1964.

ABSTRACT

Among other things, weld filler wire was investigated for its contribution to porosity. Aside from having a clean surface, it was also concluded that problems could exist within the wire. Occluded gas from original ingots was said to be a problem and eddy-current tests were recommended to detect faulty wire.

A-22. Rupert, E. J., and Rudy, J. F., "Analytical and Statistical Study on the Effects of Porosity Level on Weld Joint Performance," Martin Company Technical Summary Report, Contract NAS8-11335, pp. 89-95, March 1966.

ABSTRACT

Martin's conclusions of the applicability of the various nondestructive tests for porosity detection in aluminum alloy weldments are:

Radiography - Most universally applied and accepted. Search-Ray (Vidican) - Good sensitivity but limited since defect depth cannot be determined.

Penetrants - Useful as an extension of visual inspection for surface-connected defects.

Eddy-Currents - Applicable, but limited to the extent that specialized equipment is required for each individual application.

Infrared - Does not have required sensitivity.

Ultrasonic Techniques - Well-suited for laminar defects, but requires considerable analysis for other orientations.

Color Radiography - Adds some illusion of depth but not sufficiently sensitive.

Radiography, including parallax methods, was the basic source of information for this program.

Lack of penetration in 3/4-inch thickness welds was encountered but not revealed radiographically. Porosity could be classified radiographically; however, it was emphasized that pore description was difficult to obtain except through multiple exposures and intelligent interpretation effort. The data tend to support the thesis that very fine porosity was not adequately emphasized in existing weld acceptance criteria.

A-23. Sinclair, N., "Considerations for Establishing Ultrasonic Test Acceptance Standards," Paper presented at spring Convention, SNT, March 1966.

ABSTRACT

Weld defect characteristics which govern the failure of a pressure vessel are examined, and ultrasonic methods for determining these characteristics are discussed. Assuming that data on slow crack-growth rate and critical crack size for the inception of catastrophic failure are available, a method for establishing ultrasonic acceptance standards is presented. Ultrasonic weld-inspection acceptance standards presently in use are presented for comparison.

A-24. Socky, R. B., "The Use of Ultrasonics in Fatigue Testing," <u>Materials Evaluation</u>, Vol. XXII, No. 11, p. 509.

ABSTRACT

Describes methods found by survey by which ultrasonic testing has been used in fatigue testing. Attenuation measurements, using the longitudinal mode, are made by cementing a transducer to one end of the fatigue test specimen and measuring attenuation from the exponential decay curve or the amplitude of the first signal. Through-transmission methods consist of monitoring an acoustic signal propagated through the fatigue specimen from end to end. The beam is interrupted by the fatigue crack and the amplitude of the received signal reduced proportional to the size of the crack. Surface waves generated from transducers cemented into position have also been used to detect fine surface cracks.

The author of this article is advocating the use of shear waves, claiming that no application was found in his survey and that certain advantages could be realized. His tests showed that the near field effect predicted was not apparent and a symmetrical pressure pattern was obtained. Various reflecting surfaces - notches, through-holes, partial holes - were tried and it was found that the maximum response occurred at 45° incident angle. Small cracks in carbon steel welds were detected. A fatigue testing program was initiated with shear waves as the testing medium. Ultrasonic response data was collected during cycling and compared against destructive correlation testing.

A-25. Truell, R., et al., "Ultrasonic Methods for the Study of Stress Cycling Effects in Metals," WADD TR 60-920 (AD-271067), April 1961.

ABSTRACT

The measurement of changes in ultrasonic attenuation and velocity during stress cycling are shown together with the accompanying changes in the metalographic character of the sample surface.

A-26. Wysnewski, R., "Radiographic Identification of Unknown Materials - A Nondestructive Technique," General Dynamics Convair Reliability Laboratory (Unpublished report).

ABSTRACT

A technique for nondestructive identification of a unknown material by means of X-radiography is described. This technique is specifically applicable to identification of internal discontinuities such as contamination and foreign inclusions. The technique may be used in standard radiographic laboratories if facilities are available for accurately determining optical film density and material thickness. For an unknown having a surface area of 20 square millimeters or more, standard densitometers may be employed. However, for small microscopic samples, a scanning densitometer is required to determine film density and material thickness. Accuracy in identifying an unknown material depends on: 1) accuracy of dimensional measurements; 2) accuracy in determining film density; 3) the difference in thickness between reference and unknown materials as significant errors result from large differences in thickness.

5.5 SPECIFICATIONS

S-1. "Radiographic Standard for Classification of Fusion Weld Discontinuities," National Aerospace Standard 1514, June 1963 Revision.

S-2. "Acceptance Criteria - Welding, Airborne," Martin Co., Denver, Code Ident. 38597, J. Revision, Dash No. 804-1001011.

S-3. "Fusion Welding of Aluminum Alloys," Martin Company, Process Specification EPS 55406-B, Issued 10 June 1965, Revised 7 March 1966.

S-4. "Commonly Used Specifications and Standards for Nondestructive Testing," Materials Evaluation, Vol. XXIV, No. 3, p. 158-163, Los Angeles Section, SNT.

