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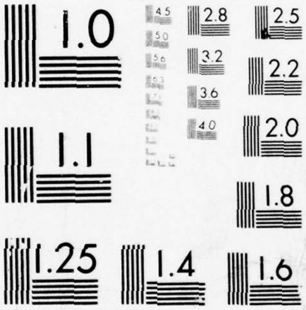

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ADVANCED WELDBONDING PROCESS ESTABLISHMENT FOR ALUMINUM

Northrop Corporation
Aircraft Group
3901 West Broadway
Hawthorne, California 90250

FEBRUARY 1979

FINAL REPORT NOV 1976 – OCT 1978

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Prepared for:
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NOTICE

This technical report has been reviewed and is approved for publication.

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This program was conducted to establish the manufacturing parameters necessary to produce structural aircraft fuselage panels by the aluminum weldbonding process. These panels were representative of adhesive bonded panels currently being employed on the USAF/Fairchild Republic A-10. A design, feasibility and trade-off study was conducted by Fairchild, and a representative test panel was designed for comparing the structural performance of weldbond vs. adhesive bonded panels on a 1:1 basis. Northrop Corporation established the manufacturing procedures and process specifications which were used to manufacture the weldbonded panels. Fatigue and damage tolerance

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tests were conducted to evaluate the effect of different manufacturing variables on fatigue life. These tests showed that weldbonded structures would compare favorably with adhesive bonded structures, and would be significantly superior to riveted structures in low-load transfer fatigue applications. The effect of weld nugget quality on structural performance was evaluated and procedures were developed by General Dynamics, Convair Division, for applying nugget expansion feedback monitors and controls to insure nugget quality. Both adhesive bonded and weldbonded panels were fabricated and then static or fatigue tested by Fairchild, and the results compared on a 1:1 basis. The structural panel tests showed that the weldbonded panels were equivalent to the adhesive bonded panels. A cost analysis was conducted which showed that cost savings can be realized and the saving is dependent upon the type of panel. With improvements in adhesive application and welding cycle improvement, weldbonding costs could be further reduced. The weldbond technology was transferred from Northrop to Fairchild successfully and actual A-10 curved fuselage panels were successfully fabricated at both Northrop and Fairchild.

PREFACE

This report was prepared by the Northrop Corporation, Aircraft Group, Hawthorne, California, under USAF Contract F33615-76-C-5412. The contract work was performed under Project No. 828-6, and was sponsored by the Air Force Materials Laboratory, Wright-Patterson AFB, Ohio. The original Air Force Project Engineer was Mr. N. E. Klarquist of the Metals Branch (LTM) of the Manufacturing Technology Division, Air Force Materials Laboratory. He was succeeded by Mr. S. G. Lee, also of the Metals Branch.

Northrop Corporation, Aircraft Group, was the prime contractor, with Mr. T. R. Croucher the Program Manager, directing all activities. Other Northrop personnel who were major contributors to the program include:

Surface Preparation	B. B. Bowen J. E. Nemo P. Sadesky J. R. Acevedo V. S. Srinath
Welding	H. E. Langman D. R. Drott
SEM and Auger Analysis	R. E. Herfert T. P. Remmel S. V. Feenstra
Fatigue Evaluation	Dr. G. R. Chanani G. V. Scarich
Mechanical Testing	B. J. Mays J. H. Fitzgerald
Reliability and Durability Testing	R. G. Hocker
Cost Analysis	T. J. Bettner

The primary Northrop responsibilities involved the optimization of the processing parameters, a fatigue and cost evaluation of the weldbond process, manufacture of weldbonded structural test panels, and the transfer of technology to Fairchild.

Fairchild Republic Corporation was a sub-contractor on the program with Mr. A. Vanaman acting as the Fairchild program manager. Fairchild was mainly responsible for the structural evaluation of the test panels and for the initiating process integration into the A-10 production line.

General Dynamics, Convair Division, acted as a subcontractor to the program with Mr. R. Szabo acting as the original program director. He was succeeded by

Mr. W.A. Roden. Convair's responsibility was the evaluation of computer oriented closed-loop feedback spot welding control procedures for use as an in-process control technique.

This report was written by T. R. Croucher with major contributions from G. V. Scarich, Dr. G. R. Chanani, R. G. Hocker and V. S. Srinath from Northrop; A. Vanaman, V. Hoar and R. Rupp from Fairchild Republic; and W. A. Roden and R. Szabo from General Dynamics, Convair Division.

The contractor report number is NOR-78-185. This report covers work from 8 November 1976 through 30 October 1978.

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PROGRAM SUMMARY

Over the past ten years, a significant effort has been expended in the United States, mostly sponsored by the Air Force Materials Laboratory, to optimize an aluminum weldbonding process (originally developed abroad) and make it acceptable for production usage on U. S. aircraft. This weldbonding process involves joining components together by resistance spot welding through a previously applied adhesive and then curing the assembly to achieve a fully bonded structure. Under Air Force sponsorship, the Lockheed Georgia Company successfully advanced the technique to enable test application to U.S. aircraft structural components. Lockheed successfully fabricated and installed a large C-130 fuselage panel on a production aircraft which currently has over 2700 hours of operation without encountering problems. The Lockheed program showed that the lap shear strength of weldbonded joints provided a fourfold increase in lap shear strength and tenfold increase in fatigue life as compared to spotwelded joints. In addition, it was shown that weldbonded structures offer significant cost savings over adhesive bonded or mechanically fastened structures.

Subsequent effort conducted at Northrop under Air Force Sponsorship resulted in the development of surface treatments which solved an environmental stress durability problem which had been characteristic of the Russian and Lockheed systems and which precluded extensive application on U.S. aircraft. This problem had necessitated extensive sealing of early production assemblies to prevent moisture intrusion into the joint and possible stress durability failure. Further developments at Northrop resulted in an integrated manufacturing methods system involving a low voltage phosphoric acid/sodium dichromate anodize in conjunction with specially developed weldbond adhesives and precise welding schedules, which eliminated the need for sealing. This weldbond process demonstrated good weldability, high lap shear strengths and fatigue properties and excellent resistance to failure when exposed under stress to an agressive environment.

The purpose of the current program, was to advance this recently developed technology to a level where it could be applied to a current production aircraft, the USAF/Fairchild Republic A-10. The program was sponsored by the Air Force Materials Laboratory with the Northrop Corporation acting as the prime contractor. Significant portions of the program were conducted by two major subcontractors, the Fairchild Republic Corporation and the General Dynamics Corporation, Convair Division.

A test component was selected by Fairchild Republic for use in the program. This component was representative of structural beaded panels located in the center fuselage section of the A-10. In current production, these panels are fabricated by adhesively bonding a 2024-T3 alclad aluminum skin to a 7075-T6 pan stiffened with formed beads. This part was selected because it represented a component which would clearly demonstrate the structural capability of the weldbond process and could easily be integrated into a production system with a minimum of integration problems while still realizing a potential cost saving. This production application on the A-10 aircraft could then be used as a basis for applying the technology to other structural applications for which even higher cost savings could be achieved.

The first portion of the program established the final weldbond process which was then used for the manufacture of the selected structural panels. This was necessary as prior work conducted at Northrop had not investigated the weldbonding of 2024-T3 alclad to 7075-T6 bare, the material combination used in this aircraft system. Surface preparation techniques were optimized, adhesive characteristics and control parameters were established and the welding schedules for the achievement of Class A spotwelds were accomplished. Supporting technical efforts were conducted prior to the fabrication and testing of the full scale structural panels in order that sufficient confidence would be developed in the process prior to applying the panels to actual aircraft. These efforts involved (1) evaluation of commercially available in-process welding controls and monitors to determine the level of control necessary to insure quality welds, (2) an extensive fatigue evaluation to determine the effects of manufacturing and process variables on the fatigue and fracture behavior of the weldbonded joints, (3) an evaluation to determine the reliability and repeatability of the weldbonding process over a wide range of standard manufacturing variables to insure that the process could be successfully integrated into a production operation, (4) a durability evaluation to prove that the surface preparation and adhesive system being used resulted in an assembly that was not susceptible to environmental stress cracking in normal aircraft environments.

Following successful fabrication and testing of structural panels, the feasibility of other aerospace companies successfully employing the process was effectively demonstrated in a technology transfer program in which the entire process was successfully transferred from Northrop to Fairchild Republic. A cost analysis was conducted at both companies to determine the cost benefits of the process as compared to the current adhesive bonding technique of manufacturing the structural panels.

An extensive fatigue evaluation was undertaken to determine the effect of different manufacturing variables on the resulting fatigue and crack-growth properties of weldbonded joints. Testing was conducted both on specimens in low-load transfer and high-load transfer modes in a direct one-to-one comparison with similar specimens which were assembled using adhesive bonding and riveting. The results showed that under the structural conditions of low-load transfer, which occurs in most aircraft structures, the fatigue life of weldbond joints was somewhat less than the fatigue life of adhesive bonded joints and was significantly superior to comparable riveted joints. This latter advantage was made possible by the elimination of rivet holes which resulted in a much lower stress concentration factor (K_t,) and the advances made in surface preparation and welding techniques which enabled achievement of defect free Class A spotwelds through the complex interface of alclad, oxides, and adhesives. Under conditions of high-load transfer, weldbond specimens showed higher fatigue properties than riveted specimens but slightly lower than adhesive bonded specimens.

The structural test program conducted by Fairchild was conducted on a one-to-one basis comparing flat structural bonded beaded panels which were weldbonded by Northrop to similar panels which were adhesive bonded by Fairchild. Testing involved diagonal panel shear, shear fatigue, pressure fatigue and the environmental effects on lap-shear and fatigue properties. The results showed that structural panels assembled by the weldbonding process were equivalent to those which were adhesively bonded. As a result of the weldbonded panels being judged by Fairchild to be equivalent to the adhesive bonded panels which are currently used in the A10 aircraft production, Fairchild has initiated a program, sponsored by AFML, to integrate the weldbonding process into their production operation.

Prior to establishment of the weldbond process at Fairchild, the ability of the process to be integrated into a standard manufacturing environment was substantiated by a reliability evaluation and a technology transfer program. In the reliability program, a series of weldbonded test panels were manufactured over a wide range of manufacturing variables including different lots of adhesive and aluminum materials, which were processed on different days with different personnel. These panels were subsequently lap shear tested to develop statistical lap-shear values and to establish a degree of user confidence regarding the flexibility of the process. Following the reliability effort the entire process was successfully transferred from Northrop and established in a production environment at Fairchild Republic. Fairchild then successfully fabricated a series of weldbonded structural panels which met the established requirements and were equivalent to panels previously fabricated at Northrop.

During the final optimization of the surface preparation procedure a revised deoxidizing procedure was successfully achieved which resulted in a more consistently weldable surface. This procedure enabled the production of higher quality resistance spotwelds which were free of cracks and expulsion and also lengthened the life of the bath significantly. This achievement was made possible by (1) modification of the previously used deoxidizer bath with additional etching and sequestering agents, (2) modification of the rinsing techniques and (3) inclusion of bath agitation and filtration techniques to improve bath performance.

Weld schedules were successfully developed for the four material thickness combinations used in this program. To achieve these weld schedules, it was necessary to develop a new welding approach for resistance spot welding through adhesive/anodized surfaces involving 2024-T3 alclad material. This approach was made possible through the incorporation into the program of a microprocessor resistance weld controller which enabled cycle-by-cycle heat slope control and extremely precise weld schedule modifications. This technique enabled the initiation, growth, and solidification of the weld nugget to be achieved under precise metallurgical control. Nineteen structural panels, of three different panel combinations, which included a total of 2052 welds were spot welded using these techniques with achievement of 100 percent Class A quality with no evidence of any weld cracking or expulsion.

The feedback monitor and control program evaluated various commercially available equipment and techniques for monitoring and controlling weld nugget growth and quality. Conclusions drawn from this investigation showed that the Duffers current monitor and Convair total energy monitor could be effective in-process aids for weldbonding operations although the total energy monitor would need modification to be effective for weld schedules characterized by the long current up/down slopes, required in this program. The Pertron nugget expansion monitor and feedback control equipment was found to be the most effective tool for in-process weld nugget control. Used as a monitor, this unit can be programmed to arrest an abnormally growing nugget by turning off the welding machine or by automatically transferring the weld schedule into a repair-weld mode. It was demonstrated that if the computer is properly programmed, a weld nugget growing out of control could be arrested before expulsion occurred. Even a minor crack could be repair welded to successfully achieve a Class A weld and avoid damaging a panel. The nugget expansion feedback technique was also shown to be an extremely effective tool for controlling nugget growth to achieve consistent quality, but the technique requires additional engineering effort to enable the fine tuning of proper weld schedules to achieve maximum effectiveness.

As a result of this program, the aluminum weldbonding process was shown to be an effective manufacturing technique for the assembly of aircraft structural components. Panels made by the process were shown to be structurally equivalent to those made by the adhesive bonding process. As a result, the process is now recommended for production implementation.

SECTION I
INTRODUCTION

Three common techniques have been used in the United States to join components or assemblies in the manufacture of aluminum airframes. These are metallic fastening, adhesive bonding, and spot welding. The most widely accepted technique has been the use of fasteners – rivets, bolts, etc. Millions are used by all major airframe companies because they are easy to install, have high shear values and can be replaced easily in the field. Over the past few years, adhesive bonding has increased in use for fabricating structural components. This is the result of the development of higher strength, higher quality adhesives and the fact that high strength adhesive bonded structures generally show improved fatigue life over riveted structures. Resistance spot welding was widely used during World War II because it was an efficient low cost joining process. However, during the past twenty years, the application of resistance spot welding on aircraft structures has decreased due to many factors, including low fatigue strength of spot welds, inconsistent weld quality, and the need for more acceptable non-destructive inspection procedures.

While the application of resistance spot welding decreased in aircraft manufacturing in the United States, a weldbonding process was developed abroad which incorporated the technology and economic advances of both resistance spot welding and adhesive bonding. This process involved joining components together by spot welding through a previously applied adhesive and then curing the adhesive to achieve a fully bonded structure.

The process was introduced in the United States, and Lockheed/Georgia Company evaluated the process under Air Force sponsorship. Their experience showed that the strength of a weldbonded joint as compared to a spot welded joint when tested under high load transfer conditions was increased fourfold in static strength and tenfold in fatigue life. In addition, weldbonded structures appeared to offer a significant cost savings over adhesively bonded or mechanically fastened structures However, due to complex problems involving the production of adequate surfaces for achieving environmental durability while at the same time allowing for an ease of spot welding, the weldbonding process had not yet been accepted as a production process for use on aircraft.

Lockheed/Georgia Company used a spot welding etch to clean the surface of components to be weldbonded. This etching procedure reduced the contact resistance of the component and permitted formation of Class A welds with ease. It was determined however, that a weldbonding surface cleaned in this manner, and tested in an aggressive environment, will typically fail in an undesirable mode, along the adhesive to aluminum surface oxide. Gasko (Reference 1) et al felt that this failure mode could be attributable to the method of surface preparation. However, despite this problem, Lockheed, by adequately sealing the panel, has successfully fabricated, installed and flown a large C-130 fuselage panel. This panel has now flown over 2700 hours without encountering problems.

Northrop, in an Independent Research and Development Program, determined that in order to obtain adequate corrosion resistance, a layer of boehmite oxide ($\alpha Al_2O_3 \cdot H_2O$) must be formed on the surface. The bondline durability then increases with increasing oxide thickness. Unfortunately, the weldability decreases with increasing oxide thickness. Therefore, welding procedures to obtain a Class A weld with a corrosion resistant surface needed to be developed.

During the performance of Contract F33615-74-C-5027, "Development of Corrosion Resistant Surface Treatments for Aluminum Alloys for Spot-Weldbonding," (Reference 2) several improved surface treatments were identified and characterized, several adhesives were investigated, and the weldability of various surface treatment/adhesive systems was determined. Class A welds were successfully obtained for some of the surface treatments through a fundamental approach to the problem. First, the differences in surface condition between the spot-weld etched and adhesive bond etched surfaces were distinguished. Then, welding schedules which resulted in high quality welds through the protective oxide of the adhesive bond etched surface were developed. The results of that program provided the basic technology necessary for development of a manufacturing process. This process was developed in the program "Advanced Aluminum Weldbond Manufacturing Methods," Air Force Contract F33615-75-C-5083 (Reference 3). During this program, a significant step in the development of a weldbond system was achieved and the system was proven to be ready for manufacturing scale-up. An integrated system was developed utilizing (1) a low voltage phosphoric acid/sodium dichromate anodize in conjuntion with (2) a newly developed B. F. Goodrich A-1444B adhesive and (3) a precise welding schedule. This system resulted in a weldbond process which demonstrated good weldability, high lap shear and fatigue strengths and excellent resistance to failure when exposed under stress to an aggressive corrosion environment.

As a result of the process developed in that program, the major problem encountered in previous weldbond processes has been overcome, that of not being able to obtain a high degree of weldability and acceptable environmental durability at the same time. Previous aluminum weldbond systems that were sufficiently durable were difficult to weld, and systems that were weldable exhibited low environmental durability.

The purpose of the present program was to initiate the application of this developed weldbond technology to a current production aircraft, the USAF/Fairchild Republic A-10 as shown in Figure 1. Northrop conducted this program in association with the Fairchild Republic Corporation, Farmingdale, New York, the prime contractor for the A-10 and with support from General Dynamics Corporation, Convair Division. The program was based on the use of the weldbond technique to manufacture and test panels which represent structural A-10 fuselage panels that are now adhesively bonded. These panels are located in the aircraft as shown in Figures 2 and 3. The panel tests were conducted by Fairchild on a direct one-to-one comparison with adhesively bonded panels using the FPL etch/BR-127 primer/FM-123-2 adhesive system. In order to scale-up the process to full-size fuselage panels, Northrop conducted preliminary optimization studies to expand the developed technology to the 2024-T3 alclad/7075-T6 bare combination used by Fairchild. In addition, damage tolerance, environmental durability, and reliability evaluations were conducted on the developed system and available feedback control and monitoring systems were evaluated with the purpose of improving the reliability of manufacturing the weldbonded joints. Cost studies were also made to develop baseline cost data for implementing weldbonding on the production line.

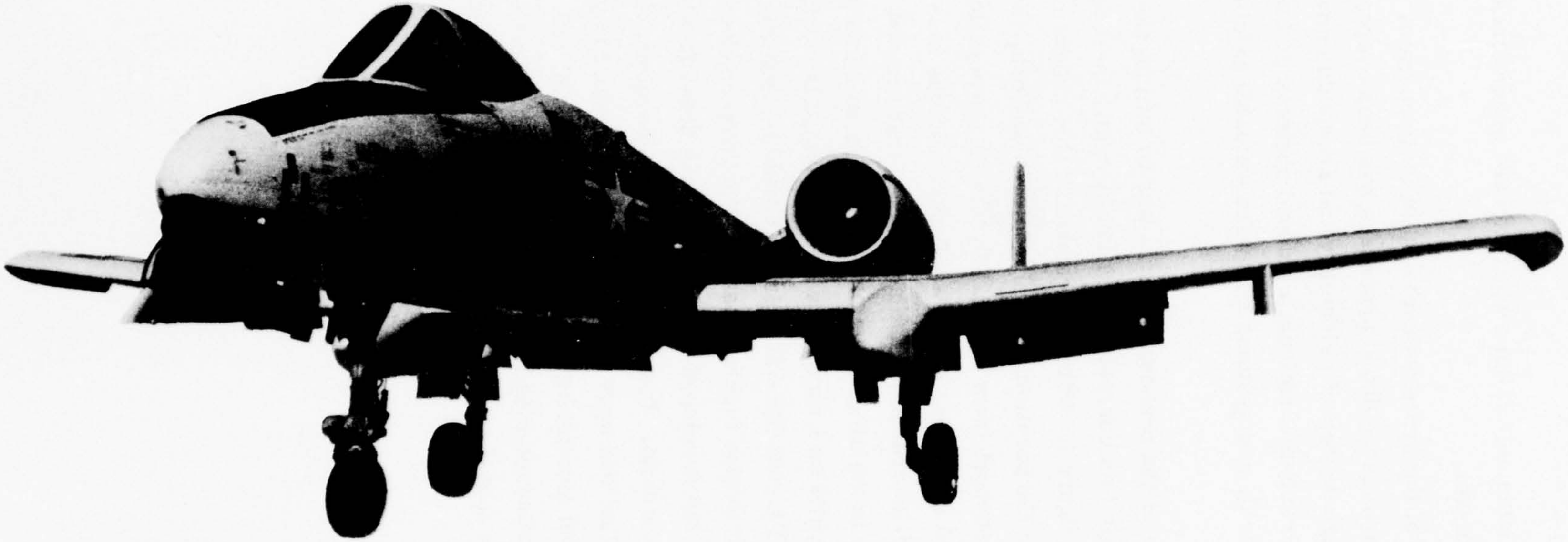

FIGURE 1. USAF/FAIRCHILD REPUBLIC A-10 AIRCRAFT

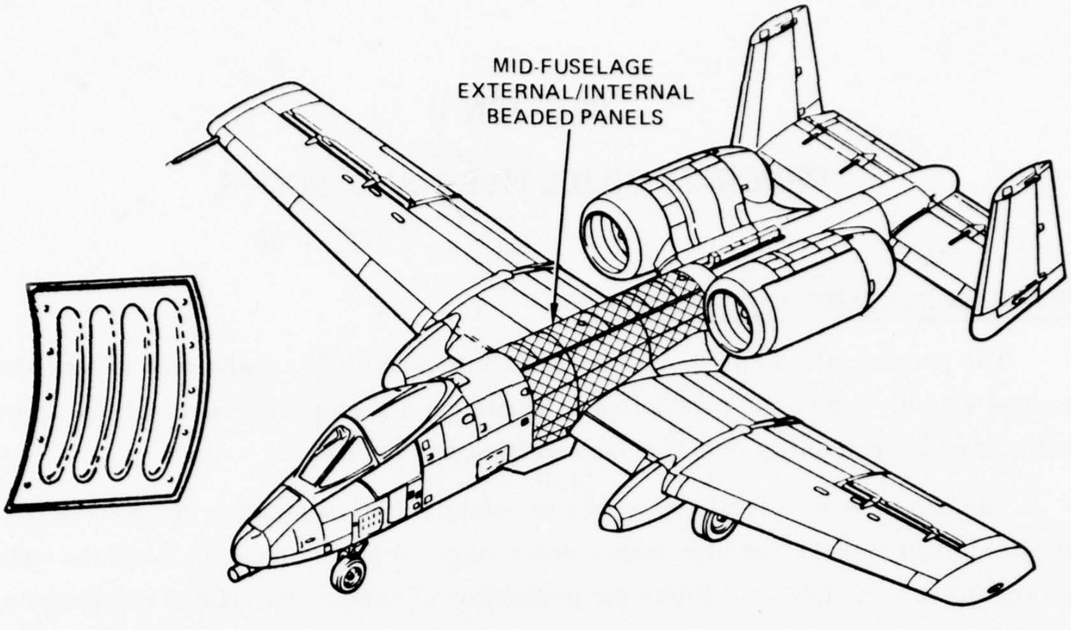

FIGURE 2. APPLICATION OF BEADED PAN STIFFENED SKIN PANELS TO A-10A FUSELAGE CENTER SECTION

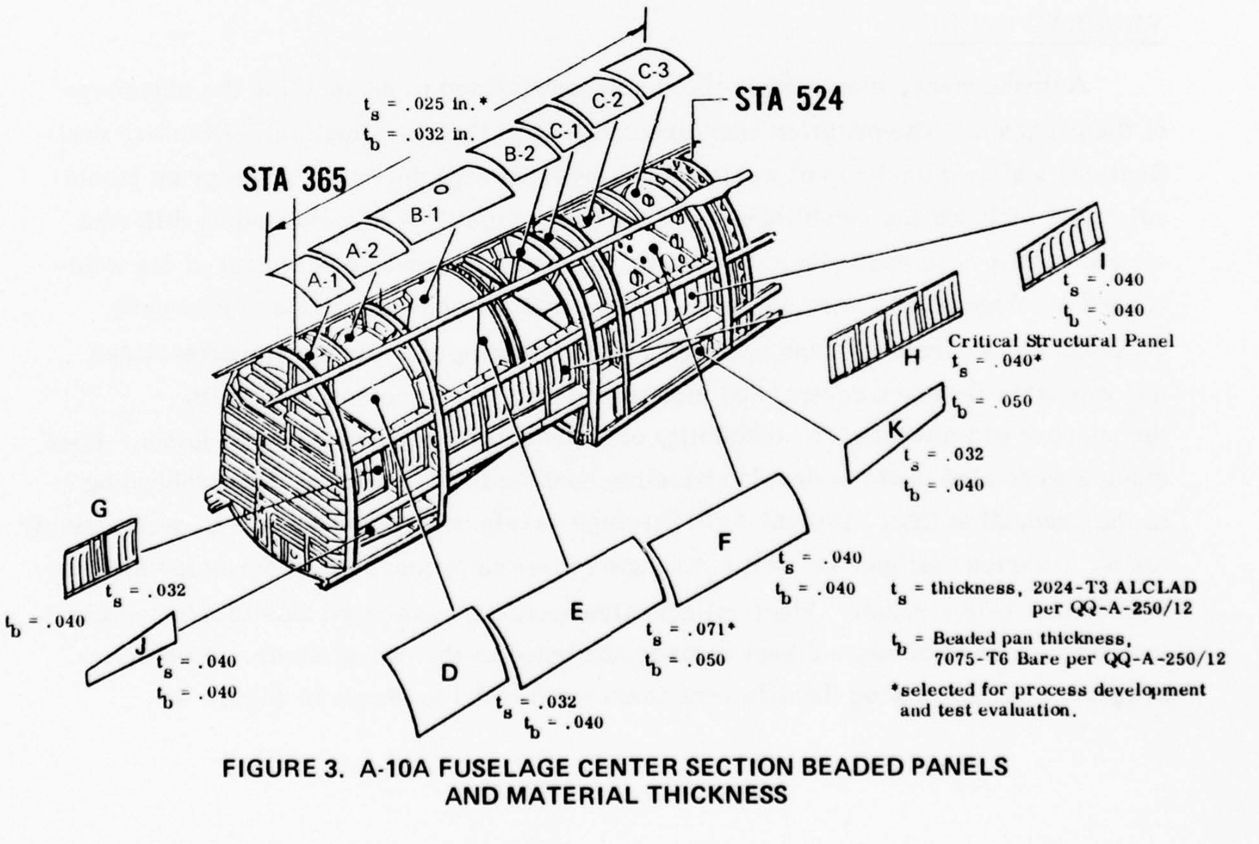

FIGURE 3. A-10A FUSELAGE CENTER SECTION BEADED PANELS AND MATERIAL THICKNESS

SECTION II

PROGRAM OBJECTIVES AND SCOPE

PROGRAM PURPOSE AND OBJECTIVE

The purpose of this program was to establish and test an advanced weldbonding process suitable for use in production of aluminum aircraft structural panels, and to obtain cost and reliability data for such weldbonded structures.

The objective of this program was to establish the fabrication and assembly parameters required to weldbond aluminum alloy structural panels so as to make the weldbonding process a viable candidate for production of panels and related components. In addition, damage tolerance, nondestructive inspection and fabrication cost information vital to such applications was obtained.

PROGRAM SCOPE

A three phase, eleven task effort was inaugurated to accomplish the objectives of the program. The program was directed toward the specification, reliability verification, and cost analysis of weldbonded aluminum structures. The program technical effort included the establishment of the proper methods of weldbonding different aluminum alloys to each other through various surface conditions typical of the weldbonded fuselage panels used on the A-10 aircraft. In addition, damage tolerance, environmental durability, and reliability of the developed system were determined and available feedback control and monitoring systems were evaluated with the purpose of improving the reliability of manufacturing the weldbonded joints. Cost studies were also made to develop baseline cost data for implementing weldbonding to the production line. Typical A-10 fuselage panels were weldbonded and destructively tested in various fatigue and static strength modes to prepare the process for application on the A-10 aircraft. Identical adhesive bonded panels were also fabricated and tested in order to obtain a direct comparison between the two systems. A complete program outline showing the different phases and tasks is shown in Figure 4.

PHASE 1,
DESIGN, FABRICATION AND PROCESS OPTIMIZATION

TASK	EFFORT
1	COMPONENT DESIGN AND SELECTION
2	ESTABLISH WELDBOND PROCESS
3	ESTABLISH MANUFACTURING PLAN
4	DESIGN AND FABRICATION OF TOOLING AND DETAIL PARTS
5	FABRICATE FULL SCALE FLAT TEST PANELS
6	DURABILITY AND RELIABILITY EVALUATION

PHASE II,
WELDING CONTROLS AND DAMAGE TOLERANCE

TASK	EFFORT
1	EVALUATION OF DAMAGE TOLERANCE WITH RESPECT TO MANUFACTURING VARIABLES
2	IN PROCESS WELDING CONTROL ESTABLISHMENT

PHASE III,
COST ANALYSIS AND STRUCTURAL PANEL EVALUATION

TASK	EFFORT
1	TEST PROGRAM FOR FLAT PANELS
2	DESIGN, FABRICATE AND EVALUATE CURVED PANELS
3	COST ANALYSIS

FIGURE 4. PROGRAM OUTLINE

SECTION III

TECHNICAL DISCUSSION

TEST COMPONENT SELECTION AND PRELIMINARY PANEL EVALUATION

As the purpose of this program was to establish a weldbond process suitable for the production of aluminum aircraft structural panels, with the target application being the USAF/Fairchild Republic A-10, it became necessary to select a representative test panel for evaluation. The criteria for selecting this test component was that it had to be (1) suitable for determining the adequacy of using the weldbonding process for aircraft structural panels and (2) of such a design to enable direct one to one comparison to existing adhesive bonded structural panels to justify direct substitution.

After the test component selection process was completed by Fairchild, a preliminary panel static and fatigue evaluation was conducted to obtain preliminary design information on the merits of the weldbonding process directly from structural panel tests. This was necessary so that any design modifications necessitated by a difference in the structural performance of a weldbonded panel versus an adhesive bonded panel could be made early in the program. The effort was conducted before the cleaning and welding procedures for the 2024-T3 alclad were optimized and prior to the design of the final demonstration test panel. Thus, in order to obtain results in a timely manner, the tests were conducted on panels fabricated from existing tooling which had been used in a previous Fairchild test program.

The actual design of the test panel, the test program rationale, and actual test results are described later in this report.

TEST COMPONENT SELECTION

The fuselage center section of the A-10 aircraft contains two fuel cells. To maximize the fuel volume of these cells, the number of internal frames was limited to those required for structural purposes, such as wing support or fuel cell separation, by the use of beaded pans attached to the skins. These beads stabilize the relatively large skin panels in shear and support the loads due to fuel pressure, particularly in those panels that are relatively flat. This skin and beaded pan section of the fuselage is shown in Figure 2.

In the initial design phases of the A-10, it was planned to assemble the beaded pans to the skin using a weldbonding process. It soon became evident through development work performed at Fairchild and by others, that methods of surface preparation had not been developed that permitted spotwelding through a surface finish and adhesive that possessed sufficient bondline durability to be acceptable under service applications. With no changes in the detail design of the panels, the assembly method was changed to autoclave bonding using American Cyanamid Company's FM 123-2 adhesive with the details prepared for bonding using an FPL etch and BR127 primer.

There are twenty-three beaded skin panel assemblies in the fuselage center section as shown in Figure 3, seven along the top of the fuselage and eight per side. The surface area of these panels is approximately 110 square feet. The thickness of the beaded pans and skins vary depending on the induced shear and fuel pressures.

After extensive study of the A-10 structure, it was concluded that these panels were the optimum choice for the advanced weldbonding process establishment for the following reasons:

- The panels are primary aircraft structure and there are a large number of assemblies (23) for each A-10.
- The panel designs are completely compatible with weldbonding, and indeed were initially intended to be weldbonded.
- No structural redesign is required in order to fabricate demonstration or production aircraft components.
- The variation in material thicknesses in the aircraft panels are sufficient to develop and demonstrate flexibility of the process.
- They provide a reasonable base for a cost effectiveness demonstration for weldbonding.

Figure 3 also shows the skin and beaded pan thicknesses of the various cover and panel assemblies. These panels vary from the 0.025 inch skin/0.032 inch beaded pan thickness for the panels and removable covers along the top centerline to the 0.070 inch skin and 0.050 inch beaded pan thickness of the upper-center-side panel. The center-side through panel is, by analysis, the most critically loaded panel of the fuselage center section in that it has the minimum static margin for shear stability. This panel has an 0.040 inch skin and an 0.050 inch beaded pan.

The materials of the skins and beaded pans are:

Skins – 2024-T3 alclad per QQ-A-250/5

Beaded Pans – 7075-T6 bare per QQ-A-250/12

Therefore, the above materials and the following thicknesses were used in the process development and test demonstration phases of the program.

- 0.025 in. skin - 0.032 in. beaded pan as the minimum combination of material thicknesses, designated as 0.025/0.032 inch panels or combination.
- 0.070 in. skin - 0.050 in. beaded pan as the maximum combination of material thicknesses, designated as 0.071/0.050 inch panels or combination.
- 0.040 in. skin - 0.050 in. beaded pan as the interim thickness combination and as representative of the most critical structural panel, designated as 0.040/0.050 inch panels or combination.

PRELIMINARY PANEL STATIC AND FATIGUE EVALUATION

As previously indicated, this evaluation was conducted on panels made from existing tooling early in the program in order to identify possible design modifications that might be required. Static shear and constant amplitude fatigue tests were conducted on 24 inch x 30 inch beaded panels fabricated from 0.050-inch 7075-T6 bare aluminum sheet. The test panel configuration is shown in Figure 5. Four weldbonded and four adhesively bonded panels were fabricated. Diagonal panel shear testing of two adhesive bonded and two weldbonded panels was performed by Northrop utilizing the Fairchild-supplied picture frame testing fixture shown in Figure 6. Three strain gauges were attached to each panel and the strains at the three different locations were monitored. Fairchild conducted both diagonal panel shear tests and fatigue tests on the adhesive bonded and weldbonded panels. The results of the static tests are shown in Table 1, and are discussed below:

TEST RESULTS AT NORTHROP

Northrop conducted diagonal panel shear tests on two weldbonded and two adhesive bonded panels. The objective of this test was to compare the mode of failure and ultimate failure loads for all panels. In addition, differences in the buckling characteristics of the panels were noted. The panels were tested on a 200-KIP MTS testing machine. Load was applied in a slope control mode at a rate of 1/4-inch ram deflection per minute which resulted in a loading rate of approximately 625 pounds/second.

NOTES: 1. DIMENSIONS ARE IN INCHES.
2. OUTSIDE DIMENSIONS REPRESENT THE PORTION OF THE PANEL AS DEFINED BY THE CENTER OF THE TWO CORNER LOADING FIXTURE ATTACHMENT BOLTS.

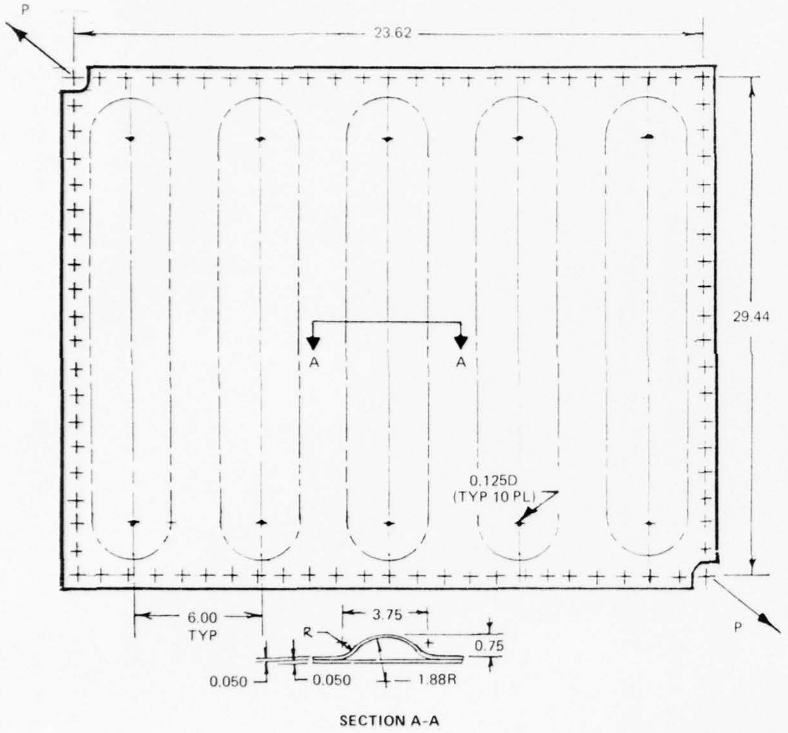

FIGURE 5. PRELIMINARY TEST PANEL CONFIGURATION

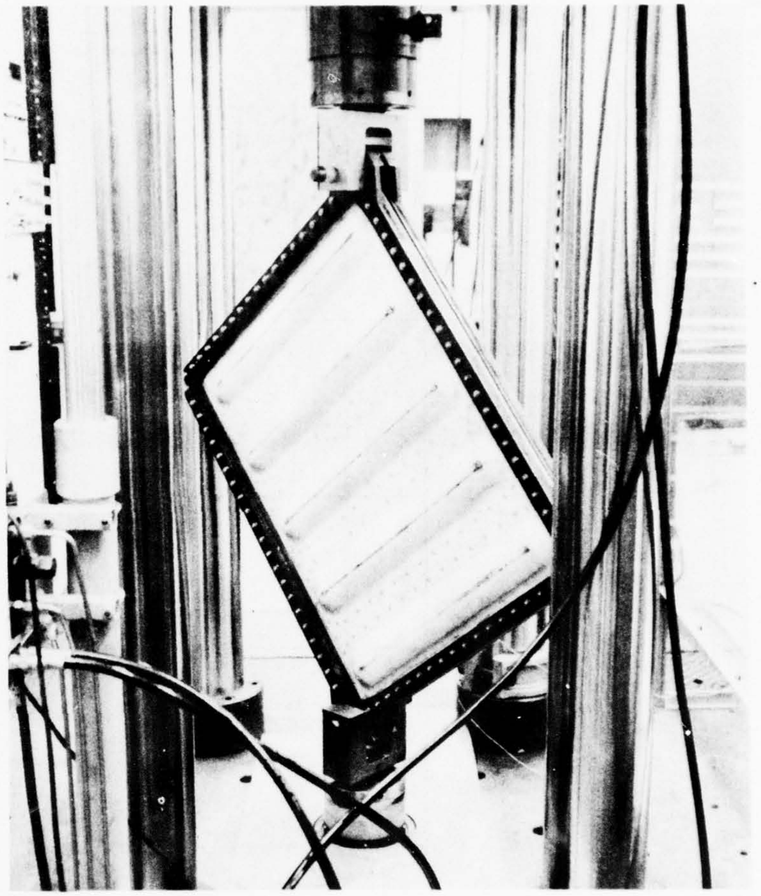

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FIGURE 6. PICTURE FRAME TESTING OF WELDBOND PANEL

As shown in Table 1, the ultimate failure loads of the adhesive and weldbonded panels tested at Northrop were all between 105,000 and 107,000 pounds. Thus, despite the differences in the bonding method, there was no apparent difference in the ultimate panel strength. The onset of buckling occurred at approximately 60,000 pounds for all panels and progressed until ultimate failure. A series of photos showing the degree of buckling as a function of the load applied in a typical panel is shown in Figure 7.

TABLE 1. STATIC DIAGONAL PANEL SHEAR TEST RESULTS FOR THE PRELIMINARY PANELS

TEST LOCATION	TYPE TEST	ADHESIVE BONDED	WELDBONDED
NORTHROP	STATIC	105,000	106,000
		106,000	107,000
FAIRCHILD	STATIC	94,700	108,600

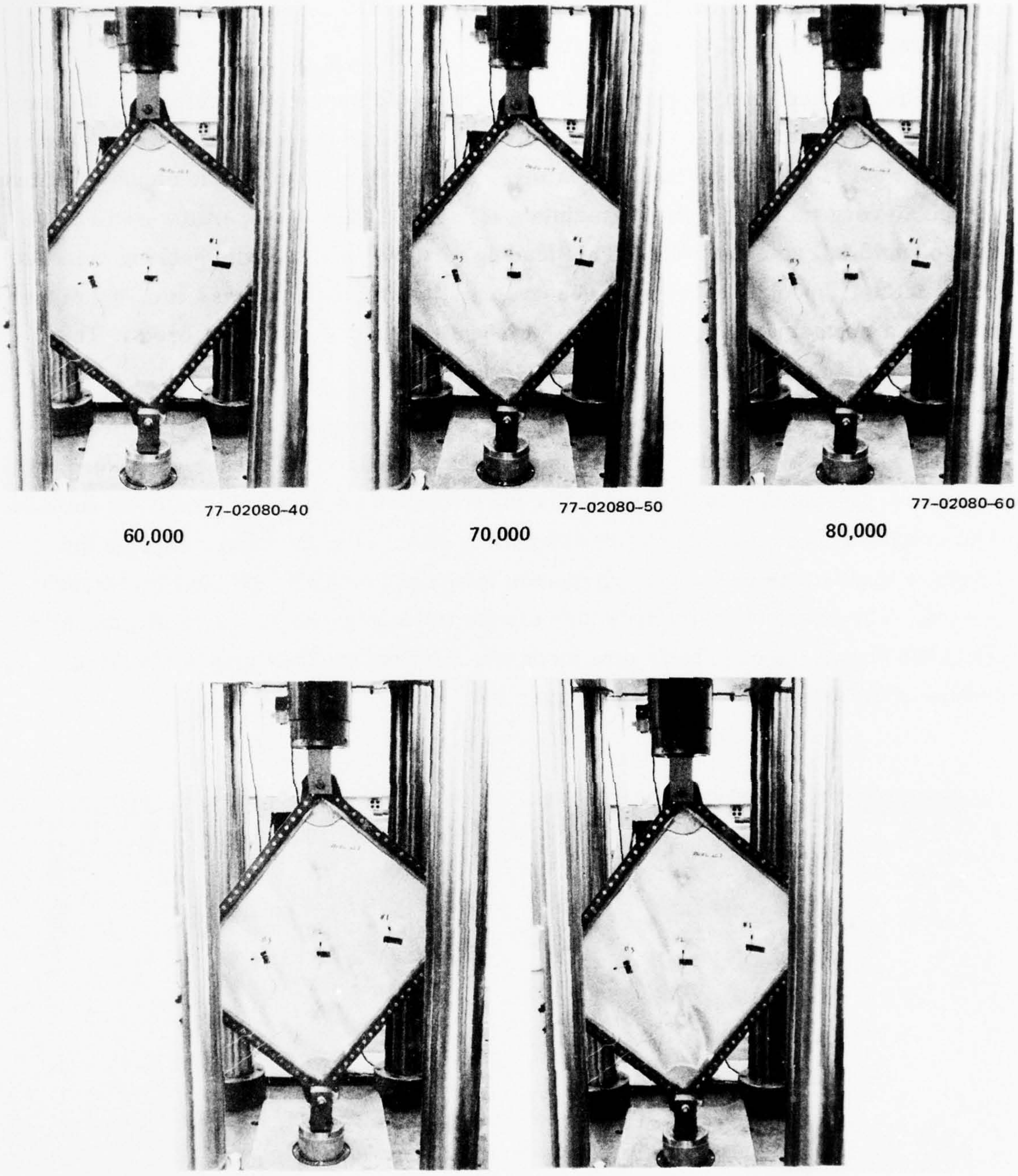
The panel failure mode was nearly identical for all four panels tested. At failure, a single buckle occurred in the second bead approximately two inches from the main load path. Typical failed adhesive bonded and weldbonded panels are shown in Figure 8.

TEST RESULTS AT FAIRCHILD

Static Tests

The system was programmed to load in 5000 pound increments from 0 to 125,00 pounds. A dial gage was positioned to measure the diagonal displacement between the panel loading bolts as readings were taken at 5000 pound loading increments. The dial gage was removed at 90,000 pounds of applied load to prevent damage when the panel failed. Print-outs of actual panel loads obtained from strain gage readings were obtained at each increment of loading (for comparison to the commanded load), and at panel failure. Loading was continued to failure of the panel.

The adhesive bonded panel failed at an applied load of 94,700 pounds. The diagonal distance between the loading fixture attachment bolts is 39.15 inches.



77-02080-40
60,000

77-02080-50
70,000

77-02080-60
80,000

77-02080-70
90,000

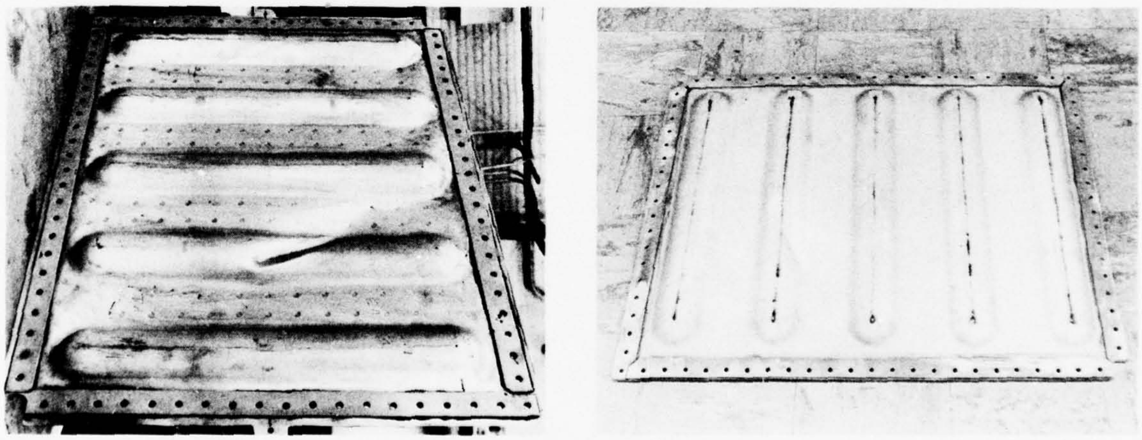
77-02080-80
100,000

FIGURE 7. TYPICAL PANEL BUCKLING AT DIFFERENT LOADS DURING DIAGONAL PANEL SHEAR TESTING

Therefore, the panel shear intensity at failure was 2510 pounds/inch, i.e., $N_{xy} = 94,700/37.74 = 2,510$ pounds/inch.

The test had been programmed to go into a hold mode in the event that the permissible loading tolerance was exceeded, i.e., the load the equipment was trying to achieve would remain constant. At failure, the servo valve controlled loading cylinder retracted very rapidly, trying to maintain the load, before the operator could close the solenoid fail safe manifold. This loading tore the panel apart, masking evidence of the failure mode. From visual observation, the failure mode was buckling of the beads in a manner very similar to the weldbonded panel shown in Figure 8. The panel diagonal deflections are presented in Figure 9.

For the subsequent weldbond test, the control program was changed to automatically dump the cylinder load if the permissible loading tolerance was exceeded. At failure, the panel load dropped below the tolerance limit and the load was dumped. The weldbonded panel failed at 108,600 pounds which is in the same range as the ultimate loads obtained for the four panels tested at Northrop, 105,000 to 107,000 pounds. The shear intensity at failure for the weldbonded panel tested at Fairchild was 2880 pounds/inch. The failure mode was very apparent as a shear buckling failure of the beads as is shown in Figure 8.



77-208

WELDBONDED

77-02081-110

ADHESIVE BONDED

FIGURE 8. APPEARANCE OF TYPICAL FAILED PANELS, – DIAGONAL PANEL SHEAR TEST

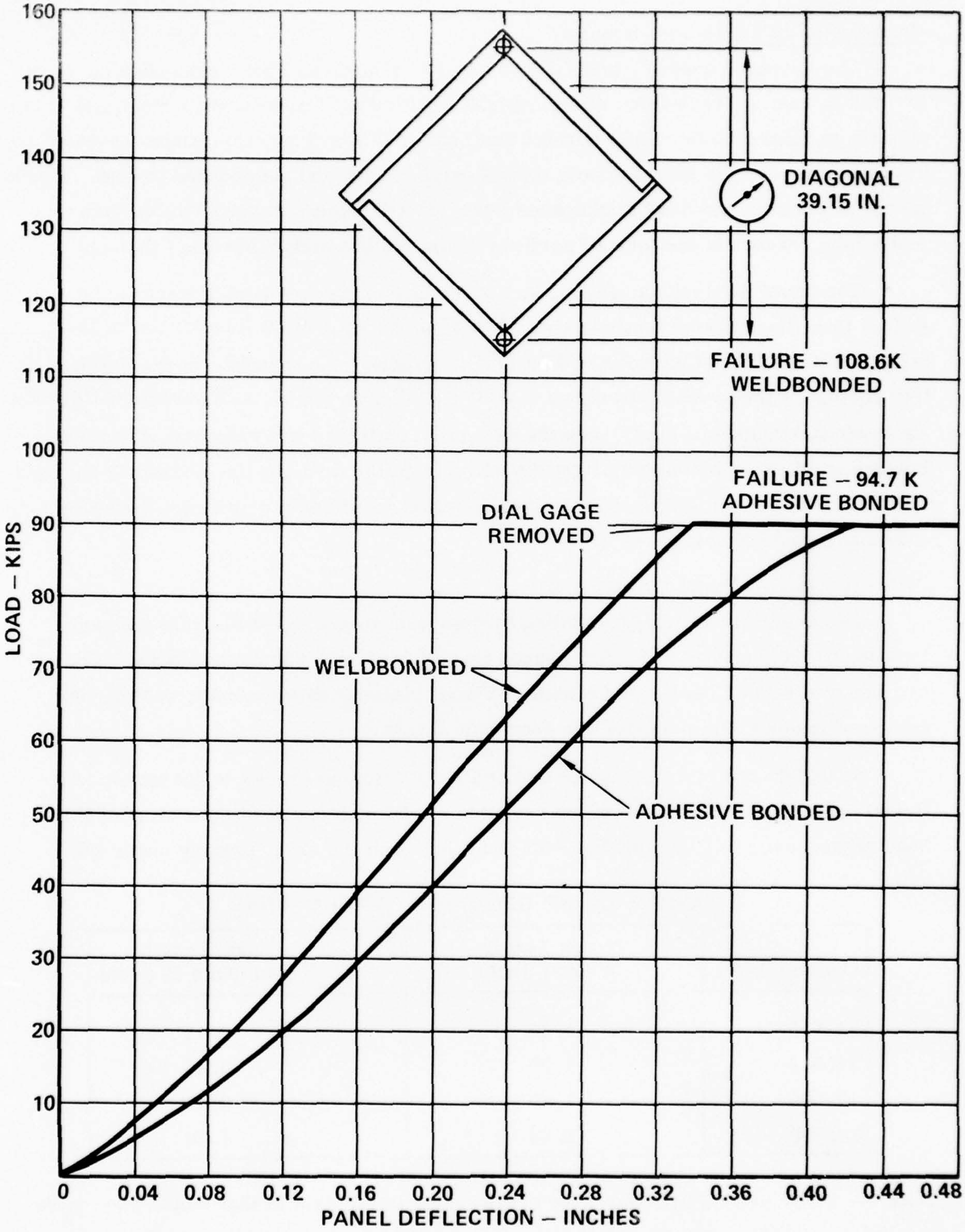


FIGURE 9. DEFLECTION OF STATIC TEST PANELS

Comparison of Static Test Results

The adhesive bonded panel failed at 94,700 pounds and the weldbonded panel at 108,600 pounds. There is no ready explanation for the 13 percent difference and it is slightly excessive to be within normal test scatter. Post test examination revealed cohesive failures of the bond for both the adhesive bonded and weldbonded panels. Measurements of the skin and bead thicknesses revealed a thickness range of 0.049 inch to 0.051 inch, except in the formed portions of the beads which experience thin-out.

