11 October 1967 RSIC-701

REVIEW OF NONDESTRUCTIVE TESTING TECHNIQUES FOR DETECTING LACK OF PENETRATION IN ALUMINUM FUSION WELDS

by

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ABSTRACT

A literature search was made to determine the effectiveness of various nondestructive testing techniques for detecting lack of penetration, i. e., incomplete penetration, in butt joints in aluminum alloys fusion welded from both sides. Under certain conditions, conventional ultrasonic and radiographic techniques may fail to detect such incomplete penetration.

Two approaches to radiographic inspection also are reviewed which might be developed into satisfactory inspection techniques for improved reliability in detection of incomplete joint penetration. One approach involves the measurement of radiographic density variations in weld areas. The other approach involves creating a readily detectable flaw which is completely removed when joint penetration is complete.

In addition, two approaches to improve ultrasonic inspection are reviewed. One approach is to increase the sensitivity of the test method by increasing the test frequency. The other approach involves creating a readily detectable flaw which is completely removed when complete penetration is obtained, a similar approach to that proposed for radiographic inspection.

Recommendations are made for future research to develop the potential of these approaches.

FOREWORD

This report summarizes a literature survey on the detection of imcomplete penetration in butt joints in aluminum fusion welded from two sides. The survey was made at the request of the Research Branch, Redstone Scientific Information Center, U. S. Army Missile Command, Redstone Arsenal, Alabama. The scope of this study was outlined by the Quality Assurance Laboratory of the Marshall Space Flight Center. This report was prepared as part of Contract No. DAAH01-67-C-1921 and covers information published since 1963 and available as of July 1967.

Two computerized searches were made in connection with this study; one searched the NASA holdings and the other searched the DDC holdings. These searches plus the RSIC library holdings gave a complete covering of U. S. Government documents. The open literature was searched through the use of published abstracts as well as a complete review of selected journals.

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1. Introduction

In the aerospace industry, aluminum alloy plates often are butt welded using fusion processes. Occasionally in designs calling for complete penetration welds, joints with incomplete penetration may be encountered due to variations in the welding procedure. Incomplete penetration in a fusion-welded joint is defined as any case in which penetration is less than that specified. In a complete penetration butt joint welded from both sides, incomplete penetration is simply failure of the two fusion zones to meet, as shown in Figure 1.

The effect of incomplete penetration is to reduce the strength of the joint. This loss of strength results from a reduction in welded sectional area and, in some cases, from notch effects caused by the remaining gap. The reduction in strength depends on the load conditions encountered in service and on the ductility of the metal.[1] The greatest reduction in service performance occurs under cyclic loading. Incomplete penetration can also cause premature joint failure when the joint is subjected to impact loading, even when it is subjected to static loading conditions. The reduction in static strength is usually proportional to the loss of cross-sectional area.

Under certain conditions, however, some degree of incomplete penetration may be acceptable. Even so, it is important to be able to detect and measure the extent of penetration by nondestructive testing techniques. It is here that a problem arises. A wide variety of nondestructive techniques has been developed for detecting various defects in welded structures. Two of these techniques, ultrasonics and radiography, are commonly used to detect subsurface defects, such as incomplete penetration in aluminum weldments. But these two methods appear to have a common limitation; neither will reliably detect incomplete penetration in a case where shrinkage stresses from the weld beads force the unfused interfaces of the plate tightly together. With these inspection methods, a very small unwelded area might be easily detected if there is a gap between the edges of the plates, but a much larger unwelded area in which the edges of the plate are in tight contact may defy detection. Because of this apparent limitation of the ultrasonic and radiographic techniques, a literature search was conducted with the objective of finding other methods for detecting incomplete penetration or of finding means for assuring the reliability of either ultrasonics or radiography.