S-5. "Military Specification Radiographic Inspection, Soundness Requirements for Fusion Welds in Aluminum and Magnesium Missile Components," MIL-R-45774 (ORD), 28 June 1962.

S-6. "Military Standard, Inspection, Radiographic," MIL-STD-453.

S-7. "Radiographic Inspection: Soundness Requirements for Fusion Welds in 1/4-Inch and Thicker Aluminum and Magnesium Alloy Plate Material, Specification For (Space Vehicle Components)," MSFC-Spec. 259, 16 November 1962.

S-8. "Manufacturing Process for the Acceptance of Spooled Type 2319 Aluminum Weld Filler Wire for the S-1C Vehicle," NASA-MSFC-M-ME-MPROC-700.1, 4 December 1962.

Table 1. Major Welding Parameters to be Used in This Program

PARAMETER	0.063-INCH SHEET		1.00-INCH PLATE	
PROCESS	AUTOMATIC GTA-DCSP	MANUAL REPAIR GTA-AC	AUTOMATIC GTA-DCSP/2 PASS	MANUAL REPAIR GTA-AC/MULT. PASS
VOLTAGE	14.5 ± 1.0 Volts	24 ± 2 Volts	11.0 ± 0.5 Volts	18 ± 2 Volts
CURRENT	40.0 ± 5.0 Amperes	125 ± 15 Amperes	475 ± 5 Amperes	160 ± 20 Amperes
TRAVEL SPEED	12 ± 2 In./Min.	Approx. 6 In./Min.	3.5 ± 0.5 In./Min.	Not Applicable*
FILLER WIRE	3/64 In. Dia.-2319	3/32 In. Dia.-2319	None	3.32 In.
WIRE FEED RATE	20 ± 2 In./Min.	Approx. 12 In./Min.	None	Not Applicable
COVER GAS	60 CFH of Helium	40 CFH of Argon	85 CFH of Helium	30 CFH of Argon
BACK-UP GAS	12 CFH of Argon	15 CFH of Helium	None	None
ELECTRODE	3/32 In. Dia. 2% Thoriated W 45° Angle Tip	3/32 In. Dia. 2% Thoriated W Ball Tip	5/32 In. Dia. 2% Thoriated W Blunt Tip	1/8 In. Dia 2% Thoriated W Ball Tip
BACK-UP BAR	Mild Steel, 1/8" Deep x 3/8" Wide Groove	Copper, 0.040" x 0.187" Grove	None	None

Note:

* Not Applicable When Filling a Cavity.

Table 2. Various Weld Procedures for 0.063-Inch 2219-T81 Aluminum Sheet

REF.*	PROCEDURE	SHIELDING GAS/ CFH	ELECTRODE TYPE; DIA.-IN.; TIP ANGLE	FILLER WIRE/ DIA.-IN.	BACKUP GAS/ CFH	BACKUP TOOLING	VOLTAGE (volts)	CURRENT (amps)	TRAVEL SPEED (ipm)	WIRE FEED (ipm)	HEAT INPUT (kj in./in.)	0.063-IN. DIA. WIRE IN./IN. OF WELD
Q1	AC-Bal.WV	Argon/ 12	NA; 1/8; Ball	4043/ 1/16	None	S.S.	10	130	12	40	108	3.3
Q2	DC-SP	Helium/ 50	2% Th; 1/16; NA	2319/ 3/64	Helium/ 5	Cu	12	65	11	18	71	1.2
Q3	DC-SP	Helium/ NA	2% Th; 1/8; 120°	2319/ 1/16	None	NA	NA	NA	NA	NA	NA	NA
Q5	AC-Bal.WV	75% He 25% Ar	2% Th; 1/8; 30°	2319/ 0.045	Argon/ 40	Cu	9	100	17	48	53	2.0
Q7	AC-Bal.WV	Argon/ 35	Pure W; 0.093; Long Taper	2319/ 0.062	None	NA	NA	NA	NA	NA	NA	NA
Q9	DC-SP	Helium/ 60	2% Th; 5/32; 60°	2319/ 0.045	None	Cu	18	125	60	60	38	0.7
Q10	DC-SP	Helium/ 50	2% Th; 0.093; 45°	2319/ 0.045	Argon/ 12	Mild Steel	14.5	40	12	20	48	1.2
Q13	DC-SP	Helium/ 30	2% Th; 0.094; 120°	2319/ 0.063	None	NA	12	110	20	40	66	2.0
Q14	DC/AC	Helium/ NA	2% Th; NA; NA	2319/ 1/16	NA	NA	NA	NA	NA	NA	NA	NA
Q15	AC-Bal.WV	Helium/ 80	2% Th; 3/32; Round	2319/ NA	None	Yes	12	85	8	10	127	1.25
Q16	DC-SP	Helium/ NA	2% Th; NA; NA	2319/ NA	None	None	NA	NA	NA	NA	NA	NA
Q17	AC-SQ.WV	Argon/ 50	2% Th; 1/8; Blunt	2319/ NA	None	Clamp Type	8	65	12	20	43	1.2
56	DC-SP	Helium/ 40	2% Th; 1/8; NA	2319/ 0.035	None	Cu	15	55	10	24	83	1.4
17	DC-SP	Helium/ 30	2% Th; 3/32; NA	2319/ 1/16	None	Steel	12	110	20	40	66	2.0
51	DC-SP	Helium/ 30	2% Th; 3/32; NA	2319/ 1/16	None	NA	15	120	20	40	90	2.0
10	DC-SP	Helium/ 40	2% Th; 1/8; NA	2319/ NA	None	Cu	15	70	6	NA	175	NA
58	DC-SP	He - Ar/ 25	2% Th; 3/32; NA	2319/ 1/16	None	None	12.5	73	19	55	48	2.9
Pgm	DC-SP	Helium/ 60	2% Th; 3/32; 45°	2319/ 3/64	Argon/ 12	Mild Steel	14.5	40	12	20	48	1.2