The panel deflections, Figure 9, also indicated the weldbonded panel to be stiffer than the adhesive bonded panel. The slop of tne straight line portion of the adhesive bonded panel curve is 0.38×10^{-5} inch/pound and the slope of the straight line portion of the weldbonded curve is 0.33×10^{-5} inch/pound, a 15 percent difference. Up to 90,000 pounds of load, when the deflection dial gage was removed, the weldbonded panel exhibited only a slight deviation from the straight line portion of the load deflection curve, while the adhesive bonded panel exhibited a significant deviation, indicating impending failure.

Adhesive Bonded Panel Fatigue Test

The computer controlled loading system was programmed to cycle the panel between 5,500 pounds and 55,000 pounds tension load in 2,000 cycle blocks. The cycling rate was 30 cycles per minute. Visual inspections were made each 2,000 cycles of loading with periodic dye penetrant checks.

At 10,000 cycles, a complete dye check revealed no cracks in the panel. At 11,650 cycles, a visual examination revealed a 1.00 inch crack in the radius of the bead adjacent to the lower loading bolt and a crack in the skin, running under the

TABLE 2. CRACK GROWTH IN FATIGUE PANEL

Cycles	Crack Length in Bead (inch)	Crack Length in Skin (Note 1) (inch)
11,650	1.00	0.45
12,000	1.25	0.45
13,000	1.60	0.65
14,000	2.20	4.20

Note 1 - Prior to 14,000 cycles, the crack length in the skin is that length projecting beyond the doubler. By 14,000 cycles, the crack had propagated beyond the doubler at both ends.

quarter moon doubler, and extending beyond the doubler by 0.45 inch. At 12,000, 13,000 and 14,000 cycles, the crack length was measured with the results shown in Table 2: (Figure 10 shows the extent of the crack in the skin at 14,000 cycles with the doubler removed).

It has been concluded that the failure initiated in the skin at the edge of the doubler (see Figure 10) due to the stress concentration induced at the edge of the doubler. As the crack progressed, load was transferred around the radius and eventually the bead developed fatigue cracks. The only explanation as to why this type of failure had not occurred during the A-10 development test program, in which identical panel dimensions, doubler dimensions and loading frame were used, is that the skin on the previously tested panels was 2024-T3 and in this panel it was 7075-T6.

In order to reduce the stress concentration induced at the edge of the doubler, the doubler radius was increased from 3.0 inches to 4.0 inches and the radial edge of the doubler was beveled from the thickness of 0.10 inch at the 3.5-inch radius to 0.02 inch at the 4.0-inch radius.

Weldbonded Panel Fatigue Tests

The weldbonded panel was tested in the same manner as the adhesive bonded panel except that the new corner doubler configuration was used. No cracks were observed in the panel until 22,180 cycles of loading when cracks were visually observed at the ends of three beads along the bead radius. Figures 11 through 13 show these cracks in the three beads. After these cracks were observed, a residual strength static test was conducted to determine the degradation of panel load carrying capability. The panel failed at 94,045 pounds or 87 percent of the static strength of the undamaged static panel. Figure 14 shows the panel after static failure. The failure initiated at the fatigue crack as shown in Figure 11.

Comparison of Test Results

The premature fatigue failure of the adhesive bonded panel precludes a direct comparison of the fatigue test results of the weldbonded panel with the adhesive bonded panel. However, for a prior A-10 development test program, a fatigue test was conducted for an adhesive bonded panel having the same overall dimensions, bead geometry and spacing (Reference 4), but with a 0.040 inch skin instead of a 0.050 inch skin. Table 3 summarizes the materials, dimensions and test results of this earlier test panel and the weldbonded panel tested in the current program.

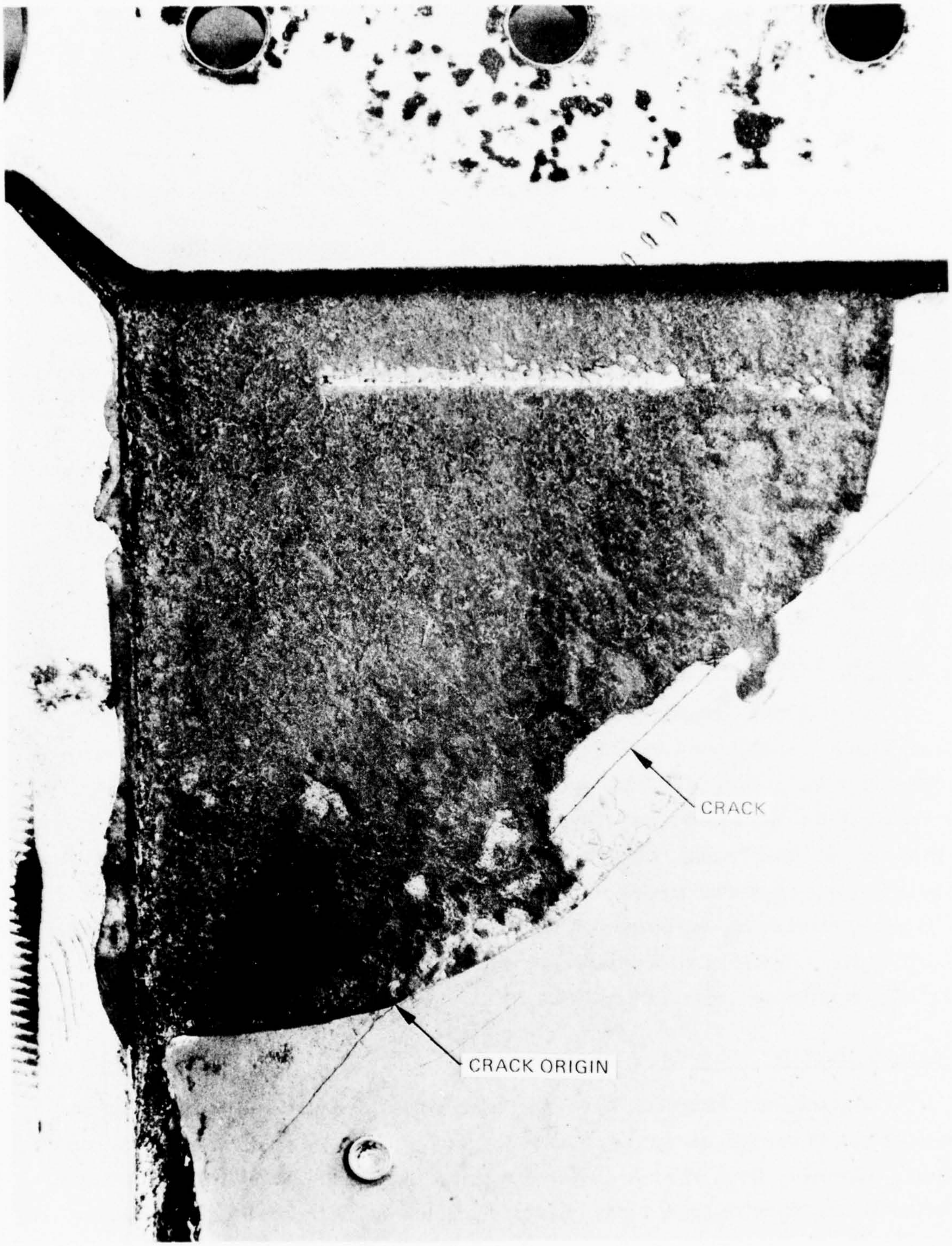


FIGURE 10. ADHESIVE BONDED PANEL SKIN FATIGUE CRACK LOADED CORNER

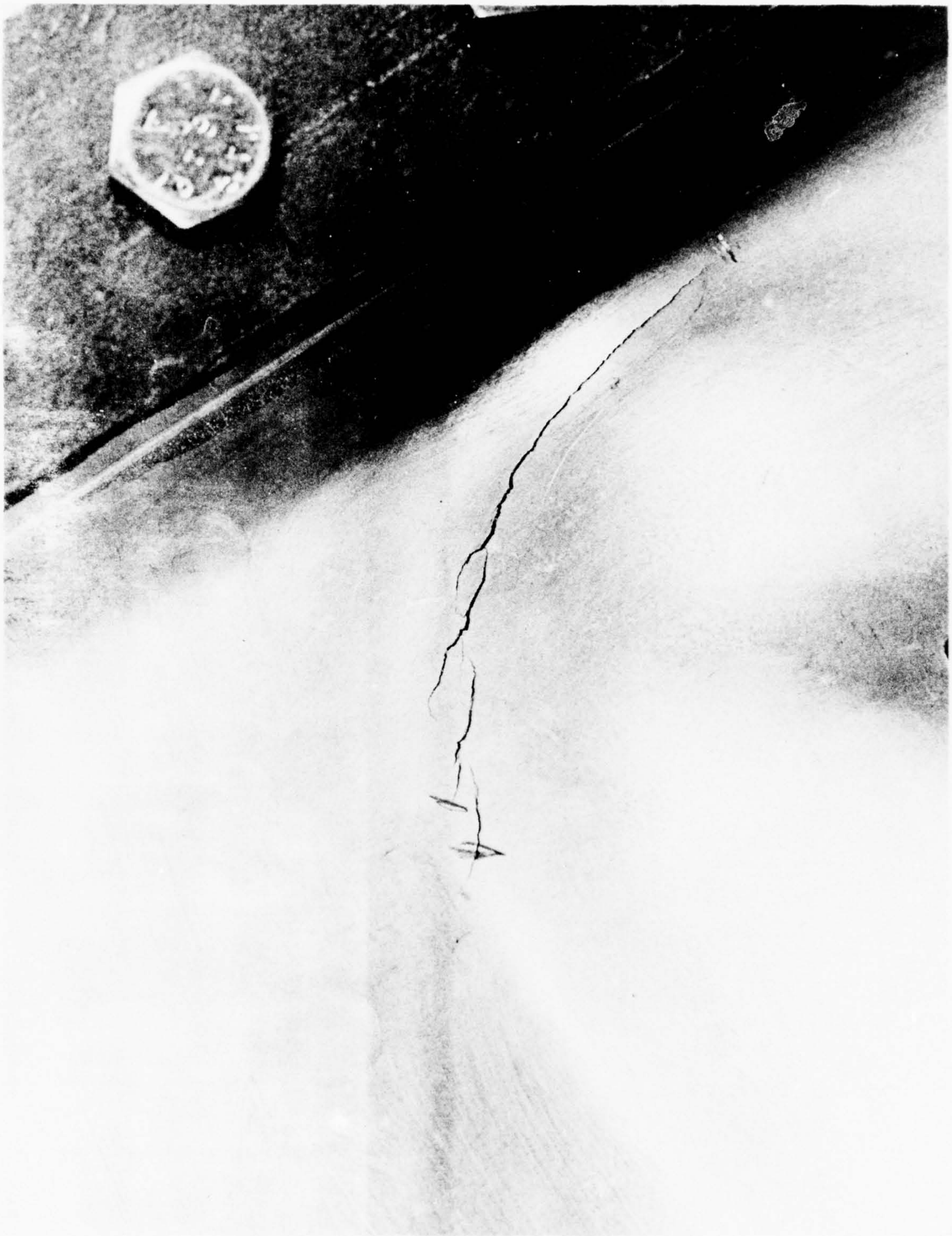


FIGURE 11. WELDBONDED PANEL FATIGUE CRACK AT 22,180 LOADING CYCLES, BEAD A

FIGURE 12. WELDBONDED PANEL FATIGUE CRACK AT 22,180 LOADING CYCLES, BEAD B

FIGURE 13. WELDBONDED PANEL FATIGUE CRACK AT 22,180 LOADING CYCLES, BEAD C

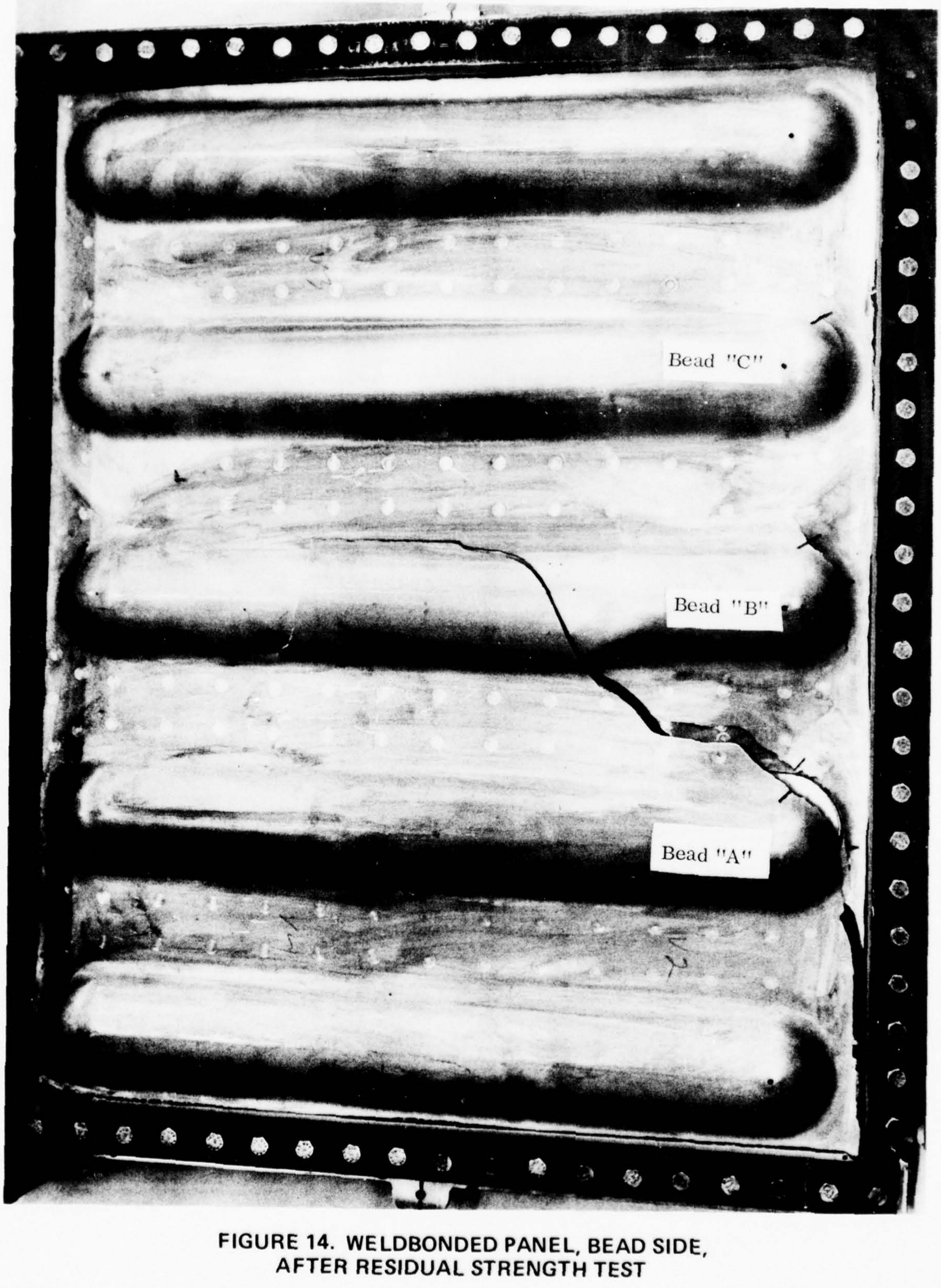


FIGURE 14. WELDBONDED PANEL, BEAD SIDE, AFTER RESIDUAL STRENGTH TEST

Even though the fatigue loading was 12 percent higher for the weldbonded panel than for the adhesive bonded panel, the total sheet thickness of the weldbonded panel was 10 percent higher than that of the adhesive bonded panel. Therefore the stress level induced in both panels would be equal. Cracks developed in the bead ends of the adhesive bonded panel in the same relative location as on the weldbonded panel. The number of cycles to fatigue crack initiation was only slightly greater for the weldbonded panel. The higher residual strength of the weldbonded panel is attributable to the greater thickness of the skin (i.e., 0.050-inch instead of 0.040-inch) of the weldbonded panel.

Conclusions of the Preliminary Panel Testing

The static tests conducted at Northrop revealed that the ultimate loads of the adhesive bonded and weldbonded panels were equal, 105,000 pounds to 107,000 pounds. The weldbonded panel tested at Fairchild confirmed the results at Northrop with an ultimate load of 108,600 pounds. The adhesive bonded panel tested at Fairchild did fail at a load which was approximately 13 percent lower than the adhesive bonded panels tested at Northrop. However, one low test value is not considered to be significant.

TABLE 3. COMPARISON OF PANELS AND FATIGUE TEST RESULTS CONDUCTED AT FAIRCHILD

ITEM	PRIOR PROGRAM ADHESIVE BONDED PANEL	WELDBONDED PANEL
SKIN	0.040-IN. 2024-T3 CLAD	0.050-IN. 7075-T6 BARE
BEAD	0.050-IN. 7075-T6 CLAD	0.050-IN. 7075-T6 BARE
LOADING	5000 POUNDS TO 50000 POUNDS	5500 POUNDS TO 55000 POUNDS
CYCLES TO BEAD CRACKING	22,180	23,250
STATIC TEST FAILING LOAD (1)	72000 POUNDS	108600 POUNDS
RESIDUAL STRENGTH - PANEL WITH CRACKED BEADS	73600 POUNDS	94045 POUNDS

(1) TEST OF PANEL WITHOUT FATIGUE CYCLING.

The results of the fatigue tests show that within normal test scatter the same number of cycles were required to initiate fatigue cracks in the adhesive bonded panel as in the weldbonded panel.

The results of the preliminary panel testing indicated that the weldbonded structural panels would perform comparably to adhesive bonded panels. It was concluded that no design change would be needed in the structural test panel due to any apparent shortcomings of the weldbond process. Therefore, the structural test panel to be used in the program would be fabricated by the two processes from identically fabricated details and testing would be conducted on a direct one-to-one basis.

ESTABLISH WELDBOND PROCESS

The purpose of this effort was to establish and specify in detail the weldbond process to be used in fabricating A-10 fuselage panels. The surface preparation procedures, adhesive controls, welding procedures, and quality control requirements were finalized and specifications were prepared to enable implementation of the process into manufacturing operations by other companies.

Each of the areas mentioned is discussed in detail in the following section. The discussion includes not only a description of the finalized process but also of the problems which were encountered while optimizing the weldbonding procedures and the solutions to these problems.

SURFACE PREPARATION

In the effort previously discussed, Fairchild Republic selected for test the following material/thickness combinations as representative of panels used on the A-10:

Interior Beaded Panel Weldbonded	to	Exterior Skin
0.050-inch 7075-T6 bare	to	0.071-inch 2024-T3 alclad
0.050-inch 7075-T6 bare	to	0.040-inch 2024-T3 alclad
0.032-inch 7075-T6 bare	to	0.025-inch 2024-T3 alclad

The two thicker material combinations represent A-10 panels which are designed for high structural loads. The thinnest material combination represents the minimum thickness panel combination used for the A-10.

Most of the prior weldbond work conducted at Northrop under Air Force Contracts F33615-75-C-5083 and F33615-74-5027 involved the evaluation of 7075-T6 bare and 2024-T3 bare alloys in thickness combinations greater than 0.040-inch. No effort had been expended on alclad materials, or on thinner gage sheet. As a result modified surface treatment parameters were required to process the 2024-T3 alclad material for this program. Also, welding parameters needed to be established both for the thinner gage materials used in the A-10 panels and for the alclad alloy. The same adhesive was used for the current program, i.e., B.F. Goodrich adhesive A-1444B, (the supplier has changed its designation from the previously used A1396B-0500 PE130).

Optimization of Surface Preparation Procedures.

The surface preparation procedure for the 7075-T6 bare sheet material was established during the two prior Air Force contracts. This was the 1.5v phosphoric acid-sodium dichromate anodize procedure which developed a boehmite $(Al_2O_3 \cdot H_2O)$ aluminum oxide on the part surface of approximately 400-700Å thick. The oxide, when formed on 7075 bare sheet provided good weldability and excellent environmental durability characteristics as measured in the laboratory by the 24 hour wedge test with exposure to 95 to 100 percent relative humidity at 120°F and the constant load/salt water immersion test. Because of this previous effort, it was concluded that no further surface preparation effort would be required for the 7075 bare material.

The initial surface preparation effort of the current program was directed toward the formation of the proper boehmite thickness on the 2024 alclad material to achieve both weldability and durability. The 1.5 volt, phosphoric acid/sodium dichromate (1.5vPSD) treatment developed previously was used for preliminary evaluation. It was found that 2024 alclad developed a thicker oxide than the 7075-T6 bare material and the 1.5vPSD treatment produced an oxide coating in excess of 1000Å in thickness.

Earlier weldability tests on the 7075-T6 bare alloy showed that when the oxide thickness reached 1000 Å, inconsistent weld quality resulted. It was believed that the quality of the weld was not only a function of oxide thickness but also of the chemical character and morphology of the oxide developed. Due to possible chemical differences in the alclad oxide, it was necessary to determine if the 1000Å coating on this material could be welded. A weldability evaluation was conducted by resistance spot welding the 1.5vPSD 2024 alclad samples to 7075 bare 1.5vPSD samples with A-1444B adhesive at the interface using a sheet material thickness of 0.063-inch. As in the case of the bare alloys, the 1000Å thick oxide present on the alclad sheet did result in poor quality welds using existing weld schedules. A second series of 2024 alclad samples was anodized for twenty minutes at 1.3 volts in an effort to reduce oxide thickness. This technique resulted in an oxide layer thickness of approximately 900 Å and poor weldability. A third series of 2024 alclad samples, anodized at 1.0 volt, resulted in the desired oxide thickness of approximately 675 Å. The weldability of these samples was greatly improved. Radiographic examination of these welds revealed no cracks and no expulsion. Based on the weldability results and the oxide thickness achieved it was concluded that this modified surface preparation procedure, i.e., 1.0vPSD, should provide an acceptable surface for weldbonding 2024-T3 alclad material. The appearance of the oxide coating resulting from the different anodizing voltages is shown by the scanning electron microscope (SEM) photographs of Figure 16.

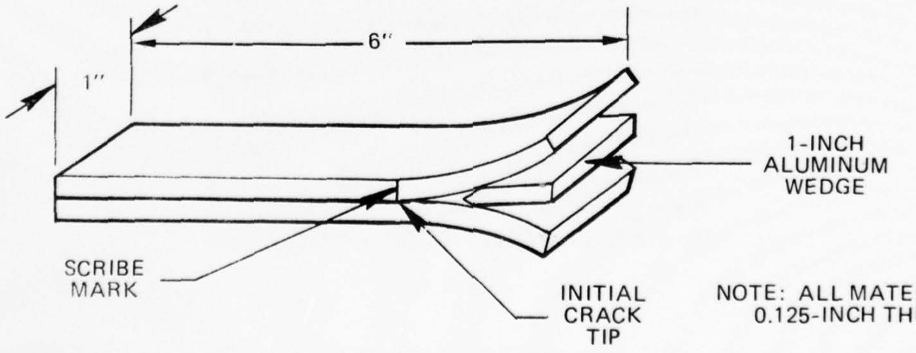
Thus, a satisfactory surface treatment was established for the 2024-T3 alclad material in terms of weldability and thickness of the anodized layer. However, durability tests were required to determine if the 1.0vPSD surface treatment provided the same degree of protection against the combined effects of stress and corrosion as that obtained for the 7075 material anodized with 1.5vPSD.

Durability Testing Background.

One of the prime concerns in the use of adhesive bonded structural components is premature structural failure due to time dependent crack growth in the bond joint under combined conditions of an applied stress and a corrosive environment, termed "environmental stress cracking". Achievement of adequate environmental stress durability characteristics is a prime consideration in the processing of an adhesive bonded system.

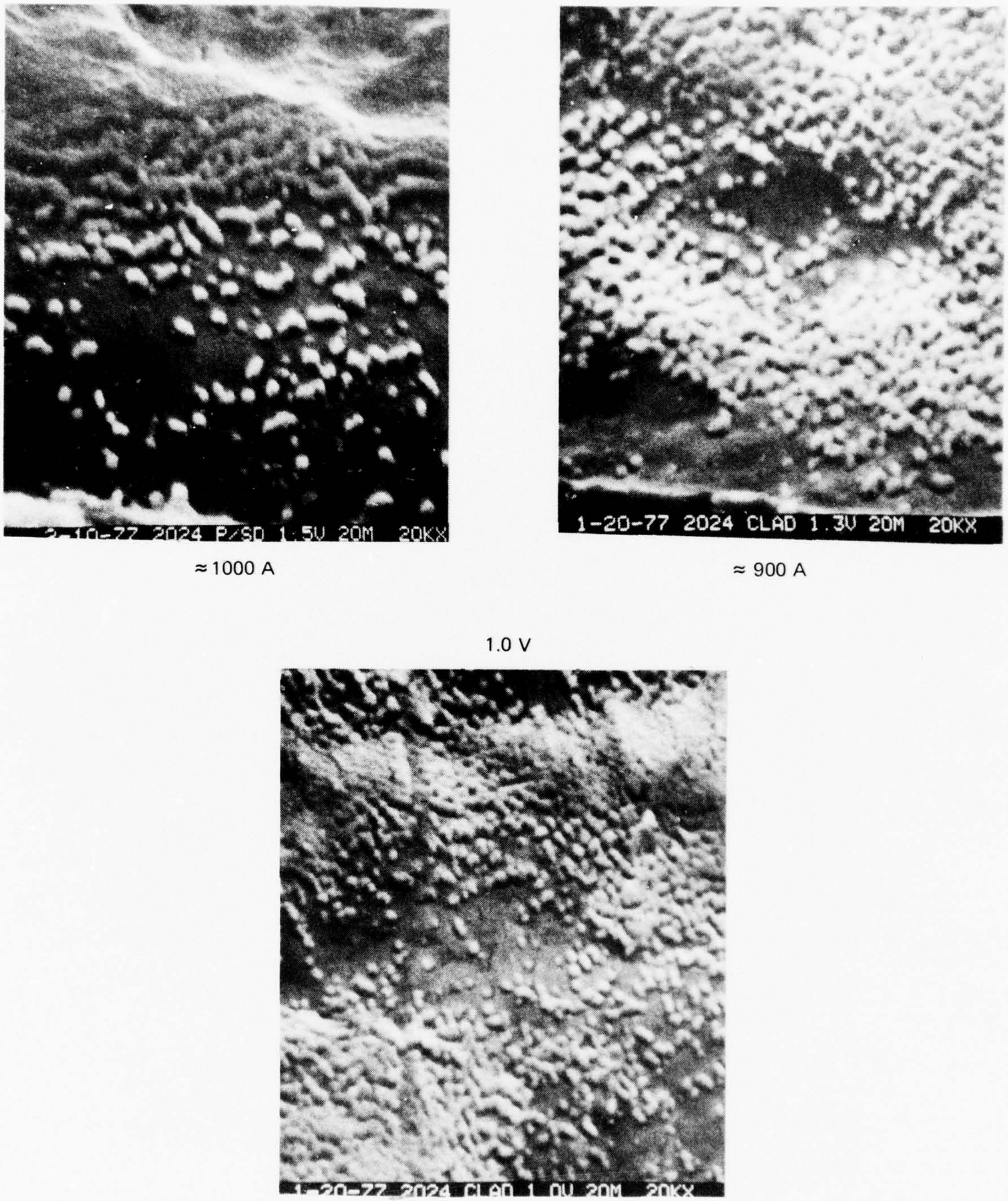
Many different stress durability tests have been used to evaluate the relative environmental stress cracking characteristics of adhesive systems. The most accepted test today is the wedge test. This test is widely used both for evaluating adhesive systems and as a quality control test for determining the adequacy of the surface preparation procedure. This test, however, is conducted under a wide variety of temperature and corrosive conditions and for different exposure times.

The wedge test involves the insertion of a wedge into the bond line of a test coupon to a depth of approximately one inch as is shown in Figure 15. The location of the initial crack tip is scribed on the edge of the coupon and is measured to the nearest



NOTE: ALL MATERIAL – 0.125-INCH THICK

FIGURE 15. STANDARD WEDGE TEST



1.5 V ≈1000 A

1.3 V ≈ 900 A

1.0 V ≈ 675 A

FIGURE 16. APPEARANCE OF SURFACE OXIDE ON 2024-T3 ALCLAD ANODIZED AT THREE DIFFERENT VOLTAGES

0.01 inch. The specimen is then exposed to an aggressive environment for a specified period of time to accelerate crack growth. After the desired exposure time, the crack growth is measured.

In prior weldbond programs, Northrop developed the Constant Load/Salt Water Immersion Test (CL/SWIT) for evaluating the environmental stress durability characteristics of weldbonding systems. This test involves the dead weight loading of a bonded or weldbonded lap shear specimen which is exposed continuously for 1000 hours to a high load while immersed in a 3-1/2 percent salt water solution. After exposure, the specimen is mechanically tested and must show no appreciable loss (less than 15 percent average) in strength when compared to the average strengths of control specimens lap shear tested without exposure. A schematic of the test is shown in Figure 17 and the test rig at Northrop is shown in Figure 18. This fixture is a series of dead weight loading frames similar to a creep fixture.

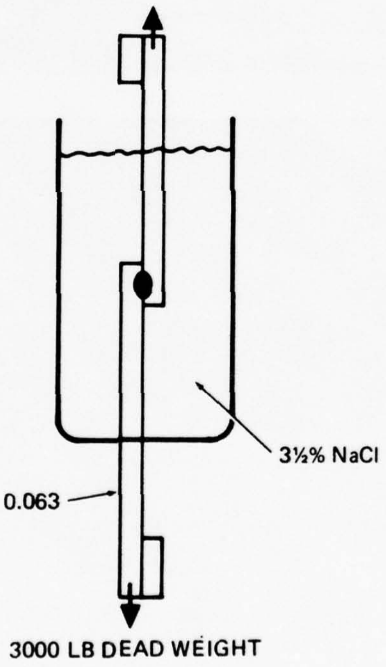
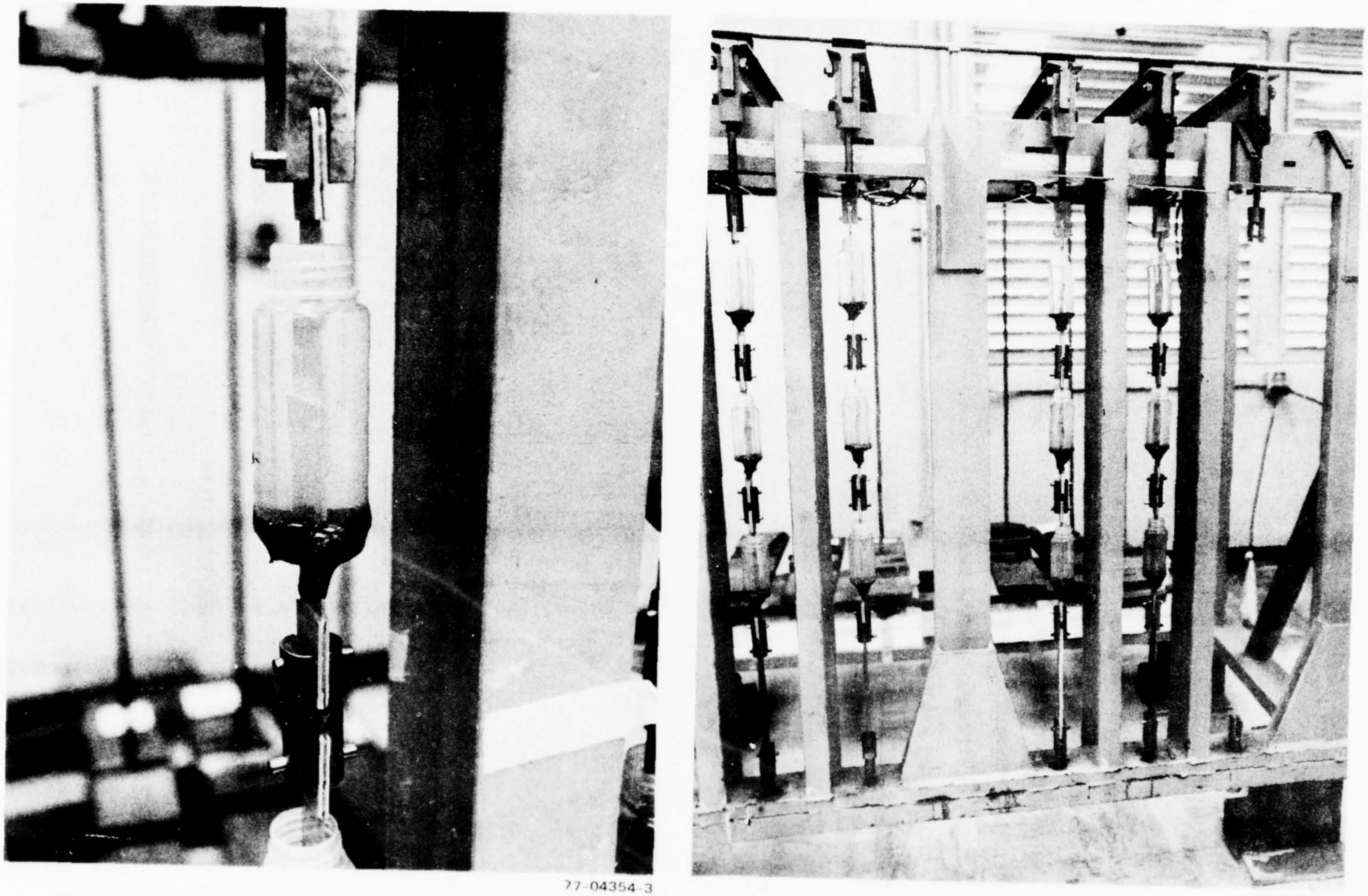


FIGURE 17. CONSTANT LOAD/SALT WATER IMMERSION TEST



TEST SPECIMEN LOADED IN SALT WATER CONTAINER

TEST RIG

FIGURE 18. CONSTANT LOAD/SALTWATER IMMERSION TEST RIG

In prior work, Northrop found that the CL/SWIT method appeared to be more discriminating than the 24 hour wedge test for evaluating acceptable weldbonding systems. It was thus decided, that for the purpose of this program, the CL/SWIT method would be used to evaluate durability of different material combinations and the adequacy of processing procedures.

Initial Environmental Stress Durability Evaluation of a 1.5v 7075-T6/1.0v 2024-T3 System.

To evaluate the environmental stress durability characteristics of the 1.0vPSD surface procedure for the 2024-T3 alclad material, CL/SWIT durability samples were prepared using 0.063-inch 7075-T6 bare 1.5vPSD weldbonded to 0.063-inch 2024-T3 alclad sheet 1.0vPSD. These samples were loaded on the test rig with a constant load of 3000 pounds, i.e., 3000 psi on the one inch overlap joint. This load had been used in previous tests. The test joint area was then immersed in a 3.5 percent NaCl solution which was contained in a plastic bottle surrounding the specimen.

Three test samples failed to pass the 1000 hour exposure with failure times of 260, 845 and 845 hours. In comparing these results with previous data, it was determined that although the 3000 pound load level was suitable for evaluating the durability of 7075-T6 bare, this load level was too high for a fair evaluation of the surface treatments for the 2024-T3 alclad material based on its lower yield and tensile strengths. The 3000 pound load stresses the 7075-T6 material to 61 percent of its design ultimate strength and 68 percent of its design yield strength (MIL-HDBK-5B). However, this same load stresses the 2024-T3 alclad material to 77 percent of the design ultimate strength and 106 percent of its design yield strength. With a high stress concentration occurring at the edge of the overlap, it was concluded that local yielding occurred on the surface of the 2024-T3 alclad, which cracked the thin anodized layer and allowed the salt solution to attack the unprotected 2024 beneath the adhesive layer. Therefore, it was decided to standardize the CL/SWIT at 61 percent of the design ultimate strength of the weakest component of the joint, i.e., 2380 pounds for the 2024-T3 alclad material and 3000 pounds for the 7075-T6 bare material. Therefore, if the 1.0vPSD 2024-T3 alclad/1.5v PSD 7075-T6 bare combination would pass this test and definite discrimination was obtained between specimens "deoxidized only" (which was recognized as an unacceptable condition) and others anodized at 1.0 volt, the process would be considered acceptable.

A second set of weldbonded 0.063-inch 7075-T6 bare 1.5vPSD to 2024-T3 alclad 1.0vPSD durability specimens was loaded at 2380 pounds. This time, failure occurred for one specimen after 782 hours exposure. During these tests, however, premature failures were also noted for twelve 7075-T6 bare 1.5vPSD control specimens with failure times ranging from 186 hours to 986 hours. As this system had previously exhibited excellent environmental stress durability characteristics, it appeared that a problem existed somewhere in the processing or sample preparation procedure.

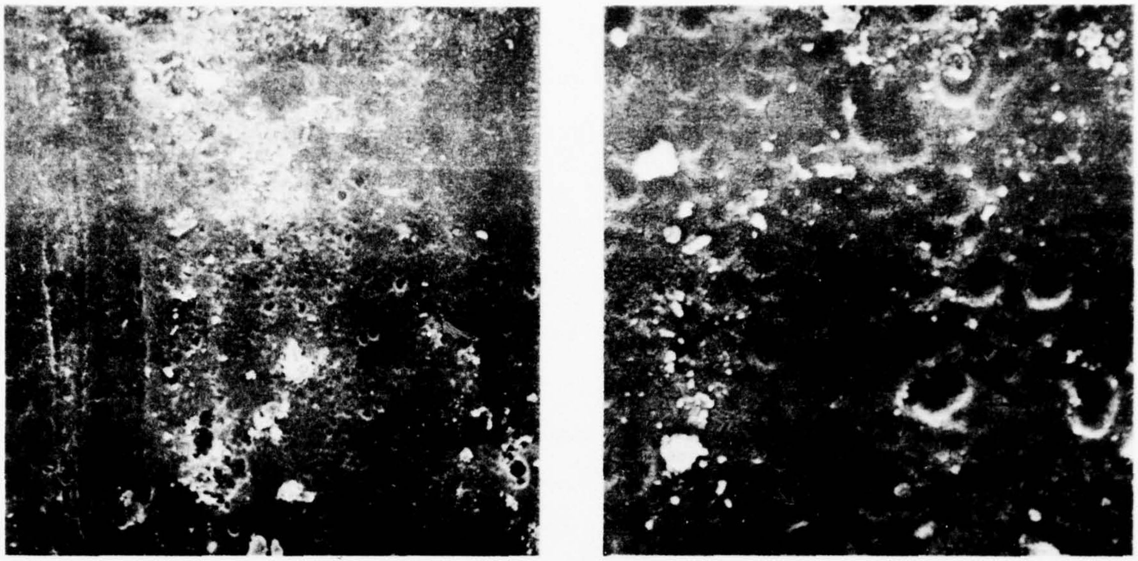
It had been noted that inconsistent results were being obtained from the standard HNO_3/Amchem-7 deoxidizer bath in the laboratory. Visual and SEM examination of processed samples indicated that inadequate deoxidization occurred periodically. Contaminated areas were randomly present (Figure 19) and the depth of the etch that had previously been achieved (Figure 20) was not evident. This was occurring even though the chemical analysis of the bath indicated that it was within the existing specification tolerances.

To conclusively determine if the deoxidizer bath was the source of the problem, a series of SEM examinations were conducted on specimens processed in both the 20 gallon and 100 gallon deoxidation tanks. Inconsistency was evident not only in the cleanliness of both alloys and grain boundary etching characteristics of the 7075 alloy but also in the thickness of the oxide coating which was formed during the subsequent anodizing treatment. These examinations showed that under the existing operating conditions, use of the deoxidizer bath resulted in a surface condition which would not be acceptable in a weldbond manufacturing operation.

Re-Evaluation of the Deoxidizing Process.

Based upon the previous examination, it was apparent that either (1) the existing bath had to be modified to achieve more consistent results, (2) a new deoxidizer bath had to be developed, or (3) an additional stronger cleaning step such as an FPL etch was needed prior to final deoxidiation to achieve consistency. Inasmuch as the option (2) was beyond the scope of this program, it was decided to concentrate on options (1) and (3).

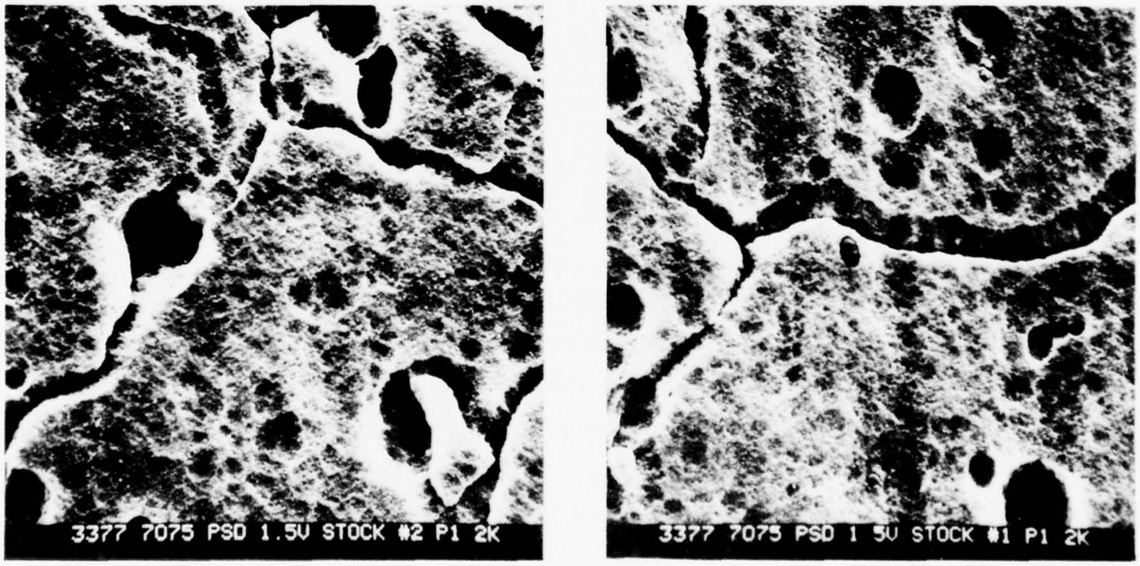
Evaluation of a Precleaning Solution. Initially it was felt that the short bath life and inconsistent results from the deoxidizer bath were due to either a metallic ion or an oxide contamination occurring in the tank, and that this condition might be alleviated if a precleaning step were added prior to final deoxidization. To determine if precleaning could provide improved results, an evaluation was undertaken using an FPL etch as the precleaner. Three different concentrations of $Na_2Cr_2O_7$ (2 percent, 4.5 percent and 9 percent) were selected for evaluation. It had been previously determined that the thickness of the boehmite oxide left on the surface after FPL etching



2000X 10,000X

2024-T3 ALCLAD

FIGURE 19. TYPICAL SURFACE CONTAMINATION



10,000X 10,000X

7075-T6 BARE

FIGURE 20. DEPTH OF ETCH ON SAMPLES OBSERVED IN PREVIOUS WORK

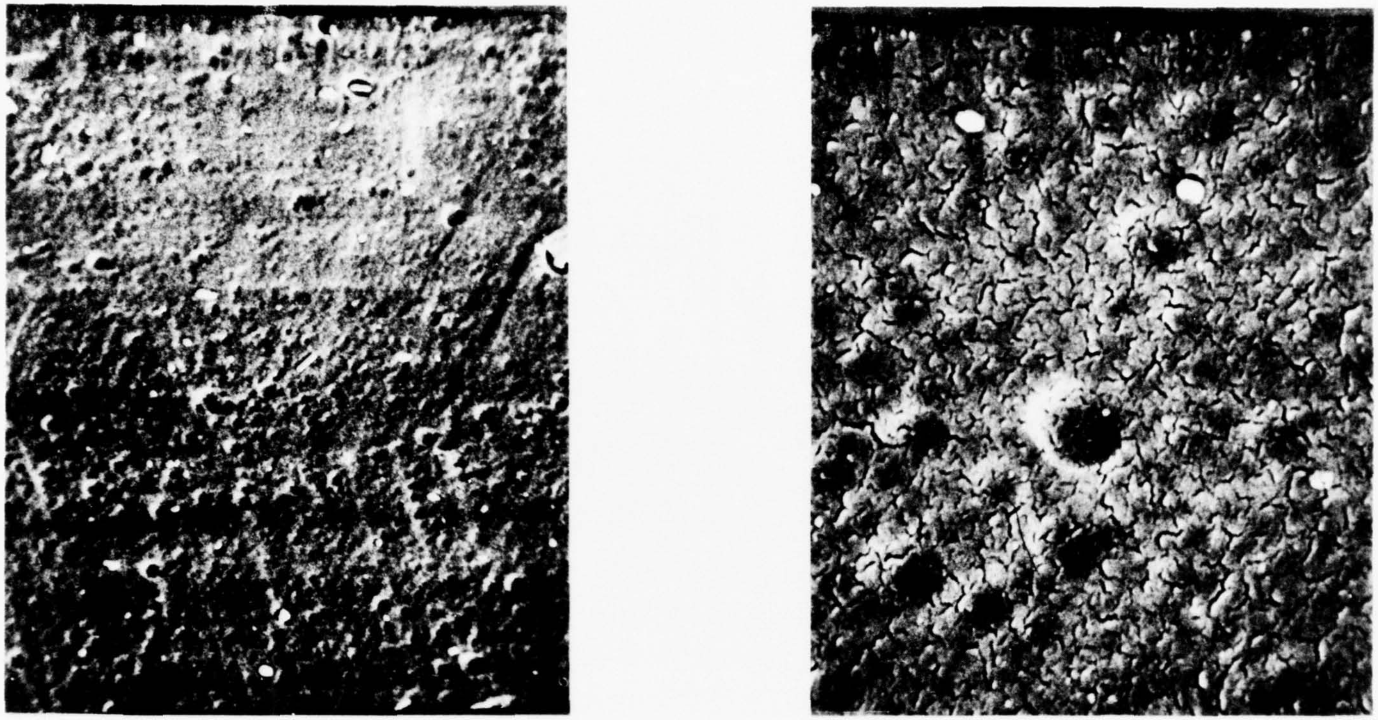
increased with the $Na_2Cr_2O_7$ content of the FPL etch and also with time. Five different cleaning times were evaluated (2, 4, 7, 10 and 15 minutes).

The pre-cleaning was conducted prior to the final deoxidation in a fresh HNO_3/ Amchem-7 solution.

The initial results for samples etched 10 minutes indicated that welding difficulty increased significantly with increased $Na_2Cr_2O_7$ content and that at a 9 percent concentration, welding results were unacceptable. The 9 percent concentration was thus eliminated from further consideration.

SEM evaluations and welding tests were then conducted on specimens pre-cleaned in the FPL etches using 2.0 percent and 4.5 percent $Na_2Cr_2O_7$ concentrations for five different cleaning times (2, 4, 7, 10, and 15 minutes). Durability tests were conducted on specimens processed for four and seven minutes. Although the durability results were acceptable, welding tests showed that much higher heat inputs were needed to achieve Class A welds as compared to surfaces that were only deoxidized before anodizing, especially when the samples were etched with either $Na_2Cr_2O_7$ concentration over 7 minutes. It was felt that the surface condition created by a prior FPL etch might lead to expulsion and distortion problems during production welding. SEM analysis as shown in Figure 21 revealed that random contamination (although not as extensive as sometimes observed) was still evident on samples precleaned with the FPL etch. The conclusion drawn from this evaluation, was that even with the FPL etch as a precleaner, the final deoxidizer bath was not producing the desired surface. It was thus concluded that the deoxidizer bath had to be modified to achieve an adequate surface condition for subsequent anodizing.

Modification of Deoxidizer Bath. Discussions were held with representatives of Amchem Products Inc. in an effort to determine a sound method, whereby the bath could be modified to achieve consistent results. Because of the proprietary nature of the Amchem-7 system, the specific composition was not divulged, but sufficient guidance was obtained to allow an investigation of different techniques for improving the bath performance and for controlling the bath. The consensus resulting from these meetings was that the etch rate of the bath should be increased and then controlled to tight limits by one of several techniques. The Northrop investigation then centered on developing the means of increasing and controlling the etch rate of the deoxidizer bath.