2. Recent Research and Development on Nondestructive Testing of Aluminum Welds

As mentioned in the introduction, there is a wide variety of nondestructive testing techniques in use for inspecting welds. Most of these techniques were developed before 1960. The use of microwaves and infrared

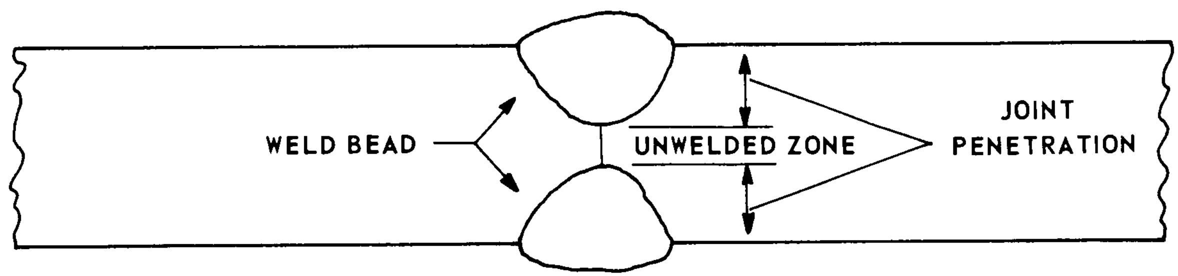

FIGURE 1. CROSS SECTION OF BUTT JOINT SHOWING INCOMPLETE PENETRATION

radiation in nondestructive testing was developed in the early 1960's. Since the latter developments, no new test tools have been introduced, but the literature shows many modifications and refinements of the earlier procedures and equipment. However, ultrasonics and radiography still appear to present the most reliable means of detecting incomplete penetration, although some refinement of one of these might be necessary to detect defects in all cases. All of the other nondestructive testing methods, some of which have been tried experimentally to detect incomplete penetration, appear to have some shortcomings. These methods involve the use of penetrants, anodic electroluminescence, radiofrequency waves, microwaves, eddy currents, infrared heating, magnetic particles, and photostress coatings. A description and reasons for their unreliability in detecting incomplete penetration are given briefly in the Appendix.

The following discussion is limited to radiography, ultrasonics, and certain promising refinements of these test methods.

a. Radiography

Radiography offers an advantage over ultrasonics in that it provides a permanent visual record of the weld condition; however, radiographic techniques usually require access to both sides of a weld. This requirement is not necessarily valid when evaluating welds in pipe and tubing. In this case the X-ray beam may be directed through both walls of the pipe and, depending on diameter, the welds in either one or both walls can be X-rayed in a single exposure.

Radiographic evaluation is normally performed with industrial X-ray equipment. Gamma radiation from isotopes of cobalt, iridium, and cesium also may be used. But in the case of aluminum, they are suitable only for very heavy sections. Radiographic inspection is performed by transmitting X-rays through the weld and recording the radiographic image on film. A slow-speed fine-grain film is normally used to provide high contrast, high resolution, and maximum detail. On the radiographic film, defect areas appear darker because a greater amount of radiation has passed through the object in these areas. Incomplete penetration appears on the radiograph as a continuous or intermittent dark line at the center of the weld.[2] The response of incomplete penetration to radiography has been defined as good to fair.[3] Again, as with ultrasonics, the limitation appears to be in cases where unfused interfaces are drawn tightly together. However, it is possible to detect as small as one percent or less of the material thickness with radiographic techniques.[4]

(1) Intentional Defects. One possible way of improving the detection of incomplete penetration when the unfused edges are in tight contact

is being investigated experimentally at Marshall Space Flight Center.[5,*,**] A readily detectable defect is intentionally created in the weld. This defect will be completely eliminated with proper weld penetration. If this intentional defect is not detected in radiographic examination of the weld, penetration is assumed to be complete.

Work at MSFC involves plating the interface to be welded with a material that is relatively opaque to X-rays, such as copper, and also metallurgically compatible with the base metal. During welding, all of the plated copper is dissolved in the fusion zone. When complete penetration occurs, no layers of copper remain. If penetration is incomplete, layers of copper remain and are readily detected by radiographic techniques.

During the MSFC work, slight porosity was observed in the fusion zone of the plated specimens. Apparently gases, probably hydrogen, became entrapped on the base metal during plating. Work is now being carried out which indicates that the porosity may not be serious and that improved plating techniques might overcome the problem.

An interface defect could also be created by placing a shim or foil between the abutting surfaces or by depositing metal on the weld joint surfaces by means other than plating. In either case, the material would have to be relatively opaque to X-rays, be readily dissolved in molten aluminum, and be metallurgically compatible with aluminum.