NOTES:

+ All are one pass, square butt, and automatic GTA welds.

* Q - refers to the questionnaire response number.

NA Not Available.

Table 3. Various Weld Procedures for 1.00-Inch 2219-T81 Aluminum Sheet

REF.*	SHIELDING GAS/ CFH	ELECTRODE TYPE; DIA.-IN.; TIP ANGLE	WIRE DIA. in.	BACKUP GAS/ CFH	BACKUP TOOLING	WELD POS. (1)	JOINT DESIGN	NO. OF PASSES	PASS NO.	VOLTAGE (volts)	CURRENT (amps)	TRAVEL SPEED (ipm)	WIRE FEED (ipm)	HEAT INPUT(2) (kj in./in.)
Q1(3)	Helium/ NA	2% Th; 1/8; 30°	1/16	None/ NA	S.S.	All	Square Butt	2	NA					NA
Q2	Helium/ NA	2% Th; 1/8; NA	3/64	None/ NA	None	F	V-Groove	8	1,2 3-8	12 12	265 332	7 4.5	42 42	NA
Q3(3)	Helium/ 100	2% Th; 5/32; 8° Taper to D/2	1/16	None/ NA	None	All	Square Butt	2	NA					NA
Q4	Helium/ 50	2% Th; 3/16; Taper to 3/16	None	None/ NA	None	All	Square Butt	2	1,2	11.6	480	4	0	84
Q5	Helium/ NA	NA; 1/8; 90°	NA	Argon/ 40	Cu	F,H	Square Butt	2	1,2	12	450	3	78	108
Q6(4)	Helium/ 110	2% Th; 5/32; NA	1/16	None/ NA	None	H	Square Butt	2	NA					NA
Q7	He-Ar/ 70	NA;NA;NA	NA	None/ NA	None	All	U-Groove	6	NA					NA
Q10	Helium/ 80	1% Th; 5/32; 60°	1/16	None/ NA	None	F	Square Butt	4	1,2 3,4	13.5 13.5	370 360	4 4	0 22	75
Q14	He-Ar/ NA	2% Th; NA;NA	1/16	NA/NA	NA	NA	U-Groove	8	NA					NA
Q15	Helium/ 100	2% Th; 1/8; 60°	NA	None/ NA	None	All	U-Groove	4	1 2 3,4	15 11 13	150 275 275	12 6 8	0 0 60	NA
Q16	Helium/ NA	2% Th; NA;NA	NA	None/ NA	None	All	Square Butt	3	2	12	490	4	0	88
Q17	Helium/ NA	2% Th; 1/4; Blunt	NA	None/ NA	None	All	Square Butt	4	1,2 3,4	11 13	460 250	6 10	0 35	51
1	Helium/ 85	1% Th; 1/8; NA	None	None/ NA	None	F,V	Square Butt	2	1,2	13.5	370	3	0	100
1	Helium/ 85	1% Th; 1/8; NA	3/64	Argon/ 5(5)	None	H	Square Butt	4	1,2 3,4	13.5 14	360 270	3 14	0 55	98
11	Helium/ 100	2% Th; 1/8; NA	1/16	None/ NA	None	F	Square Butt	2	1,2	15.5	400	7	22	53
Pgm	Helium/ 85	2% Th; 5/32; Blunt	None	None/ NA	None	F	Square Butt	2	1,2	11.0	475	3.5	0	89

NOTES:

+ All automatic GTA-DCSP welds with 2319 Filler Wire - where used.
* Q - refers to the Questionnaire Response Number.

(1) F - flat, V - vertical, H - horizontal, and All - all three positions.

(2) First pass of square butt welds.

(3) 0.75-inch plate.

(4) 0.810-inch plate.

(5) First pass only.

NA Not Available.