2000X

10,000X

FIGURE 21. CONTAMINATION REMAINING ON A 2024-T3 SURFACE AFTER A 4 MINUTE FPL ETCH AND 7 MINUTE DEOXIDATION

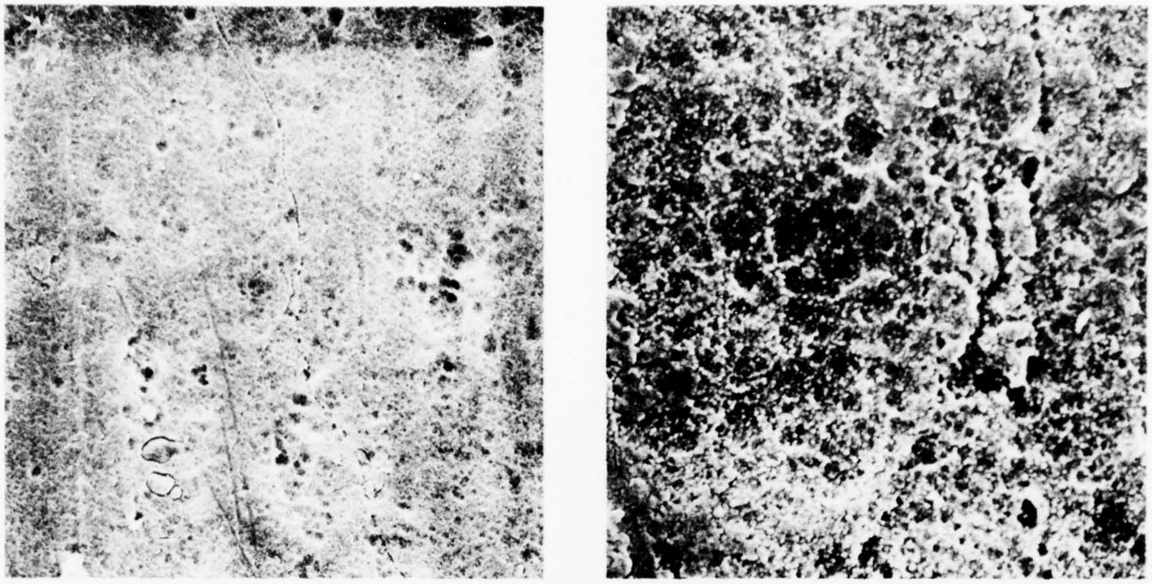
It was determined that the main etching ingredient in this bath is active fluoride. A series of tests were conducted to determine the optimum fluoride level (as measured by etch rate) that should be maintained in the bath to insure proper surface preparation. The etch rate for this program was determined by measuring the total weight loss, d, (in grams) of a 7075-T6 sample (0.063 x 3.0 x 3.0 inches), after etching in an unagitated bath for 20 minutes. The total weight loss is converted to an etch rate, E, in terms of mils/side/hour, by using the following equation: (The derivation for the equation is given in Appendix F.

$$E = d/2 \times 7.333$$

During this investigation it was also decided to determine if variations in the nitric acid concentration had an effect on the final etch rate and surface condition. A series of tests was conducted starting with a 9 percent HNO_3,3.2 percent Amchem-7 bath. Etch rate and SEM analyses were conducted at each step. The results obtained on the 9 percent HNO_3 bath indicated that it was unacceptable, as insufficient etching of the 7075-T6 surface resulted, as shown in Figure 22, and excessive contamination was present on the 2024-T3 alclad surfaces, as shown in Figure 23. The measured etch rate for the bath as it is normally used in manufacturing operations was 0.131 mils/side/hour, which was within the acceptable tolerance range of the deoxidizer. However, the specific etch rate required to achieve the adequate grain boundary etching for weld-bond processing had not been previously determined.

Increasing the nitric acid concentration of the bath to 11 percent did not result in any significant improvement as shown in Figures 24 and 25. An etch rate of 0.133 mils/side/hour was obtained, and the surface still exhibited an inadequate etch condition in the grain boundary area of the 7075 and contamination was still present on the surface of the 2024.

An addition of two ml/l of Alodine-45 (a proprietary solution of Amchem Inc. containing the active fluoride) was made to the bath which resulted in an increase in the etch rate to 0.200 mils/side/hour. Some improvement in grain boundary etching characteristic also resulted as shown in Figure 26, but surface contamination was still present on the 2024-T3 material as shown in Figure 27. A further addition of two ml/l of Alodine-45 (to a total of four ml/l resulted in etch rate increase to 0.284 mils per side per hour and greatly improved grain boundary etching characteristics as shown in Figure 28. The most significant improvement was the absence of the 2024-T3 surface contamination, as shown in Figure 29.



2,000X

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FIGURE 22. INADEQUATE SURFACE ETCHING OF A 7075-T6 BARE SAMPLE DEOXIDIZED IN A 9% HNO_3 – 3.2% AMCHEM-7 BATH

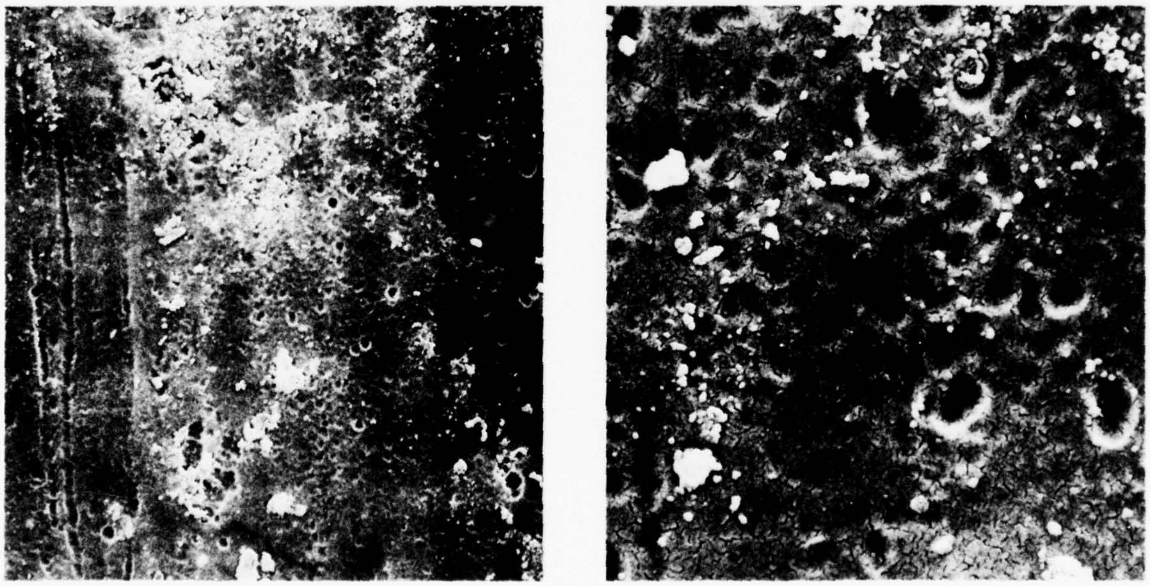

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FIGURE 23. CONTAMINATION PRESENT ON 2024-T3 ALCLAD DEOXIDIZED IN A 9% HNO_3 – 3.2% AMCHEM-7 BATH

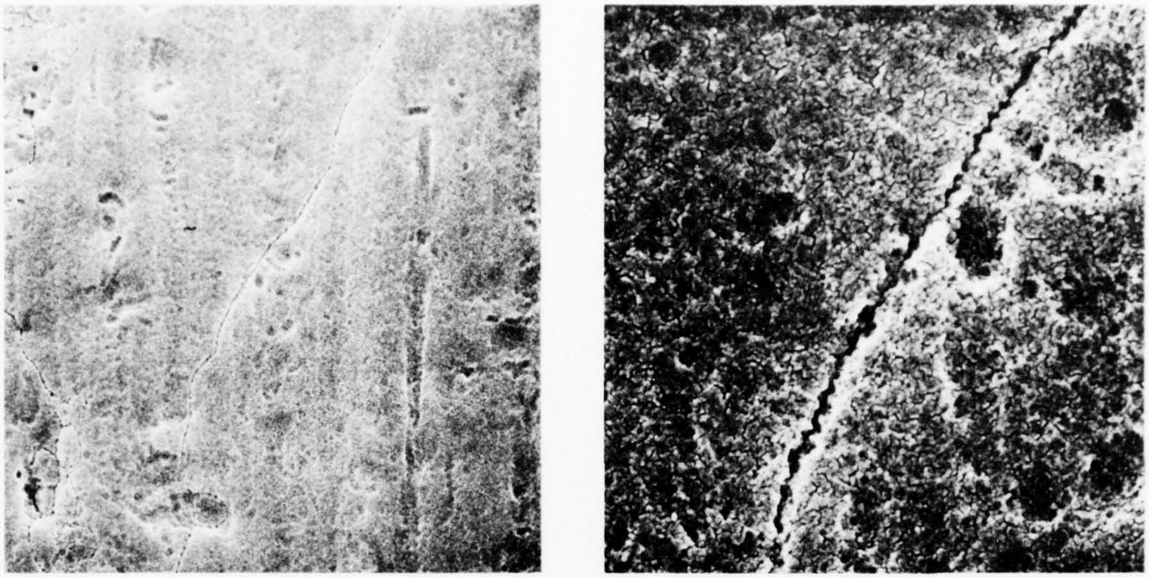

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FIGURE 24. DEGREE OF ETCHING IN A 7075-T6 BARE SAMPLE DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH

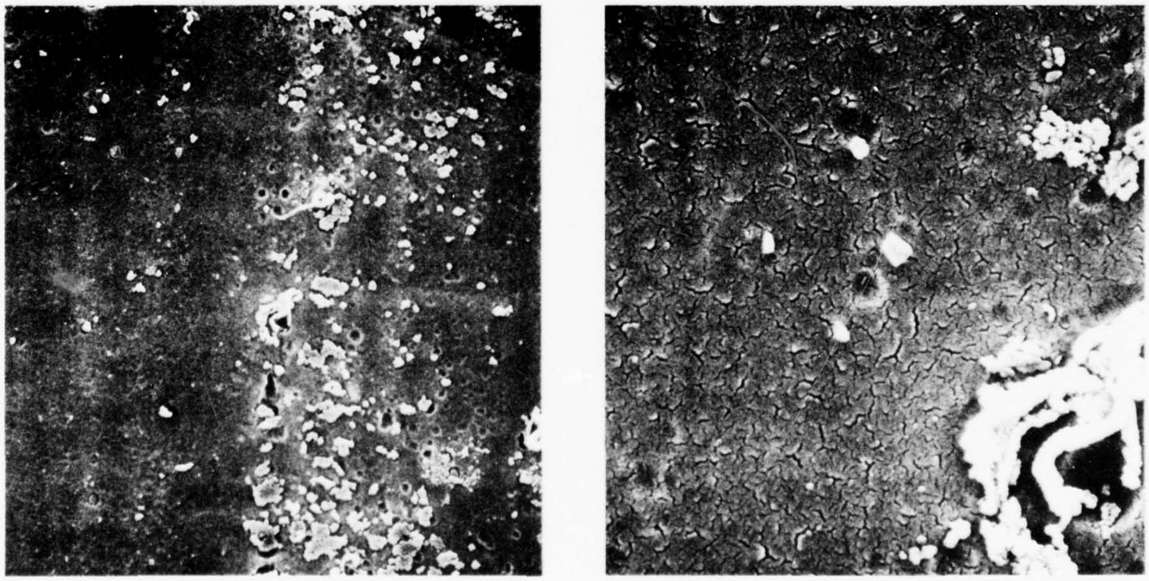

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FIGURE 25. CONTAMINATION PRESENT ON 2024-T3 ALCLAD DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH

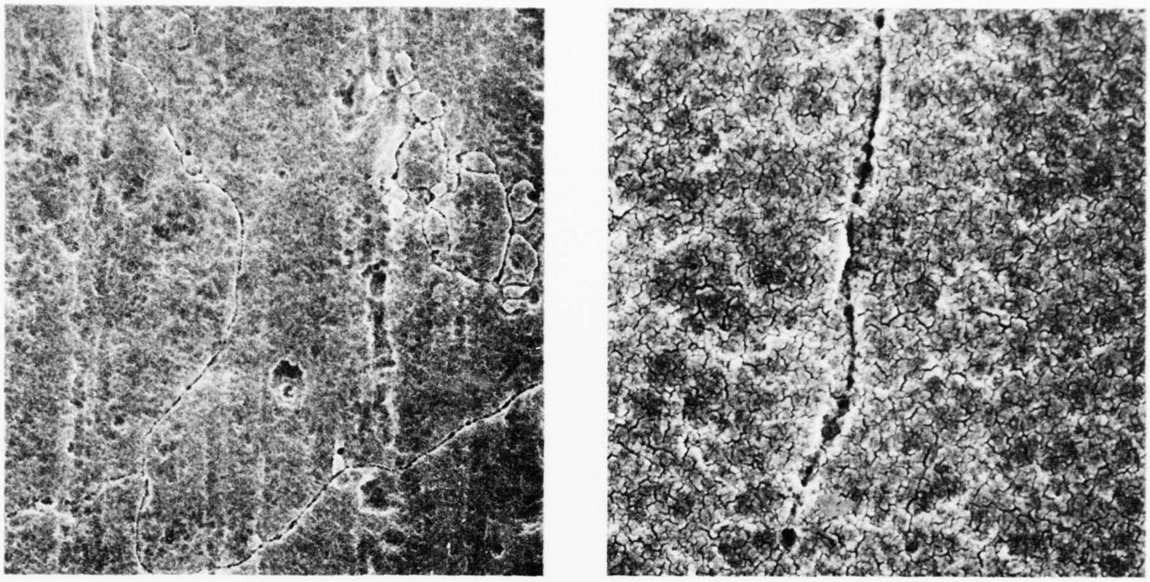

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FIGURE 26. DEGREE OF ETCHING IN A 7075-T6 BARE SAMPLE DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH MODIFIED WITH ALODINE-45, 2 ml/l (ETCH RATE 0.200 mils/side/hour)

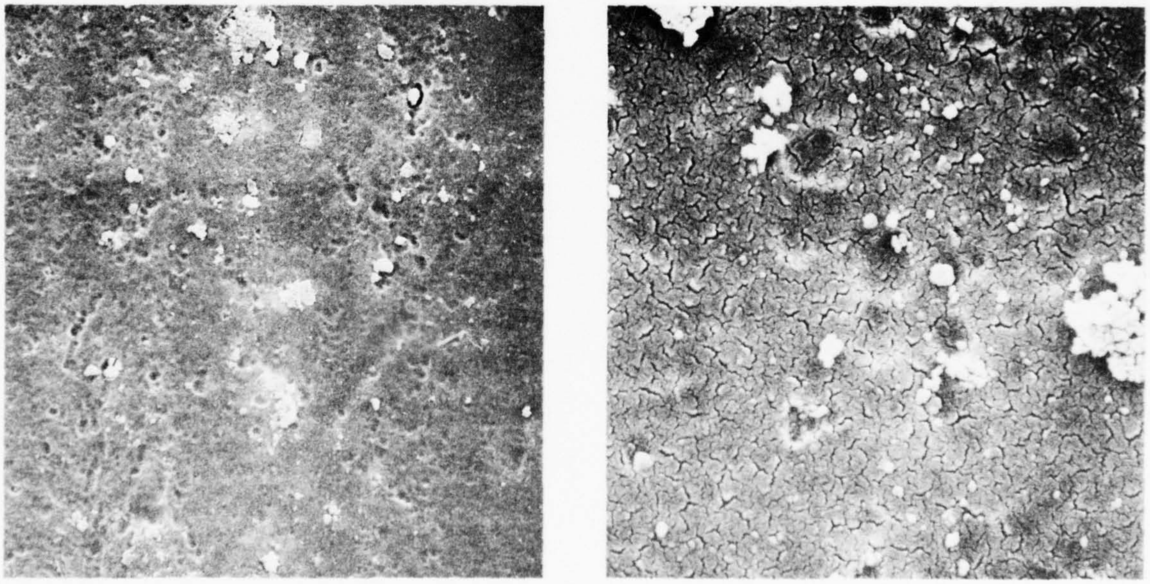

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FIGURE 27. CONTAMINATION PRESENT ON A 2024-T3 ALCLAD SAMPLE DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH MODIFIED WITH ALODINE-45, 2 ml/l (ETCH RATE 0.200 mils/side/hour)

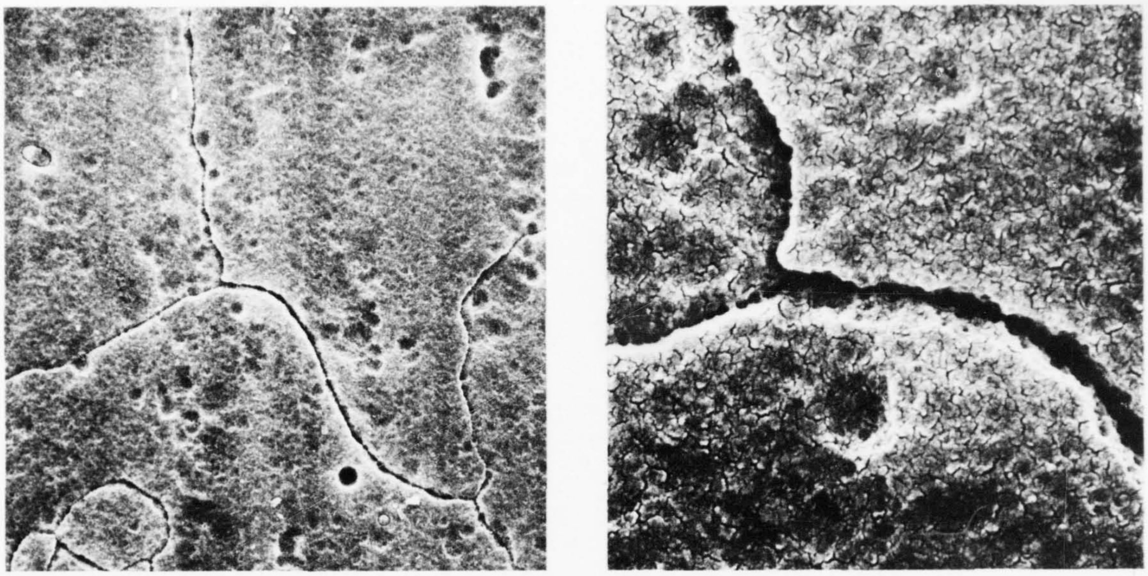

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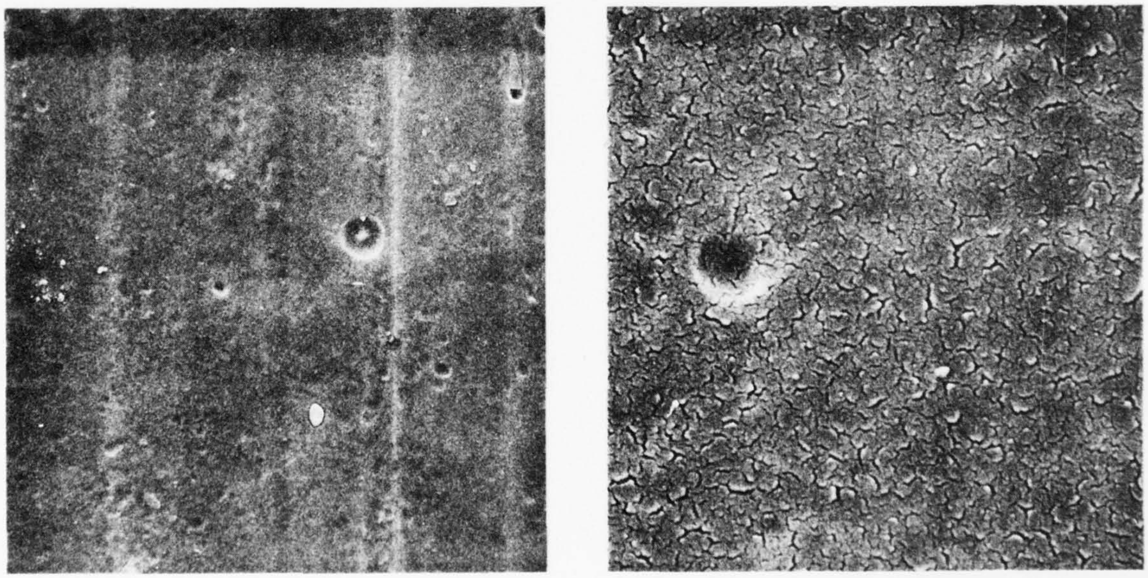
FIGURE 28. DEGREE OF ETCHING IN A 7075-T6 BARE SAMPLE DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH MODIFIED WITH 4 ml/LITER ALODINE-45 (ETCH RATE 0.284 mils/side/hour)



2,000X 10,000X

FIGURE 29. SURFACE CLEANLINESS OF 2024-T3 ALCLAD SAMPLE DEOXIDIZED IN A 11% HNO_3 – 3.2% AMCHEM-7 BATH MODIFIED WITH 4 ml/LITER ALODINE-45 (ETCH RATE 0.284 mils/side/hour)

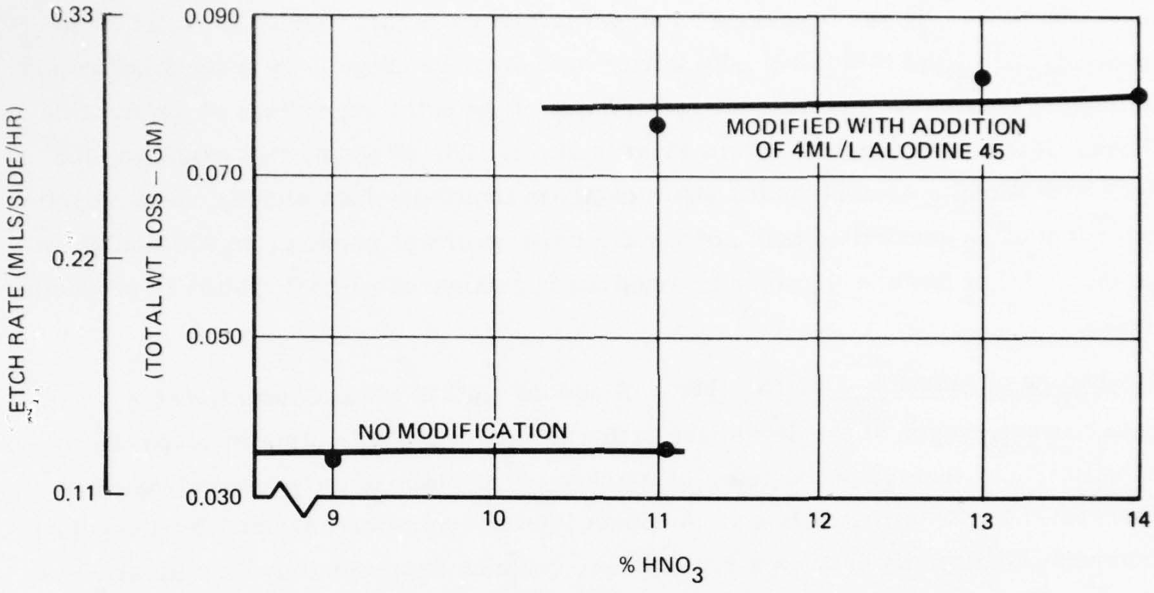


FIGURE 30. EFFECT OF NITRIC ACID CONCENTRATION ON ETCH RATE OF A 3.2% AMCHEM – 7/HNO_3 DEOXIDIZING BATH

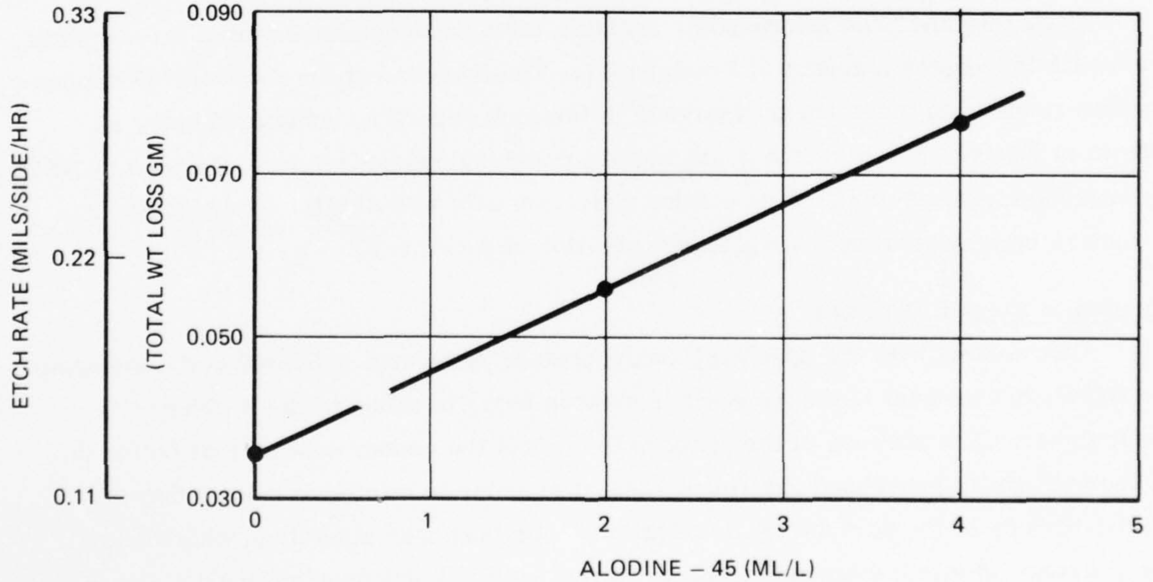


FIGURE 31. EFFECT OF ALODINE – 45 ADDITIONS ON ETCH RATE OF A 11% HNO_3 – 3.2% AMCHEM-7 DEOXIDIZING BATH

Subsequent etch rate tests were made with the four ml/l Alodine-45 modified bath at 13 percent and 14 percent nitric acid levels and no significant change in etch rate was noted. It was concluded as shown in Figure 30 that varying the nitric acid concentration level in this type deoxidizer bath over the range 9-14 percent has no significant effect on the etch rate characteristics of the bath, regardless of the fluoride level. It was also concluded from Figures 26, 27, 28, 29 and 31 that modifying the bath with Alodine-45 contributed significantly to improving bath etching characteristics over that of an unmodified bath and for the purpose of weldbonding, an addition of two to four ml/l of Alodine-45 would be required to achieve consistent results in production tanks.

Evaluation of Amchem-7/17 Bath Mix. A second method of improving the etch rate characteristics of the deoxidizer bath was also evaluated. This involved the substitution of various percentages of Amchem-17 in place of the previously used Amchem-7 in the initial bath mix. Amchem Products personnel advised Northrop that Amchem-17, normally used as a replenisher, contains approximately four times more fluoride ion than Amchem-7. A higher fluoride content increases the etch rate of a deoxidizer bath as shown in the previous Alodine-45 evaluation. Therefore, it was felt that the higher etch rate bath required by the weldbonding process could be achieved by using an initial bath consisting of a significant percentage of Amchem-17.

Etch rate and SEM microscopic analysis tests were conducted for a three-gallon bath with increasing amounts of Amchem-17. The increase of the Amchem-17 concentration resulted in a significant increase in the etch rate of an unagitated bath, as shown in Figure 32, and of the grain boundary etching characteristics revealed by SEM microscopic examination. This etching characteristic was similar to the grain boundary etching obtained with a 4 ml/l addition of Alodine-45.

Control of Copper Deposits.

Discussions with the Amchem, Incorporated, personnel indicated that a sequestering agent, not present in the Amchem-7 makeup bath, is added to the Amchem-17 replenisher. The purpose of the agent is to control the copper content that builds up in the bath (from processed aluminum sheets) in order to minimize copper deposit on the surface of the part during deoxidation. For purposes other than weldbonding, the presence of small amounts of copper in this bath is not a problem until a significant amount of aluminum has been processed through the tank. This was not the case, however, when the deoxidizer was used as part of the weldbonding surface preparation procedure. During the bath optimization study, it was noticed that the welding of

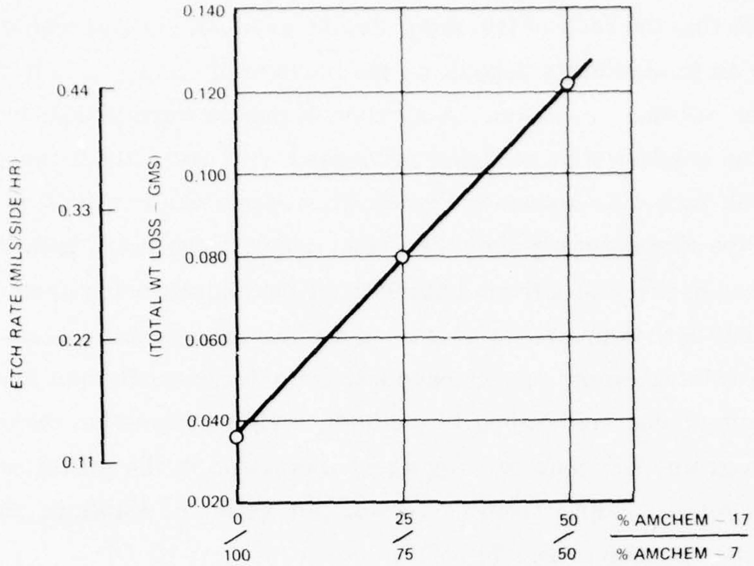


FIGURE 32. EFFECT OF AMCHEM-17/7 PROPORTIONS ON ETCH RATE OF A 13% HNO_3 -3.2% AMCHEM-17/7 DEOXIDIZING BATH

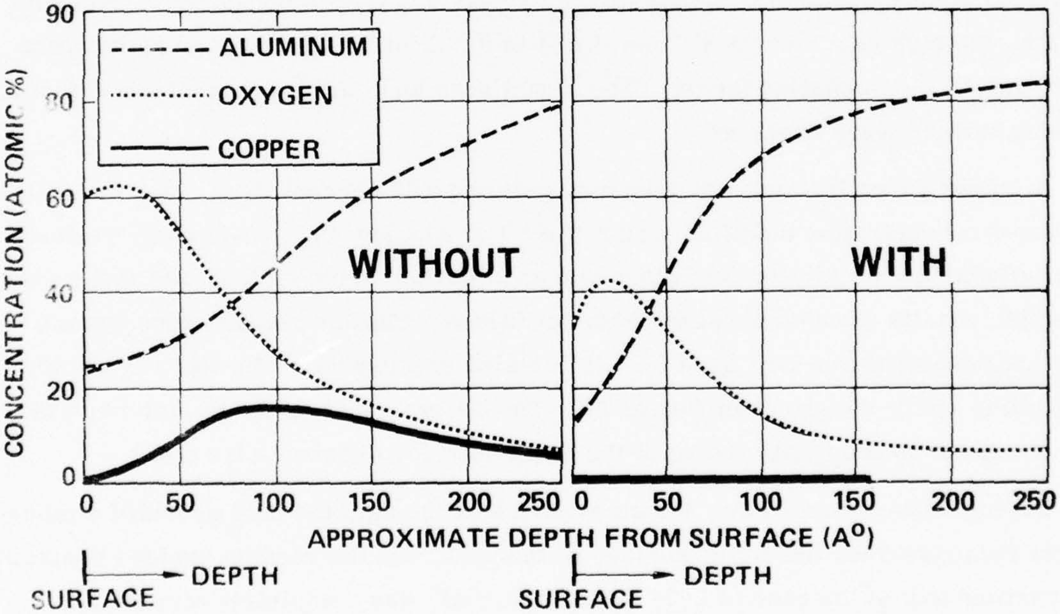


FIGURE 33. EFFECT OF A SEQUESTERING AGENT ON THE COPPER CONTENT OF THE DEOXIDIZED SURFACE

material processed in a freshly charged tank was inconsistent and that random expulsions occurred. It was felt that the lack of the sequestering agent in the bath could be allowing free copper to immediately deposit on the surface of the aluminum sheets which then caused the welding problems. A number of panels were processed and an Auger analysis was conducted on samples processed with and without the sequestering agent in a fresh bath. As shown in Figure 33, copper was not present on the surface when the sequestering agent had been added to the fresh bath but, a significant amount was present in a fresh bath without the sequestering agent. It was concluded that the final bath composition must contain the sequestering agent to avoid the tendency toward welding expulsion. Subsequent experience confirmed that as long as the sequestering agent was maintained in the bath, welding expulsion was not a problem. In this program, the sequestering agent was added to the initial bath in the form of 13.2 to 13.4 ml of Alodine 1200E Activator per gallon of solution, and was maintained through the addition of Amchem-17.

Evaluation of Bath Agitation

The effect of bath agitation was then studied to determine if agitation would aid in achieving more consistent results. A recirculating pump was used to agitate the 3.6 gallon bath, charged with 11 percent HNO_3, 3.2 percent Amchem-7 and 11.3 ml/gallon solution Alodine-45, and an etch rate and microscopic analysis conducted. With bath agitation, the etch rate increased from 0.284 to 0.772 mils/side/hour or an increase of 2.71 times, i.e. agitation factor. The cleanliness and surface characteristics of a resulting surface were excellent.

A larger 20-gallon tank was then charged with a 14 percent HNO_3, 3.2 percent Amchem-7 concentration modified with 3.2 ml/l of Alodine-45. Tests were conducted in the agitated and unagitated conditions and an agitation factor of 2.03 was measured. Acceptable results were obtained for both conditions. Similar results were obtained on the 100 gallon production tank used for all full-size test panels. The test results for the agitation study are shown in Figure 34. The difference in agitation factors in these baths is related to the relative size of the pump used for different size tanks.

During later observations, it was evident that the agitated bath provided a more uniform etch rate over the entire surface of the part, and the random surface contamination, particularly in the case of 2024 alclad material, was completely eliminated.

Control of Alclad Stains

A problem was uncovered involving the presence of a redish-brown stain on the 2024-T3 alclad material after anodizing during the cleaning of the first full-size panel skins. This stain occurred adjacent to the holding clips or fastening points used on the

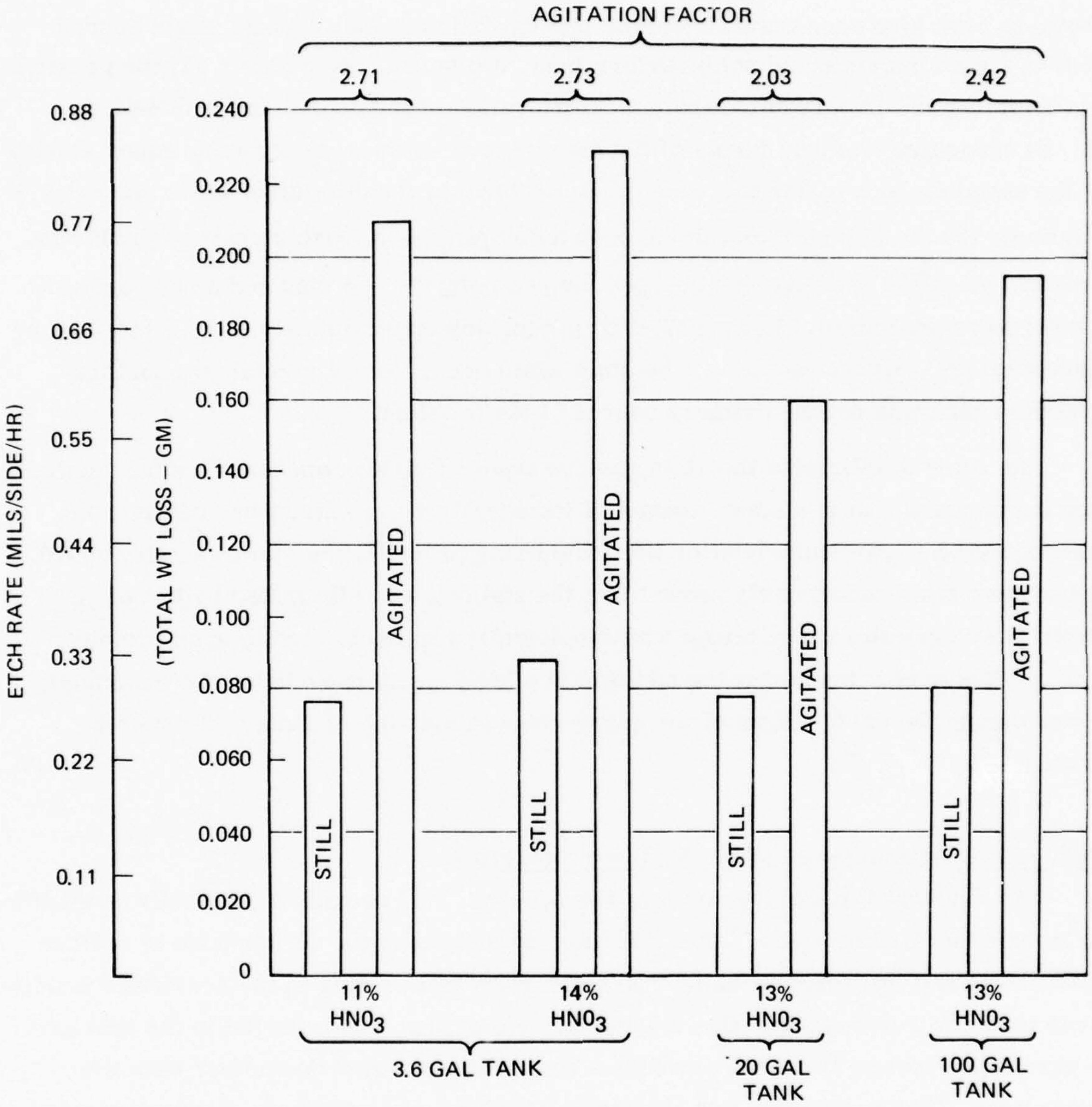


FIGURE 34. EFFECT OF AGITATION ON BATH ETCH RATE OF DIFFERENT SIZE DEOXIDIZER TANKS

material. The frequency of this stain appeared to increase significantly as the usage of the deoxidizer increased. The stain was only observed on the 2024-T3 alclad material.

Auger analysis was made on the material with and without the stain. The stain was shown to have high concentration of iron and chromium. Although the exact source of this contamination could not be determined, two possibilities exist: (1) the presence of chromium and iron resulted from a deterioration of the deoxidizer bath with use, (2) the chromium and iron levels of the bath were being increased due to minor etching of the stainless tank by the increased fluoride level of the deoxidizer bath. In order to eliminate the staining problem in the production panels, a freshly charged production tank of 100 gallon capacity was charged using a polyethylene tank and a new series of panels were processed. However, after processing approximately four square foot of aluminum per gallon of solution, the stain again occurred which indicated that the stainless tank was not the primary source of the problem.

In order to eliminate the stain various types of rinsing operations were studied and it was found that if a small amount of industrial or tap water were added to the rinsing system, particularly after the deoxidizing process, the stain was eliminated. Subsequent tests conclusively proved that the staining was eliminated by use of an industrial or tap water rinse mixed with the deionized water in a ratio approximately 1 to 1. It was also found that the addition of a hand spray rinse using the industrial water during the early stages of the spray rinse would also eliminate the staining problem.

Bath Life Characteristics of the Modified Deoxidizer.

As discussed in a prior section, the Amchem 7-17 deoxidizer system was modified to include the Alodine 45 and 1200E additions to overcome the deficiencies of surface cleanliness and inadequate etching characteristics that existed in the previous deoxidizer when used for weldbonding. One other shortcoming that was reported in the previous program (Reference 2) needed attention - that of the apparent deoxidizer bath life limitation. This deoxidizer bath limitation would present economic constraints which would limit the use of weldbonding in a production environment. Thus, an investigation was undertaken to determine if the controls and replenishing procedures established for the modified Amchem 7-17 deoxidizer bath were adequate to give good bath life of at least 25 square feet of aluminum surface processed per gallon of solution before discarding the bath which is the average bath life of this type deoxidizer in normal plant operations.

Approach. The previous study carried out on the etch rate of the deoxidizer established an optimum etch rate of 0.20 to 0.30 mils/side/hour (0.052 to 0.080 gms. weight loss measured on a 3-inch x 3-inch 7075 bare aluminum test coupon, deoxidized for 20 minutes in an unagitated bath). This procedure produced consistently clean deoxidized surfaces. In the bath life study, an alternate procedure was developed which was found to be equivalent and resulted in a significant time saving. In this procedure, etch rates were measured using the agitated bath for a 7 minute duration. It was found that this procedure may be used on a given tank after the etching characteristics and the agitation factor for that tank have been accurately determined. For this program, "bath aging" was defined as the total square feet of aluminum processed per gallon of agitated solution per seven minute duration.

To reproduce production processing and contamination build-up of dissolved aluminum, copper and other alloying elements, both 7075 bare and 2024 clad aluminum materials in a 50:50 ratio were used. Weldability and environmental durability test specimens were deoxidized in a bath which had various amounts of aluminum processed per gallon in the bath, i.e., 0, 4, 8, 12, 16, 20, and 25 square feet. These specimens were then anodized using the low voltage phosphoric acid - sodium dichromate solution. During the study the effect of bath aging on the following characteristics of the deoxidizer bath were studied.

1. Etch rate
2. Anodized oxide thickness
3. Weldability
4. Durability

Procedure. A six-gallon deoxidizer bath was prepared and 25 square feet of aluminum per gallon was processed using the following procedure:

a. Analyze chemical composition, check etch rate, adjust to specification limits.

b. Clean and deoxidize weldability and durability panels.

c. Analyze chemical composition, check etch rate, adjust to specification limits.

d. Clean and deoxidize 7075 bare and 2024 clad panels until a total of four square feet of aluminum had been processed.

e. Repeat steps (a) to (d) in increment of 4 square feet of aluminum processed per gallon, until the total area processed reaches 25 square feet of aluminum per gallon deoxidizer.

Etch Rate Maintenance. Etch rate was maintained by addition of Amchem-17 to bring the Amchem-7 content to 3.2 oz/gal. However, if this did not produce the desired etch rate of 0.30 mils/side/hour (on a 3-inch x 3-inch -7075 bare coupon) per 7 minutes, Alodine-45, was added. It was found that 1 ml. of Alodine-45 per gallon of deoxidizer raises the etch rate approximately 0.037 mils/side/hour depending upon the type and degree of agitation used.

Summary and Results. This laboratory study indicated that the Northrop modified Amchem 7-17 deoxidizer bath has a useful life of greater than 25 square feet of aluminum per gallon of deoxidizer which is comparable to a standard deoxidizer bath used in manufacturing operations. Satisfactory weldbonding surfaces can be obtained over the span of this bath life using the recommended control and replenishment procedures.

Specific observations and conclusions made during the study are as follows:

1. Weldability or expulsion problems were not encountered during the study, and the weld nugget size and shapes were within acceptable limits. Lap shear strengths of uncured weldbonded coupons were also satisfactory.
2. No appreciable change in oxide thickness or structure as measured by SEM was observed as the bath aged.
3. No durability failure were noted in specimens processed in a bath which had been aged for 25 square feet of aluminum per gallon of deoxidizer. Eight specimens successfully passed the 1000 hour CL/SWIT test with an average 98% residual lap shear strength after exposure.
4. Variation of nitric acid concentration as a function of bath aging was not appreciable.
5. Alodine-1200E activator, which contained the sequestering agent, complexes dissolved copper and prevents copper from being deposited on the aluminum. After the initial make-up, addition of Alodine-1200E was not needed, as the addition of Amchem-17 which also contained the sequestering agent was sufficient to maintain a satisfactory level of sequestering agent in the bath.
6. Approximately 1 ml Alodine-45 gal. of deoxidizer was needed to raise the etch rate by 0.037 mils/side/hour on a 3-inch x 3-inch -7075 bare coupon and to maintain the etch rate after the bath had aged by processing 12 square feet and 22 square feet of aluminum per gallon of deoxidizer. This indicates that depletion of fluoride content was not fully restored by addition of Amchem-17.

7. Amchem -7 content dropped approximately 0.1 oz/gal. for every one square foot of aluminum processed per gallon of deoxidizer.

8. Etch rate drop depends upon the degree and type of agitation used. The deoxidizer under study was a moderately circulated and filtered bath. Initially, the etch rate dropped about 0.037 mils/side/hour (on a 3-inch x 3-inch -7075 bare coupon) for every decrease of 0.10 oz/gal. of Amchem -7 content. Processing of one square foot of aluminum per gallon of deoxidizer caused these decreases. The etch rate dropped appreciably more as the bath aged.

9. No appreciable change was observed in the dissolved copper content. Alodine-1200E removed copper from the bath by forming an insoluble compound with copper.

Conclusion. Based upon the results obtained from this work, the life of the modified deoxidizer bath is greater than 25 square feet of aluminum processed per gallon deoxidizer.

Durability Qualification of the Final Surface Preparation Procedures

Upon establishment of the final surface preparation procedure, it was necessary to prove that this cleaning procedure and low voltage anodizing treatment would provide acceptable environmental stress durability in a weldbond joint. Therefore, a durability evaluation using the 1000 hour Constant Load-Salt Water Immersion Test (CL/SWIT) was initiated.

All specimens were prepared according to the surface treatment procedures shown in Table 4. This procedure included the use of a modified deoxidizer in an agitated bath with a deionized water rinse. The first test series FC, FA, FB, and CA included the evaluation of two material combinations, i.e., 7075-T6 bare weldbonded to 7075-T6 bare, and 2024-T3 alclad weldbonded to 7075-T6 bare. The results shown in Table 5 reveal that all test specimens completed the 1000 hour exposure with no loss in lap-shear strength. The failure mode for these specimens was greater than 85 percent cohesive.

For test series FC, FA, and FB, an extra specimen was allowed to remain under load for 3200 hours or 4000 hours. The residual strength loss ranged from 15 percent to 35 percent, as compared to zero percent loss for the 1000 hour specimens. This loss is considered to be small compared to the length of exposure, and therefore, helps to substantiate good durability for weldbonded joints.

TABLE 4. FINAL SURFACE PREPARATION PROCEDURE

OPERATION	MATERIAL	PROCESS
VAPOR DEGREASE	1-1-1 TRICHLOROETHANE	VAPOR 60 SECONDS; CONDENSED FLUID-60 SECONDS; COOL, REPEAT.
ALKALINE CLEAN	TURCO 4215-S, 6-8 OZ/GAL SOLUTION	12-15 MINUTES, 125-165F
SPRAY RINSE	COLD DEIONIZED WATER WITH TAP WATER MIX	5-7 MINUTES
DEOXIDIZE	NITRIC ACID/AMCHEM -7 (MODIFIED) NITRIC ACID – 11-14% BY VOLUME, BE^{o} 42 (70% HNO_3) AMCHEM -7: 2.9 – 3.3 WT OZ/GALLON SOLUTION ALODINE -45: 11.2 – 11.5 ML/GALLON SOLUTION ALODINE 1200E ACTIVATOR – 13.2 - 13.4 ML/GALLON SOLUTION BALANCE – DI WATER	6-8 MINUTES, ROOM TEMPERATURE IN AGITATED TANK.
SPRAY RINSE	COLD DEIONIZED WATER WITH TAP WATER MIX	5-7 MINUTES
ANODIZE	PSD SOLUTION PHOSPHORIC ACID – 1.2 - 1.5 FL OZ/ GALLON SOLUTION (85% H_3PO_4) SODIUM DICHROMATE DIHYDRATE:– 1.3 - 1.5 OZ/GALLON SOLUTION	20-25 MINUTES, ROOM TEMPERATURE VOLTAGE – 1.4-1.6 VOLTS, DC FOR BARE ALLOYS 0.9-1.1 VOLTS, DC FOR CLAD ALLOYS
SPRAY RINSE	COLD DEONIZED WATER WITH TAP WATER MIX	5-7 MINUTES
OVEN DRY	CIRCULATING HOT AIR	30-40 MINUTES, 150± 10F

TABLE 5. DURABILITY QUALIFICATION FOR 2024-T3 ALCLAD AND 7075-T6 BARE WELDBOND SYSTEMS

SURFACE PREPARATION	TEST SERIES	MATERIAL	AVERAGE CONTROL STRENGTH (LBS)	TEST LOAD (LBS)	RESIDUAL STRENGTH (LBS) 1000 HOUR EXPOSURE (% COHESIVE FAILURE)				LONGER EXPOSURE
					1	2	3	AVG.	
DEOXIDATION AND ANODIZE	FC	7075-T6 BARE/ 7075-T6 BARE	4500	3000	4700 (98%)	5000 (100%)	4900 (1)	4870	3200 HRS 2970 LBS (40%)
	FA	2024-T3 ALCLAD TO 7075-T6 BARE	3900	2380	4000 (100%)	3700 (98%)	3800 (85%)	3830	4000 HRS 2750 LBS (70%)
	FB		3900	2380	4100 (100%)	4100 (100%)	3500 (90%)	3900	4000 HRS 3350 LBS (60%)
	CA		4100	2380	3800 (90%)	4300 (100%)	4200 (100%)	4100	
DEOXIDATION ONLY	FE	7075-T6 BARE/ 7075-T6 BARE	4750	3000	6(2)	105(2)	8(2)		
	FD	2024-T3 ALCLAD/ 7075-T6 BARE	3800	2380	323(2)	82(2)	294(2)		

(1) BASE METAL FAILURE
(2) HOURS TO FAILURE

A second test series FE, and FD, which was used to determine the durability of weldbonded joints for which the aluminum was cleaned and deoxidized only (spot weld etch procedure), is also shown in Table 5. These specimens failed during the CL/SWIT exposure in less than 323 hours.

These tests proved that the final surface preparation procedure provided a durable surface. These results also showed that test specimens, for which the aluminum surfaces were deoxidized only prior to weldbonding, will not pass the 1000 hour CL/SWIT exposure, and therefore the deoxidized only surface is not acceptable in terms of environmental stress durability.

A third durability test series was used to evaluate the use of industrial water for the rinsing operation. It had been previously proven that by hand spraying industrial water during the first 60 seconds of rinse, the staining problem which occurred when processing large 2024-T3 alclad panels was eliminated. Test series GB was used to evaluate the industrial water spray plus the deionized water rinse, test series GC was used to evaluate the use of industrial water only, and test series GA were control specimens which were processed using deionized water only.

The results for these tests are presented in Table 6, and show that all three test series passed the 1000 hour CL/SWIT exposure, with no loss in lap shear strength, except for one test specimen in the GC test series. This specimen failed in 895 hours and the failure mode was 50 cohesive. This failure was attributed to poor specimen preparation (in which an unprotected edge was present in an area of a high stress concentration) which led to premature failure. However, since three other corresponding specimens passed the qualification exposure and since the survival time before the premature failure was 90 percent of the 1000 hour exposure, the test series was considered to be acceptable.

These test results indicate that the use of deionized water is not necessary in the weldbonding process, and that the use of industrial water to eliminate the alclad stain is perfectly acceptable. It is recommended, however, that since the mineral content of industrial water will vary in different locations, before industrial water is used in a weldbond cleaning procedure, tests be conducted to verify acceptable environmental durability properties. Minor contamination in the water may degrade the resulting bond joint by causing residual elements to remain on the bond surface.

Later in the program, the Air Force requested Northrop to conduct additional testing to evaluate and compare different bonding systems and to compare different test methods for evaluating environmental stress durability. Therefore, additional durability testing is being conducted as an addendum to this program.

TABLE 6. DURABILITY QUALIFICATION FOR USE OF INDUSTRIAL WATER RINSE, WELDBOND SYSTEMS

SURFACE PREPARATION	TEST SERIES	MATERIAL	AVERAGE CONTROL STRENGTH (LBS)	TEST LOAD (LBS)	RESIDUAL STRENGTH (LBS) 1000 HOUR EXPOSURE				
					1	2	3	4	AVG.
DEIONIZED AND INDUSTRIAL WATER	GB	2024-T3 ALCLAD/ 7075-T6 BARE	3900	2380	3850	3750	3650	3850	3775
INDUSTRIAL WATER ONLY	GC	2024-T3 ALCLAD/ 7075-T6 BARE	3800	2380	3850	3800	3800	3650	3775
		7075-T6 BARE/ 7075-T6 BARE	4800	3000	4600	4900	(1)	4800	4765
CONTROL TESTS	GA	2024-T3 ALCLAD/ 7075-T6 BARE	3800	2380	3750	3850	3650	3850	3775
		7075-T6 BARE/ 7075-T6 BARE	5075	3000	5000	4800	4600	4900	4825

(1) FAILED IN 895 HOURS WITH 50% COHESIVE FAILURE

The objective of this additional work is to compare the environmental durability of the weldbonding system with that of two other adhesive bonding systems. These include the FPL etch, BR-127 primer, FM-123-2 adhesive system, which is currently used to bond A-10 panels, and the phosphoric acid anodize, BR-127 primer, FM-73 adhesive system being used for the PABST Program at McDonnell Douglas. Four material combinations are being evaluated: 2024-T3 alclad to 7075-T6; 2024-T3 to 7075-T6, 2024-T3 to 2024-T3; and 7075-T6 to 7075-T6. Test methods include the CL/SWIT at two loads for 1000 hour and 2000 hour exposure; and the wedge test in 5 percent salt fog at 95°F and 95 to 100% relative humidity at 120°F for 90-day exposures. Wedge test specimens will also be exposed at the McDonnell Douglas beach site in El Segundo, California, for 12 months with crack growth measurements made each month. This evaluation will be completed in July 1979 and a final addendum report will be written.