There are obvious advantages to plating or coating the surfaces as opposed to the use of a shim or foil. First, when plating is used, there are only two surfaces as possible sources of contamination rather than four as with shim or foil. Second, a joint plated with copper or silver does not require the extensive cleaning prior to joining that bare aluminum does. However, as pointed out in the MSFC work, care must be taken not to entrap porosity causing gases during plating. Regardless of how the material is plated, there must be assurance that undesirable alloying effects do not impair joint properties.

One other possible means of creating intentional defects is to score or slit the weld interfaces prior to welding. These slits would be eliminated during welding if penetration were complete and would be easily detected by radiography if not eliminated. The scoring operation would have to be carefully controlled to assure that the marks were deep enough to be detected but not so deep as to impair the quality of the joint.

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*Private Communication, R. L. Brown, Marshall Space Flight Center, July 1967.

**Private Communication, W. N. Clotfelter, Marshall Space Flight Center, July 1967.

(2) Density Variations. Another possible solution to the problem has been uncovered in work at North American Aviation, Space and Information Systems Division.[6,7] Although their method has been reported as a feasible means of detecting incomplete penetration, the work done thus far does not appear conclusive. The technique proposed involves a means of measuring weld bead overlap to insure complete penetration in a butt weld. It is assumed that the radiographic density of the weld metal differs from that of the parent material. A radiation source is placed on one side of the weld and a detector on the other. The amount of radiation reaching the detector depends on the thickness and density of the material. Welds are machined to uniform thickness so that all variations in radiation are attributable to density differences. Experiments using this method have shown that weld specimens in which weld beads did not overlap gave readings different from either the base metal alone or a complete penetration weld. However, neither the effects of porosity nor of compositional variances within the weld zone itself were considered. These, and other possible causes of density changes, could affect the readings to a greater extent than incomplete penetration. It is possible that a technique along these lines can be developed, but additional research is needed.

b. Ultrasonics

Ultrasonic testing uses high frequency radiation beyond the audible range to detect flaws and defects. A beam of ultrasonic energy is directed into the specimen. Measurement is made either of the energy transmitted through the specimen or of the energy reflected from areas within the specimen. Defect detection is based on the fact that the waves are reflected at surfaces. Any loss of energy as the beam passes through the specimen or reflection of energy back is the result of reflection of the beam at defects. When properly calibrated and under favorable conditions the technique will show the defect size, type, and location.[8-10]

For ultrasonic testing of welds, the energy is usually directed at a predetermined angle from the normal. This is called the shear-wave mode. A longitudinal mode is also used in some instances. High frequencies are required to detect small defects or discontinuities because ultrasonic waves will not interact with objects whose dimensions are less than the wavelength.[4] Frequencies of 1 to 5 mc are commonly used to inspect welds, 2.5 mc being perhaps the most common.

Ordinarily, ultrasonic testing is very sensitive to planar defects such as incomplete penetration in butt welds performed from two sides. In the case of complete penetration butt welds in aluminum, however, areas of incomplete penetration may be closed up so tightly as a result of the heat and forces generated by welding that they are undetectable.

This was confirmed in an experiment which used aluminum plates butted together to simulate an area of incomplete penetration. The plates were forced together so tightly that the interface between them was undetectable by ultrasonic shear-wave testing at 5 mc.[11] However, it was necessary to apply both pressure and high temperature to abutting aluminum plates to simulate the undetectable condition; pressure alone, up to the point of yielding, did not prevent detection.

The exact reason why the interface cannot be detected under these conditions is unknown. One possible explanation is that the planar area of incomplete penetration may be broken up into many small areas due to the formation of microbonds under the conditions of high temperature and force. The resulting unbonded areas would then be very difficult to detect by ultrasonic testing because of their small size.

There are two possible approaches to increasing the effectiveness of ultrasonic testing in detecting incomplete penetration in aluminum weldments. One approach is to increase the sensitivity of the process. This can be accomplished by increasing the test frequency. By increasing the frequency, the wavelength of the sound in the test object becomes shorter and smaller defects can be detected. An increase in frequency, however, is accompanied by a loss of energy (attenuation). This in turn causes a rise in random reflections, or noise, which limits the upper frequency that can be used for testing a material.[9] If the frequency could be raised to say 25 mc with aluminum, defects as small as approximately 0.0005 in. could be detected, which might be sufficient to detect the areas of incomplete penetration.