Table 4. General Effects of Varying the Major Welding Variables in Automatic GTA-DCSP Welding of 2219-T81 Aluminum

VARIABLE	CHANGE*	EFFECT	GENERAL RANGE
Voltage (V)	I	Increase in heat input. Decrease in electrode life.	For all thicknesses up to 1.5 inch - 11 to 15 volts.
	D	Increase in bead width. For heavy plate - decrease in penetration.	
Current (A)	I	Increase in penetration. Increase in heat input.	Increases with increasing thickness from 40 to 500 amps.
	D	If sufficiently low, the arc will become unstable, and in heavy plate there will be lack of penetration.	
Travel Speed (T)	I	Increase in porosity, due to less time to outgas.	For 0.063-inch sheet: 8 to 20 ipm. For 1.00-inch plate: 3 to 7 ipm.
	D	Decrease in heat input. Increased cost (time). For heavy plate - increased penetration.	
Ratio of Current to Travel Speed (A/T)	I	Increase heat input. Decrease strength, increase ductility.	
	D	Decrease heat input. Increase strength, decrease ductility.	
Shielding Gas(1) (F)	I	Increase cost. For sheet - increase sensitivity and reduce stability.	For sheet: 50 to 60 CFH - Helium. For plate: 85 to 100 CFH - Helium.
	D	Increase contamination.	

Notes:

* I - increase; D - decrease.

(1) Helium is preferred for GTA-DCSP, because it has a higher arc voltage and gives deeper penetration.

Table 5. Typical Mechanical Properties of 0.063-Inch 2219-T81 Aluminum Sheets and Weldments

	BASE METAL			WELD METAL				15N HARDNESS			
TEST TEMP. (°F)	TENSILE STRENGTH (ksi)	YIELD STRENGTH (ksi)	ELONGATION (% in 2 inches)	TENSILE STRENGTH (ksi)	ELONGATION (% in 2 inches)	JOINT EFFICIENCY (%)	BASE IN REDUCED SECTION	BASE AT FRACTURE EDGE	HEAT AFFECTED ZONE	WELD METAL (Center)	REF.
75°	65	50	10	48	2.0	73	54.4	53.5	47.8	34.0	10
	71	59	9	51	2.0	72					9
-100°	71	54	10	45	1.7	64	54.6	52.4	49.2	33.7	10
	76	63	9	50	4.0	66					9
-320°	81	59	10	58	2.5	71	54.7	52.4	49.5	38.0	10
	89	70	11	61	2.0	69					9
-423°	97	67	11	68	0.8	70	55.2	54.8	47.3	30.8	10
	105	76	14	73	1.0	69					9

REFERENCES: (9) Longitudinal Sheet - Weld Bead Intact.

(10) Transverse Sheet - Weld Bead Ground Flush.

Table 6. Typical Mechanical Properties of 1.00-Inch 2219-T81 Weldments

TEST TEMP. (°F)	MECHANICAL PROPERTY	GTA AUTO. (1)	GMA AUTO. (1)	GTA MANUAL (2)★	GTA AUTO. REPAIR OF GTA AUTO. (2)	GTA MAN. REPAIR OF GTA AUTO. (2)	GTA MAN. REPAIR OF GMA AUTO. (2)	GTA MANUAL REPAIR OF GTA MANUAL (2)
75	Tensile Strength (ksi)	42	43	43	41	40	38	42
	Elongation (% in 1-inch)	14	11	15	6	9	6	11
	Elongation (% in 2-inch)	9	6	8	3	6	4	7
	Weld Efficiency (%)	64	66	66	63	60	57	65
-320	Tensile Strength (ksi)	55	55	48	50	50	44	50
	Elongation (% in 1-inch)	11	8	8	4	7	5	7
	Elongation (% in 2-inch)	8	5	4	2	5	3	4
	Weld Efficiency (%)	66	67	58	60	60	54	61
-423	Tensile Strength (ksi)	63	62	52	55	54	48	56
	Elongation (% in 1-inch)	9	7	6	4	4	4	7
	Elongation (% in 2-inch)	6	4	4	2	2	2	4
	Weld Efficiency (%)	64	64	53	56	55	49	57
75	Longitudinal Bend Angle	100°	63°	105°	30°	34°	37°	34°
	Transverse Bend Angle	105°✱	47°✱	41°	17°	14°	20°	22°
-320	Longitudinal Bend Angle	61°	64°	NA	30°	26°	22°	25°
	Transverse Bend Angle	105°✱	63°✖	60°	11°	12°	14°	16°
-423	Longitudinal Bend Angle	38°	31°	33°	18°	22°	13°	14°
	Transverse Bend Angle	26°	25°✱	20°	9°	13°	7°	9°

NOTES:

- ǂ All Welds DCSP.
- ★ Average Weldor.
- (1) Average of Flat, Vertical, and Horizontal Welds.
- (2) All Flat Position Welding.
- ✱ Transverse Bend Angle of Horizontal Welds is Approximately 50 percent of this Value.
- ✖ Transverse Bend Angle of Horizontal Welds is Approximately 25 percent of this Value.
- NA Not Available.