Conclusions of the Surface Preparation Studies

The results of the preceding investigations indicated that the aluminum weldbonding deoxidizer bath must contain sufficient fluoride to provide an etch rate in an unagitated bath between 0.20 - 0.30 mils/side/hour. It was determined that this etch rate could be achieved either by adding fluoride in the form of Alodine-45 or by initially preparing a proper mix of Amchem-7 and Amchem-17. The optimum bath also must contain the proper sequestering agent to minimize copper deposits. This agent can be added through the use of an initial charge of Amchem-17 or by proper additions of the Alodine-1200E activator. It was decided that for the purpose of this program, the 11-14 percent HNO_3 - 3.2 percent Amchem-7 basic bath modified with an addition of Alodine-45 to increase the fluoride content and with a proper addition of the sequestering agent in the form of the Alodine-1200E activator would be easier to control. Subsequent investigation showed that the use of this bath consistently resulted in acceptable deoxidized surfaces. The final deoxidizer bath composition specified and used for all remaining portions of this program is shown in Table 4.

The results of the surface preparation studies showed also that bath agitation is required in order to achieve a uniform — contamination-free surface. It was concluded that a properly agitated bath will increase the etch rate over that of a still bath by a factor of approximately 2.7. However, an increased etch rate range of 2.0 to 3.0 times is sufficient and will provide a suitable deoxidized surface. A bath can be agitated by moving the solution with a pump, a submerged impeller or by bubbling air through the bath.

During the life of the bath, the chemistry and etch rate must be maintained by standard additions of Amchem-17. Subsequent additions of Alodine-45 were needed during extensive bath usage. Also, it was found that minor additions were required if it was desired to keep the bath on the high side of the etch rate tolerance. It should be noted that in this program, the etch rate tolerance range specified was one which was found to give consistantly acceptable results. If the bath etch rate was below the 0.20 mils/side/hr, poor results were obtained. The high limit tolerance was established arbitrarily. No tests were conducted to determine the effect of using a bath above the upper limit.

It was also found that the Alodine-1200E Activator added to the initial bath to control the copper content of the thin oxide film remaining on the part after deoxidation is usually sufficient for the life of the bath. The additional sequestering agent added through the Amchem-17 replenisher was adequate and additional Alodine-1200E Activator should not be needed after the initial charge.

The final surface preparation procedure is shown in Table 4. Using the aforementioned modifications to the deoxidizer bath, sufficient surface quality and bath life characteristics are achieved using the deoxidizer alone, thus, precleaning (as with an FPL etch) was not found to be necessary. Specific analytical control procedures for the surface preparation tanks are given in Appendix C and SEM procedures for the inspection and control of the prepared surfaces are given in Appendix D.

ADHESIVE CHARACTERISTICS AND CONTROL

Introduction

The strength and durability of weldbonded aluminum aircraft components are critically dependent on the nature and thickness of the anodized oxide film on the aluminum surface and the use of proper adhesive in bonding. The oxide film must be pure boehmite aluminum oxide (α $Al_2O_3 \cdot H_2O$) approximately 500-700 Angstrom units thick. This oxide can be obtained by a controlled anodizing process described previously. With any given adhesive, the cure time, cure temperature, filler content, and corrosion inhibitor level will affect both the strength and durability of the joint. The strength and durability of weldbonded aluminum components is also dependent on obtaining and maintaining the stable boehmite oxide on the surface and on achieving a stable bond between the boehmite oxide surface and the adhesive. Durable weldbonded aluminum aircraft components can thus be fabricated only by maintaining appropriate quality control standards and tests for both the anodizing process and the adhesive.

The Goodrich A-1444B adhesive used for this weldbonding program was originally developed in prior programs at Northrop. The adhesive went through three development stages. First, it was evaluated for weldability. Aluminum test coupons prepared with a standard FPL-etch surface, without primer, and coated with A-1396B (the base resin system) were found to be weldable. However, adhesive run-off was excessive if test coupons were cured in a vertical position. The A-1396B resin system was modified using Cab-O-Sil in varying percentages. A 7-percent addition of Cab-O-Sil gave the reduced run-off desired and did not interfere appreciably with weldability. The next modification to the base resin system was the addition of chromates to improve the durability of the adhesive under stress corrosion testing involving the exposure of stressed specimens to a 3.5 percent salt water at room temperature using 61 percent of the design ultimate strength of the aluminum as the constant load. An adhesive composition was achieved (A-1396B base resin + 3 percent strontium chromate and 7 percent Cab-O-Sil) which resulted in a system that was weldable, had the desired stress corrosion resistance, and exhibited adequate flow at cure temperature. This formulation is now the Goodrich-A-1444B adhesive. Other paste adhesive systems were evaluated and initial tests conducted on some of them were satisfactory. However, it was shown that these materials were not reproducible as some lots were unsatisfactory. Also, attempts to add chromate corrosion inhibitors were unsatisfactory. Thus, the only commercially available adhesive with a successful background of weldbond durability testing at the time of the initiation of this current contract was the Goodrich A-1444B adhesive.

Objective

The objective of this task was to establish quality control standards for the A-1444B adhesive and prepare a materials specification for use in the production of weldbonded aircraft components.

Results and Discussion

At the beginning of this program, the primary control tests were adhesive lap shear strength, weldability, weldbond strength and stress corrosion resistance, as measured by immersing weldbonded or adhesively bonded specimens in 3.5 percent salt water at room temperature under 61 percent of the design ultimate strength of the weakest component of the joint. In the case of 7075-T6 bare weldbonded to 7075-T6 bare, the applied load is 3000 lbs. The 3.5 percent salt water durability test was effective in distinguishing between good and poor surface treatments.

The adhesive specification developed in this program for the A-1444B adhesive was based on a gradual build-up of data on eight lots of adhesives. Data was obtained as each lot of adhesive was received, as improvements were made in the cleaning and anodizing process, and as the results of modifications to the existing tests were completed. Data on all eight lots, in some instances, is incomplete, as the lots became too old due to usage before the specification procedures were fully developed.

The basic resin chemical formulation of the adhesive is a proprietary formulation of the B. F. Goodrich Company and, as a result, no chemistry control of the basic resin was developed at Northrop. However, at the beginning of this program, one lot of adhesive was obtained which obviously had asbestos in it as a thixotropic agent instead of Cab-O-Sil. This adhesive did not pass the 24-hour humidity test at 120F and 95-100 percent R.H. Therefore, control procedures were developed to guarantee that strontium chromate and Cab-O-Sil were in the adhesive rather than the two most probable alternatives, zinc chromate and asbestos. These procedures are given in the specification in Appendix B.

Table 7 lists the strontium chromate and Cab-O-Sil analyses of five different lots of A-1444B adhesive. Only one of these lots, lot G, was slightly outside the initial specification limits (Cab-O-Sil 6-8% and strontium chromate 2-4%). All lots passed the weldbond lap shear test. Data in Table 8 shows that all of the lots tested exceeded the minimum specification value lap shear strength of 4500 lbs. All lots also successfully passed the adhesive flow test. Some of the durability data developed during this time period was invalid as modifications and improvements were continuing to be made in the cleaning and anodizing process. However, all lots properly processed to the final surface preparation requirements passed the 3.5 percent salt water durability test. Lot "C" was not subjected to a proper salt water durability test because this lot was only a special order 16 oz. can. By the time the surface preparation procedure had been finalized, insufficient sample remained for a proper test. All other lots were retested and were acceptable, as shown in Table 8.

TABLE 7. STRONTIUM CHROMATE AND CAB-O-SIL CONTENTS IN DIFFERENT LOT SAMPLES OF A-1444B ADHESIVE

Lot No.	Percent Wt. Loss	Total Inorganic Solids - %	Strontium Chromate Percent	Cab-O-Sil Percent
C	89.9	10.1	2.85	7.25
D	91.13	8.87	2.85	6.02
E	89.63	10.37	2.7	7.67
F	89.66	10.34	2.56	7.78
G	91.37	8.63	2.76	5.87

TABLE 8. WELDBOND LAP SHEAR STRENGTHS OF A-1444B ADHESIVE LOTS ON 7075-T6 ALUMINUM

Adhesive Lot No.	Control Lap Shear Strength, R.T. psi	Residual Lap Shear Strength After 1000 Hrs, 3.5% Salt Water R.T. - 3000 psi
A	4950	4600
B	4950	5030
C	4825	Not Tested
D	4750	4520
E	4800	3950
F	4850	4900

As indicated in the previous section, near the end of the program, Northrop became involved in a comparison of different adhesive systems using the wedge crack extension test as a measure of environmental durability. This test, with specimens exposed to a 5 percent salt fog at 95F for long times was found to be much more discriminating between various good systems than the 3.5 percent salt water immersion test.

During the wedge testing of A-1444B adhesive, one lot of adhesive gave unexpectedly poor results. The deficiency was finally traced to undercuring of the adhesive. This undercure condition was evaluated using Differential Scanning Calorimetry (DSC), which was shown to be an effective test method to determine the cure condition of the adhesive after various cycles. The original specified cure cycle for the A-1444B adhesive was one hour at 250F. Differential Scanning Calorimetry analysis was performed on lots E, F, G, and J of adhesive after cures at 250F and 275F. Results and cure conditions are given in Table 9. Lots E and G were completely cured by heating at 250F for one hour. Lots F and J were incompletely cured after one hour at 250F but could be completely cured by one hour at 275F or by two hours at 250F. Figure 35 shows the DSC curves of lots E, F, and J after one hour cure at 250F. The curve for lot E is relatively flat from 100C to 200C indicating complete cure. The curves for lots F and J show peaks in this same temperature range indicating incomplete cure. For comparison purposes, DSC curves for uncured adhesive from lots E, G, and J are shown in Figure 36. To insure complete cure, Northrop is currently recommending a curing cycle of 2-3 hours at 250F for production application. Figure 37 shows the DSC

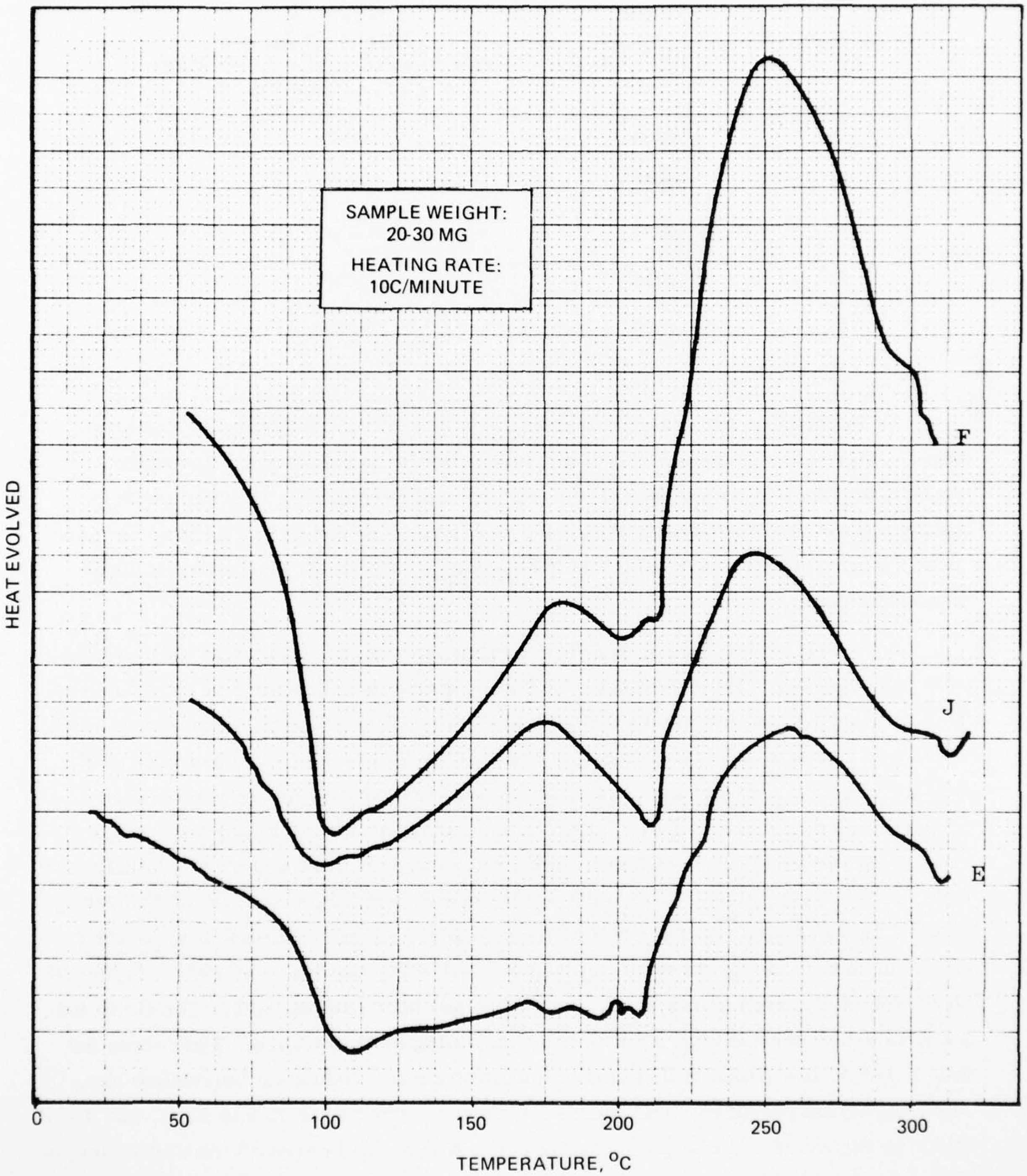


FIGURE 35. DSC ANALYSIS OF 1444B ADHESIVE, LOTS E, F, AND J AFTER CURE OF ONE HOUR AT 250F

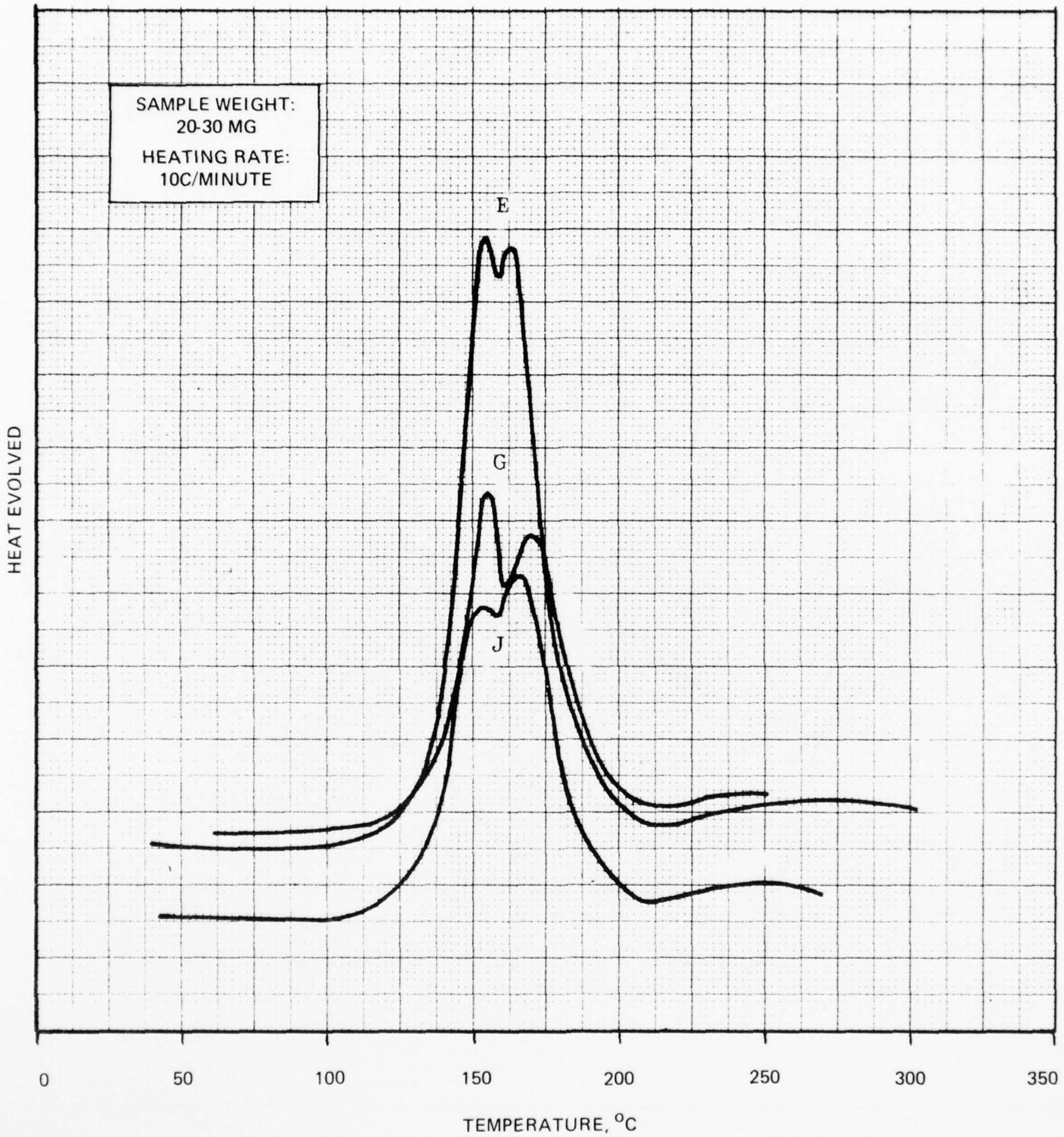


FIGURE 36. DSC ANALYSIS OF UNCURED A1444B ADHESIVE LOTS E, G AND J

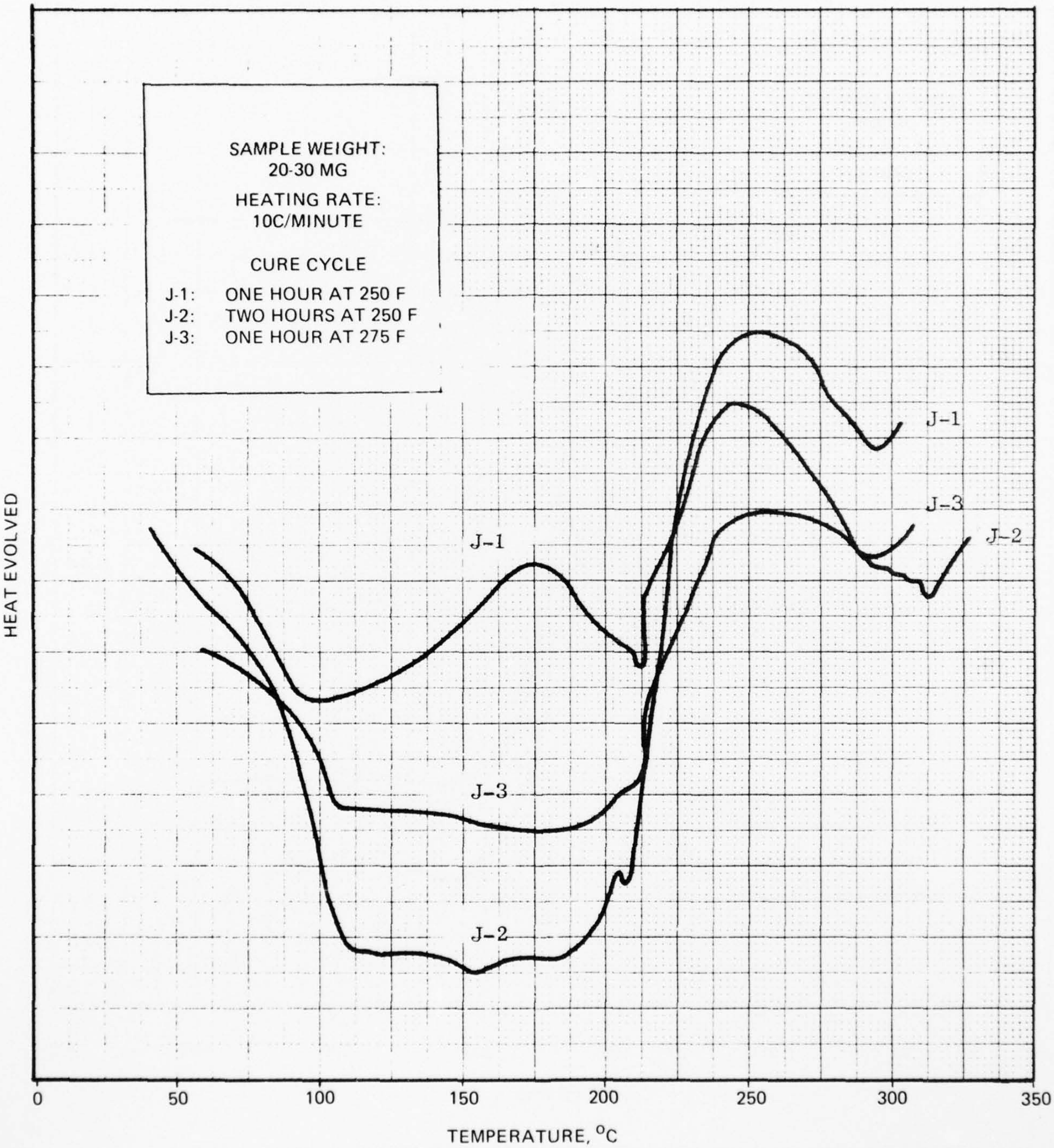


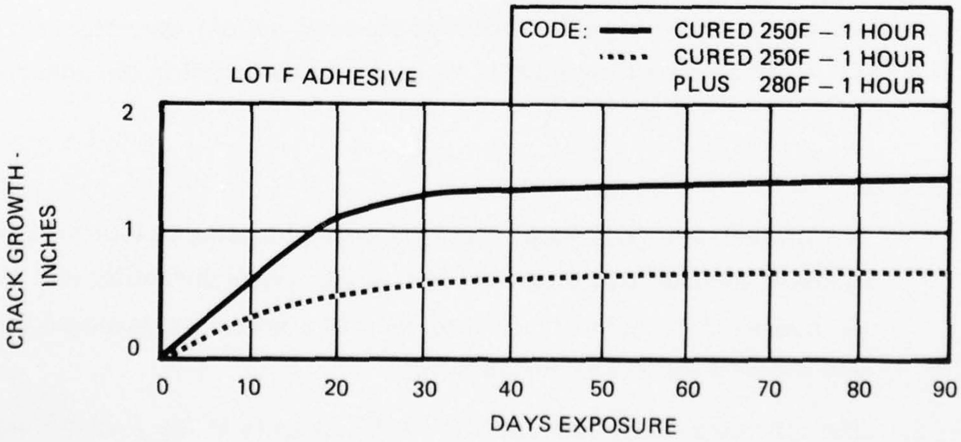
FIGURE 37. DSC ANALYSIS OF A1444B ADHESIVE, LOT J AFTER VARIOUS CURES

TABLE 9. DIFFERENTIAL SCANNING CALORIMETRY OF LOTS OF A-1444B ADHESIVE

Lot No.	Temperature	Time	Result
E	250F	1 Hour	Cured
F	250F	1 Hour	Incomplete Cure
F	275F	1 Hour	Cured
G	250F	1 Hour	Cured
J	250F	1 Hour	Incomplete Cure
J	250F	2 Hours	Cured
J	275F	1 Hour	Cured

curves of lot J adhesive after various cures. Both cures, two hours at 250F or a one-hour cure at 275F were satisfactory.

Lot F gave essentially the same DSC curves as Lot J. A 250F cure for one hour was inadequate; a two-hour cure at 250F or a one-hour cure at 275F was satisfactory. Wedge tests were performed on Lot F adhesive using undercured specimens (cured for one hour at 250F) and using completely cured specimens (cured for one hour at 250F plus one hour at 280F). Specimens were exposed to 5 percent salt fog at 95F for 90 days. Wedge crack growth of these specimens is shown in Figure 38. The undercured specimens show a crack growth of 1.4 inches in 90 days;



NOTES: 1. DATA REPRESENT AN AVERAGE OF SIX TESTS.
2. ADHERENDS WERE 2024-T3 BARE BONDED TO 7075-T6 BARE.

FIGURE 38. EFFECT OF CURE ON SALT FOG WEDGE TEST DURABILITY OF A-1444B ADHESIVE LOT F

the completely cured specimens show a crack growth of only 0.6 inch in 90 days. This demonstrates that degree of cure has an effect on durability as measured by the wedge test.

The wedge test in 5 percent salt fog at 95F readily characterizes a good system and was shown to identify deficiencies due to an undercured adhesive. It was therefore concluded that this wedge test in 5 percent salt fog would be the most effective test for measuring the durability characteristics of both the oxide and the adhesive. This test method was then incorporated as a requirement in the adhesive specification.

Summary

A prepared Materials Specification for the A-1444B adhesive is included in Appendix B of this report. This contains the detailed laboratory procedures for the qualification and control of the A-1444B adhesive. The quality control tests and acceptable test values are as shown in Table 10. It should be noted that tighter tolerances than originally specified for the strontium chromate and Cab-O-Sil contents have been imposed in the specification. This was agreed to by the adhesive manufacturer (B. F. Goodrich) as it was felt that these tolerances could effectively be met in production of the adhesive and tightening these limits would tend to improve the consistency performance of the adhesive.

The laboratory study indicated that the control parameters established in the current weldbond specification are adequate to insure satisfactory bond strength and durability in weldbonded aluminum aircraft components. However, viscosity is critical and the proposed control levels for the total solids, strontium chromate and Cab-O-Sil will maintain the required viscosity as reflected in the adhesive flow.

Conclusions

1. The limited data generated on quality control testing of lots A-1444B adhesive indicate that a critical test is the stress durability test as measured by wedge crack extension with specimens exposed to 5 percent salt fog at 95F for 30 days.
2. The strontium chromate and Cab-O-Sil contents of the A-1444B adhesives were within the original specification limits except for the Cab-O-Sil content of lot G; however, no correlation between these results and mechanical strength or durability was observed.

TABLE 10. A-1444B ADHESIVE SPECIFICATIONS

	Specification Developed in this Program
Volatile Content (Maximum), %	0.1
Viscosity, cps (Minimum)	500,000
Inorganic Solids Content, %	10 ± 0.5
Cab-O-Sil Content, %	7 ± 0.3
Strontium Chromate Content, %	3 ± 0.2
Weldbond Lap Shear Strength (Minimum psi)	4,500
T-Peel Strength (Minimum) lb/in.	20
Adhesive Flow, inches	1.0 to 3.0
Wedge Crack Extension (Maximum), inch-95F, 5 % salt, fog, 30 day exposure	0.5 inch

3. A one-hour cure of the A-1444B adhesive was found to be unsatisfactory for lots F and J. A cure cycle of two hours at 255 ± 5F is recommended for production.

4. DSC is a practical method for quality control of the degree of cure on the adhesive.

5. Undercured wedge test specimens show greater crack extension than completely cured specimens.

ESTABLISH WELDING PARAMETERS FOR CLASS A WELDS

Objectives

The objective of the welding portion of this program was to develop weld schedules for weldbonding the selected test panels and for the required fatigue and durability test specimens. Based upon the test panel selections made by Fairchild, weld schedules were needed for the following material-thickness combinations:

REQUIREMENT	MATERIAL COMBINATIONS		
	2024-T3 Alclad	to	7075-T6 Bare
Test Panels	0.025		0.032
	0.040		0.050
	0.071		0.050
Fatigue and Durability	0.062		0.062

Initial Welding Approach

In the previous weldbond manufacturing methods program (Reference 3), it was determined that an accurately programmed slope control welding schedule was required to achieve quality spotwelds in the weldbond process. This was necessary because of the high contact resistance of the anodized surface and the problems associated with welding through an adhesive. A typical weldbond welding schedule previously developed for 7075 bare sheet material is compared to a conventional aluminum spot weld schedule and shown in Figure 39. It can be seen that a higher electrode force was used for making weldbond joints of the 7075-T6 bare/7075-T6 bare combination as compared to conventional aluminum spot welded joints. Also, the weldbond welding heat schedule has a longer current up slope and down slope than conventional aluminum spot weld schedules. The shape of the current trace required for successful weldbond resistance spot welds was achieved using a Sciaky Decatron controller with a Sciaky 3-phase resistance spot welding machine.

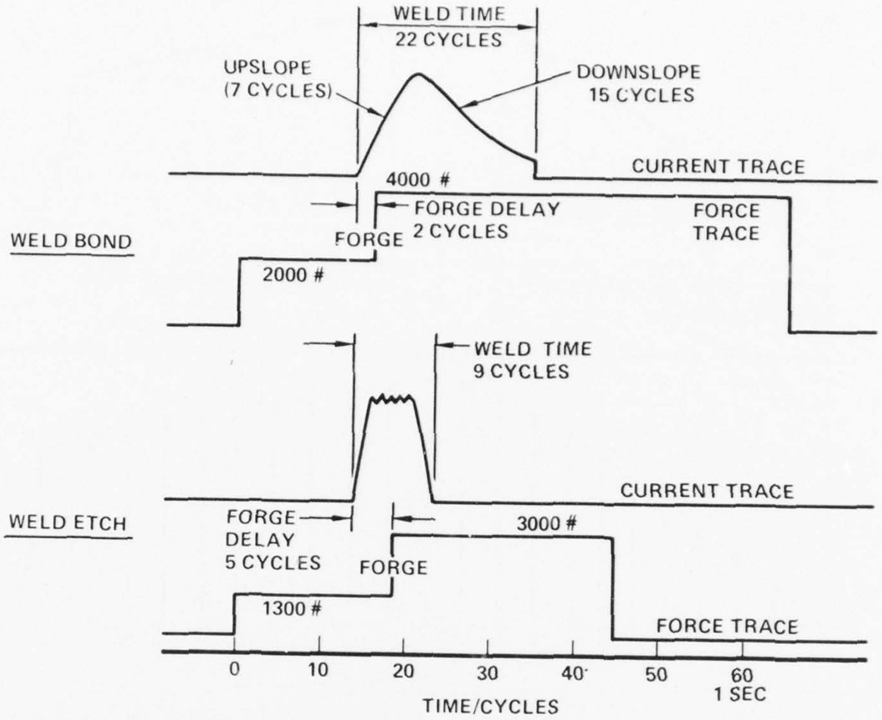


FIGURE 39. TYPICAL SPOTWELD AND WELDBOND WELD PROFILES

Early in the current program, it was decided to include and evaluate a microprocessor resistance weld controller equipped with nugget monitoring and feedback control capabilities. This equipment was supplied by the Pertron Corporation, Van Nuys, California. Two units were installed for early evaluation in the program, one at Northrop and one at Convair. After the preliminary evaluations were completed, a third unit was installed on a production spot welding machine at Fairchild.

All units featured a linear digital transducer attachment that makes nugget expansion information available for monitoring or controlling weld nugget growth. This feature is described in detail later in this report.

Although the original intent of installing the microprocessor welding controller was to evaluate its nugget expansion monitoring and feedback features, it was found early in the program that the Pertron controller contained two other features which would greatly aid in the program.

(1) The accuracy and repeatability of the microprocessor was improved over the existing Decatron controller.

(2) The weld heat schedule could be controlled on a cycle-by-cycle basis resulting in increased flexibility with which to develop optimum weld schedules, and to achieve more precise control over the growth of the weld nugget.

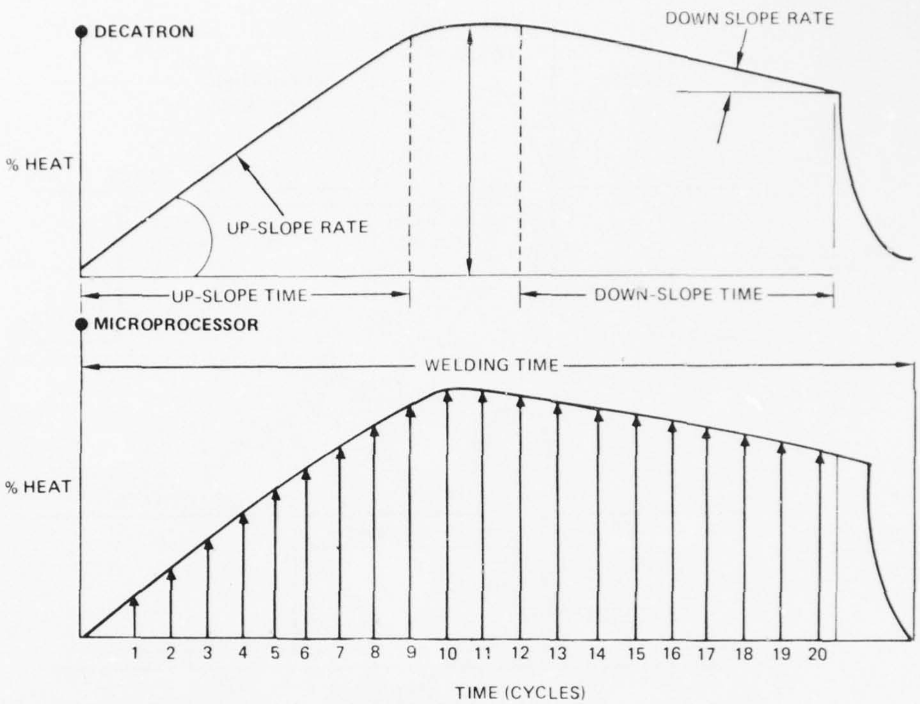


FIGURE 40. WELDING CURRENT SLOPE CONTROL ACHIEVED BY DIFFERENT WELDING CONTROLLERS

Thus, in order to achieve uniformity between the welding performed at the different companies and to obtain maximum effectiveness of feedback control spot welding, all weld schedules were oriented toward microprocessor control.

Programs were prepared for the Pertron microprocessor controller at Northrop, to duplicate the weld schedules, i.e., weld current shapes, that were established in prior weldbond programs using the Decatron control. The Sciaky Decatron and the Pertron microprocessor controls differ in the manner in which they establish the welding current shape. The differences can be best illustrated by referring to Figure 40. The welding current shape is obtained by controlling four settings on the Sciaky Decatron controller: (1) maximum weld heat, (2) the up slope time and welding time, in cycles, (3) the down-slope time, in cycles, and (4) the slope rates. However, the welding current shape is obtained with the microprocessor controls by setting the amplitude of welding current for each firing cycle. Thus, the welding current is programmed cycle by cycle. As a result, more complex multislope welding current shapes, can be achieved with the microprocessor controller than with the Decatron controller, and minor changes in the maximum heat applied can be achieved by changing heats as little as 1 percent in only one cycle.

AD-A071 016 NORTHROP CORP HAWTHORNE CA AIRCRAFT GROUP F/G 1/3
ADVANCED WELDBONDING PROCESS ESTABLISHMENT FOR ALUMINUM.(U)
FEB 79 T R CROUCHER F33615-76-C-5412
UNCLASSIFIED NOR-78-185 AFMI -TR-79-4006 NL

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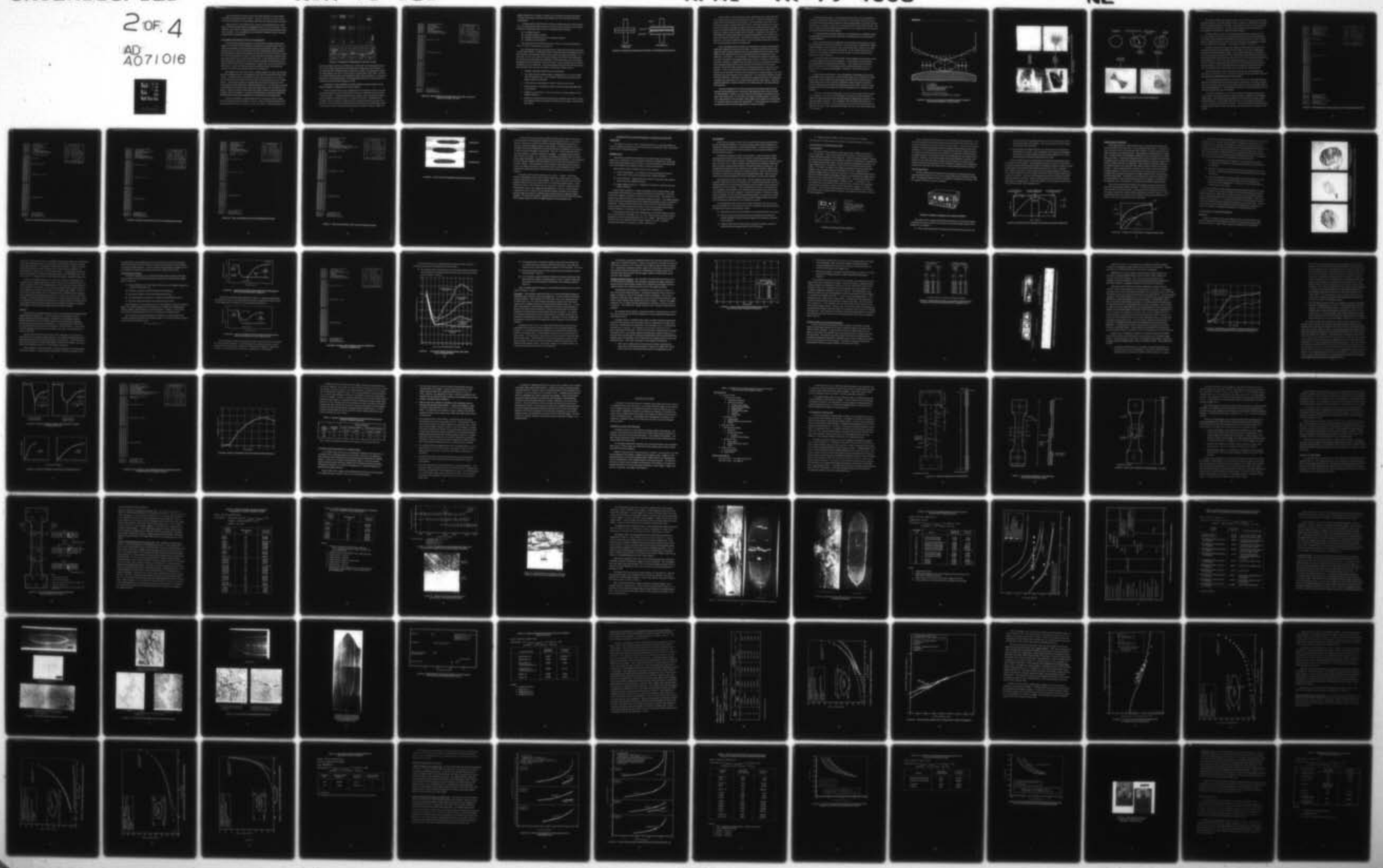

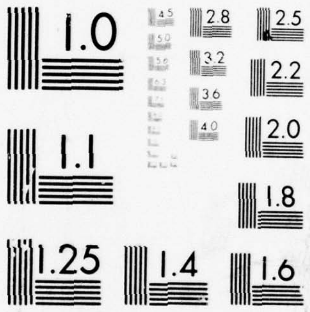

MICROCOPY RESOLUTION TEST CHART
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The microprocessor control system can readily duplicate all current shapes produced by the Decatron control system. However, the Decatron control system is not able to duplicate all current shapes produced by the microprocessor controller.

Microprocessor weld schedules were prepared which duplicated weld current shapes previously established for weldbonding 7075-T6, 0.063 to 0.063 inch. These schedules were used for welding the durability and damage tolerance specimens used in this program. New weld schedules were needed for welding the thinner materials and the 2024-T3 alclad material.

Weld Schedule Development for 2024-T3 Alclad Material

In the previous weldbond program, it was found that the highest quality weld nuggets for the 7075/7075 bare material combination were achieved using slope controlled weld schedules with high weld and forge forces (2000/4000 pounds). In that program however, only bare materials of like alloy combinations were weldbonded. In attempting to develop the weld schedules for the 2024-T3 alclad/7075 bare combination, the first approach was to utilize a 6 inch electrode tip diameter with high forces and current slopes similar to those previously used. It was found that welds could be achieved that were expulsion free and met CLASS A strength and indentation requirements for 2024 alclad/7075 bare combinations of thicknesses equal to or greater than 0.050/0.040. It was also found that to achieve optimum results, multislope heat schedules were necessary using the high weld force approach.

The original 0.063-inch 7075-T6 bare welding schedule was used as the starting point for developing the new weld schedules for the 2024-T3 alclad/7075-T6 bare combination. Consistent expulsion was observed which was believed to be the result of the 1000 Å oxide coating being formed on the 2024-T3 alclad material by the 1.5vPSD anodize. The results of previous work indicated that an oxide coating of 600-700 Å was optimum for achieving the best welding characteristics. It was felt that an increase of the electrode force and/or the up-slope time might minimize the occurrence of expulsion. Various up-slope current rates were used in an effort to eliminate expulsion but these were not successful. It was also found that these procedures increased the distortion which would not be acceptable for aircraft exterior skin applications.

A series of specimens was then welded with low current and various welding times to determine when the expulsion occurred. Figure 41 shows that expulsion was occurring within the first 4 cycles at a very low current. This indicated that the

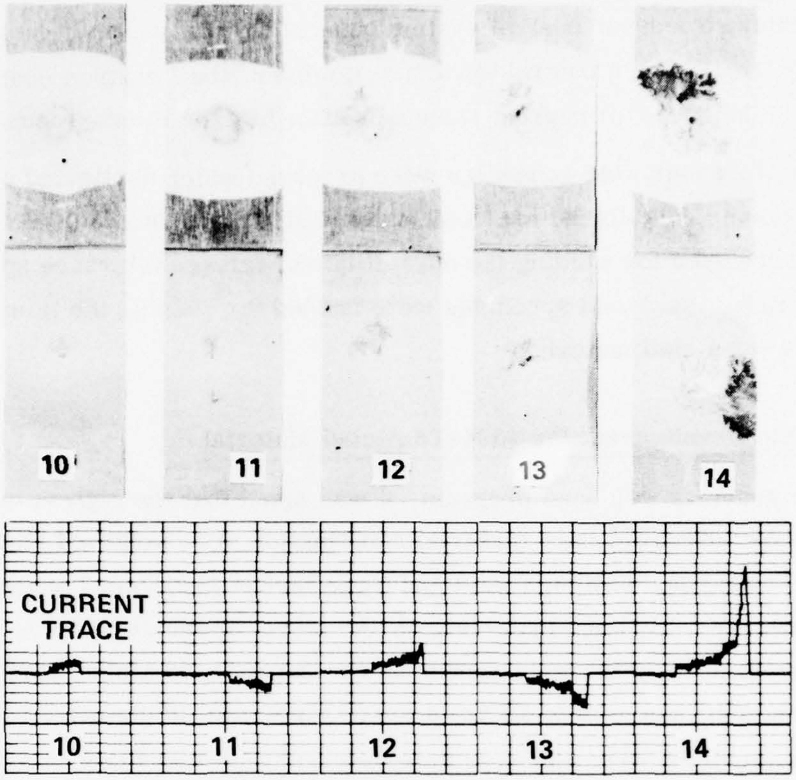

FIGURE 41. EVIDENCE OF EXPULSION AT LOW HEAT VALUES

expulsion probably could not be avoided with 1.5vPSD 2024-T3 alclad material using the current welding approach due to the thick oxide coating which was developed. It was concluded that a modified surface preparation procedure was necessary to reduce the oxide coating on the 2024-T3 alclad sheet to approximately 600Å -700Å , and that a new welding schedule needed to be developed for that surface treatment. As previously discussed, it was determined that 1.0vPSD anodizing of the 2024-T3 alclad material resulted in the desired oxide thickness of 675Å.

A program was then undertaken to develop adequate welding schedules for the different thickness combinations used in the program.

Several electrode/forge force combinations were evaluated to achieve a successful welding schedule for the 1.5vPSD 7075-T6 bare to 1.0vPSD 2024-T3 alclad (both 0.063-inch thick). A welding schedule (shown in Figure 42) was developed by modifying the schedule for welding 0.063-in. 1.5vPSD 7075-T6 bare. Although the spot strengths of this combination ranged from 670 to 1290 pounds with an average of 950 pounds for 50 tests (which met the MIL-W-6858 minimum shear strength requirements of 670 pounds minimum value/840 pounds minimum average for Class A welds), the

00/401	000	01	TURN-ON – APPLY WELD PRESSURE
01/002	000	97	TEST FOOT SWITCH
02/800	000	06	CONTACT GAGE CHECK
03/403	000	01	TURN-ON – BRUSH RECORDER
04/800	060	00	HOLD – 60 CYCLES
05/001	000	00	DO NOTHING
06/498	000	01	RE-ZERO FEEDBACK ENCODER
07/498	000	00	START READING FEEDBACK EXPANSION
08/402	002	01	APPLY FORGE PRESSURE – AFTER 2 CYCLES
09/191	023	18	HEAT UP-SLOPE – 9 CYCLES
11/000	000	22	
13/000	000	26	
15/000	000	30	
17/000	000	34	
19/000	000	39	
21/000	000	45	
23/000	000	55	
25/000	000	58	
27/000	000	46	HEAT DOWN-SLOPE – 14 CYCLES
29/000	000	44	
31/000	000	42	
33/000	000	40	
35/000	000	39	
37/000	000	38	
39/000	000	37	
41/000	000	36	
43/000	000	35	
45/000	000	34	
47/000	000	33	
49/000	000	32	
51/000	000	31	
53/000	000	30	
10/255	000	00	EXPANSION MONITORING
12/255	000	00	
14/255	000	00	
16/255	000	00	
18/255	000	00	
20/255	000	00	
22/255	000	00	
24/255	000	00	
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30/255	000	00	
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34/255	000	00	
36/255	000	00	
38/255	000	00	
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42/255	000	00	
44/255	000	00	
46/255	000	00	
48/255	000	00	
50/255	000	00	
52/255	000	00	
54/001	000	00	
55/403	000	00	TURN-OFF BRUSH RECORDER
56/800	300	00	HOLD 300 CYCLES
57/498	000	01	RESET FEEDBACK ENCODER
58/003	000	00	FINISH WELD, RETURN TO STEP 00

0.063/0.063 PANEL SPECIMENS		
0.063	0.063	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8″	5/8″	ELECT – DIA
6″	6″	TIP RADII
1	1	CLASS
2000 LBS /	4000 LBS	WELD/FORGE

FIGURE 42. WELD SCHEDULE FOR 0.063-2024-T3 ALCLAD, 1.0V PSD TO 0.063-7075-T6 BARE, 1.5V PSD

nuggets obtained were irregular in shape and inconsistent in strength and quality. The same situation also occurred when welding the 0.071/0.050 and 0.040/0.050 combinations.

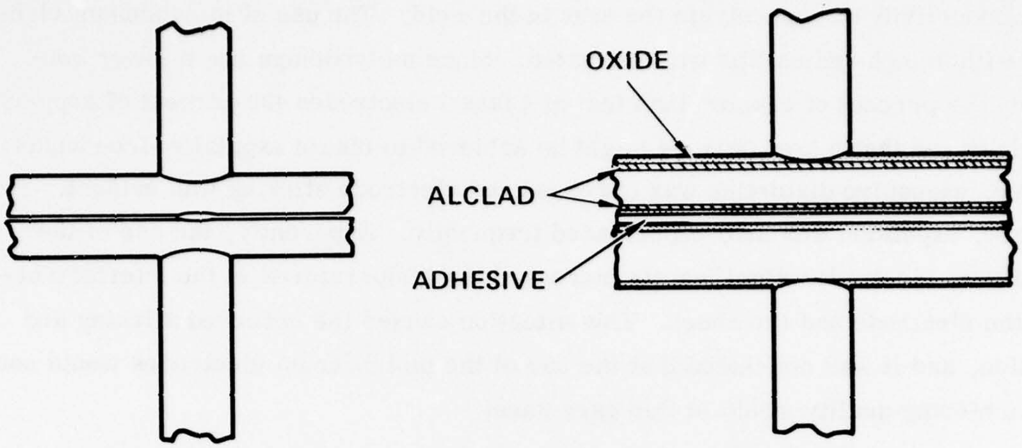
As higher quality welds had been previously obtained using only 7075 bare material, it was believed that this problem was inherent in the process due to the complex situation of weldbonding these particular combinations which involved:

(1) two different alloys
(2) an alclad coating on the 2024
(3) oxides on the different alloys of a different character
(4) an adhesive at the interface.

The complexity of this situation compared to that of a normal spotwelding procedure is shown in the schematic in Figure 43.

The weld schedule for the 0.025-inch 2024-T3 alclad/0.032-inch 7075-T6 proved to be the most difficult. An approach similar to that used while developing the previous weld schedules was attempted resulting in poor welds with significant expulsion. At this point, in order to (1) achieve successful welding of the 0.032/0.025 combination, (2) to improve the weld quality and consistency of all combinations, and (3) to take full advantage of the microprocessor welding controller, it was concluded that a new welding approach must be attempted. The existing approach had demonstrated the following shortcomings which would be unacceptable in production welding of panels:

1. Welding of thin gage combinations was not possible.
2. The welds achieved in thicker gages, although they met CLASS A strength and were expulsion free, were irregular in shape and consistently round nuggets could not be achieved.
3. Weld consistency requirements of MIL-W-6858 could not be met.
4. Small variations in cleaning and surface resistance made large differences in weld quality.
5. Expulsion occurred early at very low heat levels, making feedback control methods ineffective.
6. Sliding of the electrodes during welding was constantly evident and an irregularly shaped electrode impression was observed, particularly on the 2024-T3 alclad sheet.



NORMAL SPOT WELDING

WELDBONDING

FIGURE 43. SPOTWELDING CONDITION OF NORMAL VS WELDBONDING SITUATION

The first effort in the new approach was to evaluate the use of electrodes with lower conductivity to concentrate the heat in the weld. The use of molybdenum electrodes with 3-inch radius tips was evaluated. Since molybdenum has a lower conductivity (48 percent of copper) than that of Class I electrodes (90 percent of copper), it was believed that a heat balance might be achieved to obtain expulsion-free welds. However, excessive distortion was observed and electrode sticking was evident. Furthermore, expulsion was still experienced frequently. Apparently, the use of the molybdenum electrodes significantly increased the temperatures in the interface between the electrode and the sheet. This situation caused the observed sticking and distortion, and it was concluded that the use of the molybdenum electrodes would not aid in achieving quality welds in thin gage sheet.