A second approach, suggested by the intentional defect procedure with radiography is to introduce intentional defects into the plate surfaces, such as small notches, which would be fused when complete penetration is obtained, but which are readily detectable by ultrasonic testing in the event of incomplete penetration. The notches would have a suitable size and shape so that they would be readily fused under proper conditions, but would not be crushed shut in the event of incomplete penetration. If the notches are oriented perpendicular to the plate surface, then the depth of the incomplete penetration could also be determined.

3. Conclusions and Recommendations

The following conclusions have been reached as a result of this study:

1) Ultrasonic and radiographic techniques can be used to detect incomplete penetration in butt welds in aluminum plate fusion welded from two sides. However, with both techniques, it is

difficult to detect this defect in cases where the plate interfaces have been drawn tightly together by shrinkage forces.

2) A review of the literature has revealed no further basic techniques that will reliably detect incomplete penetration in welded joints in aluminum.

3) It might be possible to detect the incomplete penetration even when the interfaces are drawn very tight, with ultrasonic techniques if sufficiently high frequencies could be used.

4) By creating readily detectable defects which are eliminated with complete penetration, it might be possible to detect all cases of incomplete penetration by radiographic or ultrasonic techniques. This would have the advantage that the results obtained by one test method could be confirmed by the other.

5) A technique for measuring radiographic density variations might be developed in the future, but at present it requires more research.

On the basis of this study and the above conclusions, the following recommendations are made:

1) Studies should be made to determine the highest frequencies that can practically be used to detect incomplete penetration in aluminum weldments by ultrasonic techniques.

2) Work should be continued on the use of plated interfaces as an aid in detecting inadequate penetration by radiographic inspection. If tests show that this process does not impair joint properties, this approach may solve the problem.

3) Work should be continued on the possibility of introducing intentional defects, such as notches, into the weld region which are easily fused when complete penetration is obtained, but which are readily detected by ultrasonic or radiographic testing in the event of incomplete penetration.

4) The North American Aviation approach of measuring variations in radiographic density might be continued. It is recommended that the effects of porosity and compositional variances be closely studied.

5) Battelle would suggest one other possible means of solving the problem. A tensile load applied during radiographic inspection might possibly "open up" interfaces sufficiently wherever incomplete penetration existed to allow detection of this defect. There are no reports of this being done, but it appears at least worthy of investigation. Since many structures undergo tensile loading in any case, this could be easily incorporated into an inspection program.

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APPENDIX

There are many nondestructive testing techniques used on weldments that have not been discussed in the main body of this report. None of these appear reliable for detecting incomplete penetration in aluminum joints, but each is discussed briefly here for reference purposes.

Penetrant Methods

Penetrant methods are used extensively for detecting surface flaws and cracks and are not intended for locating subsurface defects. A suitable low-viscosity fluid is applied to the surface of the test part and allowed to penetrate into cracks and other discontinuities in the surface. The excess fluid is removed from the surface, but a small amount is retained by any defects. The remaining fluid which seeps out of the defects is detected by means of a developer which absorbs the penetrant.[3] The penetrant may fluoresce under ultraviolet light or it may be colored with a dye (usually red).

Anodic Electroluminescence

During barrier-layer anodizing of aluminum and its alloys, a glow can be seen at the anode in a dark room. This electroluminescence occurs only above certain voltages and only when certain chemicals are present in the anodizing solution. The wavelength or intensity of the flow changes with impurities in the aluminum. This phenomenon may be valuable in nondestructive testing of aluminum weldments, but probably only for surface defects.[12]

Radio Frequency Waves

Radio-frequency waves or electromagnetic waves in a frequency range of approximately 10^5 to 10^{11} cps, have been tried experimentally for detecting unbonded areas in 1- to 2-in. thich aluminum but have not proved feasible.[13] The failure was caused by electromagnetic energy in this range which was highly reflected and activated by the metal under test. However, an electromagnetic energy mode known as the "helicon-wave" mode did show promise for further research, although not presently practical for inspection purposes. The mode has been obtained experimentally only in very pure, high-conductivity metals at temperatures near 0°K in the presence of a high-static magnetic field. Under these conditions, the mode propagates with less attenuation than normal modes. No experimental evidence has been found to show that it will not propagate in ordinary metals at room temperatures.