Table 7. Various Manual GTA Weld Repair Procedures for 0.063-Inch 2219-T81 Aluminum Sheet

QUESTIONNAIRE RESPONSE NO.:	Q1	Q3	Q5	Q7	Q9	Q10	Q13	Q14	Q15	Q16	Q17	Pgm
Repair Process	AC	AC/DC	AC	AC/DC	AC	AC/DC	DCSP	AC	DCSP	DCSP	AC	AC
Shielding Gas	Argon	NA	He-Ar	Argon	Argon	(1)	Helium	Helium	Helium	Helium	Argon	Argon
Flow Rate (CFH)	12	NA	NA	NA	60	(1)	30	NA	80	NA	30	40
Electrode Material	Zirc	NA	2% Th	Pure W	Pure W	2% Th	2% Th	2% Th	2% Th	2% Th	2% Th	2% Th
Diameter (In.)	1/8	NA	1/8	1/16	NA	0.093	0.094	3/32	NA	NA	1/8	1/8
Tip Angle	Ball	NA	30°	NA	NA	45	120°	NA	NA	NA	Blunt	Ball
Filler Wire	4043	NA	2319	2319	2319	2319	2319	2319	2319	2319	2319	2319
Diameter (In.)	3/32	NA	NA	NA	NA	0.045	0.063	1/16	NA	NA	1/16	3/32
Allowable No. of Repairs	3	•	2	3	NA	3	1	NA	3+	1	NA	3

NOTES: (1) 40 CFH Helium for DCSP and 20 CFH Argon for AC.

• Refer all repairs to cognizant Engineers.

NA Not Available.

Table 8. Various Manual GTA Weld Repair Procedures for 1.00-Inch 2219-T81 Aluminum Plate

QUESTIONNAIRE RESPONSE NO.:	Q1	Q3	Q5	Q6	Q7	Q10	Q14	Q15	Q16	Q17	Pgm
Repair Process	AC	DCSP	AC/DC	DCSP	DCSP	AC/DC	AC	DCSP	NA	AC	AC
Shielding Gas	He-Ar	Helium	Helium	Helium	He-Ar	Helium	Helium	Helium	Helium	Argon	Argon
Flow Rate (CFH)	NA	NA	NA	NA	NA	70	NA	100	NA	30	30
Electrode Material	Zirc	2% Th	2% Th	2% Th	NA	1% Th	2% Th	2% Th	2% Th	2% Th	2% Th
Diameter (In.)	5/32	5/32	1/8	3/32	NA	NA	1/8	NA	NA	1/8	1/8
Tip Angle	Ball	(1)	30°	NA	NA	45°	NA	NA	NA	Blunt	Ball
Filler Wire	2319	2319	2319	2319	2319	2319	2319	2319	2319	2319	2319
Diameter (In.)	1/8	NA	NA	3/32	NA	1/16	1/16	NA	NA	1/16	3/32
Allowable No. of Repairs	3	•	2	3+	3	3	NA	3+	1	NA	3

NOTES: (1) 8° taper down to 1/2 diameter.

• Refer all repairs to cognizant Engineers.

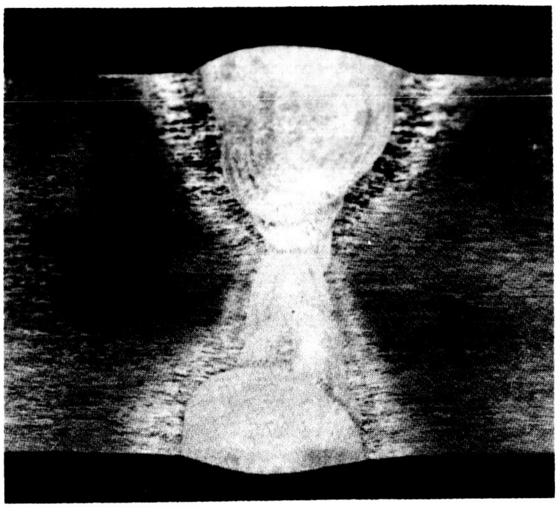
NA Not Available.

Table 9. Tabulated Results of the Questionnaire on the Welding and Repair Welding of 2219-T81 Aluminum