A new weld nugget formation model was developed and a series of experiments conducted to determine the basis of the model. It had been observed that the initial nugget formation and the expulsion which occurred during the first few cycles of heat application was apparently occurring at the edge of the area of electrode contact rather than at the center. It was therefore concluded that the effective resistance of the oxide to current flow and nugget initiation was higher in the center of the contact area than at the edge. It appeared that this effect was due to some physical characteristics including compressibility of the boehmite oxide formed on the 2024 alclad material, and that the oxide resistance was directly proportional to the level of compression. Thus, as the threshold voltage and resulting current to initiate a weld should occur at the point of minimum oxide resistance, the natural tendency is for weld initiation at the outer diameter of the contact area. The soft alclad material on the surface of the 2024 alloy would tend to increase this compressibility factor by minimizing cracking of the oxide layer as it is being compressed into a soft surface. Therefore, expulsion tendencies would be enhanced for the alclad material, and indeed this had been observed.

Previous welding theory involving resistance spot welding through anodized surfaces had advocated the use of extremely high pressures early in the heat cycle to avoid expulsion. However, in cases where the weld initiation occurred at the outside of the contact area, as in the case of the 2024-T3-alclad material, it was felt that a high pressure on the off-center molten puddle as the nugget was formed tended to cause early expulsion rather than eliminating it. The high pressure at the edge of the electrode contact would be aggrevated by a smaller tip radius.

To alleviate these effects, it was hypothesized that effort must be undertaken to initiate the weld as close as possible to the center of the electrode contact area, and to increase the pressure balance between the molten nugget puddle (P_N) and the electrode pressure (F_c), as shown in Figure 44, by increasing the tip radius of the electrode. The use of a larger tip radius spreads the electrode force over a greater area, thus reducing the center pressure on the molten puddle.

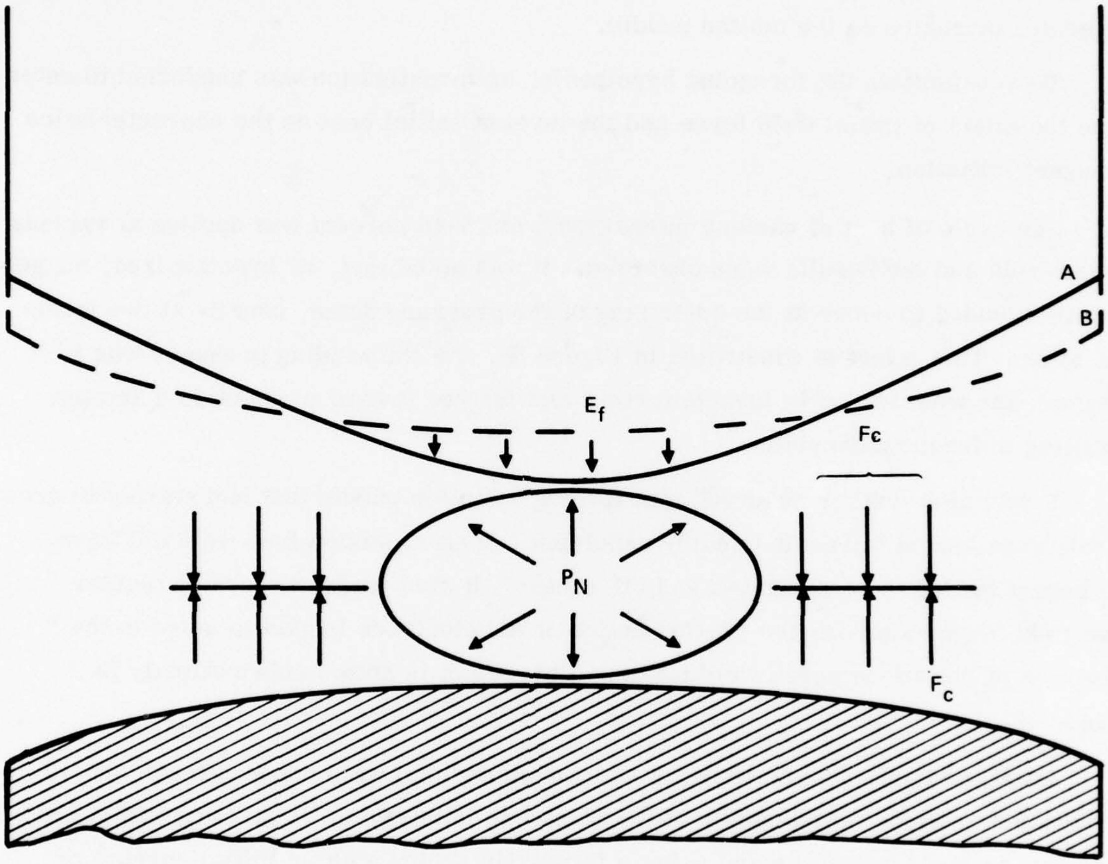
To substantiate the foregoing hypothesis, an investigation was conducted to determine the effect of initial weld force and the level of initial heat on the characteristics of nugget initiation.

One cycle of heat of various intensities from 5-40 percent was applied at various force levels and the results were observed. It was noted that, as hypothesized, nugget initiation tended to occur at the outer ring of the pressure dome, usually at two initiation sites. This effect is illustrated in Figure 45. As the welding pressure was increased, the weld tended to initiate further and further toward the outside diameter resulting in frequent expulsion.

It was also further observed that forging a molten puddle that had started to grow in this area tended to result in early expulsion. If an expulsion free weld did form, the nugget tended to be elongated and off-center. It also tended to form irregular electrode impressions as the forging action of the electrode tended to move in the direction of the off-centered weld puddle. This effect is shown schematically in Figure 46.

Based on these observations, it was concluded that weld nugget growth should be initiated as close to the center of the electrode impression by starting with a weld pressure as low as possible and using a larger tip radius with an initial current or voltage spike of one cycle of sufficient magnitude to break through the oxide layer. As the microprocessor controller was programmed cycle by cycle, this was an easy programmable task and this approach could be used effectively in a production weld schedule.

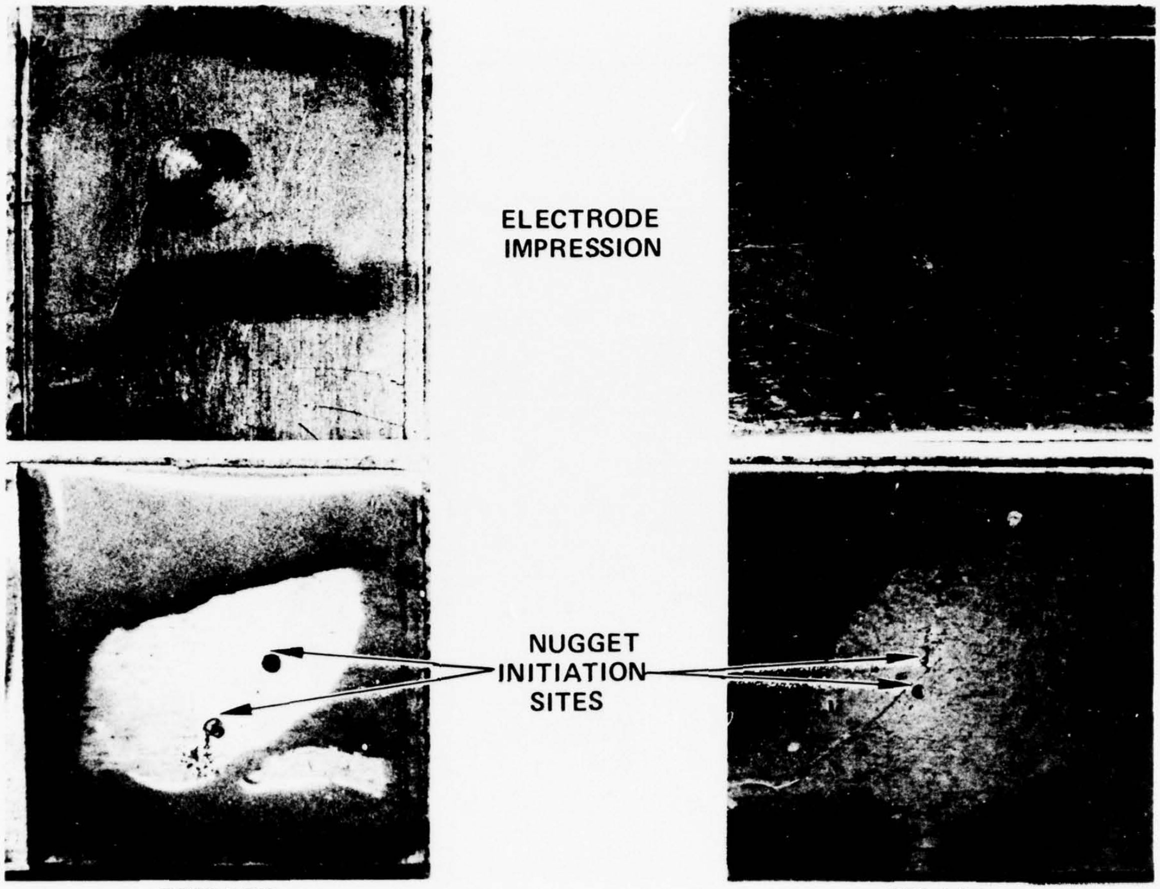
A series of experiments showed that a one-cycle current spike of 25-40 percent which resulted in a current of 12-20,000 amps at a pressure of 400-500 pounds resulted in an ideal electrical contact and weld initiation, appropriately centered, from which the nugget could grow. This compared to the 1000-2000 pound weld forces previously used. In order to obtain consistency and to insure that the heat from the spike was not a part of the weld growth heat input, 200 cool cycles were initially used after the spike.



A = 6" TIP RADIUS
B = 10" TIP RADIUS
E_f = ELECTRODE FORCE ON NUGGET PUDDLE
F_c = ELECTRODE CLAMPING FORCE
P_N = NUGGET EXPULSION FORCE

WHEN $P_N + E_f > F_c$, EXPULSION OCCURS.
FOR LARGER TIP RADIUS, E_f DECREASES AND F_c INCREASES.

FIGURE 44. EFFECT OF ELECTRODE TIP RADIUS ON NUGGET PRESSURE BALANCE AND TENDENCY FOR EXPULSION



2000 LBS

750 LBS

FIGURE 45. EFFECT OF WELD FORCE ON LOCATION OF NUGGET INITIATION SITES

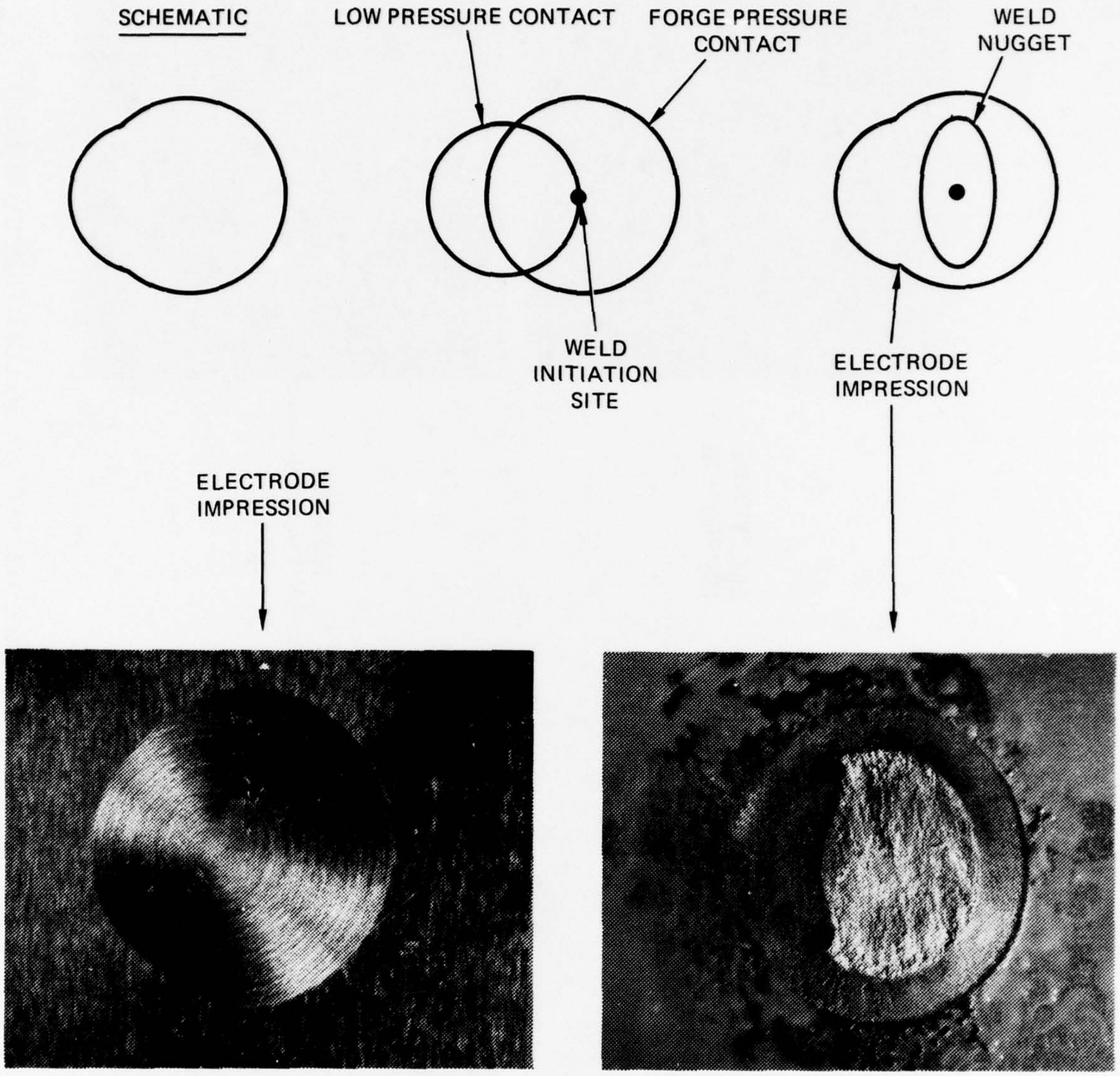


FIGURE 46. SHIFTING OF ELECTRODE IMPRESSION

The first successful weld schedule for the 0.025/0.032 inch panel was developed using this approach. This weld schedule, shown in Figure 47. achieved Class A quality welds with weld strengths of 350-475 lbs. The nuggets met MIL-A-6858 requirements for roundness and consistency. The flat production panels which were fatigue and shear tested by Fairchild were welded using this schedule.

In a later technical review, it was determined that the total weld duration for this weld schedule was too long to be economically feasible in a production operation. As a result, further tests were conducted and it was found that a few cycles of cooling after the voltage spike for the 0.025/0.032 inch combination were adequate to obtain a more cost effective weld schedule. This schedule is shown in Figure 48.

During the welding of the first three weldbonded test panels of the 0.040/0.050 combination using the welding schedule shown in Figure 49, the weld roundness and consistency deficiencies became evident. At this point in the program, the welding of production panels was delayed and new weld schedules were developed using the low pressure/heat spike approach for the 0.040/0.050, the 0.071/0.050 and the 0.062/0.062 inch combinations. During this weld schedule development, it was found that one cool cycle after the voltage spike was sufficient if minor modifications were made to the heat schedule. Thus, the voltage spike was successfully incorporated into the basic heat schedule thereby eliminating need for the 200 cycle post-spike hold.

The weld schedules shown in Figures 50 and 51 are the weld schedules that developed from this effort. All 0.071/0.050 inch panels and the remaining 0.040/0.050 inch panels were welded utilizing these weld schedules.

In developing these schedules it was found that there was a significant shunting effect due to multiple welds in the panel as shown in Figure 52. As a result, the welding current for panel welds had to be increased slightly over that of individual welds to achieve full nugget growth. The technique used to finalize the welding schedule to overcome the shunting effect was the following:

A series of individual 1-1/4 x 2-1/2 inch coupons were welded so that ten consecutive welds were achieved that met Class A strength, roundness, and consistency requirements. Sub-sized test panels measuring 6 x 10 inches were welded to study the shunting effect. Twenty-eight welds (four rows of seven welds each) spaced at 1-1/2 inch intervals were welded in the panel. The panel was then X-rayed and metallographic samples taken to check weld quality before the final full size test panels were welded.

00/401	000	01	TURN-ON – APPLY WELD PRESSURE
01/002	000	00	TEST FOOT SWITCH
02/800	060	06	HOLD 60 CYCLES, CHECK CONTACT GAGE
03/900	065	00	JUMP TO STEP 65 FOR VOLTAGE SPIKE
04/001	000	00	DO NOTHING
05/403	000	01	TURN-ON BRUSH RECORDER
06/498	000	00	RE-ZERO FEEDBACK ENCODER
07/800	060	00	HOLD 60 CYCLES
08/402	006	01	APPLY FORCE PRESSURE-AFTER 6 CYCLES
09/191	025	01	FINISH PRESPIKE COOL
11/000	000	01	
13/000	000	01	
15/000	000	01	
17/000	000	17	HEAT UP-SLOPE – 5 CYCLES
19/000	000	30	
21/000	000	42	
23/000	000	44	
25/000	000	50	
27/000	000	42	HEAT DOWN-SLOPE – 16 CYCLES
29/000	000	40	
31/000	000	40	
33/000	000	40	
35/000	000	40	
37/000	000	40	
39/000	000	32	
41/000	000	31	
43/000	000	30	
45/000	000	29	
47/000	000	28	
49/000	000	27	
51/000	000	26	
53/000	000	25	
55/000	000	01	
57/000	000	01	
10/255	000	00	EXPANSION MONITORING
12/255	000	00	
14/255	000	00	
16/255	000	00	
18/255	000	00	
20/255	000	00	
22/255	000	00	
24/255	000	00	
26/255	000	00	
28/255	000	00	
30/255	000	00	
32/255	000	00	
34/255	000	00	
36/255	000	00	
38/255	000	00	
40/255	000	00	
42/255	000	00	
44/255	000	00	
46/255	000	00	
48/255	000	00	
50/255	000	00	
52/255	000	00	
54/255	000	00	
56/255	000	00	
58/001	000	00	
59/403	000	00	TURN-OFF – BRUSH RECORDER
60/800	300	00	HOLD 300 CYCLES
61/498	000	01	RESET FEEDBACK ENCODER
62/003	000	00	FINISH WELD, RETURN TO STEP 00
65/131	001	30	APPLY VOLTAGE SPIKE, 1 CYCLE, 30% HEAT
66/800	200	00	HOLD 200 CYCLES
67/131	001	01	FLUX BALANCE – 1 CYCLE
68/900	005	00	RETURN TO WELD CYCLE, STEP 05

0.032/0.025 PANEL WELDS		
0.025	0.032	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
10" +	10"	TIP RADII
1	1	CLASS
500 LBS /	2000 LBS	WELD/FORGE

FIGURE 47. FIRST SUCCESSFUL WELD SCHEDULE FOR THE 0.025/0.035-INCH PANEL

00/401	000	01	TURN-ON APPLY WELD PRESSURE
01/002	000	97	TEST FOOT SWITCH
02/800	000	06	CONTACT GAGE CHECK
03/403	000	01	TURN-ON – BRUSH RECORDER
04/800	060	00	HOLD – 60 CYCLES
05/001	000	00	DO NOTHING
06/498	000	01	RE-ZERO FEEDBACK ENCODER
07/498	000	00	START READING FEEDBACK EXPANSION
08/402	007	01	APPLY FORGE PRESSURE – AFTER 7 CYCLES
09/191	025	25	VOLTAGE SPIKE – 1 CYCLE AT 25%
11/000	000	01	COOL CYCLES
13/000	000	01	
15/000	000	01	
17/000	000	01	
19/000	000	01	
21/000	000	19	HEAT UP-SLOPE – 5 CYCLES
23/000	000	33	
25/000	000	44	
27/000	000	47	
29/000	000	52	
31/000	000	42	HEAT DOWN-SLOPE – 14 CYCLES
33/000	000	40	
35/000	000	40	
37/000	000	40	
39/000	000	40	
41/000	000	40	
43/000	000	32	
45/000	000	31	
47/000	000	30	
49/000	000	29	
51/000	000	28	
53/000	000	27	
55/000	000	26	
57/000	000	25	
10/255	000	00	EXPANSION MONITORING
12/255	000	00	
14/255	000	00	
16/255	000	00	
18/255	000	00	
20/255	000	00	
22/255	000	00	
24/255	000	00	
26/255	000	00	
28/255	000	00	
30/255	000	00	
32/255	000	00	
34/255	000	00	
36/255	000	00	
38/255	000	00	
40/255	000	00	
42/255	000	00	
44/255	000	00	
46/255	000	00	
48/255	000	00	
50/255	000	00	
52/255	000	00	
54/255	000	00	
56/255	000	00	
58/001	000	00	
59/403	000	00	TURN OFF – BRUSH RECORDER
60/800	180	00	HOLD – 180 CYCLES
61/498	000	01	RESET FEEDBACK ENCODER
62/003	000	00	FINISH WELD, RETURN TO STEP 00

0.025/0.032 PANEL WELDS		
0.025	0.032	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
10" +	10"	TIP RADII
1	1	CLASS
500 LBS /	2000 LBS	WELD/FORGE

FIGURE 48. FINAL WELD SCHEDULE FOR THE 0.025/0.032-INCH PANEL

00/401	000	01	TURN-ON – APPLY WELD PRESSURE
01/002	000	97	TEST FOOT SWITCH
02/800	010	06	CONTACT GAGE CHECK, HOLD TEN CYCLES
03/403	000	01	TURN ON – BRUSH RECORDER
04/800	060	00	HOLD – 60 CYCLES
05/001	000	00	DO NOTHING
06/498	000	01	RE-ZERO FEEDBACK ENCODER
07/498	000	00	START READING FEEDBACK EXPANSION
08/402	002	01	APPLY FORGE PRESSURE – AFTER 2 CYCLES
09/191	023	14	HEAT UP-SLOPE – 9 CYCLES
11/000	000	18	
13/000	000	22	
15/000	000	26	
17/000	000	30	
19/000	000	34	
21/000	000	40	
23/000	000	45	
25/000	000	50	
27/000	000	48	HEAT DOWN-SLOPE – 14 CYCLES
29/000	000	44	
31/000	000	42	
33/000	000	40	
35/000	000	39	
37/000	000	38	
39/000	000	37	
41/000	000	36	
43/000	000	35	
45/000	000	34	
47/000	000	33	
49/000	000	32	
51/000	000	31	
53/000	000	30	
10/255	000	00	EXPANSION MONITORING
12/255	000	00	
14/255	000	00	
16/255	000	00	
18/255	000	00	
20/255	000	00	
22/255	000	00	
24/255	000	00	
26/255	000	00	
28/255	000	00	
30/255	000	00	
32/255	000	00	
34/255	000	00	
36/255	000	00	
38/255	000	00	
40/255	000	00	
42/255	000	00	
44/255	000	00	
46/255	000	00	
48/255	000	00	
50/255	000	00	
52/255	000	00	
55/403	000	00	TURN-OFF BRUSH RECORDER
56/800	200	00	HOLD 200 CYCLES
57/498	000	00	RESET FEEDBACK ENCORDER
58/403	000	00	FINISH WELD, RETURN TO STEP 00

0.040/0.050 PANEL WELDS		
0.040	0.050	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
6"	6"	TIP RADII
1	1	CLASS
1500 LBS /	3000 LBS	WELD/FORGE

FIGURE 49. ORIGINAL WELD SCHEDULE FOR THE 0.040/0.050-INCH PANEL

```
00/401  000  01      TURN-ON – APPLY WELD PRESSURE
01/002  000  97      TEST FOOT SWITCH
02/800  000  06      CONTACT GAGE CHECK
03/403  000  01      TURN-ON – BRUSH RECORDER
04/800  060  00      HOLD – 60 CYCLES
05/001  000  00      DO NOTHING
06/498  010  01      RE-ZERO FEEDBACK ENCORDER
07/498  010  00      START READING FEEDBACK EXPANSION
08/402  005  01      APPLY FORGE PRESSURE – AFTER 5 CYCLES

09/191  025  30      VOLTAGE SPIKE – 1 CYCLE AT 30
11/000  000  01      COOL CYCLE
13/000  000  09  ⎫
15/000  000  19  ⎪
17/000  000  26  ⎪
19/000  000  30  ⎬   HEAT UP-SLOPE – 7 CYCLES
21/000  000  36  ⎪
23/000  000  59  ⎪
25/000  000  61  ⎭
27/000  000  52  ⎫
29/000  000  46  ⎪
31/000  000  44  ⎪
33/000  000  44  ⎪
35/000  000  42  ⎪
37/000  000  40  ⎪
39/000  000  37  ⎪
41/000  000  34  ⎪
43/000  000  30  ⎬   HEAT DOWN-SLOPE – 16 CYCLES
45/000  000  29  ⎪
47/000  000  28  ⎪
49/000  000  27  ⎪
51/000  000  26  ⎪
53/000  000  25  ⎪
55/000  000  24  ⎪
57/000  000  24  ⎭

10/255  000  00  ⎫
12/255  000  00  ⎪
14/255  000  00  ⎪
16/255  000  00  ⎪
18/255  000  00  ⎪
20/255  000  00  ⎪
22/255  000  00  ⎪
24/255  000  00  ⎪
26/255  000  00  ⎪
28/255  000  00  ⎪
30/255  000  00  ⎪
32/255  000  00  ⎪
34/255  000  00  ⎬   EXPANSION MONITORING
36/255  000  00  ⎪
38/255  000  00  ⎪
40/255  000  00  ⎪
42/255  000  00  ⎪
44/255  000  00  ⎪
46/255  000  00  ⎪
48/255  000  00  ⎪
50/255  000  00  ⎪
52/255  000  00  ⎪
54/255  000  00  ⎪
56/255  000  00  ⎭

58/403  000  00      TURN-OFF – BRUSH RECORDER
59/800  150  00      HOLD – 150 CYCLES
60/498  000  01      RESET FEEDBACK ENCODER
61/003  000  00      FINISH WELD, RETURN TO STEP 00
```

0.040/0.050 PANEL WELDS		
0.040	0.050	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
10" +	10"	TIP RADII
1	1	CLASS
500 LBS / 3000 LBS		WELD/FORGE

FIGURE 50. FINAL WELD SCHEDULE FOR THE 0.040/0.050-INCH PANEL

```
00/401 000 00   TURN-ON – APPLY WELD PRESSURE
01/002 000 00   TEST FOOT SWITCH
02/800 120 06   CONTACT GAGE CHECK
03/403 000 01   TURN-ON – BRUSH RECORDER
04/800 000 01   SPARE HOLD COMMAND
05/001 000 00   DO NOTHING – ONE CYCLE
06/498 011 01   RE-ZERO FEEDBACK ENCODER AFTER 11 CYCLES
07/498 010 00   START READING FEEDBACK EXPANSION – AFTER 10 CYCLES
08/402 005 01   APPLY FORGE PRESSURE – AFTER 5 CYCLES

09/191 025 30   VOLTAGE SPIKE – 1 CYCLE AT 30%
11/000 000 01   ONE CYCLE COOL
13/000 000 13
15/000 000 26
17/000 000 31
19/000 000 36
21/000 000 44   HEAT UP-SLOPE – 8 CYCLES
23/000 000 56
25/000 000 44
27/000 000 65
29/000 000 48
31/000 000 46
33/000 000 43
35/000 000 42
37/000 000 40
39/000 000 40
41/000 000 39
43/000 000 37   HEAT DOWN-SLOPE – 15 CYCLES
45/000 000 37
47/000 000 35
49/000 000 34
51/000 000 33
53/000 000 31
55/000 000 31
57/000 000 30

10/255 000 00
12/255 000 00
14/255 000 00
16/255 000 00
18/255 000 00
20/255 000 00
22/255 000 00
24/255 000 00
26/255 000 00
28/255 000 00
30/255 000 00
32/255 000 00   EXPANSION MONITORING
34/255 000 00
36/255 000 00
38/255 000 00
40/255 000 00
42/255 000 00
44/255 000 00
46/255 000 00
48/255 000 00
50/255 000 00
52/255 000 00
54/255 000 00
56/255 000 00

58/403 000 00   TURN-OFF BRUSH RECORDER
59/800 200 00   HOLD 200 CYCLES
60/498 000 01   RESET FEEDBACK ENCODER
61/003 000 00   FINISH WELD, RETURN TO STEP 00
```

0.071/0.050 PANEL WELDS		
0.071	0.050	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8″	5/8″	ELECT – DIA
10″	10″	TIP RADII
1	1	CLASS
500 LBS /	3000 LBS	WELD/FORGE

FIGURE 51. FINAL WELD SCHEDULE FOR THE 0.071/0.050-INCH PANEL

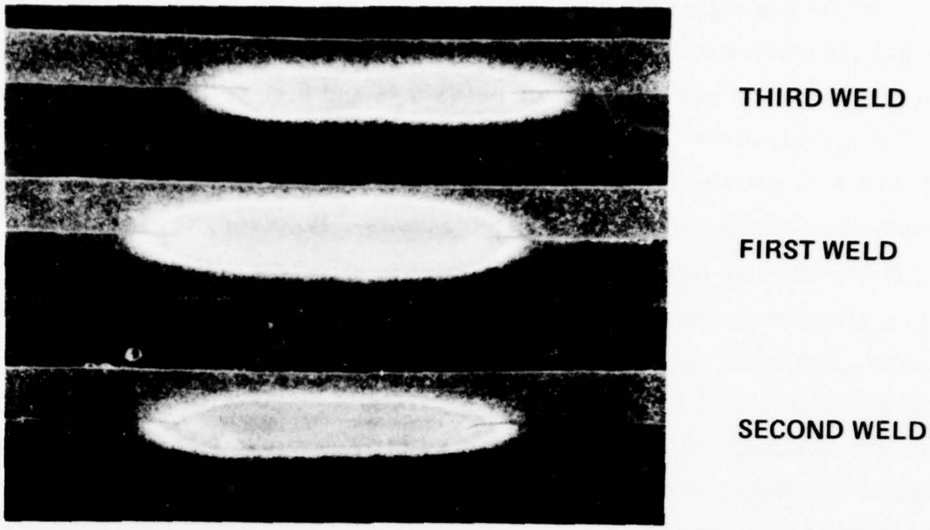


FIGURE 52. EFFECT OF WELD CURRENT SHUNTING ON WELD SIZE

It was not within the scope of this program to determine the relative importance of each parameter of the final weld schedule in achieving quality welds. It is believed, however, that the use of the lower pressures and high voltage spike is necessary to initiate a centralized nugget through the oxide coating. It is believed that the use of the larger electrode tip radius aids in minimizing expulsion and appears to be beneficial in achieving surface indentation requirements. However, it has not been ascertained positively whether this radius is essential in all gages. It is possible that electrodes with a smaller tip radius, i.e., six inches, can produce particularly effective welds in thicker gage combinations. During the welding of the production panels, it was determined, however, that the alignment of the electrodes is more critical than for standard aluminum spot welding. It was found that in order to achieve ideal oxide break-through and to allow the nugget to grow from a centralized location to avoid expulsion that the electrodes must be aligned properly so that the electrode contact point is accurately centered.

It was also observed that the simple use of a 500 lb. - 3,000 lb. weld-forge pressure relationship would not ensure quality welds from welding machine to welding machine using these particular weld schedules. This is due to the effect of the pressure dumping characteristics and the head inertia of the individual welding machine. Small differences in the air valve exhaust rate can cause large variations in nugget expansion characteristics and can vary nugget quality significantly. If the air valve exhausts at a different rate than is called for by the welding schedules developed in this program, the weld nugget may expand at a different rate, thereby resulting in different nugget qualities. To control this condition, adjustments may have to be made in the air-system of the welding machine to allow for nugget expansion at an appropriate rate.

EVALUATION OF IN-PROCESS WELDING CONTROLS AND MONITORS

OBJECTIVE

The objective of the effort was to evaluate and optimize in-process welding controls for manufacturing operations which would assure reproducible Class A spot welds, (MIL-W-6858) in weldbonded panels.

INTRODUCTION

Two different methods of controlling the spot weld process were evaluated. These were: (1) Monitors, which continually characterize weld quality by measuring various welding parameters; and (2) Controls, which automatically make adjustments to the weld schedule during nugget formation to optimize weld quality.

Three different types of welding monitors were evaluated.

(1) Total Energy Monitor — An instrument which was designed and built by Convair and is used in their production spot welding operations.

(2) Current Monitor — Manufactured by the Duffers Corporation and commonly used in many spot welding operations.

(3) Nugget Expansion Monitor — Subsystem to the Pertron PWC-300 microprocessor controller.

In the controls evaluation, a closed loop feedback control system based on nugget expansion characteristics, was evaluated to determine its potential for achieving constant size nuggets by automatic cycle-by-cycle current control. This system is a feature of the Pertron PWC-300 microprocessor welding controller. The nugget expansion control method was selected because it was sufficiently developed to utilize in production operations. Equipment used to monitor and control other spot weld characteristics such as acoustic feedback had been surveyed in the previous manufacturing methods program (Reference 3) and found to be in further need of development.

A major portion of this task was accomplished by the General Dynamics Corporation, Convair Division, San Diego, CA. Mr. R. L. Szabo acted as the initial program manager at Convair and was succeeded by Mr. W. A. Roden. This effort was an extension of their work conducted under Contract F33615-75-C-5529, "Feedback Controlled Spot Welding" sponsored by AFML, (Reference 5).

BACKGROUND

In the previous program Convair had successfully developed equipment and procedures and had demonstrated the concept of applying nugget expansion feedback controlled spot welding techniques to weldbonding processes. It was the objective of the current program to further adapt these procedures to the successful production of aircraft structural panels.

Just before the initiation of the current program, a newly developed computer microprocessor became commercially available for controlling resistance welding. This PWC-300 microprocessor controller, manufactured by the Pertron Controls Corporation, Van Nuys, CA., contains a digital incremental encoder transducer attachment which provides complete nugget expansion information during the welding cycle. By integrating this information with a feedback control software program, nugget expansion can be used either for monitoring or feedback control. This controller also has the ability to accept other weld nugget growth measurement inputs (such as acoustic monitoring) when these techniques are proven and become commercially available.

In developing the initial program plan, it became apparent that if this welding controller could be proven to be an effective tool, it would be less expensive and more readily adaptable to the manufacturing operations than the original control equipment planned for use in the program. With the cooperation of Pertron, Northrop and Convair conducted a joint evaluation of the feedback control characteristics of the equipment and found it to be easily adaptable to weldbond processing. In addition, because of the incremental cycle-by-cycle heat programming feature, the controller provided more flexibility for achieving detailed slope controlled welding schedules than either of the existing weld controllers in use at Northrop or Convair.

It was decided that both Northrop and Convair would lease PWC-300 microprocessor controllers as it was felt that the use of this controller would greatly increase the chances for success in this program in that:

(1) Increased accuracy and reproducibility of the welding controls would result.

(2) Cycle-by-cycle heat programming could be achieved which would allow greater flexibility in achieving quality nuggets in the presence of the oxide and the adhesive.

(3) Nugget growth could be monitored and a potential in-process system for achieving consistent nugget quality could be developed.

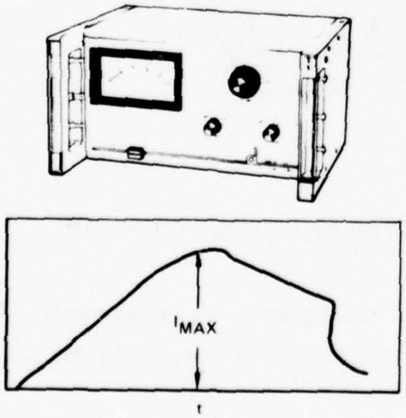
(4) Nugget expansion feedback control could be effectively evaluated.

This controller was then used for all successive welding operations in the program.

EVALUATION OF IN-PROCESS MONITORS

Current Monitor

The current monitor evaluated on this program was a Duffers model #281 as shown in Figure 53 . This monitor measures the maximum current (I max) that is achieved during the formation of one spot weld. As was previously discussed, however, the current form necessary to avoid expulsion problems in weldbonding is characterized by a long up-slope and down-slope. This was initially found necessary to achieve consistant nugget growth in the presence of the oxide and to eliminate cracking of the nugget. As a result, the quality of the nugget is dependent upon the sum of the heat impulses, and is not just a function of the maximum current. Studies made by measuring nugget quality as a function of maximum current indicated that there was no definite correlation between the strength or quality of an individual weld nugget and the maximum current reading taken from the Duffers meter. This was particularly true when welds were made utilizing expansion feedback control. For example, if the weld location has a high resistance due to the presence of a thicker oxide, additional current would be required to provide the extra heat needed to achieve a consistent quality weld. This current is automatically provided by the feedback control system, and a higher current reading would be observed on the Duffers current meter to achieve the same nugget size.



CHARACTERISTICS

- REPEATABLE
- EFFECTIVE TOOL FOR MONITORING WELDING MACHINE FLUCTUATIONS
- MEASURES ONLY MAXIMUM CURRENT
- DOES NOT CORRELATE TO WELD STRENGTH & QUALITY
- NO CORRELATIONS BETWEEN WELDING MACHINES

FIGURE 53. DUFFERS CURRENT MONITOR

While evaluating the current monitor on three different welding machines, it was found that variations in individual welding machine characteristics greatly altered the current readings that were observed on the current monitor. As much as a 25 percent variation was noted from welding machine to welding machine using equivalent weld schedules. It was concluded from this investiation that because the meter measures only maximum current and because the variations in readings from welding machine to welding machine, this instrument could not be effectively used for process control functions. However, it was shown that the meter could effectively be used as a production tool for monitoring various welding machine fluctions on a given machine. It was also shown to be an effective tool for checking the adequacy of the voltage spike utilized to provide initial weld contact and for trouble shooting particular problems.

Total Energy Monitor

The total energy monitor evaluated in this program was designed and built by General Dynamics-Convair, and is used to monitor welds in their production welding shop. The equipment shown in Figure 54 is designed to integrate the total power (I^2R) as a function of time (in cycles) for each weld.

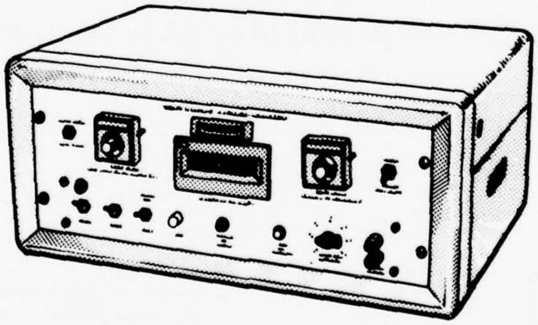


FIGURE 54. GENERAL DYNAMICS TOTAL ENERGY MONITOR

The results of the evaluation showed that the equipment, as presently designed, is ineffective for total monitoring of the long 25 cycle weld schedules utilized in this program for two reasons:

(1) Only a small percentage of the energy being monitored actually enters into

the formation of the weld nugget puddle, while much of the energy is lost in electrode and sheet metal heating. This is particularly true in the welding of the 0.025/0.032 inch panels.

(2) The equipment was designed for the more standard short cycle weld schedules utilized at Convair. Due to restrictions in the design of the Magnetic Flux Sensor, the meter tended to saturate at approximately 10 to 12 cycles, thereby creating erroneous readings beyond 12 cycles.

It was not within the scope of this program to redesign the total energy monitor to be effective in this program. Discussions held with both Convair and Pertron personnel did indicate that this equipment could be successfully modified to extend its range so that longer weld schedules could be effectively monitored. Also, by appropriately coupling the monitor with the Pertron cycle-by-cycle programmer, a timing device could be integrated into the circuitry which would create an energy window ($n_f - n_s$) as shown in Figure 55. Only the critical energy going into the formation of the weld nugget would then be measured, thereby achieving a more direct correlation between total energy and nugget quality. If this were achieved, the total energy monitor could be an effective quality control production tool.

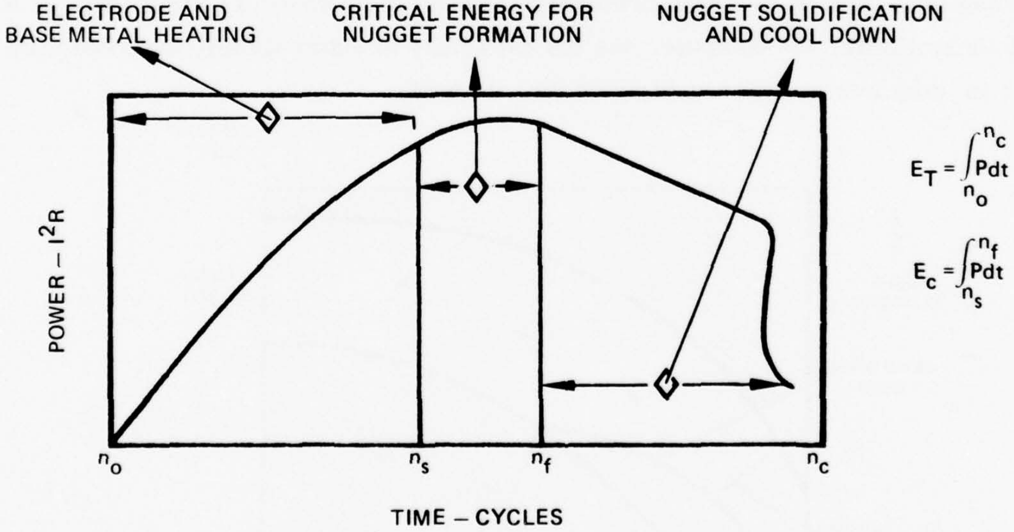


FIGURE 55. POWER/TIME RELATIONSHIP AS RELATED TO NUGGET FORMATION

Nugget Expansion Monitoring

Weld nugget expansion monitoring and control is based upon the principle that as the weld puddle melts and grows, a volume expansion takes place. This expansion causes a reverse force on the electrodes which results in a vertical movement of the upper electrode on the welding machine. This expansion is proportional to the nugget size. If nugget growth and subsequent solidification occur at a proper rate, a quality nugget will result. Continually modifying the heat or pressure input to the weld during the nugget growth to achieve this idealized nugget expansion/contraction condition will result in a quality weld which is repeatable. The movement in the upper electrode of the welding machine can be measured with a digital encoder mounted on the welding machine. A signal representing the movement of the encoder, which is proportional to nugget expansion, is then sent to a monitoring or controlling device. The microprocessor then compares this expansion to an ideal expansion curve which has been previously determined. Corrections to the weld heat input can then be made during the weld schedule to control the growth and quality of the nugget, or if necessary to terminate the weld to avoid expulsion or damage to the assembly being fabricated.

The monitoring capability evaluated in this program was part of the Pertron PWC-300 microprocessor welding controller. As the amount of expansion can be examined after each weld heat cycle, the computer has the capability to determine if the amount of expansion is within predetermined limits as shown in Figure 56. If it is outside these limits, the computer has the capability to automatically terminate the weld or to jump into a repair weld cycle or hold mode.

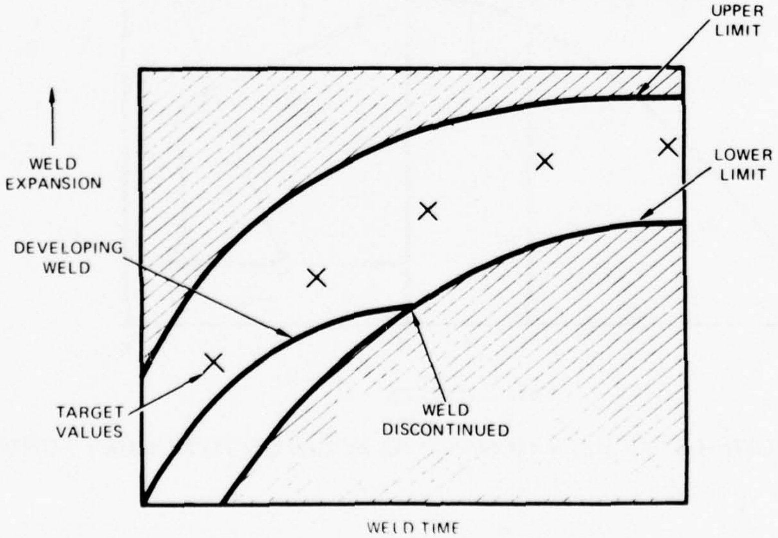


FIGURE 56. PRINCIPLE OF WELD NUGGET EXPANSION MONITORING

The monitoring capability evaluated in this program was found to be an extremely effective tool for in-process control of welds. Variations in oxide thickness, the mistaken use of an improper weld schedule, and the use of the wrong thickness of material can all be automatically detected and the welds appropriately terminated without subsequent damage to the aluminum panel. As shown in Figure 57, a specific weld can be terminated in sufficient time to preclude damage to the aluminum panel and a repair weld can be successfully made that meets Class A quality. The effective use of the monitoring capability is predicated on the following items:

(1) An accurately determined weld expansion curve must be determined for an idealized weld schedule so that appropriate numbers can be placed into the computer.

(2) The upper and lower weld termination limits must be determined for each weld cycle. These limits should be as liberal as possible to avoid unwanted terminations.

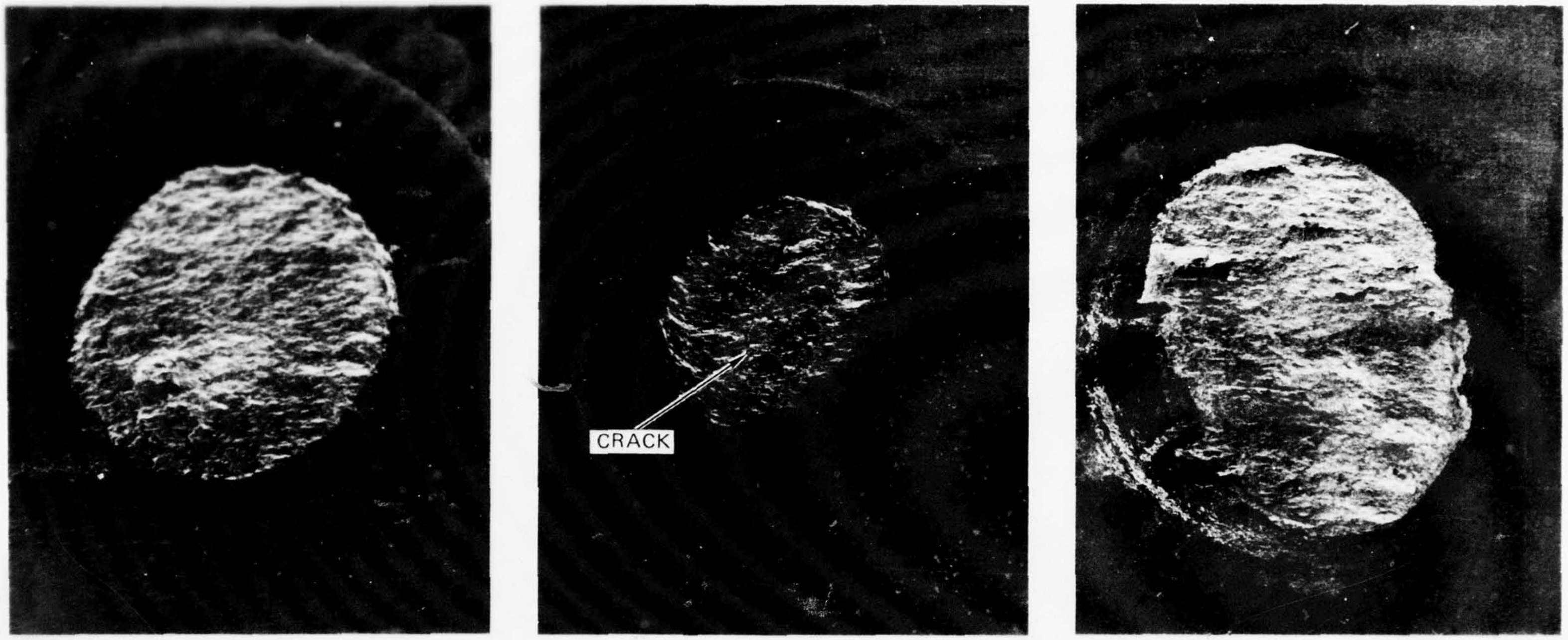
(3) An effective feedback control weld schedule must be developed which maximizes nugget expansion control characteristics so the computer can effectively monitor nugget growth. Techniques for achieving this goal are discussed later in this report.

It was concluded from this evaluation that nugget expansion feedback monitoring is the most effective tool currently available for in-process monitoring of aluminum weldbond spot welds. When this tool is used correctly, an out-of-control condition can be immediately detected and corrective action automatically taken. Other normal quality control functions, i.e., lap-shear strength tests and metallographic examination which checks weld quality should still be performed on a periodic basis. However, with the added dimension of the expansion monitoring capability, the assurance of quality weld nuggets in weldbonded components is at a high confidence level.

EVALUATION OF IN-PROCESS CONTROLS

Background

Closed-loop feedback control spot welding is based on the fact that there are certain changing physical characteristics related to the growing weld nugget puddle that can be measured. These dynamic physical characteristics are sufficiently



(A) NORMAL WELD

(B) CRACKED NUGGET TERMINATED BY WELD EXPANSION MONITOR

(C) CRACKED NUGGET OF (B) AFTER REPAIR PROCEDURE

FIGURE 57. EXAMPLE OF WELD TERMINATED BY EXPANSION MONITOR AND SUBSEQUENTLY REPAIRED

sensitive so that they can be used to accurately characterize the quality of the developing weld nugget and provide a basis for instantaneous weld schedule correction to achieve target size and quality. This principle, if successful in practice, could be a valuable weldbonding tool due to process variables such as oxide thickness, adhesive, etc. which introduce variations into the spot welding process. The technique could also be extremely beneficial in normal spot welding procedures as the welding process would not be sensitive to slight variations in the cleaning procedure, electrode conditions etc.

In previous weldbond programs, Wu (Reference 3) and Szabo (Reference 5) investigated various nugget characteristics which might be used as controlling factors to achieve feedback control. Weld nugget expansion, total energy input and acoustic emission techniques were evaluated. It was their determination that the nugget expansion method appeared to offer the most promise for controlling nugget quality. As the results of this current program were to be integrated into a manufacturing environment, and as equipment for performing nugget expansion feedback control was commercially available, this method appeared more attractive for inclusion into this program. Future developments may demonstrate that total energy or acoustic methods are practical, but as the nugget expansion technique appeared to be the furthest developed, investigation in this program was limited to the nugget expansion feedback technique.

Approach

The principle of weld nugget expansion control has been previously discussed under "Nugget Expansion Monitoring." It was the objective of the feedback controls effort to determine if spot weld nuggets, consistent in size and quality, could be obtained using cycle-by-cycle closed loop current control employing the nugget expansion principle as the basis for compensation. A significant portion of this effort was conducted by the General Dynamics Corporation, Convair Division. Their results were then integrated into the final weld schedules at Northrop, and eventually transferred to Fairchild.