Microwaves

Microwave energy can be transmitted, reflected, absorbed, and scattered. These actions can be measured to detect subsurface flaws, among other things. However, the method has been used only with dielectric materials and does not appear applicable to metals.[14]

Eddy Currents

Eddy currents are created within electrical conducting materials by exposing these materials to strong alternating magnetic fields. Such fields are interrupted by defects. These defects are detected by observing variations in secondary voltage in the instrumentation when a two-coil probe is used. The eddy-current technique offers a reliable and reproducible means of nondestructive inspection.[15] However, the method is sensitive to minor variations such as differences in heat-affected zones and compositional variations. It does not appear to be promising for detection of incomplete penetration in welds.

Infrared Techniques

Thermal radiation also can be used in detecting discontinuities in metals. The isothermal lines of heat from a uniform surface will form a regular and predictable pattern. Defects, such as holes, inclusions, or cracks, will distort this pattern. Thus, defects can be located by measuring differences in surface temperature in uniformly preheated components. The measurement of infrared energy radiated from a surface is an accurate, practical means of determining this temperature difference. Temperature can be measured within 0.1 to 0.05°C at about room temperature for an area as small as approximately 0.01 mm^2.[8]

Subsurface defects are located by heating a surface of a component and measuring the temperature on this surface a second later. Higher temperatures indicate a subsurface defect delaying heat passage through the material.[16] But, it has been shown that incomplete penetration can be detected by thermal techniques only if the contact pressure of the surfaces is very low, about 100 psi.[11] Thus, the method does not appear reliable for detection of incomplete penetration.

Magnetic Particle Method

When a magnetic field is induced in a material, any defects that are present will distort the field. This is because the defect has different magnetic properties from those of the surrounding material.[1] In magnetic particle testing, a suitable magnetic field is established in the test object (which must have magnetic properties) and magnetic particles are applied. These particles are attracted to the edges of the defects and will outline a pattern of the defects. Fluorescent particles may be used to make the pattern more visible (under ultraviolet light). The method is most sensitive to surface and near-surface defects, however.

Photostress Techniques

A photostress testing method has been tried for detecting incomplete penetration, but has not proved satisfactory.[11] This technique is based on the premise that a defective weld, with low cross-sectional area, will show greater strain under stress than will a sound weld. To measure strain, a photoelastic coating, highly sensitive to strain, is adhesively bonded to one side of the test specimen. Loads up to approximately 30 percent of the predicted ultimate strength were applied to the specimen, the relatively small loads insuring that the test remained nondestructive. In practice, no distinction could be made between weld conditions.

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1. ORIGINATING ACTIVITY (Corporate author) Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE
REVIEW OF NONDESTRUCTIVE TESTING TECHNIQUES FOR DETECTING LACK OF PENETRATION IN ALUMINUM FUSION WELDS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
None

5. AUTHOR(S) (First name, middle initial, last name)
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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
11 October 1967	21	16

8a. CONTRACT OR GRANT NO. DAAH01-67-C-1921 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) RSIC-701 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AD ________

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Redstone Scientific Information Center Research and Development Directorate U. S. Army Missile Command Redstone Arsenal, Alabama 35809

13. ABSTRACT

A literature search was made to determine the effectiveness of various nondestructive testing techniques for detecting lack of penetration, i. e., incomplete penetration, in butt joints in aluminum alloys fusion welded from both sides. Under certain conditions, conventional ultrasonic and radiographic techniques may fail to detect such incomplete penetration.

Two approaches to radiographic inspection also are reviewed which might be developed into satisfactory inspection techniques for improved reliability in detection of incomplete joint penetration. One approach involves the measurement of radiographic density variations in weld areas. The other approach involves creating a readily detectable flaw which is completely removed when joint penetration is complete.

In addition, two approaches to improve ultrasonic inspection are reviewed. One approach is to increase the sensitivity of the test method by increasing the test frequency. The other approach involves creating a readily detectable flaw which is completely removed when complete penetration is obtained, similar to that proposed for radiographic inspection.

Recommendations are made for future research to develop the potential of these approaches.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Nondestructive testing						
Welding defects						
Detection						
Incomplete penetration						
Ultrasonic inspection						
Radiographic inspection						