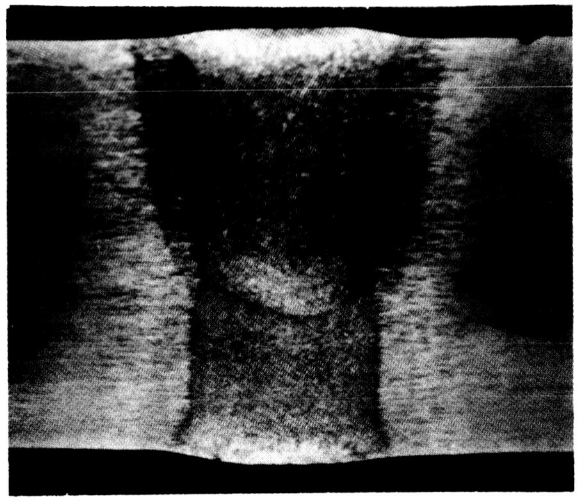
PARAMETERS	0.063-INCH SHEET	1.00-INCH PLATE
AUTOMATIC WELDING PROCESS	6 - GTA-DCSP; 0 - GTA-AC; 0 - GMA; 0 - GTA-DCRP; 5 - GTA-AC, Bal. Wave	12 - GTA-DCSP; 0 - GTA-AC; (1) 1 - GMA-DCSP; 0 - GMA-AC
SHIELDING GAS	8 - Helium; 1 - 75% Helium & 25% Argon; 3 - Argon. Helium Avg. - 54 CFH	10 - Helium; 2 - 75% Helium & 25% Argon; 0 - Argon. Avg. - 80 CFH
ELECTRODE	1 - Pure W; 0 - 1% Th; 10 - 2% Th 3/32 - Avg. Dia. Varied - Tip Angle	0 - Pure W; 1 - 1% Th; 9 - 2% Th 1/8 - Avg. Dia. Varied - Tip Angle
FILLER WIRE	11 - 2319; 1 - 4043. 5 - 1/16 and 4 - 3/64 Dia.	All - 2319; 0 - Other. 5 - 1/16 and 1 - 3/64 Dia.
BACKUP GAS & TOOLING	Gas: 8 - None; 3 - Other. Tooling: 3 - Cu; 1 - S.S.; 1 - Steel	Gas: 10 - None; 1 - 40 CFH of Argon. Tooling: 3 - None; 1 - Cu; 1 - S.S.
WELDING POSITION	Flat, Vertical, and Horizontal.	Flat, Vertical, and Horizontal.
JOINT DESIGN	All - Square Butt; 0 - V-Groove; 0 - U-Groove.	8 - Square Butt; 1 - Double V- Groove; 3 - Double U-Groove.
NUMBER OF PASSES	All - 1; 0 - 2; 0 - 3; 0 - 4.	0 - 1; 5 - 2; 1 - 3; 3 - 4; 0 - 5; 1 - 6; 0 - 7; 2 - 8. Note: All Pass 2's - Square Butt.
WELDING SEQUENCE (Multipass only)	0 - All passes one side; 0 - Sequential; 0 - Simultaneous.	1 - All passes one side; 0 - Simultaneous; 8 - Sequential. Pass 3 - Square Butt.
VARIABLES EACH PASS Voltage (volts) Current (amps) Travel Speed (ipm) Wire Feed (ipm) Joules in./in.	 Range: 8 to 18 Range: 40 to 130 Range: 8 to 60 Range: 18 to 60 Range: 38,000 to 108,000	Pass: 1 & 2 (Square Butt) Range: 11.6 to 13.5 Range: 370 to 480 Range: 3 to 4 Range: 0 to 78 Range: 75,000 to 108,000
MANUAL REPAIR WELDING PROCESS	3 - GTA-DCSP; 5 - GTA-AC; 3 - GTA-DCSP 0 - GMA-DCSP; 0 - GMA-AC. or AC.	4 - GTA-DCSP; 3 - GTA-AC; 2 - GTA-DCSP 0 - GMA-DCSP; 0 - GMA-AC. or AC.
SHIELDING GAS	5 - Helium; 1 - 75% Helium & 25% Argon; 5 - Argon. Varied 12 to 80 CFH.	7 - Helium; 2 - 75% Helium & 25% Argon; 1 - Argon. 70 to 100 He, 30 Argon - CFH.
ELECTRODE	2 - Pure W; 0 - 1% Th; 7 - 2% Th; 1 - Zirc. 3/32 - Avg. Dia. Varied - Tip Angle.	0 - Pure W; 1 - 1% Th; 8 - 2% Th; 1 - Zirc. 3/32 - Avg. Dia. Varied - Tip Angle.
FILLER WIRE	9 - 2319; 1 - 4043; 1/16 - Avg. Dia.	All - 2319; 0 - Other. 3/32 - Avg. Dia.
ALLOWABLE NO. OF REPAIRS	2 - 1; 1 - 2; 3 - 3; 1 - More.	1 - 1; 1 - 2; 3 - 3; 2 - More.

NOTE:

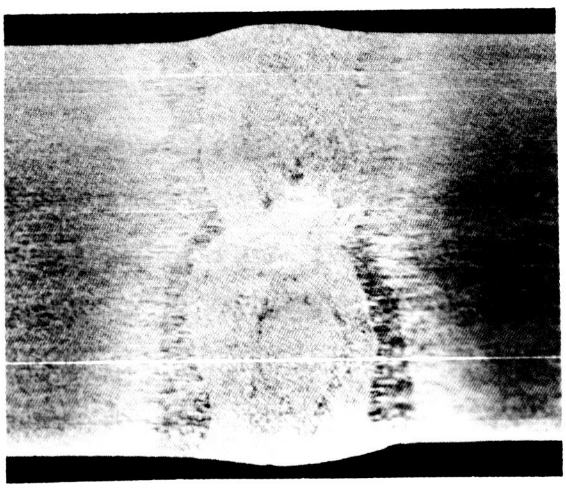
(1) Rest of compilation refers to GTA-DCSP.