The first portion of the Convair program was to determine the total amount of expansion that occurred during nugget formation when welding weldbonded panels and to determine that portion which could be attributed to nugget growth. Convair then developed a basic philosophy for programming feedback control weld schedules, and demonstrated weld schedules for the 0.071-0.050 material combination.

Upon completion of the Convair effort, Northrop determined (1) the effectiveness of using the technique on different pieces of equipment at different companies and (2) the applicability of using feedback control weld schedules for welding the test panels. These weld schedules were then utilized in welding tests conducted at Fairchild Republic during technology transfer. A guide for effective implementation of feedback control spot welding was developed by Northrop based on the results of these efforts.

Weld Expansion Evaluation

The total movement (E_t) of the welding electrodes during resistance spot welding is a result of several interrelating physical changes that occur during the welding period. These are:

(1) thermal expansion of the weld nugget which occurs as the nugget changes from a solid to a liquid state, (E_n)

(2) the thermal expansion of the base metal from heating (E_m)

(3) the thermal expansion of the electrodes themselves (E_{el})

(4) the indentation due to plastic flow of metal around the electrode tip (I)

(5) the phase relationship between the forge and current cycles

During expansion, both electrodes move to a certain degree. Because of machine design, the relative movement of each electrode is a variable and is dependent upon machine rigidity, applied pressure, and friction factors. However, in most cases, most of the electrode movement will occur in the upper or movable electrode.

The movement of the upper electrode is measured by a linear encoder which is rigidly mounted to the frame of the welding machine. If it is assumed that no forging occurs during weld formation, then

$$E_t = E_m + E_{el} + E_n - I$$

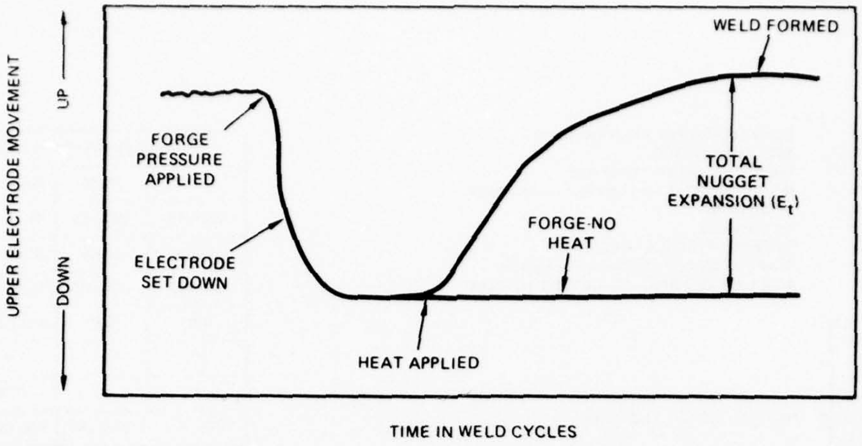


FIGURE 58. NUGGET EXPANSION CHARACTERISTICS FOR WELDS WITH HEAT APPLIED AFTER FORGE COMPLETE

This result is schematically illustrated in Figure 58. If forging occurs during the weld cycle, however, the relationship becomes more complex as is shown in Figure 59 because there is expansion occurring during the forge cycle.

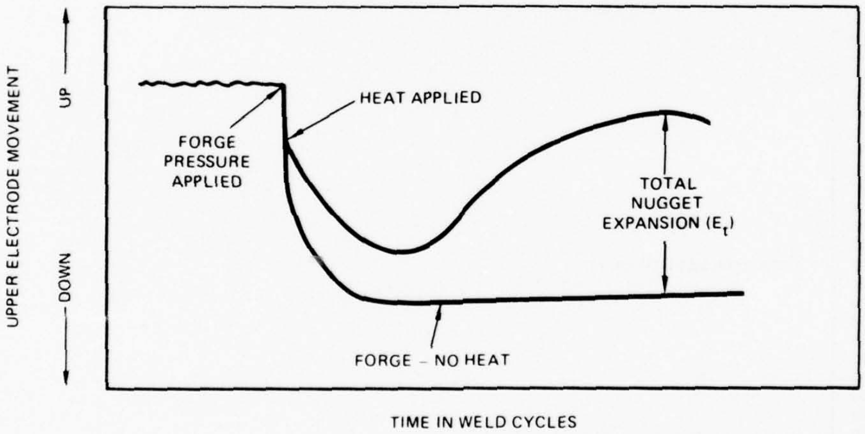


FIGURE 59. NUGGET EXPANSION CHARACTERISTICS FOR WELDS WITH HEAT APPLIED DURING INITIAL FORGE CYCLES

The weld expansion study was conducted using the 0.050-7075T6 bare/0.071-2024-T3 alclad material combination. The test samples were anodized and were welded using the weld schedule shown in Figure 60. The specimen configuration used was a 1 inch by 4 inch lap-shear panel with adhesive applied on the 1" overlap area.

00/401	000	01	TURN-ON – APPLY WELD PRESSURE
01/002	000	00	TEST FOOT SWITCH
02/403	000	01	TURN-ON – BRUSH RECORDER
03/800	060	06	HOLD – 60 CYCLES & CONTACT GAGE CHECK
04/001	000	00	DO NOTHING
05/001	000	00	DO NOTHING
06/498	000	01	RE-ZERO FEEDBACK ENCODER
07/498	000	00	START READING FEEDBACK EXPANSION
08/402	002	01	APPLY FORGE PRESSURE – AFTER 2 CYCLES
09/191	025	14	HEAT UP-SLOPE – 11 CYCLES
11/000	000	18	
13/000	000	22	
15/000	000	26	
17/000	000	30	
19/000	000	34	
21/000	000	40	
23/000	000	42	
25/000	000	44	
27/000	000	50	
29/000	000	54	
31/000	000	54	HEAT DOWN-SLOPE – 14 CYCLES
33/000	000	44	
35/000	000	42	
37/000	000	40	
39/000	000	39	
41/000	000	38	
43/000	000	37	
45/000	000	36	
47/000	000	35	
49/000	000	34	
51/000	000	33	
53/000	000	32	
55/000	000	31	
57/000	000	30	
10/255	000	00	EXPANSION MONITORING
12/255	000	00	
14/255	000	00	
16/255	000	00	
18/255	000	00	
20/255	000	00	
22/255	000	00	
24/255	000	00	
26/255	000	00	
28/255	000	00	
30/255	000	00	
32/255	000	00	
34/255	000	00	
36/255	000	00	
38/255	000	00	
40/255	000	00	
42/255	000	00	
44/255	000	00	
46/255	000	00	
48/255	000	00	
50/255	000	00	
52/255	000	00	
54/255	000	00	
56/255	000	00	
58/001	000	00	
59/403	000	00	TURN-OFF BRUSH RECORDER
60/800	300	00	HOLD – 300 CYCLES
61/498	000	00	RESET FEEDBACK ENCODER
62/003	000	00	FINISH WELD, RETURN TO STEP 00

0.071/0.050 WELD SPECIMENS		
0.071	0.050	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
6"	6"	TIP RADII
1	1	CLASS
1500 LBS /	3000 LBS	WELD/FORGE

FIGURE 60. ORIGINAL WELD SCHEDULE FOR 0.071/0.050-INCH MATERIAL COMBINATION

Four series of tests were conducted and the results are shown in Figure 61. The following expansion characteristics were determined:

(1) The welding machine characteristics were first determined by measuring the electrode motion characteristics during the forge cycle using no heat and no material. (Curve D)

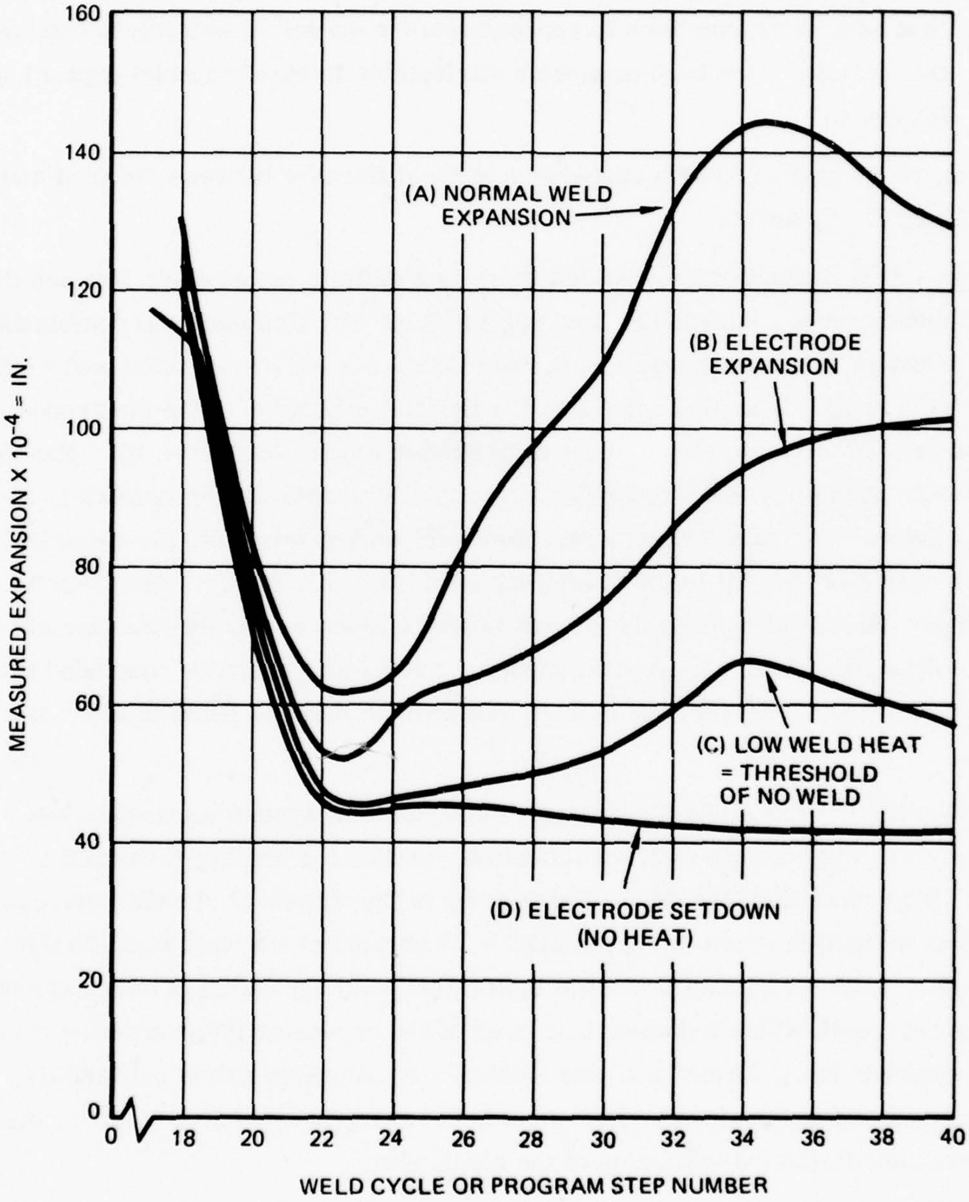


FIGURE 61 EXPANSION CHARACTERISTICS RESULTING FROM WELD EXPANSION STUDY

(2) The characteristics of electrode expansion using a full heat schedule with no material was then measured to determine that portion of the total weld expansion which could be attributed to expansion of the electrodes. (Curve B)

(3) Normal full strength Class A welds were then made and expansion measurements recorded. (Curve A)

(4) For comparison purposes threshold welds were made by reducing the weld heat so that the condition to approximate the on-set of welding to determine that portion of the total expansion attributable to base material expansion. (Curve C)

Thus, the nugget expansion appears to be the difference between Curve A and the sum of Curves B, C, and D.

Discussion - This evaluation showed that there is a definite relationship between the measured system expansion and the final nugget size. For this material combination and weld schedule, a total expansion of 0.0100 inches occurs from heating and weld formation (Curve A). It is also noted that the thermal expansion of the electrodes appears to be a significant portion of the total system expansion (Curve B). For this case, the expansion of the electrodes measured 0.0050 inches or approximately 50 percent of the weld formation expansion. However, during this test, the electrical resistance normally present in the developing weld was not a factor. As a result, the secondary current present in the circuit would be much higher and the thermal expansion of the electrodes, therefore, higher. Therefore, it can be concluded that the expansion of the electrode is something less than 50 percent of the total system expansion.

Comparing Curves A and C, it is noted that the total system expansion drops significantly when the heat is reduced sufficiently so that the welding threshold is achieved. It is concluded that the heat applied up to the threshold of weld formation results in an expansion which is approximately 20 percent of the weld formation expansion value. This expansion is caused by the sum total expansion of the electrodes and the parent metal. This indicates that most of the expansion (80 percent) occurs when the nugget is being formed and that a definite relationship exists between the nugget size and expansion signal. This signal, however, is a relative number, due to the previously discussed expansion of the electrodes.

To determine an absolute relationship between the recorded expansion and the nugget size is probably impossible. However, this study does show that the measured total system expansion can be correlated to weld nugget growth and final weld nugget size. Utilizing this information further, studies were undertaken to develop satisfactory feedback control weld schedules for weldbonding the Fairchild panels and to develop an approach philosophy whereby nugget expansion feedback control can be applied to other situations.

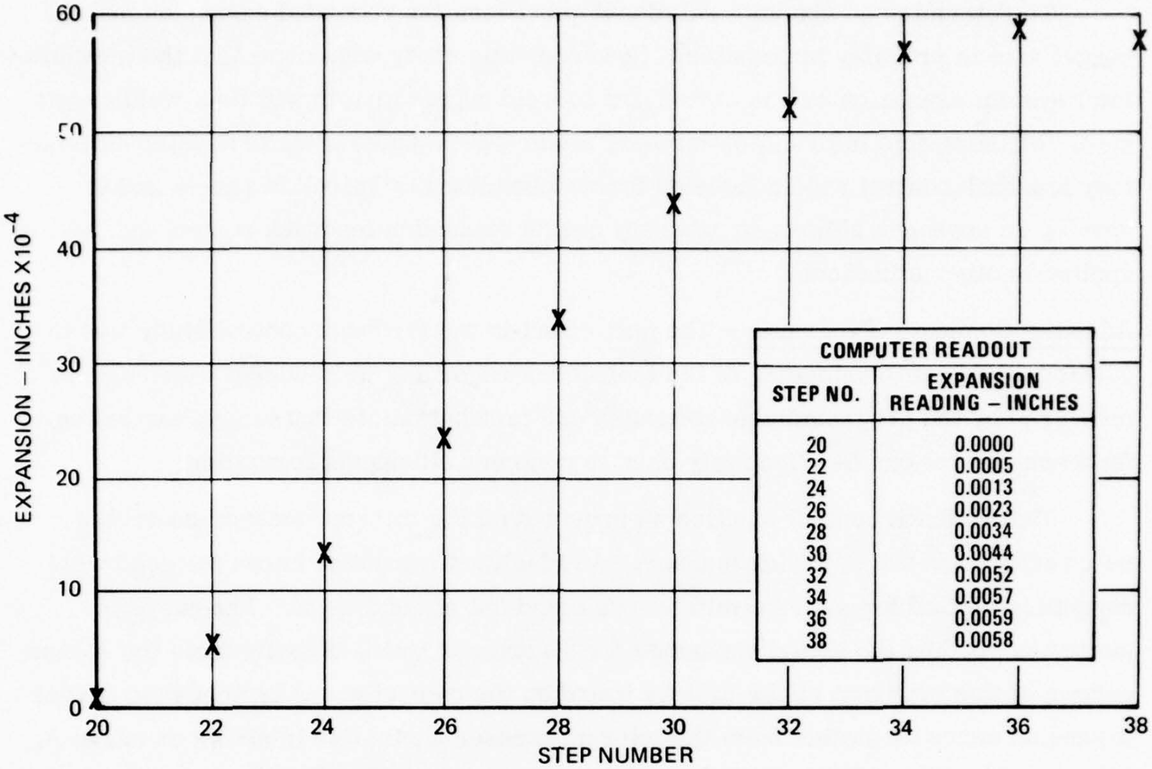
Adapting Computer Programs - The next effort in the feedback control study was to develop a basic understanding of the techniques regarding weld nugget expansion as measured by the programmable computer and to substantiate that nugget expansion feedback control can be effectively used to control weld nugget formation.

The feedback control function as provided on the microprocessor control is best reviewed in the following manner. An idealized expansion curve for good weld nuggets is plotted for a given weld schedule and set of conditions. The curve is plotted by reading the actual expansion for a series of welds directly from the A-data column of this program on the display board on the computer. A typical weld nugget expansion curve as plotted from the microprocessor controller is shown as curve A, in Figure 62. This idealized or "target" expansion curve can then be entered into the computer.

The computer has the ability to examine the amount of expansion after each weld cycle and to determine how close this expansion is to the predetermined target value of the idealized curve.

In making welds in a feedback control mode, the actual expansion measurement observed by the computer, after each cycle of heat, is compared to the target value. If there is a deviation from the target value, the percentage of error is automatically calculated by the computer. The computer then corrects the following cycle of heat to compensate for the error. The level of correction is determined by (1) amount of deviation and (2) a "percentage of heat" correction factor called the "gain factor." The gain factor required must be determined experimentally during development of the feedback control weld schedule, and is entered into the computer program prior to the applied heat cycle. The needed correction is then computed automatically.

1. If the error is negative due to the measured expansion being below the target value (which indicates growth of a subsize weld nugget) the current for the next cycle will be increased to increase the nugget growth rate.



COMPUTER READOUT	
STEP NO.	EXPANSION READING – INCHES
20	0.0000
22	0.0005
24	0.0013
26	0.0023
28	0.0034
30	0.0044
32	0.0052
34	0.0057
36	0.0059
38	0.0058

FIGURE 62. TYPICAL WELD NUGGET EXPANSION DATA POINTS AS PLOTTED FROM THE COMPUTER READOUT

2. If the error is positive due to an increase in an expansion above the target value (indicating a larger than desired nugget and possible tendency towards expulsion) the current on the next cycle will be decreased to appropriately decrease the weld nugget size.
3. After the correction is calculated and the following (corrected) cycle of heat applied, the resulting expansion is again measured and the process repeated.

The result of the cycle-by-cycle control of weld heat is to achieve uniform weld nugget growth and a consistent size nugget. Using this technique, a feedback control welding schedule was developed for the 0.050/0.071-inch combination using the weld schedule of Figure 60. The portion of the weld schedule which was modified to accomodate the feedback commands is shown in Figure 63. The effectiveness of this feedback schedule was then demonstrated at Northrop by proving that it had the ability to compensate for shunting variations. A series of welds with approximately 1-inch spacing was made using 1-inch x 8-inch samples. The final welds were then placed between two previous welds which formed a strong current shunt. The results can be seen in Figure 64. A wide variation in the size of the welds resulted when they were made without feedback control. However, even the welds made with close spacing were consistent when feedback control was applied to compensate for the current loss through the shunt weld. By its ability to detect that the weld was growing subsize, the computer automatically boosted the current to provide additional heat to allow the weld nugget to grow to full size.

Feedback Control For Revised Weld Schedules

It was at this point in the program that the problems of achieving (1) quality welds in the thin gage material and (2) round, consistent nuggets in the heavier gage material became apparent. As previously discussed, the welding philosophy was altered, and revised weld schedules which were characterized by a longer forge delay were developed. The program scope and schedule did not permit sufficient time to thoroughly investigate the application of feedback control for the revised weld schedule prior to the manufacture of the test panels. Therefore the actual test panels were manufactured without the benefit of feedback controlled spot welding.

BASIC SCHEDULE(1)
NO FEEDBACK

STEP NO./EXPANSION TARGET VALUE $X10^{-5}$ IN	GAIN FACTOR	CURRENT VALUE % MAX
25/000	000	44
27/000	000	50
29/000	000	54
31/000	000	54
33/000	000	44
35/000	000	42
37/000	000	40

MODIFIED SCHEDULE
WITH FEEDBACK CONTROL

STEP NO./EXPANSION TARGET VALUE $X10^{-5}$ IN	GAIN FACTOR	CURRENT VALUE % MAX
25/165	064	44
27/170	098	50
29/185	129	54
31/200	128	54
33/215	195	44
35/215	195	42
37/215	195	40

(1) ENTIRE BASIC WELD SCHEDULE IS SHOWN IN FIGURE 60.

FIGURE 63. COMPARISON OF BASIC AND FEEDBACK CONTROL WELD SCHEDULES FOR 0.071/0.050-INCH MATERIAL COMBINATION (1)

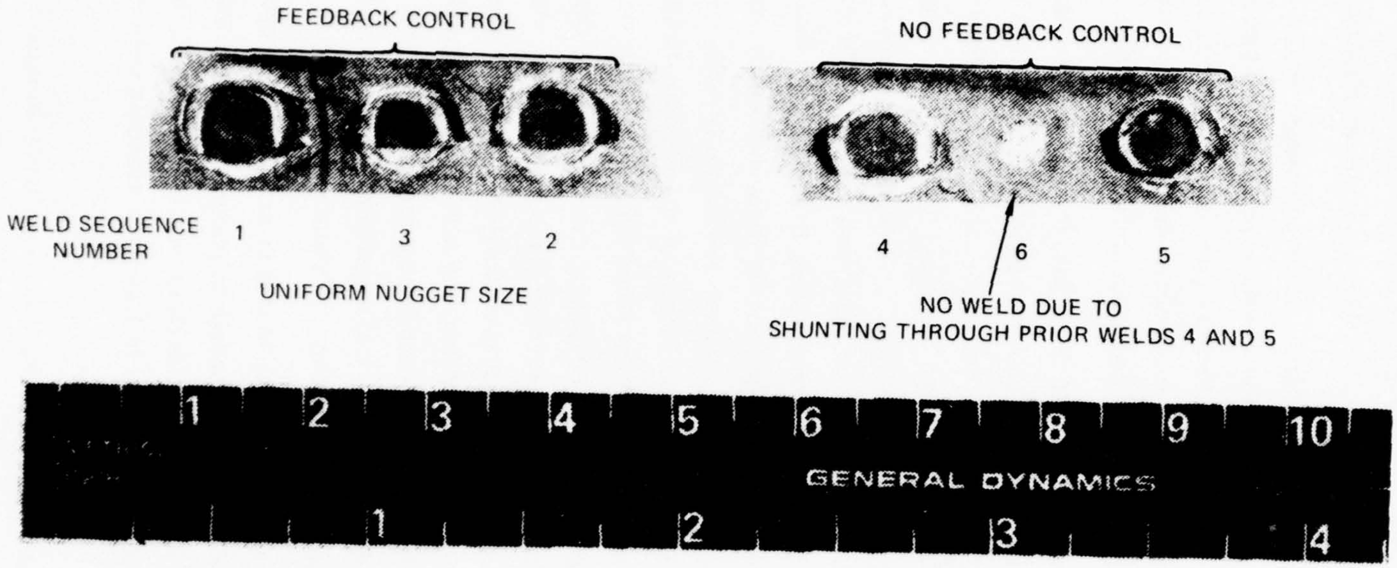


FIGURE 64. EFFECTIVENESS OF FEEDBACK CONTROL IN COMPENSATING FOR SHUNTING EFFECT

After the test panels were manufactured and shipped to Fairchild Republic, an effort was undertaken to adapt feedback control to these weld schedules. Emphasis was placed on 0.050/0.040 and 0.032/0.025 material combinations.

Although these new weld schedules achieved greater nugget roundness and consistency, applying feedback control to them proved to be more difficult than with the original weld schedules. This was due to the fact that these weld schedules were characterized by a long, forge delay after the initial application of heat which resulted in a significant reduction in the total system expansion.

Expansion for the 0.050/0.040 material combination was found to be from 0.0020 to 0.0040 inches compared to a previous value of 0.0100 inch. The measured expansion on the 0.032/0.025 material combination was so small (0.0002 to 0.0008 inch) that feedback control was not deemed practical for that weld schedule. Convair developed a feedback control weld schedule for the 0.050/0.040 combination and demonstrated its effectiveness in achieving target value expansion numbers. In attempting to apply this weld schedule to the Northrop equipment, it was noticed that the expansion values of welds made at Convair varied significantly from those at Northrop. This variation was shown to be due to slight differences in the characteristics of the air pressure and exhaust system including friction and inertia of the movable head and a damping effect which occurred at the completion of the forge cycle. It was concluded that as the forge and expansion processes are occurring simultaneously, slight variations in the movement of the welding machine head can make a significant change in the shape and magnitude of the expansion curve. It was found that a closer similarity between the two pieces of equipment could be achieved by utilizing the Convair ramp system, (Reference 3), whereby the air exhaust during forge was controlled by two exhaust valves and a controlled orifice. Typical expansion traces taken from Northrop and Convair welding machines for basically the same weld schedules are shown in Figure 65.

Further work was conducted at Northrop in an effort to optimize the feedback control features of the new weld schedule to make it effective for controlling nugget quality. It was found however, that certain characteristics made effective application of nugget expansion feedback control to this weld schedule unlikely. These characteristic were:

1. For maximum effectiveness and consistency in measuring expansion, the computer must start its measurements at the specific cycle which represents the bottom of the forge movement as shown in Figure 66. However,

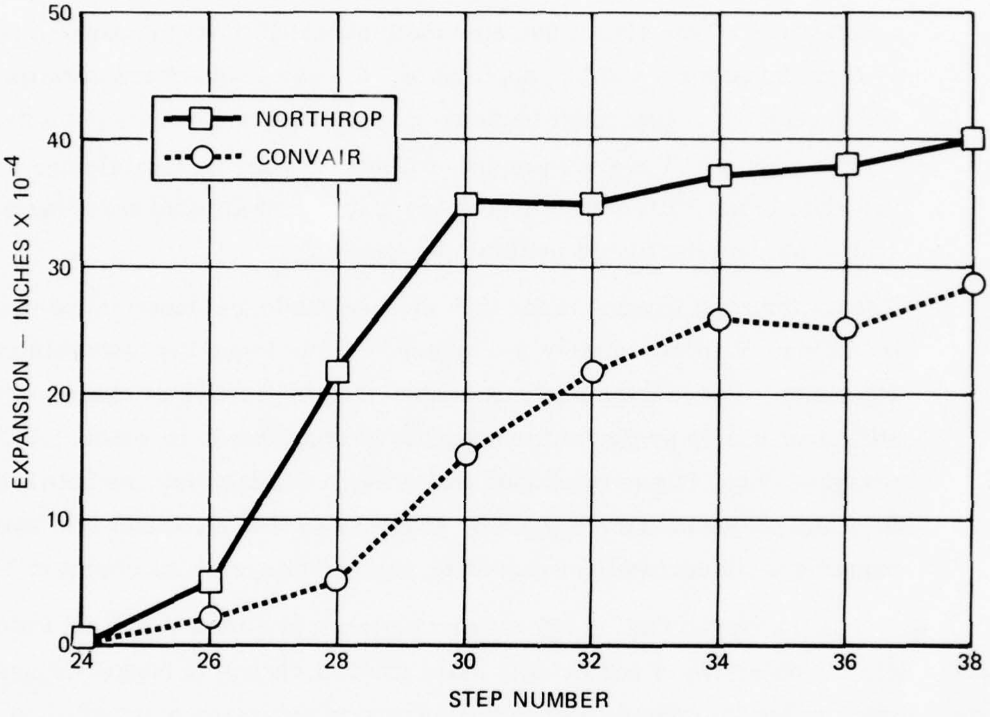
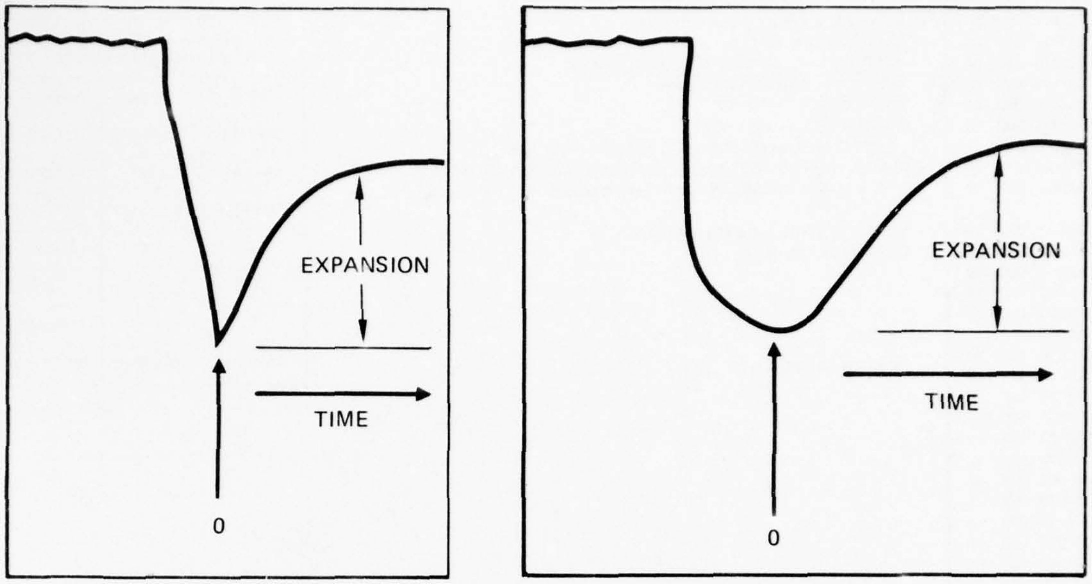


FIGURE 65. COMPARISON OF EXPANSION TRACES FOR NORTHROP AND CONVAIR WELDING EQUIPMENT FOR THE SAME WELD SCHEDULE

due to the fact that (for this particular weld schedule), both a high forge pressure and a high heating rate were being applied at the same time, the minimum expansion value varied significantly from weld to weld due to the sharp trough formed in the time expansion trace as shown in Figure 66(a). As a result, the computer could not accurately or consistenly re-zero its memory to start expansion readings at the exact minimum. In order to correct this situation, it was concluded that a more delicate balance of the weld heat and pressure curve would have to be achieved so that a more gradual trough as is shown in Figure 66(b) was formed to achieve greater consistency. This also illustrated the fact that if nugget expansion feedback is considered for a welding application, the expansion characteristics of the developing nugget must be taken into account in developing the basic weld schedule. The achievement of Class A welds by a particular weld schedule is not sufficient to guarantee that nugget expansion feedback control would be effective in maintaining quality.

2. The total nugget expansion for this weld schedule and material combination took place in approximately 2-3 cycles. It was found that with this rapid expansion, closed loop feedback control was ineffective as there were insufficient cycles available for adequate corrections to be made. As in the previous case, it was concluded that a more delicate balance between the heat and pressure curves must be achieved so that expansion and resulting nugget growth occurs over a greater number of cycles as shown in Figure 67.

It was thus concluded that an effort must be taken to revise the basic weld schedule with the objective of achieving a more gradual change in nugget expansion characteristics at the minimum expansion value and to achieve a more gradual nugget growth over a greater number of cycles. By delicately balancing the applied heat and accurately measuring the change in the expansion characteristics on a cycle-by-cycle basis, this objective was achieved. It was found that by reducing the amount of heat in the up-slope and by applying greater heat later in the weld program, that the nugget could be made to expand to the same size and quality over a 5 to 6 cycle time frame rather than a 2 to 3 cycle growth period previously experienced. It was also found that by delicately balancing the heat on the up-slope of the curve that a more gradual expansion change occurred at the minimum expansion point, thereby allowing for a more accurate zero point to be set by the computer. The resulting weld schedule is shown in Figure 68 and the nugget expansion trace is shown in Figure 69. It can be observed that the expansion characteristics were more consistant and could readily be adapted to both nugget expansion monitoring and feedback control.



(a) POOR CONTROL –
TROUGH TOO SHARP

(b) GOOD CONTROL –
TROUGH GRADUAL

FIGURE 66. INCREASED NUGGET GROWTH TIME IMPROVES FEEDBACK EXPANSION CONTROL

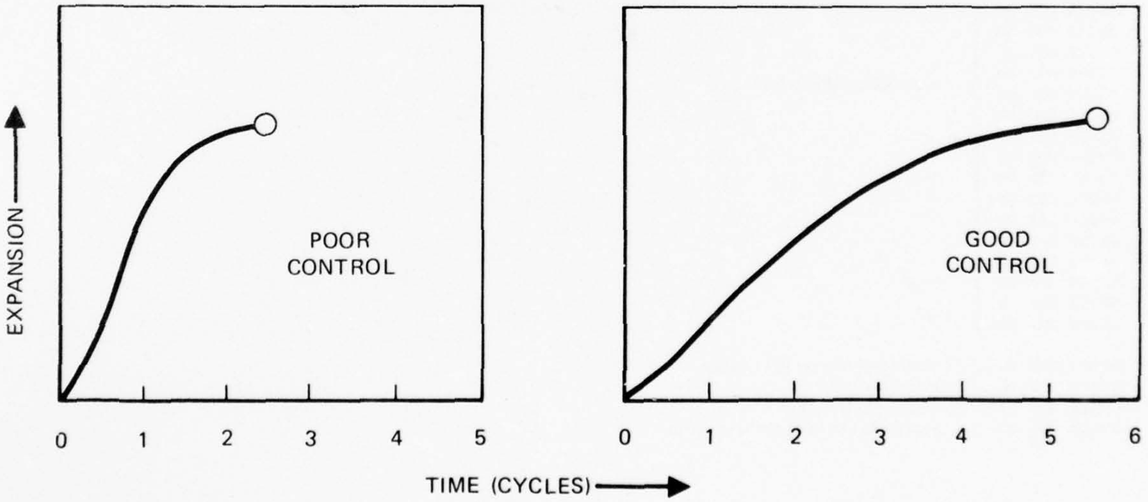


FIGURE 67. EFFECTIVE CONTROL OF ZERO POINT IN EXPANSION CYCLE

```
00/401 000 01    TURN-ON – APPLY WELD PRESSURE
01/002 000 00    TEST FOOT SWITCH
02/800 180 06    HOLD 180 CYCLES, CONTACT GAGE CHECK
03/403 000 01    TURN-ON – BRUSH RECORDER
04/800 000 00    SPARE HOLD COMMAND
05/001 000 00    DO NOTHING – ONE CYCLE
06/498 011 01    RE-ZERO FEEDBACK ENCODER AFTER 11 CYCLES
07/498 010 00    START READING FEEDBACK EXPANSION – AFTER 10 CYCLES
08/402 005 01    APPLY FORGE PRESSURE – AFTER 5 CYCLES

09/191 025 30    VOLTAGE SPIKE – 1 CYCLE AT 30%
11/000 000 01    ONE CYCLE COOL
13/000 000 09
15/000 000 19
17/000 000 27
19/000 000 31
21/000 000 30    HEAT UP-SLOPE – 9 CYCLES
23/000 000 48
25/000 000 50
27/000 000 48
29/000 000 50
31/000 000 42
33/000 000 42
35/000 000 41
37/000 000 39
39/000 000 37
41/000 000 34
43/000 000 30    HEAT DOWN-SLOPE – 14 CYCLES
45/000 000 29
47/000 000 28
49/000 000 27
51/000 000 26
53/000 000 25
55/000 000 24
57/000 000 24

10/255 000 00
12/255 000 00
14/255 000 00
16/255 000 00
18/255 000 00
20/255 000 00
22/255 000 00
24/255 000 00
26/255 000 00
28/255 000 00
30/255 000 00
32/255 000 00    EXPANSION MONITORING
34/255 000 00
36/255 000 00
38/255 000 00
40/255 000 00
42/255 000 00
44/255 000 00
46/255 000 00
48/255 000 00
50/255 000 00
52/255 000 00
54/255 000 00
56/255 000 00

58/403 000 00    TURN-OFF BRUSH RECORDER
59/800 200 00    HOLD 200 CYCLES
60/498 000 01    RESET FEEDBACK ENCODER
61/003 000 00    FINISH WELD, RETURN TO STEP 00
```

0.040/0.050 SPECIMEN WELDS MAXIMUM EXPANSION CONTROL		
0.040	0.050	GAGE
2024-T3	7075-T6	ALLOY
ALCLAD	BARE	CLAD/BARE
1.0V PSD	1.5V PSD	SURFACE PREP
5/8"	5/8"	ELECT – DIA
10"	10"	TIP RADII
1	1	CLASS
500 LBS /	2000 LBS	WELD/FORGE

FIGURE 68. WELD SCHEDULE FOR 0.040/0.050 MATERIAL COMBINATION FOR OPTIMUM NUGGET EXPANSION CONTROL

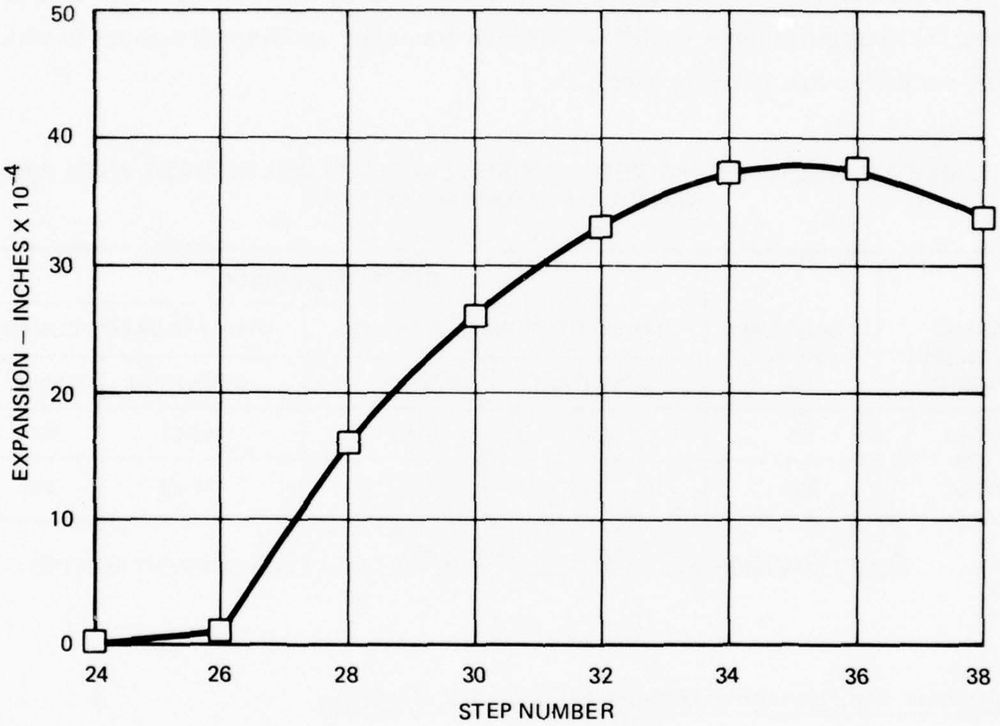


FIGURE 69. NUGGET EXPANSION TRACE FOR OPTIMIZED WELD SCHEDULE

Feedback control commands were then added to this basic weld schedule using the Convair approach, and a series of single-spotweld lap-shear specimens were made. The results, as shown in Table 11, proved that expansion consistency was improved with the application of feedback control. The average variation in expansion readings was 18 percent without feedback control but was reduced to 6 percent when feedback control was applied. However, it should be noted that this basic weld schedule (without feedback control added) was extremely effective in producing consistent quality welds. Inasmuch as only a limited (10 specimen) sampling was used, the addition of feedback control to the basic schedule did not result in improved consistency in weld strengths in spite of the improved consistency in nugget expansion characteristics. It is felt however that improvements could be expected for other welding situations in which welding variables are more critical.

TABLE 11. NUGGET EXPANSION CONSISTENCY FOR WELDS MADE WITH AND WITHOUT FEEDBACK CONTROL

SHEET THICKNESS (INCH)	MAXIMUM CURRENT (%)	NUGGET EXPANSION			
		WITHOUT FEEDBACK CONTROL		WITH FEEDBACK CONTROL	
		0.001 INCH	RANGE	0.001 INCH	RANGE
0.040 TO 0.050	53	45-55	20%	49-53	8%
	50	43-51	17%	47-49	4%

NOTE: NUGGET EXPANSION WAS MEASURED FOR 10 WELDS AT EACH CURRENT SETTING

Conclusions and Recommendations of Feedback Control

As a result of this work it can be concluded that feedback control appears to be an effective aid in maintaining nugget size and quality. However, it is imperative that a good basic weld schedule be developed considering the application of feedback control. It also must be recognized that feedback control is a tool for achieving nugget consistency with a good weld schedule and to minimize the effects of process and equipment variations. It should not be thought of as a crutch for making an inadequate weld schedule effective.

Based on this work, a guide was developed which can serve as an aid for proper use of nugget expansion feedback control in any spotwelding situation.

1. The basic weld schedule must be developed considering the expansion characteristics of the nugget. It has been found that there are many different heat and pressure combinations that will achieve Class A welds. However, the achievement of Class A welds by a particular weld schedule does not indicate that this particular weld schedule may be readily adapted to feedback control conditions.

2. Both the basic weld schedule and feedback control adaptation must be developed considering shunting effects. Certain weld schedules, particularly those with long heat up-slopes, are more prone to shunting than others. If a particular weld schedule is prone to shunting, the schedule should be developed using multiple spots rather than single spots on indivual specimens.

3. In developing the basic weld schedule, consideration must be given to controlling the zero point of the expansion trace. If the expansion characteristics of the system are rapidly changing at the minimum value, resulting in a sharp trough, as shown in Figure 66 (a), the computer is not able to accurately determine the actual zero point and large errors may result. A proper heat and pressure balance resulting in a more gradual expansion change (gradual trough) near the minimum expansion point prior to nugget expansion as shown in Figure 66 (b), should be achieved for consistency. If possible, the use of an early forge force should be used which results in most of the expansion taking place under a constant pressure condition.

4. It is imperative that the nugget growth period be maximized and occur over approximately 6 or more cycles of heat. As shown in Figure 67, if the nugget growth is too rapid, it is unlikely that feedback control will be successful.

5. Accurate target values must be determined using an adequate sampling. A minimum of 25 welds involving some process condition variables is recommended.

6. Correction gain factors should be applied in an increasing magnitude. It is advisable to apply a small gain factor in the first few cycles of expansion and to increase the gain factor as the nugget begins to grow. In certain instances, it is not advisable to apply a gain correction on the first cycle of expansion particularly if the expansion is small and a large variation occurs in the target value.

In summary, feedback control has been shown to be an effective aid to maintain consistancy with a good welding schedule. Further development and understanding of this powerful tool, however, must be forthcoming before its full utilization can be achieved. A word of caution, for the prospective user. Feedback control cannot be used as a supplement for a bad or marginal weld schedule. A good weld schedule must be developed preferably one that shows wide flexibility in accommodating variations in the processing parameters, surface conditions, and machine characteristics. We have found this to be an achievable goal utilizing microprocessor programmable control. If this approach is taken and an adequate engineering effort put forth to develop appropriate target and gain factors for a given weld schedule, feedback control can be a powerful tool for achieving consistancy in a production welding situation, and allowing for in-process control of the weld nugget. This will result in an economic benefit by reducing the amount of inspection required on the finished product.

FATIGUE EVALUATION

The effects of material and process variables on the fatigue and fracture behavior of weldbonded joints were determined: a) to establish optimum nugget size and spacing for best fatigue resistance of weldbonded structures at reduced manufacturing cost, b) to compare weldbonding with adhesive bonding and riveting and c) to determine the effects of poor weldbond processing control on the fatigue and fatigue crack growth behavior of weldbonded joints. Fractographic and metallographic investigations were performed to explain the fatigue test results and to provide a basis for meaningful process control.

OVERVIEW OF THE TEST PROGRAM

Two types of specimens were utilized for fatigue testing in this program. The majority of the testing was performed with a low-load transfer specimen geometry to simulate a commonly used aircraft construction, a skin stiffened with doublers. The other specimen geometry utilized was a lap-shear specimen which simulated the less common high-load transfer joint.

Two material combinations commonly used in aircraft structures were evaluated. These were: 1) 7075-T6 bare skin with 7075-T6 bare doublers and 2) 2024-T3 alclad skin with 7075-T6 bare doublers.

Table 12 summarizes the various parameters evaluated. The parameters receiving the most attention were changes in nugget size and nugget spacing. Nugget size and spacing influence several areas including design, fatigue behavior and manufacturing costs in the application of the weldbond process to aircraft structures. The effects of poor process control were evaluated by modifying the weld schedules and surface preparation procedures to produce subsurface and surface-cracked nuggets, nuggets with excessive indentation, and nuggets with expulsion.

TABLE 12. SUMMARY OF VARIABLES INVESTIGATED FOR FATIGUE EVALUATION OF WELDBONDED JOINTS

7075-T6/7075-T6

- Low-Load Transfer
  1. Manufacturing Variables
     a. Nugget Size and Spacing
     b. Manufacturing Defects
        - Surface Cracked Nugget
        - Subsurface Cracked Nugget
        - Nugget Porosity
        - High Indentation Nugget
        - Expulsion
        - Miscellaneous
  2. Comparison Tests
     - Adhesive Bond
     - Adhesive Bond with Anti-Peel Rivet
     - Riveted
- High-Load Transfer
  1. Manufacturing Variables
     a. Nugget Size
     b. Manufacturing Defects
        - Expulsion
        - Subsurface Cracked Nugget
  2. Comparison Tests
     - Adhesive Bond
     - Adhesive Bond with a Disbond
     - Riveted
- Fatigue-Crack Growth
  - Flawed Weldbonded
  - Flawed Riveted

2024-T3 Alclad/7075-T6

Low-Load Transfer – one nugget size and spacing

High-Load Transfer – one nugget size

All failed specimens were examined to determine fatigue-crack initiation sites. In some cases, these examinations revealed minor defects in nugget quality and material quality that would pass normal quality standards. The defects included nugget porosity, handling nicks and scratches, pits and second phase inclusions.

The weldbond fatigue behavior was compared to that of competing joining techniques commonly used in airframe assembly. For this purpose, low-load and high-load transfer specimens were fabricated by riveting, adhesive bonding and adhesive bonding with anti-peel rivets. Fatigue-crack growth testing was performed on preflawed weldbonded and preflawed riveted specimens.

EXPERIMENTAL PROCEDURE

The low-load transfer specimen shown in Figure 70 was designed to simulate a typical aircraft skin stiffened with doublers. The design is basically no-load transfer with some load transfer occurring at the doubler radius. The tests were conducted in tension-tension fatigue with a load ratio, R (minimum load/maximum load) of 0.1 in a temperature and humidity (75 ± 5F and 50 ± 5 percent rh) controlled laboratory atmosphere at a frequency of 10 Hz. A majority of the tests was performed at a maximum stress of 32 ksi to produce fatigue failure in reasonable times for the different conditions being evaluated. Several specimens were strain gaged and tested to verify alignment. The maximum bending was found to be less than two percent.

The high-load transfer specimen, used for weldbonded and adhesively bonded joints, shown in Figure 71, was designed to simulate a lap joint and to force failure to occur in the joint rather than in the base material. Failure was forced to occur in the joint by adhesively bonding doublers to the specimen as shown. Weldbond adhesive was used to bond the doublers and the assembled specimens were cured in one cycle. Preliminary testing showed that without the doublers the specimen failed near the edge of the lap which prevented comparing weldbonding and adhesive bonding. The riveted high-load transfer specimen (Figure 72) was based on MIL-STD-1312-21A for shear joint fatigue testing of fasteners. The results of tests with this specimen can be compared only indirectly to the weldbonded and adhesively bonded results because of the differences in specimen geometries. The fatigue load levels were selected to produce failures in the 10^4 to 10^6 cycle range. Tests were conducted with the same load ratio and environmental conditions as the low-load transfer tests.