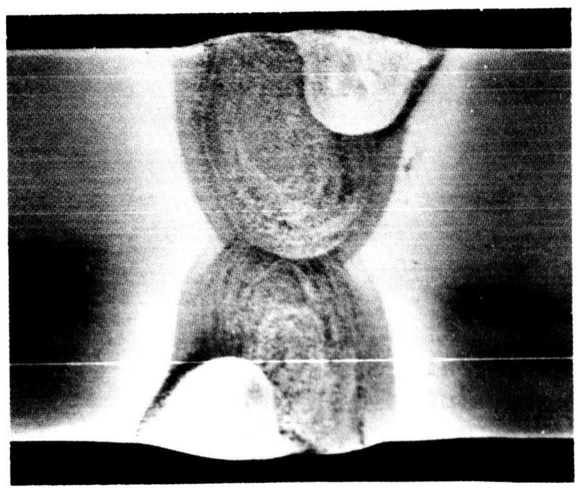
Flat Position
V-Groove Joint
7 Passes
2319 Al Filler Wire
No Backup Bar



Flat Position
Square Butt Joint
2 Passes
No Filler Wire
No Backup Bar



Vertical Position
Square Butt Joint
2 Passes
No Filler Wire
No Backup Bar



Horizontal Position
Square Butt Joint
4 Passes
No Filler Wire - Fusion Passes
2319 Filler Wire - Surface Passes
Backup Bar - First Pass Only

Figure 1. Typical Microstructures of GTA-DCSP Welds Made in 1.00-Inch 2219-T87 Aluminum Made with Different Joint Preparations or in Different Positions.[25] All Magnifications 2X.

TEST TEMPERATURES: 75°F -320°F -423°F

Flat Position
Double V-Groove
7 Passes
2319 Al Filler

Flat Position
Square Butt
2 Passes
No Filler
No Backup

Vertical Position
Square Butt
2 Passes
No Filler
No Backup

Horizontal Position
Square Butt
4 Passes
No Filler - First 2 Passes
2319 Al Filler - Last 2 Passes
Backup - Pass 1 Only

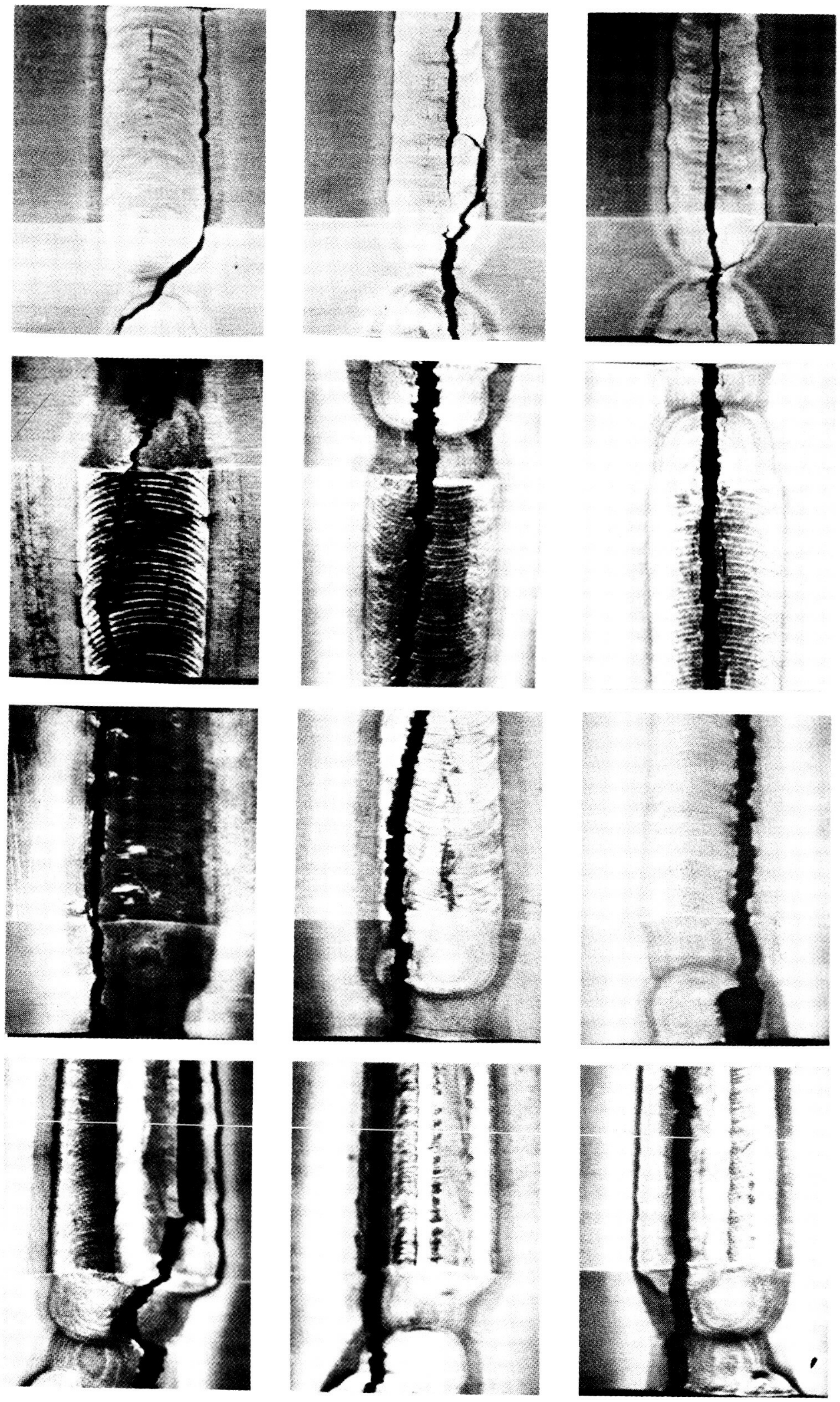


Figure 2. Typical Fracture Modes for Tensile Tests of GTA-DCSP Welds in 1.00-Inch 2219-T87 Aluminum Plate[25]

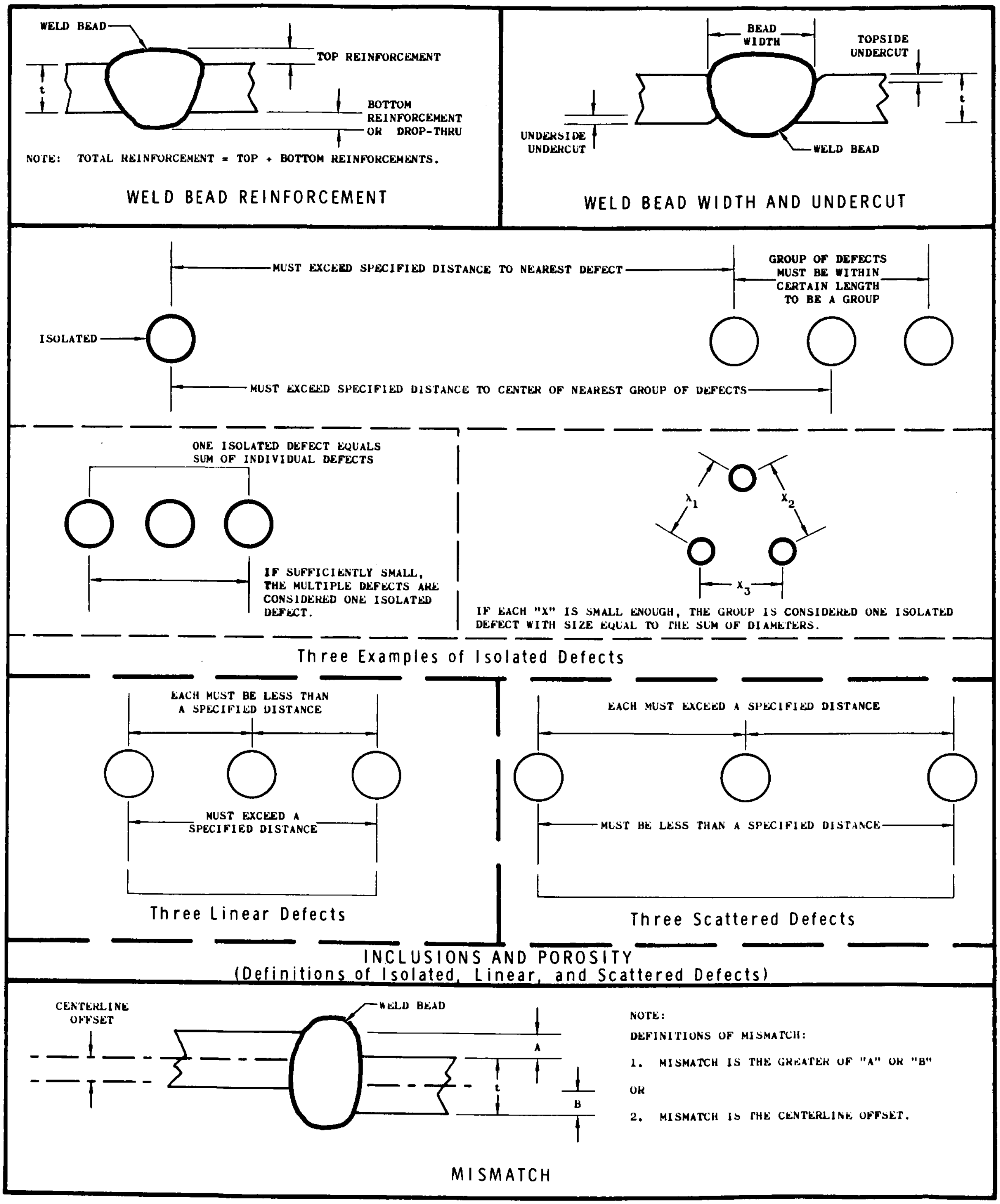


Figure 3. Definitions of Weld Specification Terminology

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