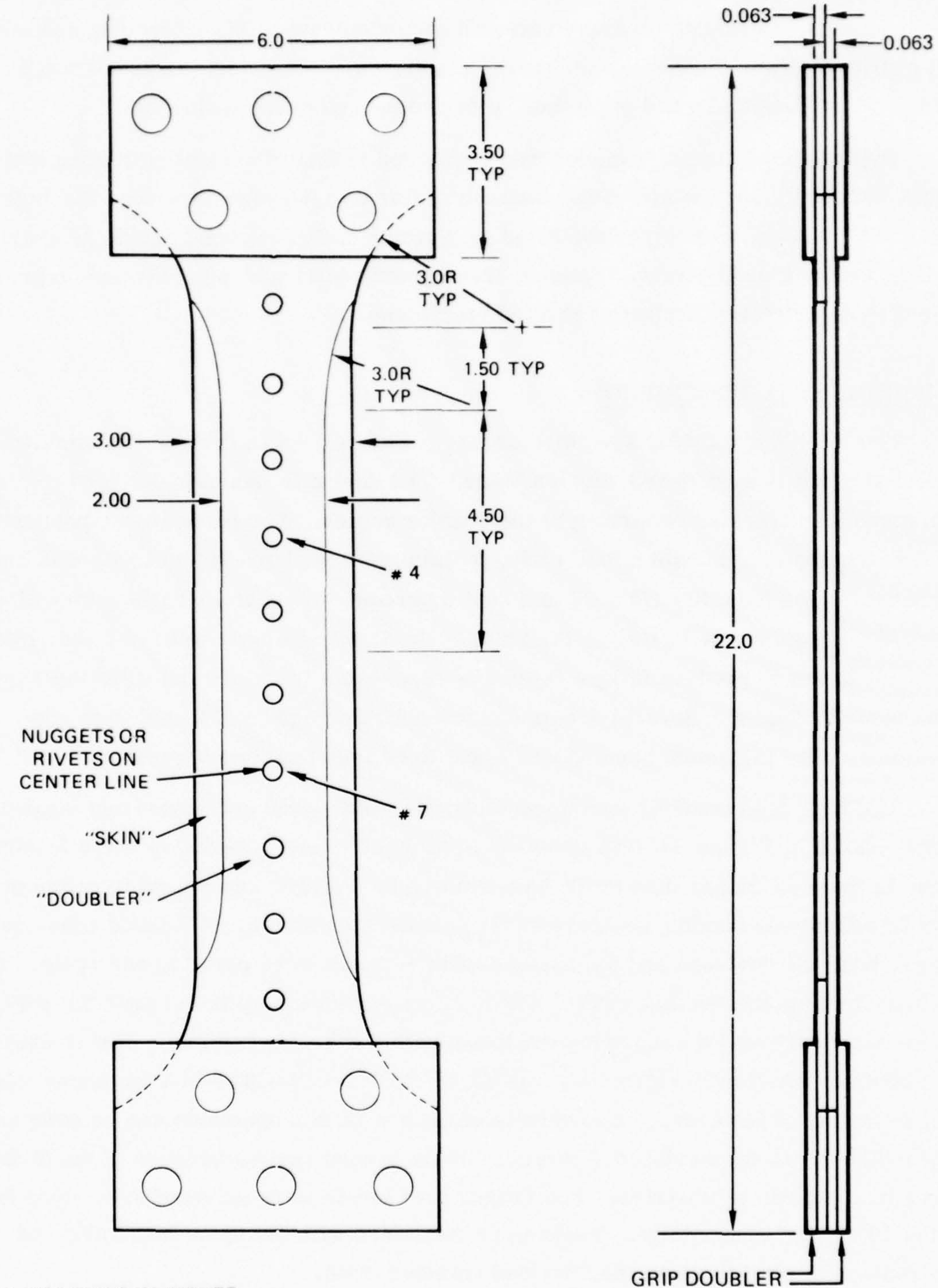


FIGURE 70 LOW-LOAD TRANSFER FATIGUE SPECIMEN

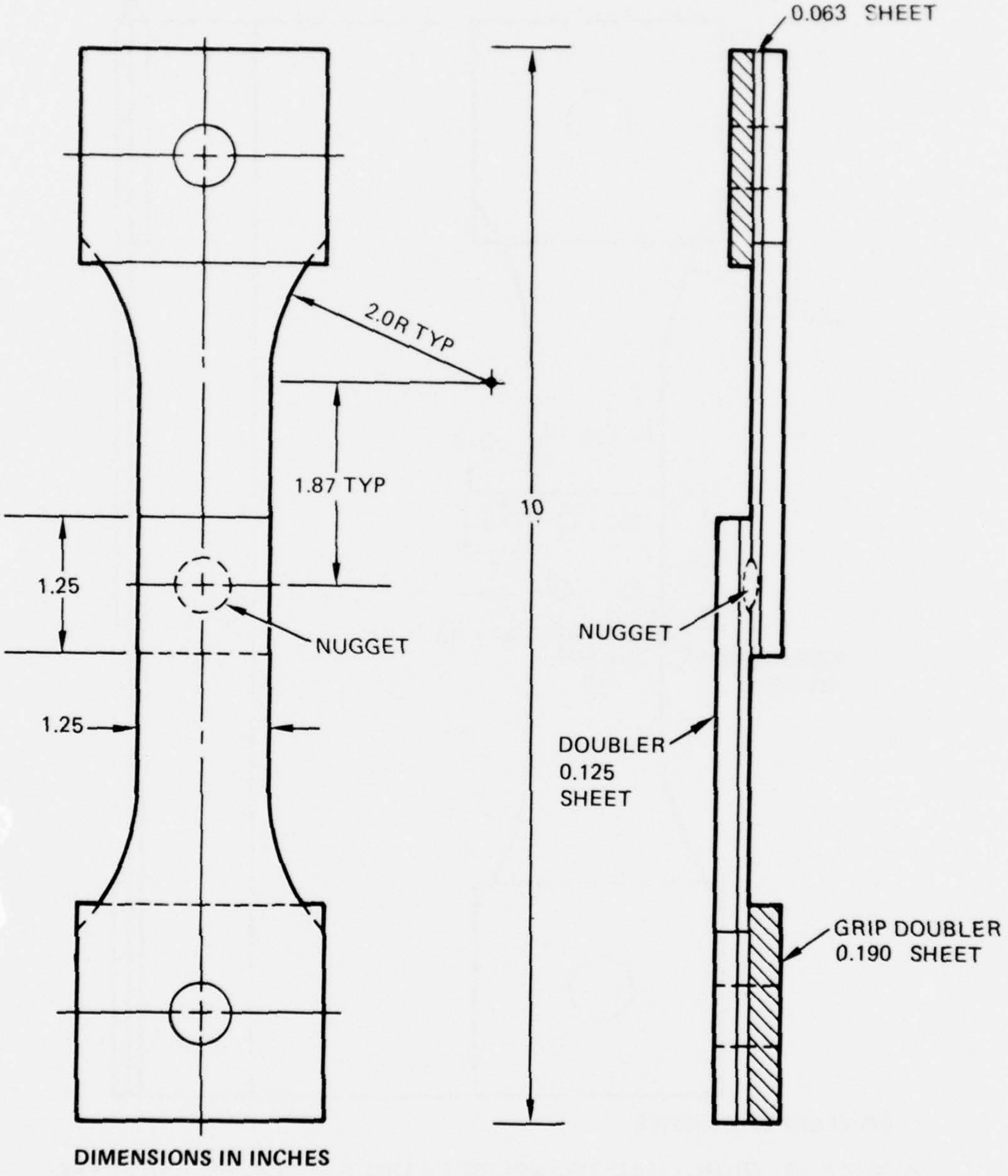


FIGURE 71 HIGH-LOAD TRANSFER FATIGUE SPECIMEN WELDBOND AND ADHESIVE BOND

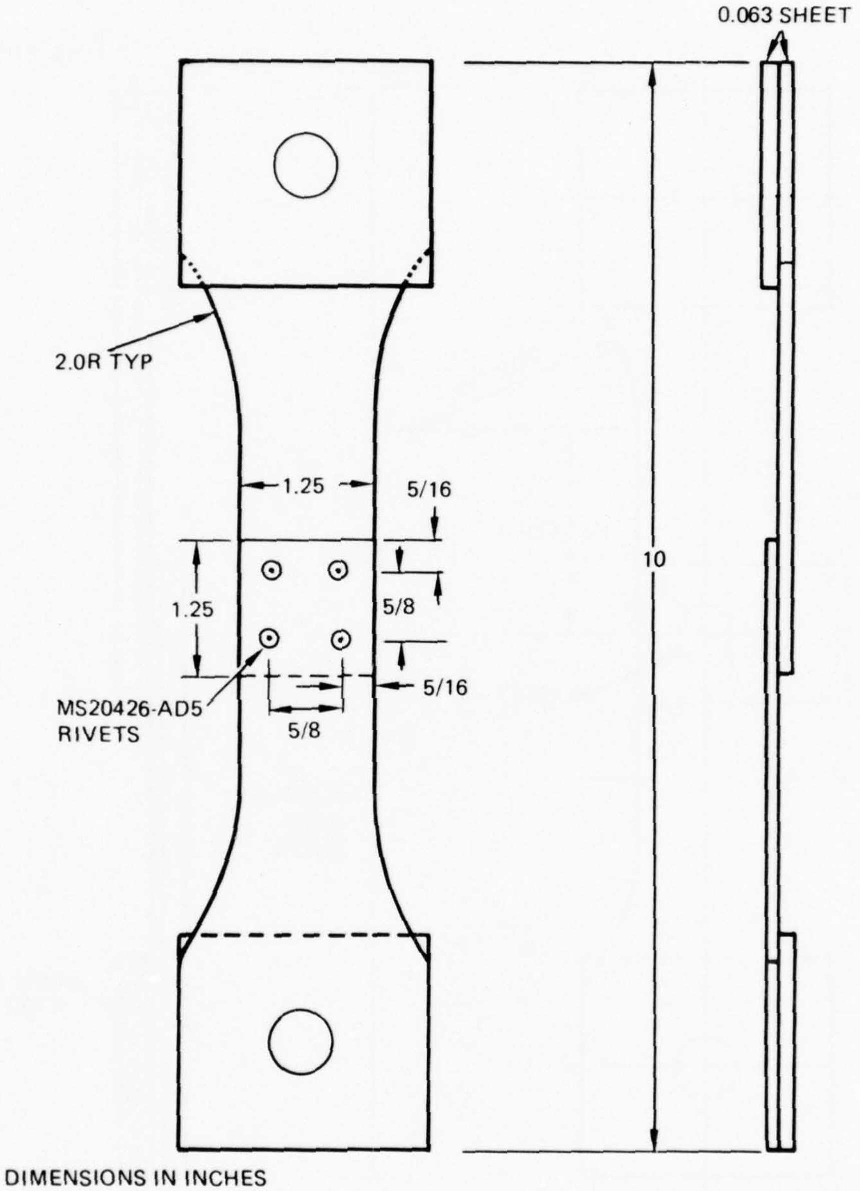


FIGURE 72. HIGH-LOAD TRANSFER FATIGUE SPECIMEN – RIVETED

To evaluate the effects of weld nugget size, the welding current was varied to produce nuggets in the size range desired. Three nugget sizes were selected based on past experience (References 3 and 5): small, with a 0.18 - 0.22-inch nugget diameter, medium with a 0.23 - 0.27-inch diameter, and large, with a 0.28 - 0.33-inch nugget diameter. Any significant variations from the intended range are noted in the tabulated results. All specimens were radiographically inspected for nugget quality and determination of nugget sizes.

Spot weld spacing was varied on low-load transfer specimens to evaluate its effect on fatigue. The weldbond process places limits on the range of spacing because the spacing must be large enough to avoid shunting and small enough to control the bondline thickness. Working within these limits, spacings of 1.0-, 1.5-, 2.0- and 3.0-inch were selected.

Various weld nugget defects were intentionally produced by deviating from the normal weldbonding weld schedule and/or surface preparation as described below. Since different deviations in the weldbond procedure were required for the various types of defects, the nugget sizes were not the same for each type of defect.

a) Cracked weld nuggets were produced by polishing the sheet at the nugget location to remove the oxide and by using a lower electrode force. Two cracked nuggets were produced on six specimens. Three specimens contained one surface cracked nugget. The other nuggets had subsurface cracks of varying crack sizes. The nugget size of the cracked nuggets was large.

b) Expulsion was produced by creating a thicker oxide and by using a lower electrode force. The size of nuggets with expulsion was medium.

c) High indentation nuggets were produced by using higher current and higher electrode force. The size of high indentation nuggets was about 0.37-inch diameter.

Fatigue-crack growth data was obtained for weldbonded specimens with surface and subsurface cracked nuggets. Data was obtained visually at regular intervals utilizing a traveling microscope after the cracks appeared on the surface of the specimen. In all the surface cracked specimens, the crack length on the surface was initially known but the actual shape of the surface crack was unknown. The actual shape and size of surface and subsurface cracks at the failed nugget was obtained by observing the fracture surface under a microscope. No information on the size and shape of initial surface or subsurface flaw was obtained for the unfailed nuggets.

The FPL/BR-127/FM 123-2 adhesive system was selected for adhesive bonding comparison testing as this system is well known and is currently being used to fabricate aircraft structure. Adhesive bonded low-load transfer specimens were also fabricated with anti-peel rivets. These specimens used two round head 1/8-inch diameter rivets (MS 20470AD) with a 4.5-inch spacing. The rivets were wet installed per MIL-S-81733, "Sealing and Coating Compound, Corrosion Inhibitive," with PR 1431G Type IV sealant.

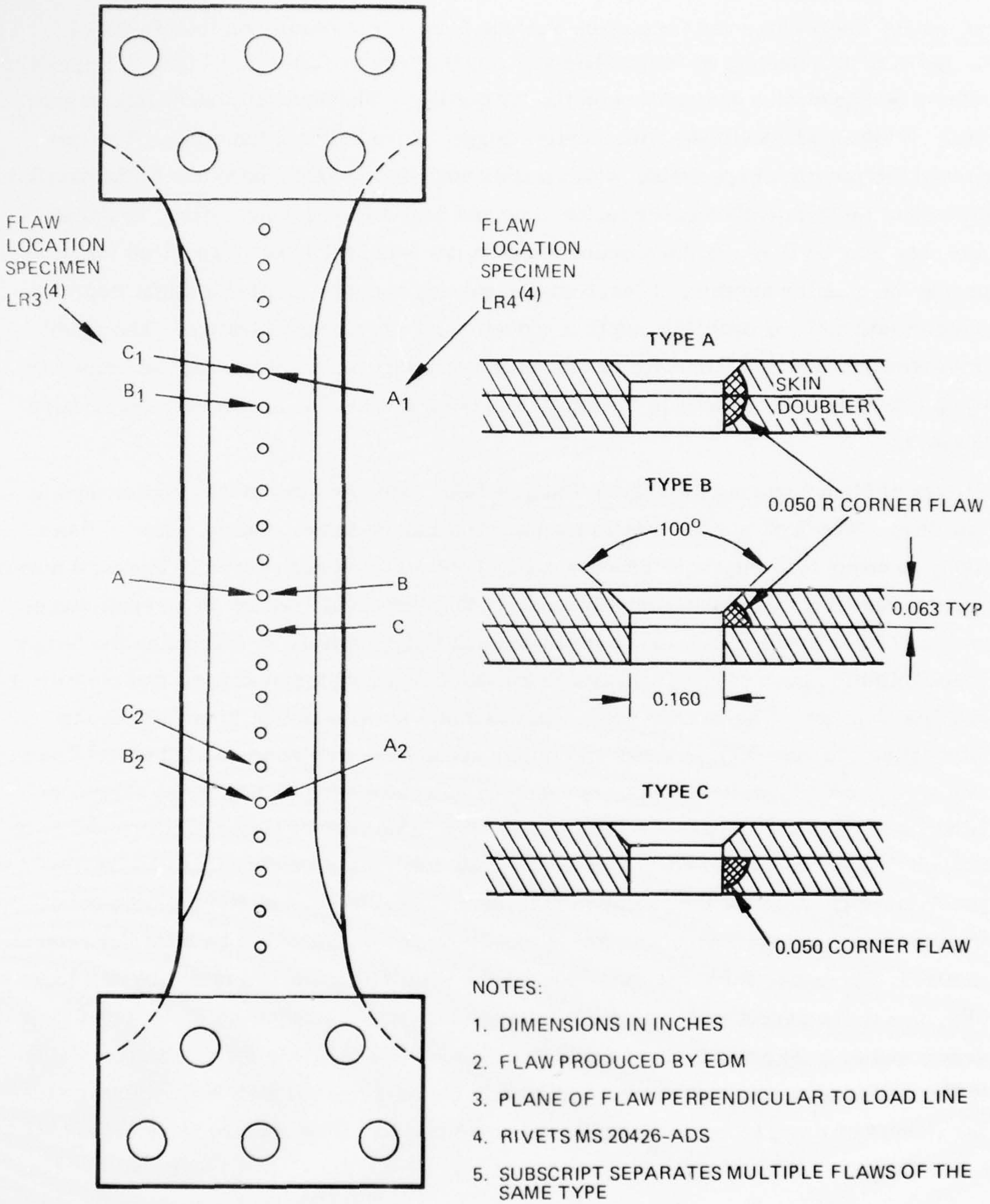
To evaluate the effect of a typical flaw that could occur in a high-load transfer adhesively bonded structure, high-load transfer specimens were fabricated with a 0.7-inch diameter disbond (approximately 25 percent of the joint area). This defect was formed by cutting a hole in the film adhesive and placing a 0.003-inch thick Teflon disc in the hole centered in the lap.

Riveted specimens as shown in Figures 70 and 72 were used for baseline riveted data. These specimens were riveted with flush head 5/32-inch diameter rivets, MS 20426-AD. The rivets were placed on 5/8-inch centers. Riveted specimens were also fabricated with EDM flaws per MIL-A-83444, "Aircraft Damage Tolerance Requirements," utilizing three combinations of flaw locations as shown in Figure 73. Fatigue crack growth data was obtained for these preflawed riveted specimens with the same techniques utilized for the weldbonded specimens with cracked nuggets.

Doublers were used in the grip areas to avoid premature failure. For riveted specimens, the grip doublers were adhesively bonded, after riveting. For weldbonded specimens the grip doublers were weldbonded, while for the adhesively bonded, the grip doublers were adhesively bonded, and the specimens and doubler assemblies were cured in one cycle.

RESULTS AND DISCUSSION

The majority of the experimental work on this program was performed on 7075-T6 bonded to 7075-T6. After completion of these tests, selected tests were performed on 2024-T3 alclad weldbonded to 7075-T6. Therefore, the results on the 7075-T6/7075-T6 will be discussed first followed by a discussion of the 2024-T3 alclad/7075-T6 results. Furthermore, for the 7075-T6/7075-T6, the low-load transfer results will be discussed first followed by the high-load transfer results.



NOTES:

1. DIMENSIONS IN INCHES
2. FLAW PRODUCED BY EDM
3. PLANE OF FLAW PERPENDICULAR TO LOAD LINE
4. RIVETS MS 20426-ADS
5. SUBSCRIPT SEPARATES MULTIPLE FLAWS OF THE SAME TYPE

FIGURE 73. LOW-LOAD TRANSFER FATIGUE SPECIMEN FOR PREFLAWED RIVET HOLE TEST

Low-Load Transfer 7075-T6/7075-T6

Effects of Nugget Size and Spacing on Fatigue Life. Test results on the effects of nugget size and spacing on fatigue life are summarized in Table 13. Figure 74 shows the effects of nugget size and spacing on the fatigue life. These results show that in general, weldbonded specimens with smaller nuggets have better fatigue life. The improved fatigue life of specimens with smaller nuggets may have been due to the smaller volume of the relatively weaker fusion zone and heat affected zone. Also, residual stresses may be lower in the smaller nuggets, as less heat input is required for producing the smaller nuggets. Closer nugget spacing appears to offer a slight improvement in fatigue life, probably due to a reduction in stress concentration. The slight improvement in fatigue life with closer nugget spacing would not warrant selecting one nugget spacing over another in the range tested because of the additional cost of extra nuggets.

Effects of Manufacturing Defects on Fatigue Life. This evaluation was approached in two ways. The first method was to intentionally induce flaws. These included flaws likely to occur with improper process control and flaws of such severity that with normal quality control measures it is highly unlikely that they would end up on aircraft structures. The second method was to evaluate each fatigue failure to determine the fatigue-crack initiation site. These evaluations revealed some material defects and inadvertent handling damage. The results were separated into those common to any aluminum fabricating process such as nicks and minor scratches, and those related to weldbonding. One type of defect, which could have been due to weldbonding or to normal aluminum fabrication and handling procedures, was pitting. One heat of material was found to be extensively and deeply pitted (0.008-0.010-inch deep) after weldbonding (Figure 75). One possible explanation for the pitting is that the material got wet in storage because of improper packaging. Therefore, these results were considered to be material related failures. However, for three other specimens with fatigue cracks initiating at small pits, one in the parent material and two within the nugget indentation (0.0004-0.001-inch deep), shown in Figure 76, it was difficult to determine whether the pits were relatable to the weldbonding process or were present in the as-received material. Nevertheless, the results of these latter tests are listed and plotted as if the failure were related to the weldbond process.

TABLE 13. EFFECT OF NUGGET SIZE AND SPACING ON WELDBONDED LOW-LOAD TRANSFER FATIGUE

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: 32 ksi maximum stress, R($\sigma_{\text{minimum}} / \sigma_{\text{maximum}}$) = 0.1,
Frequency = 10Hz, Temperature = 75 ± 5 F,
Humidity = 50 ± 5 %rh

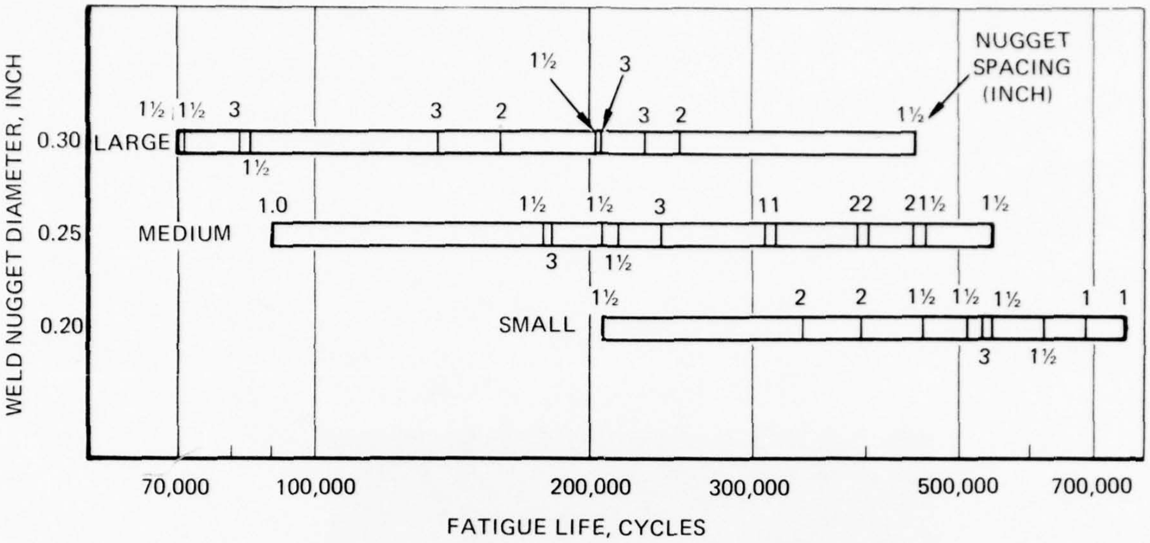
TARGET NUGGET SIZE(1)	SPOT SPACING INCH	CYCLES TO FAILURE
SMALL	1.0	695,000
SMALL	1.0	755,040
SMALL	1.5	204,450 (2)
SMALL	1.5	459,590
SMALL	1.5	514,760
SMALL (3)	1.5	544,360
SMALL (3)	1.5	611,420
SMALL	2.0	340,350
SMALL	2.0	395,420
SMALL (4)	3.0	529,600
MEDIUM	1.0	90,750
MEDIUM	1.0	313,550
MEDIUM	1.0	321,010
MEDIUM	1.5	177,700 (5)
MEDIUM	1.5	206,700
MEDIUM	1.5	215,990
MEDIUM	1.5	465,130
MEDIUM	1.5	547,380
MEDIUM	2.0	391,900
MEDIUM	2.0	403,360
MEDIUM	2.0	449,940
MEDIUM	3.0	182,120
MEDIUM (6)	3.0	240,850
LARGE	1.5	70,920
LARGE	1.5	72,420
LARGE	1.5	85,260

TABLE 13. EFFECT OF NUGGET SIZE AND SPACING ON WELDBONDED LOW-LOAD TRANSFER FATIGUE (CONTINUED)

TARGET NUGGET SIZE(1)	SPOT SPACING INCH	CYCLES TO FAILURE
LARGE	1.5	207,200
LARGE (7)	1.5	463,690
LARGE	2.0	161,380
LARGE	2.0	254,430
LARGE	3.0	83,450
LARGE	3.0	139,400
LARGE	3.0	209,530
LARGE	3.0	232,480

NOTES:

1. Peak current was varied to produce various nugget sizes.
   Small: 0.18-0.22 inch diameter, Medium: 0.23-0.27 inch,
   Large: 0.28-0.33 inch
2. Initiation site was a small depression within nugget indentation
3. Nugget diameter – 0.13 inch
4. Nugget diameter – 0.25 inch
5. Initiation site was a small pit on sheet surface
6. Nugget diameter – 0.30 inch
7. Nugget diameter – 0.35 inch
8. A specimen with a small nugget and a 2.0 inch nugget spacing was tested at 22.9 ksi maximum stress. The test was discontinued after 3,000,000 cycles.



TEST CONDITIONS: MAXIMUM STRESS = 32 ksi, R = 0.1
FREQUENCY = 10 Hz
TEMPERATURE = 75 ± 5°F,
HUMIDITY = 50 ± 5% rh

FIGURE 74. EFFECT OF NUGGET SIZE AND SPACING ON FATIGUE LIFE OF LOW-LOAD TRANSFER 7075-T6 WELDBONDED SPECIMENS

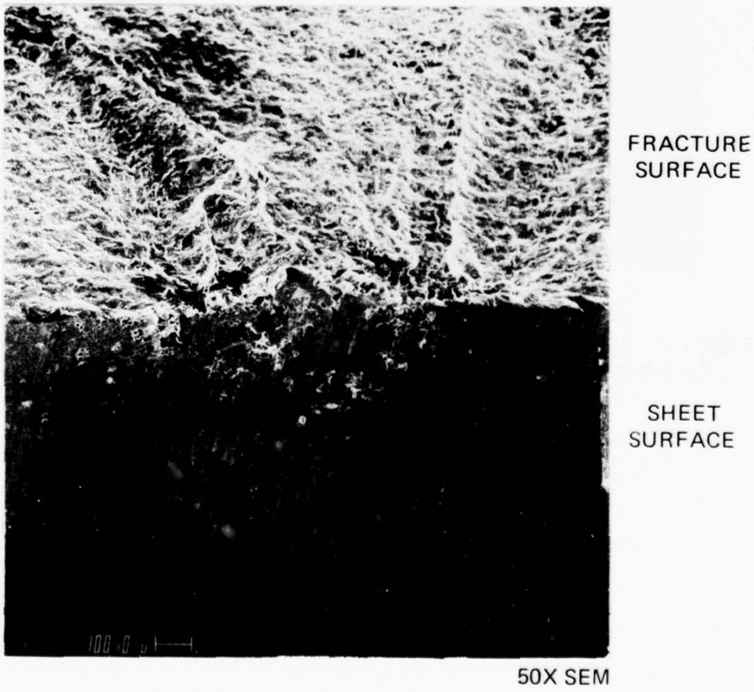


FIGURE 75. SEVERE PITTING ON THE SURFACE OF A 7075-T6/7075-T6 WELDBONDED SPECIMEN

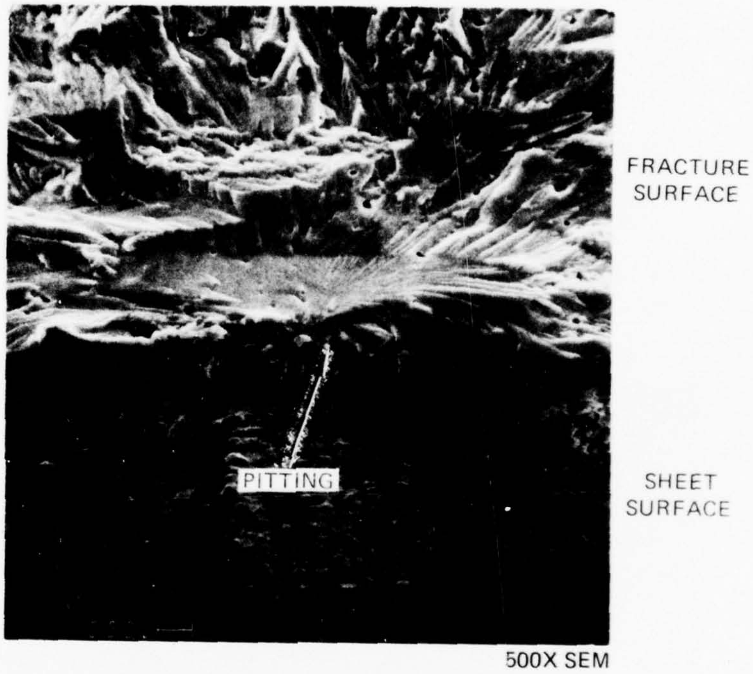


FIGURE 76. PITTED SURFACE AT ORIGIN OF FATIGUE CRACK IN 7075-T6/7075-T6 WELDBONDED SPECIMEN

The intentionally induced flaws selected for evaluation on low-load transfer specimens included: expulsion around nuggets, cracked nuggets and spot welds with high surface indentation. Cracked nuggets of two types were made, those with visible surface cracks (Surface Cracked Nugget) and those without visible cracking (Subsurface Cracked Nugget). On some subsurface cracked nuggets, a dimple could be seen on the nugget surface. Both the surface and subsurface cracks were easily detected by radiography. Crack sizes will be discussed in the fatigue crack growth section.

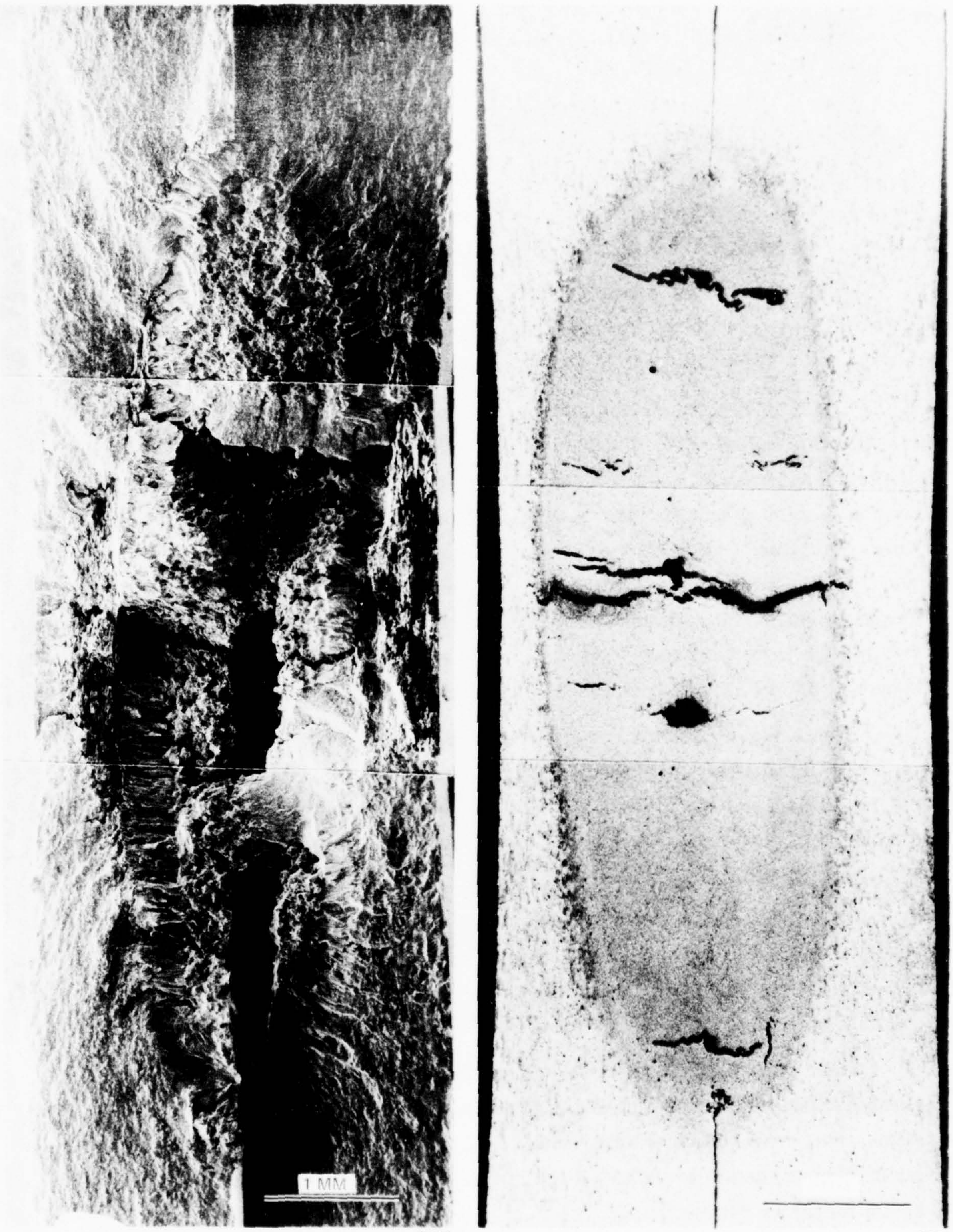
Fractographs and micrographs of typical cracked nuggets after fatigue testing are shown in Figures 77 and 78. Both figures contain a fractograph of a fatigue failed nugget and a micrograph of the same nugget from the mating fracture surface.

The fatigue results for intentionally flawed low-load transfer specimens are summarized in Table 14. These fatigue results are plotted in Figure 79, while in Figure 80 the results at a maximum stress of 32 ksi only are summarized. These figures also show results for adhesively bonded and riveted specimens which will be discussed later. It can be seen that surface and subsurface cracked nuggets significantly reduced the fatigue life of low-load transfer weldbonded specimens. This reduction is due to eliminating or shortening the crack initiation phase of the fatigue failure, which is discussed later in more detail in the section "Fatigue-Crack Growth Behavior of Weldbonded Specimens with Cracked Nuggets."

High surface indentation spot welds reduced the fatigue properties compared to weldbonded specimens with flawless nuggets of normal indentation. This is probably due to the rather large (approximately 0.37-inch diameter) nugget associated with the creation of a deep indentation as well as the increase in stress concentration due to indentation itself.

The fatigue results for specimens with expulsions were inconclusive. Only one specimen had a fatigue crack initiation directly relatable to expulsion, and it had a fatigue life less than the good weldbond. Cracks in the other two specimens initiated due to other causes as listed in Table 14.

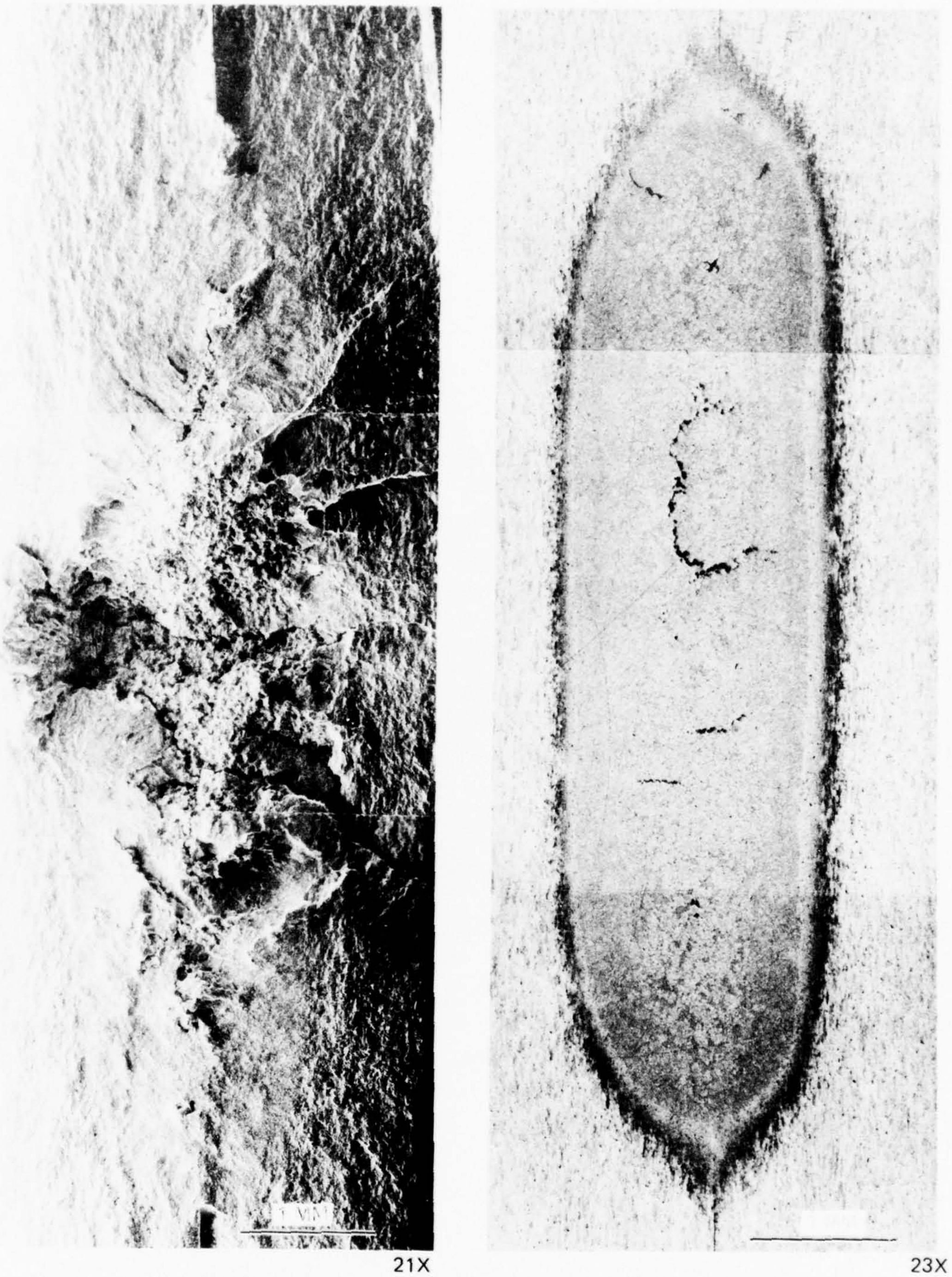
Other manufacturing defects evaluated included mechanical damage such as scratches and nicks, and inclusions. These results are summarized in Table 15. Included are results of adhesively bonded specimens that failed due to manufacturing defects. These results are also plotted in Figure 79 and summarized in Figure 80 for 32 ksi maximum stress.



a) FRACTURE SURFACE – SEM 24X

b) MICROGRAPH 26X

FIGURE 77. SURFACE CRACKED NUGGET IN A 7075-T6/7075-T6 WELDBONDED SPECIMEN



a. FRACTURE SURFACE - SEM

b. MICROGRAPH

FIGURE 78. SUBSURFACE CRACKED NUGGET IN A 7075-T6/7075-T6 WELBONDED SPECIMEN

TABLE 14. EFFECTS OF WELDBOND MANUFACTURING DEFECTS ON LOW-LAOD TRANSFER FATIGUE

Material: 7075-T6 Al, 0.063 inch thick

Nugget Spacing: 1.5 inches

Test Conditions: R($\sigma_{minimum} / \sigma_{maximum}$) = 0.1, Frequency = 10Hz
Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

SPECIMEN NO.	DEFECT	MAXIMUM STRESS, PSI	CYCLES TO FAILURE
C1	Surface Cracked Nugget	15,900	22,000
C3	Surface Cracked Nugget	9,500	87,980
S4	Subsurface Cracked Nugget (1)	32,000	11,140
S1	Subsurface Cracked Nugget	19,000	197,140
S2	Subsurface Cracked Nugget	15,900	308,530
S3	Subsurface Cracked Nugget	15,900	2,619,400
C2	Subsurface Cracked Nugget	12,700	61,000 (2)
H2	High Indentation Nugget	32,000	33,000
H3	High Indentation Nugget	32,000	51,480
H1	High Indentation Nugget	32,000	54,970
E1	Expulsion	32,000	28,530
E3	Expulsion	32,000	39,690 (3)
E2	Expulsion	32,000	77,700 (4)

NOTES:

1. Nugget spacing 1.0 inch.
2. Specimen also contained a surface cracked nugget that was estimated to be within approximately 1,000 cycles of failing.
3. Failure initiated at a pit on sheet surface within a nugget with expulsion.
4. Failure initiated at a pit on sheet surface within indentation of a good nugget.

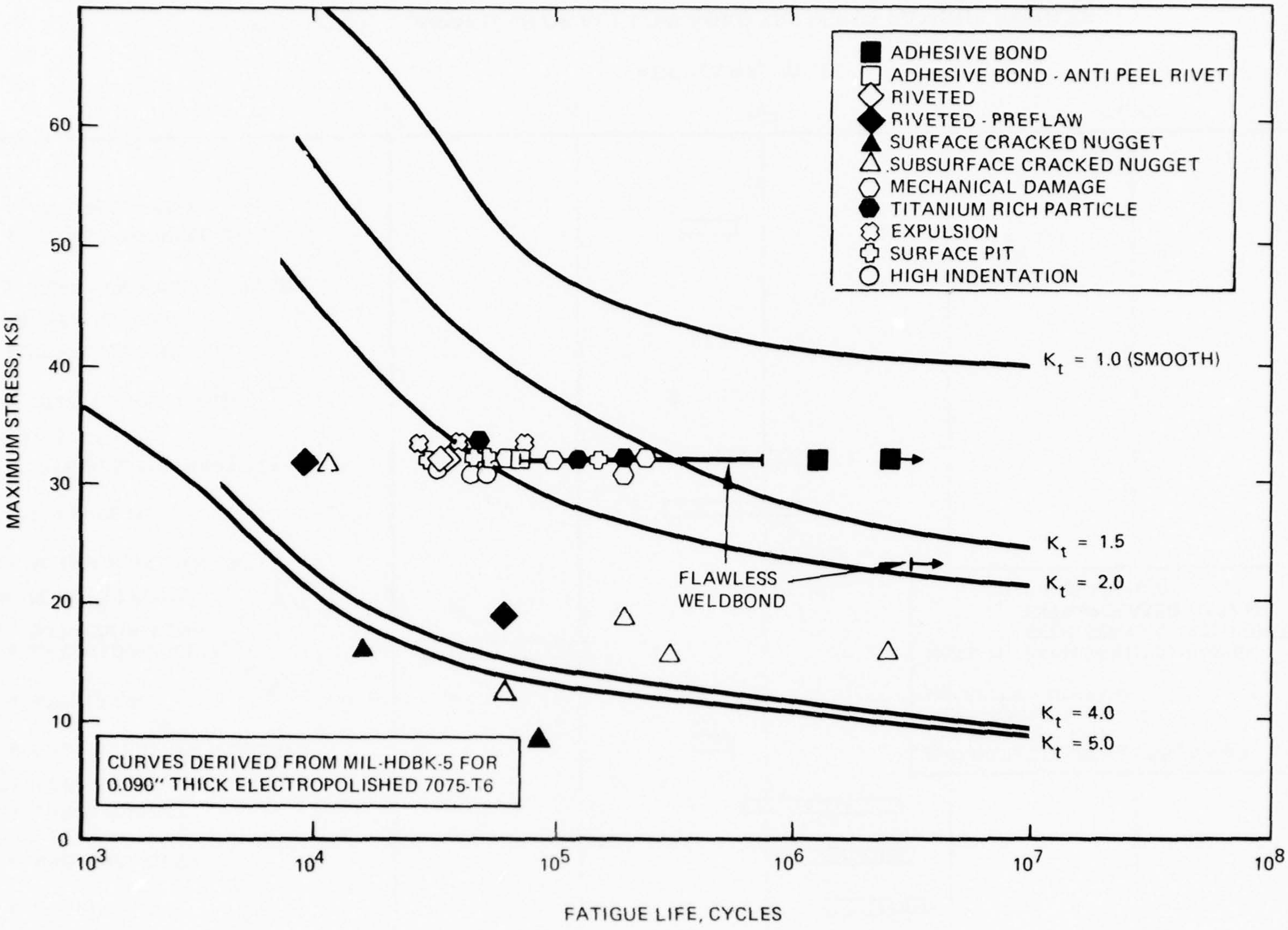


FIGURE 79. SUMMARY OF ALL FATIGUE RESULTS FOR LOW-LOAD TRANSFER 7075-T6/7075-T6 SPECIMENS

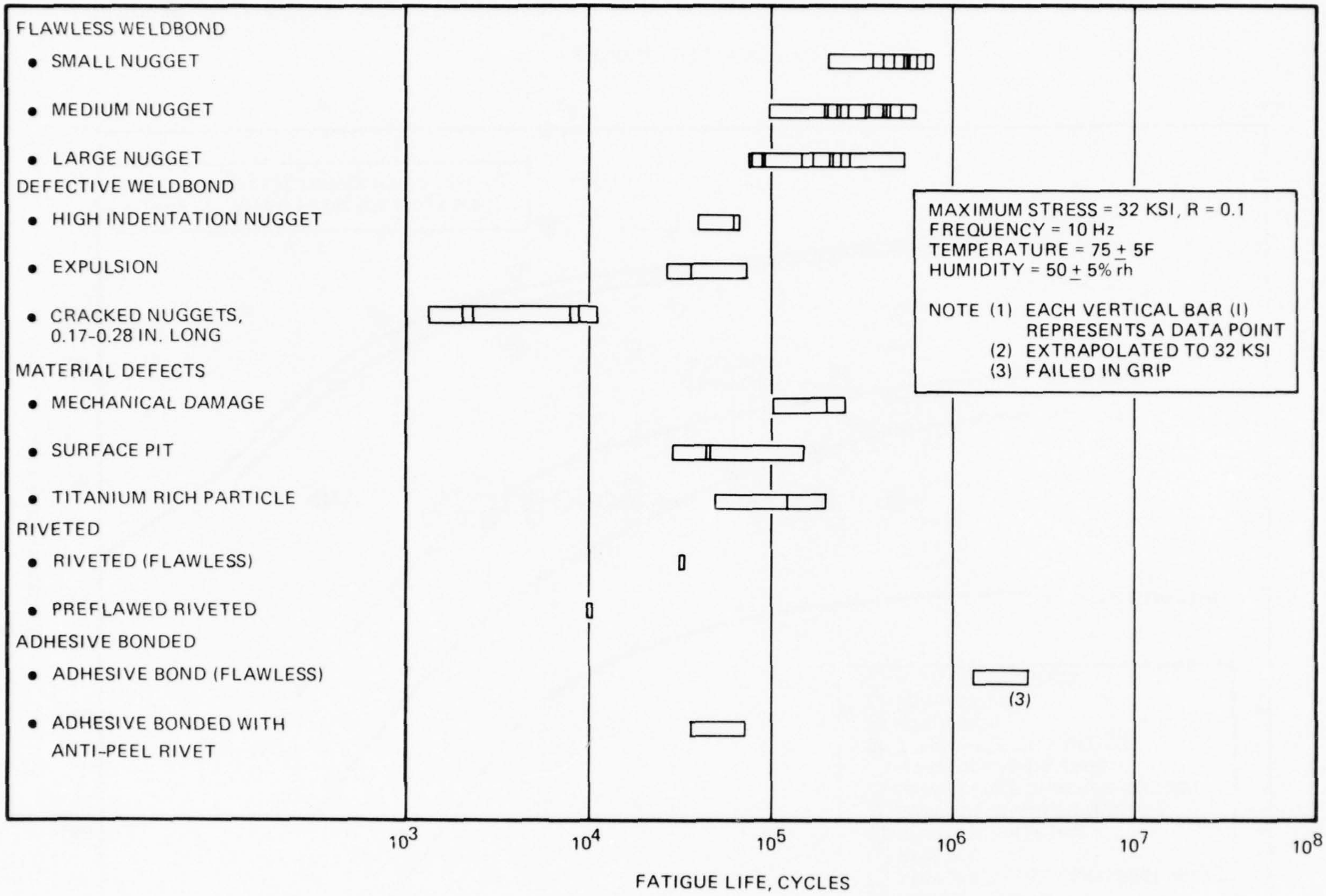


FIGURE 80. COMPARISON OF ALL LOW-LOAD TRANSFER FATIGUE RESULTS

TABLE 15. EFFECTS OF MANUFACTURING AND MATERIAL DEFECTS NOT RELATABLE TO WELDBONDING ON LOW-LOAD TRANSFER FATIGUE

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: 32 ksi Maximum stress, R($\sigma_{minimum}/\sigma_{maximum}$) = 0.1,
Frequency = 10Hz, Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

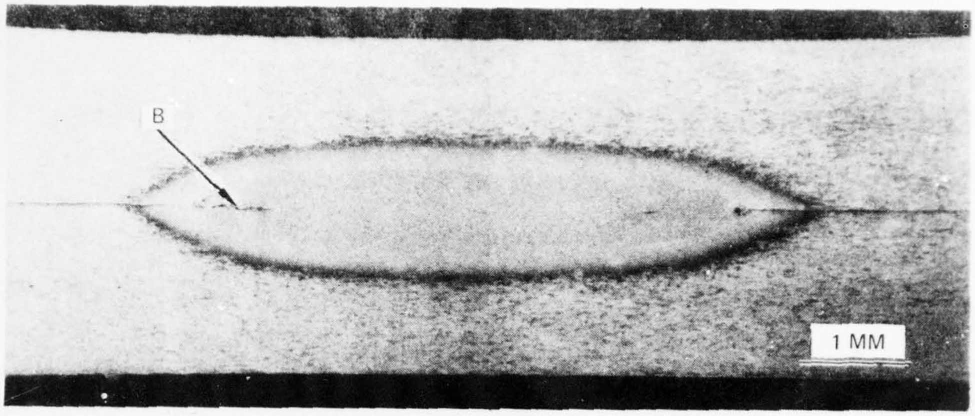
JOINING SYSTEM	CYCLES TO FAILURE	FAILURE INITIATION SITE
ADHESIVE BOND (1)	64,700	0.010 IN. DEEP NICK IN SKIN
ADHESIVE BOND (1)	153,200	SURFACE PIT, 0.001 IN. DEEP
WELDBONDED, SMALL NUGGET, 3.0" SPACING	198,980	TITANIUM RICH INCLUSION AT SURFACE, 0.001 IN. DEEP
WELDBONDED, LARGE NUGGET, 1.5" SPACING	48,400	TITANIUM RICH INCLUSION AT SURFACE, 0.002 IN. DEEP
WELDBONDED, MEDIUM NUGGET, 2.0" SPACING	124,960	TITANIUM RICH INCLUSION AT SURFACE, 0.002 IN. DEEP
WELDBONDED, MEDIUM NUGGET, 1.0" SPACING	11,140	X-RAY DETECTED WELD CRACKS (INCORRECT WELD SETTINGS)
WELDBONDED, SMALL NUGGET, 1.0" SPACING	46,610	SURFACE PIT, 0.010 IN. DEEP
WELDBONDED, SMALL NUGGET, 1.5" SPACING	48,970	SURFACE PIT, 0.008 IN. DEEP
WELDBONDED, SMALL NUGGET, 3.0" SPACING	29,240	SURFACE PIT
WELDBONDED, MEDIUM NUGGET, 1.0" SPACING	247,610	SCRATCHES, 100AA SURFACE ROUGHNESS
WELDBONDED, LARGE NUGGET, 1.5" SPACING	98,750	SCRATCHES, 100AA SURFACE ROUGHNESS
WELDBONDED WITH EXPULSION 1.5" SPACING	192,960	BURR ON SPECIMEN EDGE

1. FPL/BR127/FM123-2

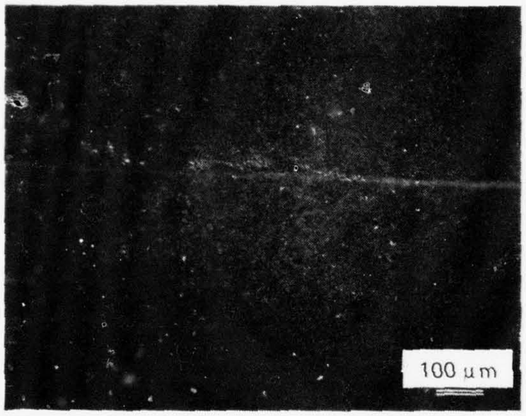
Large inclusions were found to be the initiation sites in two specimens made from different lots of material. The inclusions in both specimens were near the specimen surfaces and they were found to be titanium rich by energy dispersive analysis.

The microstructure of several representative weldbonded nuggets is shown in Figures 81, 82 and 83. Figure 81 is typical of most of the nuggets. The dark-etching crack-like area shown by an arrow in Figure 81(a) and magnified in Figure 81(b), 81(c) and 81(d) was found to be a copper-rich area by electron dispersive analysis (Figure 81(e)) which indicates the occurrence of elemental segregation in the fusion zone. The globules and streaks in Figure 81(c) are probably due to trapped adhesive. The nugget shown in Figure 82 is somewhat less typical. It has a row of dark-etching areas across the nugget (Figure 82(a)). These areas were also found to be copper rich. Porosity and incomplete fusion were also seen in some cases as illustrated in Figure 82(b). Fatigue failure in the weldbonded specimens initiated either in the fusion zone near the edge of the nugget as seen in Figure 83 or from porosity caused by alloy segregation, incomplete fusion, or trapped adhesive.

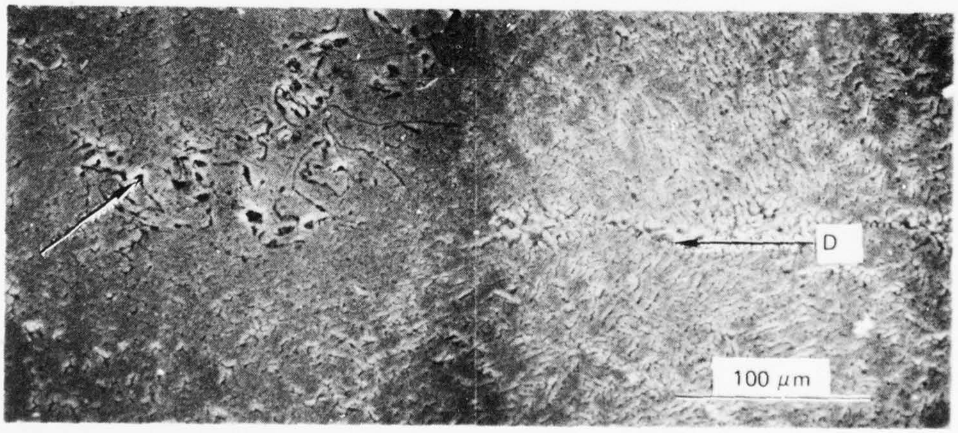
Comparison Tests. The low-load transfer fatigue results comparing weldbonding to riveting, to adhesive bonding, and to adhesive bonding with anti-peel rivets are summarized in Figure 84 at a maximum stress level of 32 ksi. The data for riveted, adhesive bonded, and adhesive bonded with anti-peel rivets are listed in Table 16. Both riveted specimens failed at about 33,000 cycles under the same loading conditions and both specimens had cracks growing from at least five other rivet holes. This indicates good reproducibility of the riveted specimen fatigue data as 12 of 42 rivet holes had cracked during the test. One adhesively bonded specimen failed at 1.2 million cycles in the radius, and the other specimen failed in the grip area after 2.5 million cycles. The two adhesively bonded specimens with anti-peel rivets failed in 37,000 and 75,000 cycles. As can be seen in Figure 84, the low-load transfer fatigue behavior of weldbonded specimens is as good or better than that for riveted specimens and adhesive bonded specimens with anti-peel rivets. However, the adhesively bonded low-load transfer specimens had better fatigue properties than the weldbonded specimens.



a. OPTICAL STRUCTURE OF NUGGET 16X

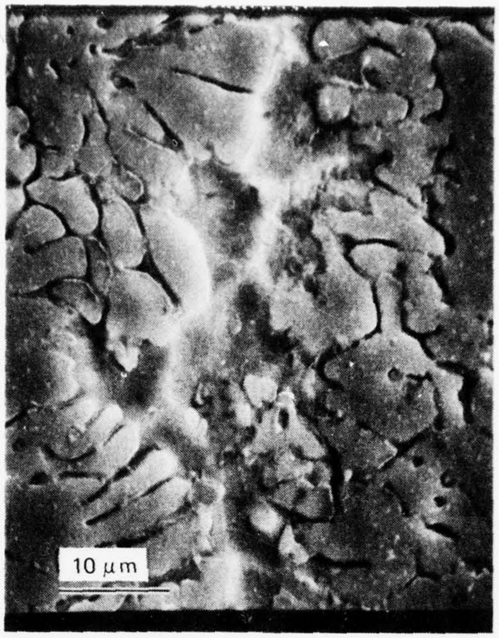


b. SEM PHOTOMICROGRAPH OF BLACK AREA B IN (a). 70X



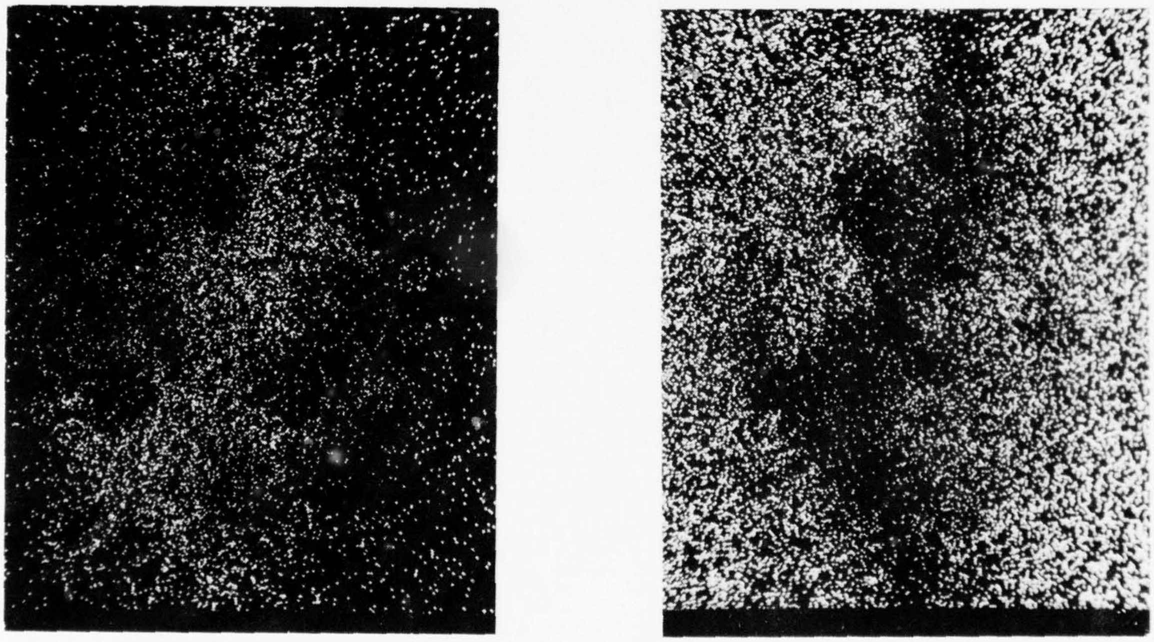
c. HIGHER MAGNIFICATION OF PART OF AREA (b). ARROW TO LEFT INDICATES POSSIBLE TRAPPED ADHESIVE. 280X

FIGURE 81. 7075-T6/7075-T6 WELDBOND-SMALL NUGGET



1600X

d. HIGHER MAGNIFICATION SEM
PHOTOMICROGRAPH OF AREA D IN (c).

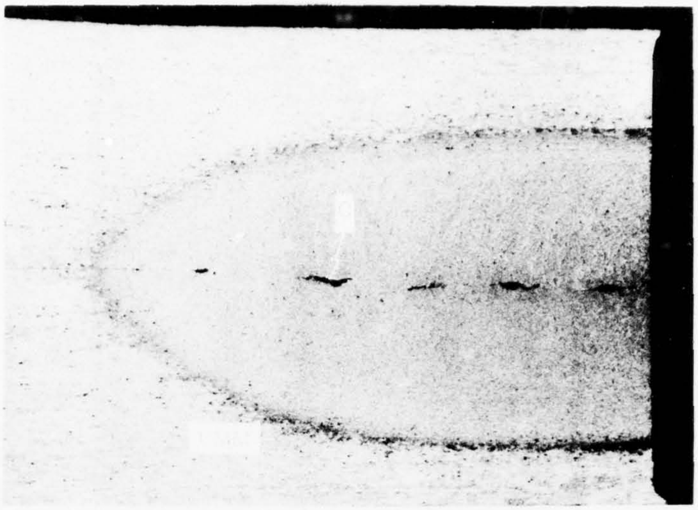


COPPER 1600X

ALUMINUM 1600X

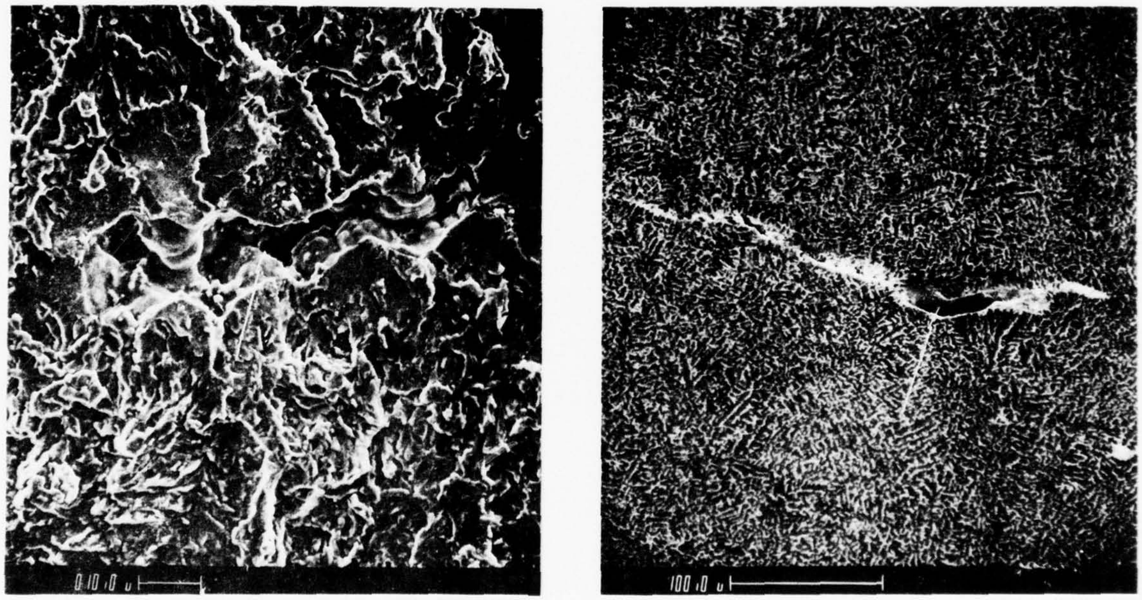
e. CHARACTERISTIC X-RAY BACKSCATTER MAPS
OF AREA IN (d).

FIGURE 81. 7075-T6/7075-T6 WELDBOND-SMALL NUGGET (CONTINUED)



23X

a. MICROGRAPH



SEM 900X

SEM 220X

b. FRACTURE SURFACE. POROSITY OR INCOMPLETE FUSION SHOWN BY ARROW.

c. SEM PHOTOMICROGRAPH OF DARK AREA INDICATED IN (a). POROSITY OR INCOMPLETE FUSION SHOWN BY ARROW.

FIGURE 82. 7075-T6/7075-T6 WELDBOND-MEDIUM NUGGET

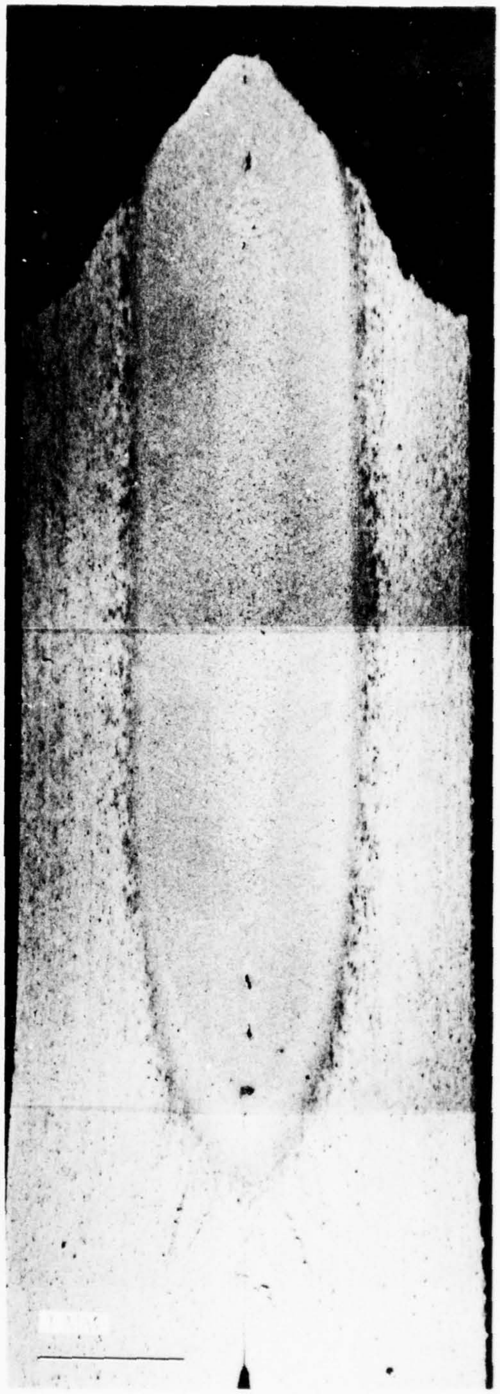


FIGURE 83. SECTION THROUGH FATIGUE FAILURE IN A 7075-T6/ 7075-T6 WELDBONDED SPECIMEN WITH MEDIUM NUGGETS

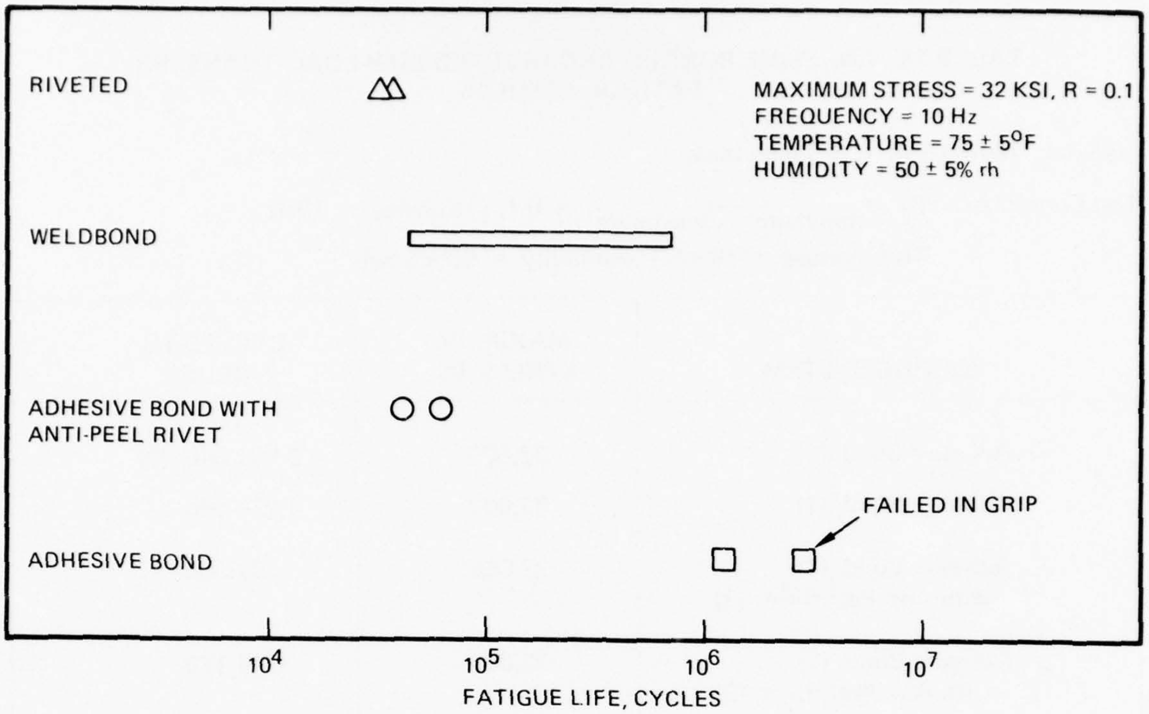


FIGURE 84. COMPARISON OF LOW-LOAD TRANSFER FATIGUE RESULTS ON 7075-T6/7075-T6 COMBINATIONS AT 32 KSI

TABLE 16. ADHESIVE BONDED AND RIVETED LOW-LOAD TRANSFER FATIGUE RESULTS

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: R($\sigma_{minimum}$/ $\sigma_{maximum}$) = 0.1, Frequency = 10Hz

Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

JOINING SYSTEM	MAXIMUM STRESS, PSI	CYCLES TO FAILURE
Adhesive Bond (1)	32,000	2,532,840 (2)
Adhesive Bond (1)	32,000	1,229,990
Adhesive Bond (1) with Anti-Peel Rivet (3)	32,000	37,300
Adhesive Bond (1) with Anti-Peel Rivet (3)	32,000	75,170
Riveted (4)	32,000	33,160
Riveted (4)	32,000	32,930

NOTES:

1. FPL/BR127/FM123-2
2. Failed in Grip
3. MS20470-AD4 Rivets
4. MS20426-AD5 Rivets

Fatigue-Crack Growth Behavior of Weldbonded Specimens with Cracked Nuggets. Six weldbonded specimens with cracked nuggets were tested at various stress levels to obtain fatigue-crack growth data. The test parameters are listed in Table 17. (The total life of these specimens is listed in Table 14.)

Specimen C1 contained one surface cracked nugget and one subsurface cracked nugget. Both cracks propagated with the final failure occurring from the surface cracked nugget. Plots of crack lengths (2a) observed on the skin and doubler faces of this specimen versus fatigue cycles for both nuggets are shown in Figure 85. The initial crack shape and size for the failed nugget (number 4 in Figure 70) is also shown in Figure 85. For nugget 4, when the crack on the doubler face was about 0.28 inch long it broke through the skin surface of the specimen. Immediately after breaking through the skin surface, the crack front in the skin propagated at a faster rate than the crack front in the doubler. This is evident from the plot of crack growth rate (da/dN) versus crack length (2a) shown in Figure 86. The crack growth rate in the skin decreased up to a crack length of about 0.45 inch and then increased with further increases in crack length. This change in the crack growth rate in the skin occurred when the crack lengths in the doubler and skin became approximately the same. The reason for the observed crack growth behavior in the skin is as follows: when the crack in the skin is not a through crack, a considerable load transfer takes place from the doubler to the skin with the result that the stress in the skin at the crack plane is considerably higher than the stress in the doubler. This will cause a higher stress intensity factor and, therefore, a faster growth rate in the skin. As the cracks in the skin and doubler propagate and the difference in the crack lengths between doubler and skin decreases, less and less load is transferred to the skin from the doubler. This causes lower stresses and stress intensity factors in the skin even though the crack length in the skin is increasing with the crack propagation. Thus, the crack growth rate in the skin decreases with the crack propagation. When the crack lengths in the doubler and skin become approximately the same there is little load transfer between the doubler and the skin. This causes the stress intensity factor and the resultant crack-growth rate in the skin to increase with crack length as it would for a through crack. Similar crack-growth behavior has been observed in two-ply adhesively bonded structure with a through crack in one ply (References 7 and 8).

TABLE 17. PREFLAWED WELDBOND FATIGUE CRACK GROWTH TESTING

Material: 7075-T6 Al, 0.063 inch thick

Nugget Spacing: 1.5 inches

Test Condition: $R(\sigma_{minimum}/\sigma_{maximum}) = 0.1$, Frequency = 10Hz

Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

Specimen Number	Type of Cracked Nugget		Initial Flaw That Caused Final Failure		Stress Level, psi
	Nugget Number 4	Nugget Number 7	Location	Size (Length x Depth)	
S1	Subsurface	Subsurface	Nugget 7	0.18'' x 0.08''	19,000
C1	Surface (Doubler*)	Subsurface	Nugget 4	0.25'' x 0.09''	15,900
S2	Subsurface	Subsurface	Nugget 4	0.21'' x 0.09''	15,900
S3	Subsurface	Subsurface	Nugget 4	0.17'' x 0.06''	15.900
C2	Surface (Skin*)	Subsurface	Nugget 7	0.32'' x 0.11''	12,700
C3	Subsurface	Surface (Skin*)	Nugget 7	0.28'' x 0.11''	9,500

*Surface where crack initially visible

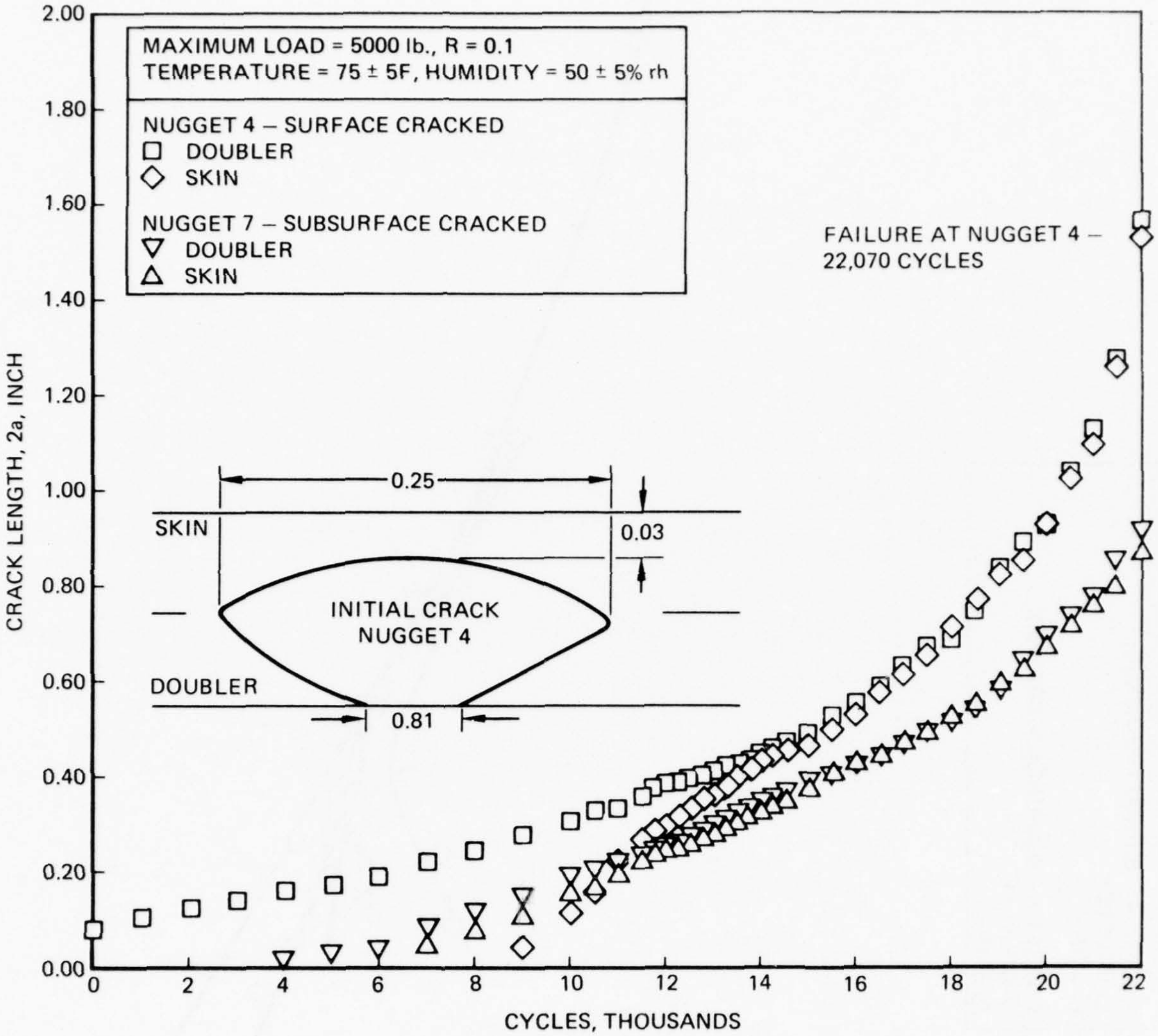


FIGURE 85. FATIGUE-CRACK LENGTH VERSUS CYCLES FOR SPECIMEN C1.

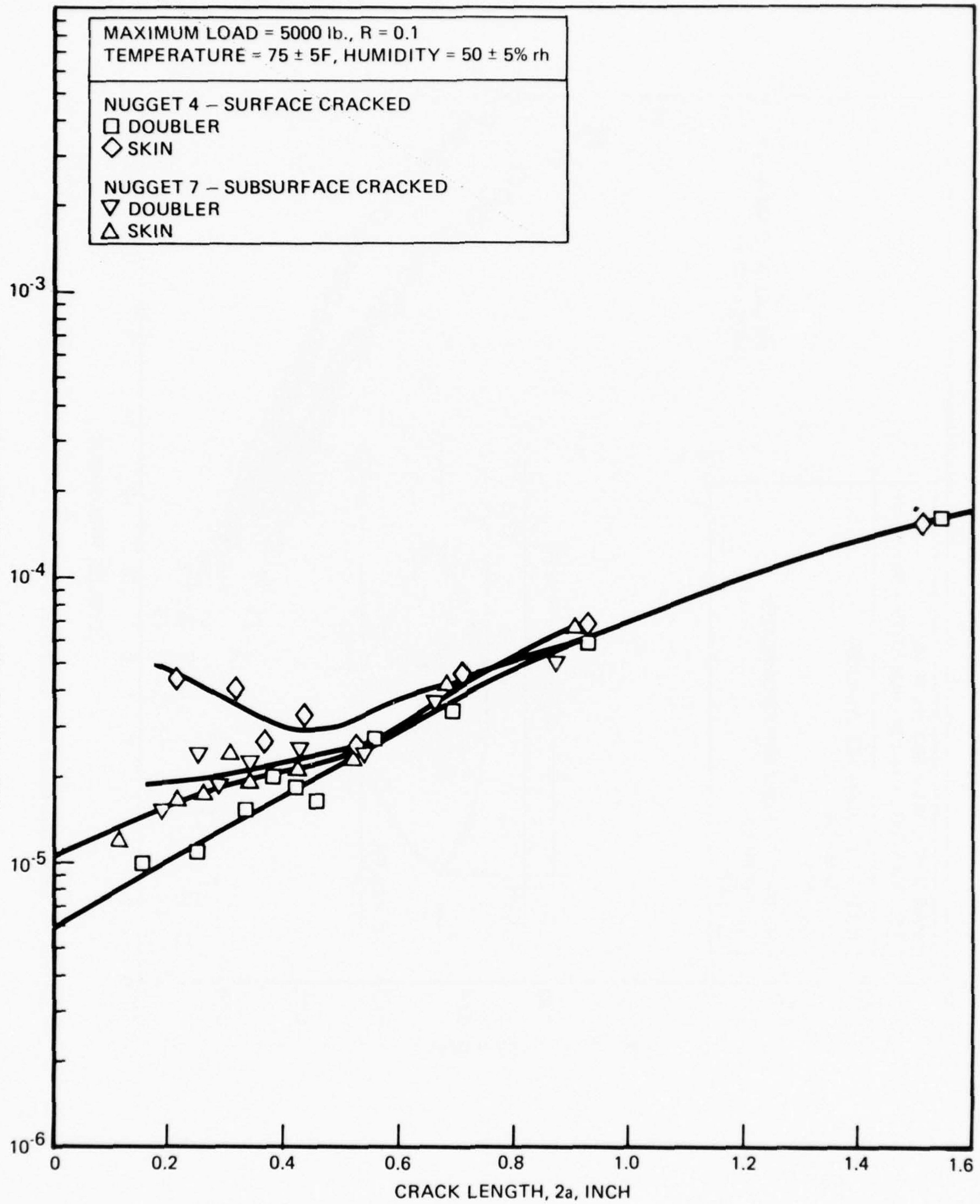


FIGURE 86. FATIGUE-CRACK GROWTH RATE VERSUS CRACK LENGTH, SPECIMEN C1.

The crack length versus cycles plot for subsurface cracked nugget 7 (Figure 85) indicates that the crack in the skin initiated when the length of surface-crack in the doubler was relatively small (about 0.08 inch). There was very little load transfer taking place from the doubler to the skin and hence, the crack-growth rate increased monotonically with the crack length in both the doubler and the skin.

For this low-load transfer specimen, when the crack lengths in the skin and doubler are approximately equal, they propagate together. This stress intensity factor can be computed from the through-the-thickness flaw analysis of cracked monolithic structure of the same configuration, assuming that load transfer compensates for the difference in the finite width correction factor of the sheets. The plot of crack growth rate (da/dN) versus stress intensity factor range (ΔK) for the case of through cracks at at nuggets 4 and 7 is shown in Figure 87. The data points are shown separately for crack lengths smaller than 0.3 inch (diameter of the nugget) and crack lengths larger than 0.3 inch. The figure also shows a fatigue-crack growth curve for 0.063-inch thick 7075-T6 aluminum alloy at $R = 0.1$ (Reference 6). The crack-growth data for crack lengths larger than 0.3 inch agrees with the monolithic 7075-T6 data, because here the crack is growing in the aluminum outside the nugget surface indentation and heat affected zone. The crack-growth rates for crack lengths smaller than 0.3 inch (within the nugget) are about two times faster than those in the basic material for the same value of stress intensity factor.

Specimen C2 had a surface cracked nugget at nugget 4 on the skin side and a subsurface cracked nugget at nugget 7. The final failure of the specimen occurred from the subsurface cracked nugget, nugget 7. The initial crack profile at nugget 7 and the plot of crack length versus number of fatigue cycles for both cracks are shown in Figure 88. In this specimen, the crack from nugget 7 broke through the surfaces on both the doubler and the skin at almost the same time.

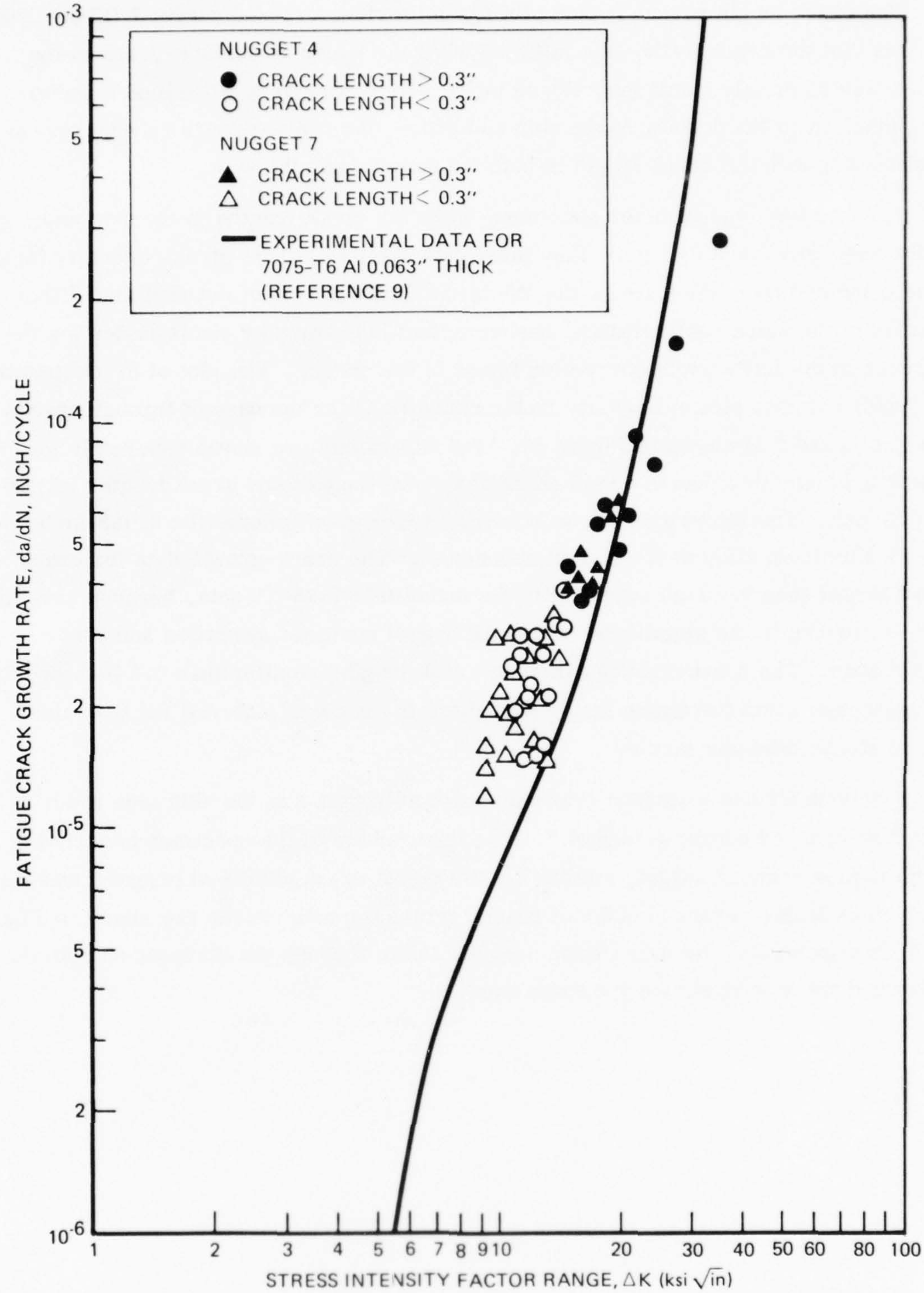


FIGURE 87. FATIGUE-CRACK GROWTH RATE WHEN CRACK IS A THROUGH CRACK, SPECIMEN C1.

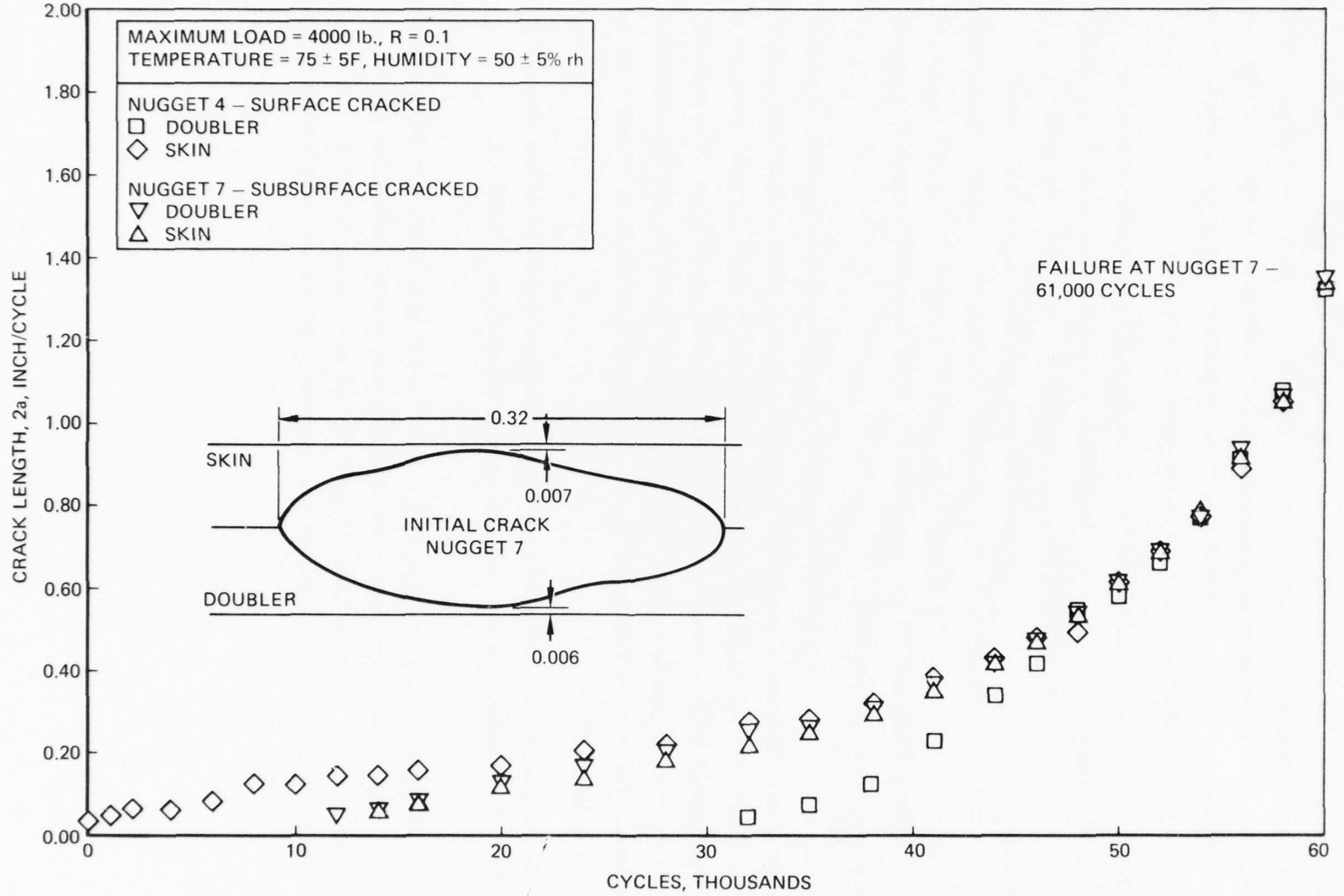


FIGURE 88. FATIGUE-CRACK LENGTH VERSUS CYCLES FOR SPECIMEN C2.

Specimen C3 had a surface cracked nugget at nugget 7 and a subsurface cracked nugget at Nugget 4. The initial crack profile at nugget 7 and a plot of crack length versus fatigue cycles are shown in Figure 89. In this case the crack became a through thickness crack in the doubler at a crack length of 0.13 inch in the skin. The behavior of the surface crack in this specimen is almost identical to that in Specimen C1 except in this case the initial crack appeared on the skin surface.

The profile of the initial subsurface crack for nugget 7 in specimen S1 is shown in Figure 90. The initial crack-front in the skin is closer to the surface than in the doubler and hence the crack would become a through crack in the skin first. This is also evident from the plot of surface crack lengths and number of cycles shown in Figure 90. When the crack breaks through in the doubler, the surface crack length in the skin is about 0.2 inch. The fatigue crack growth behavior of this specimen is similar to that of specimen C1 and specimen C3. The subsurface crack at nugget 4 did not propagate to the surface.

Figure 91 shows the initial profile of the subsurface crack observed at nugget 4 in specimen S3. The plot of surface crack lengths versus number of fatigue cycles is shown in Figure 91. Here the crack breaks through the doubler and skin surfaces after a large number of fatigue cycles due to the smaller initial crack size. The surface crack appears on the doubler side of the specimen first due to the smaller thickness of ligament in the doubler than in the skin. The subsurface crack in nugget 7 did not propagate to the surface.

The fatigue life of specimens with cracked nuggets depended on the size of the initial flaw, not whether it was a surface or subsurface flaw. (Table 17.)

Preflawed Riveted Fatigue Crack Growth. Two riveted specimens with EDM flaws were tested for comparison to the fatigue characteristics of flawed weldbonded specimens. The fatigue lives are listed in Table 18, and plotted in Figures 79 and 80. As seen in Figure 80 the total life of these specimens lies within the scatter band for the cracked nugget weldbond lives.

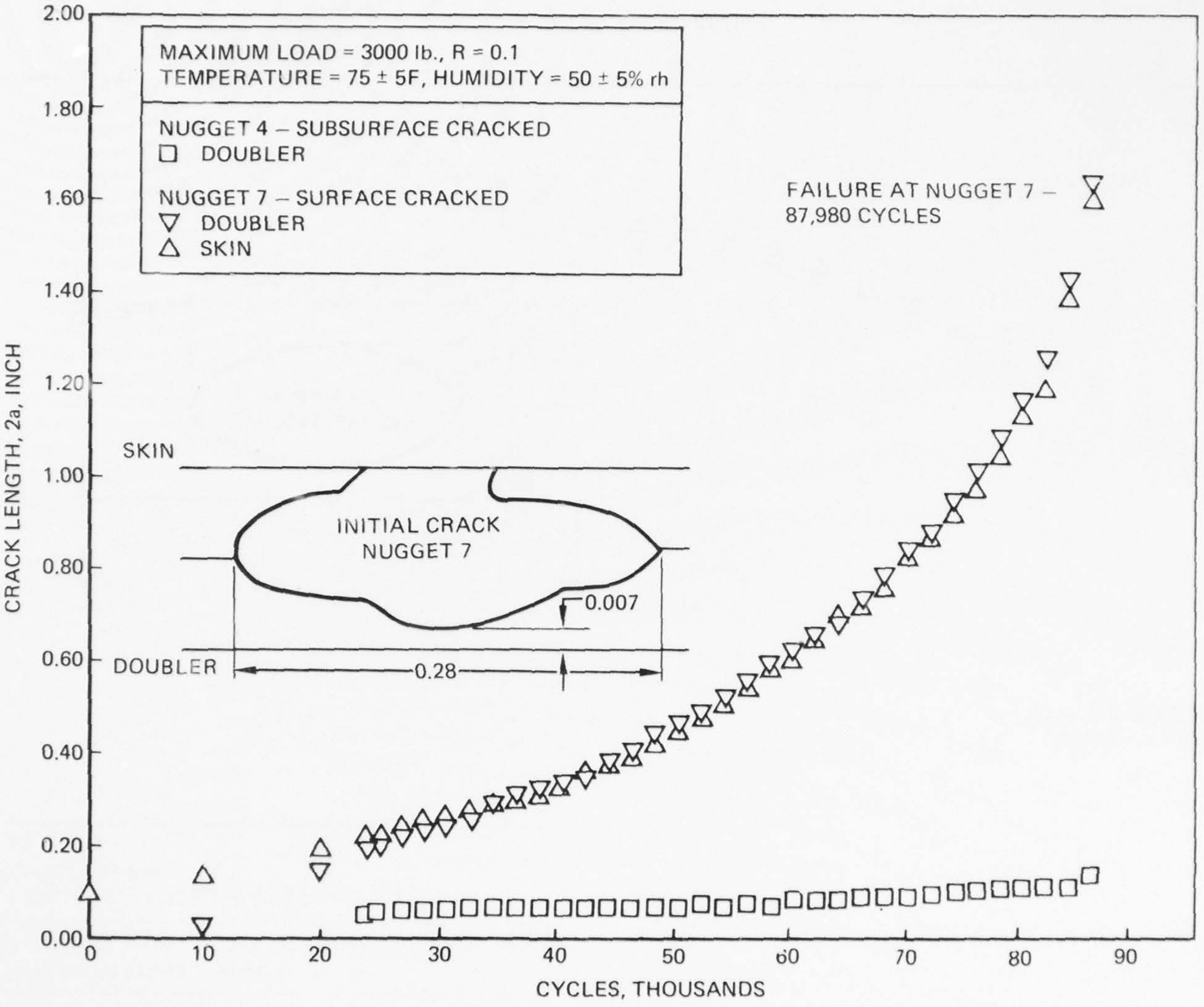


FIGURE 89. FATIGUE-CRACK LENGTH VERSUS CYCLES FOR SPECIMEN C3.

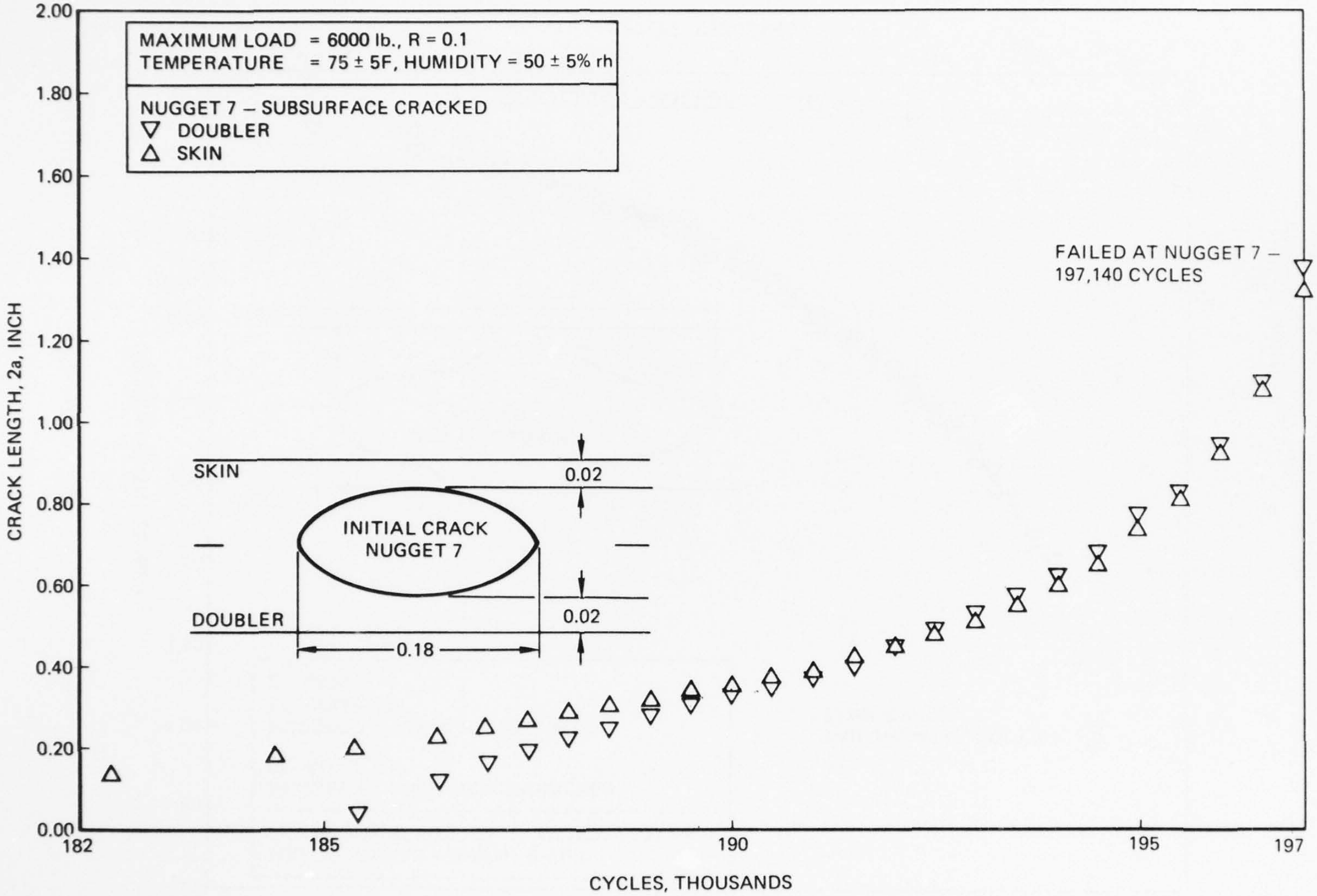


FIGURE 90. FATIGUE-CRACK LENGTH VERSUS CYCLES FOR SPECIMEN S1.

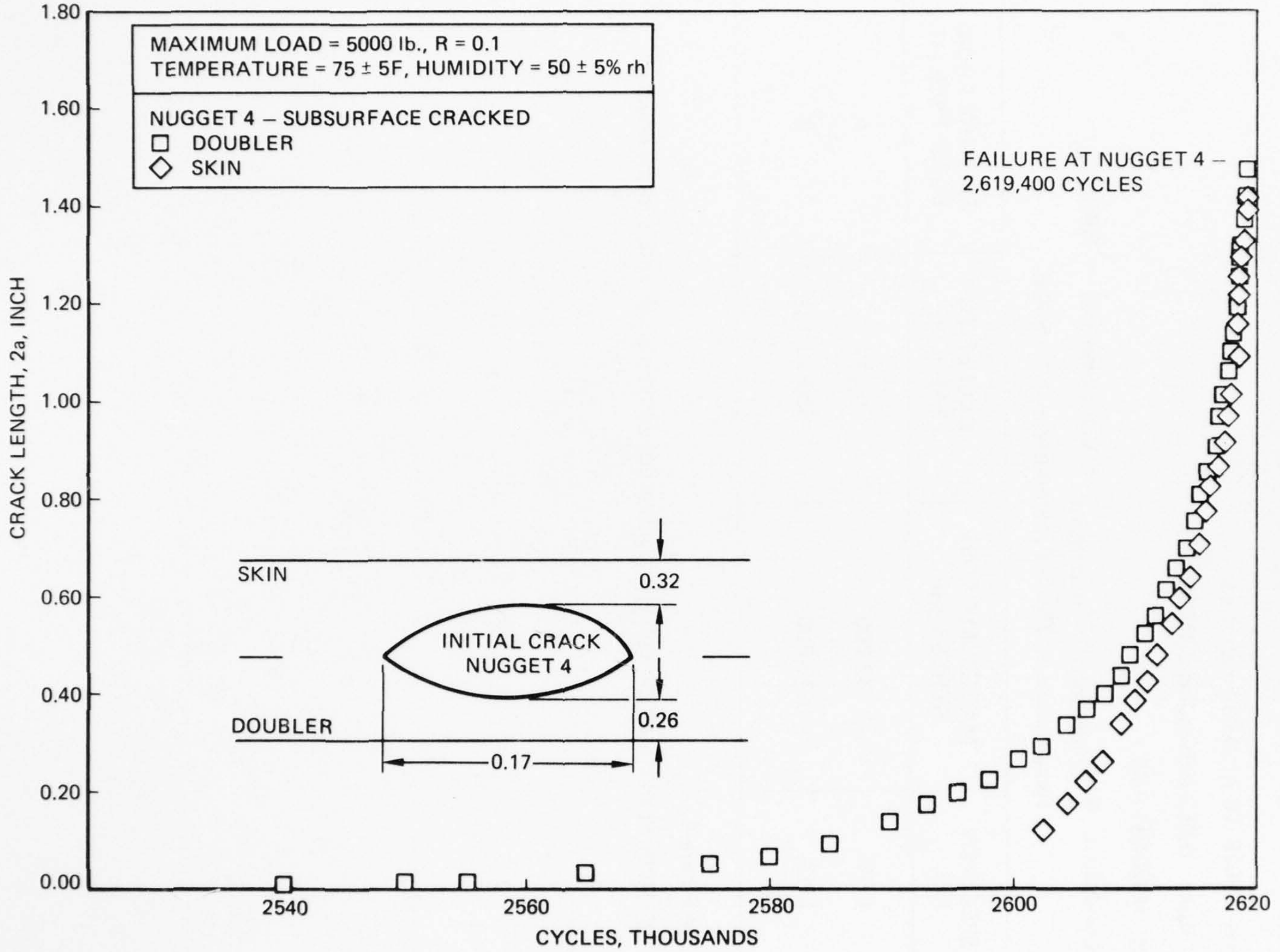


FIGURE 91. FATIGUE-CRACK LENGTH VERSUS CYCLES FOR SPECIMEN S3.

FIGURE 22

TABLE 18. LOW-LOAD TRANSFER FATIGUE RESULTS OF PREFLAWED RIVETED SPECIMENS

Material: 7075-T6 Al, 0.063 inch thick

Rivet Holes: 0.050-inch radius EDM flaw

Rivets: MS20426-AD5

Test Conditions: R($\sigma_{\text{minimum}}/\sigma_{\text{maximum}}$) = 0.1, Frequency = 10Hz
Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

SPECIMEN NO.	MAXIMUM GROSS STRESS, psi	CYCLES TO FAILURE	FAILURE FROM FLAW TYPE (1)
LR4	32,000	9,137	A
LR3	19,000	63,510 (2)	B

(1) See Figure 4.

(2) Test stopped when skin completely cracked but with no crack visible in the doubler.

The fatigue-crack growth behavior of the two specimens is shown in Figures 92 and 93. For a large portion of the life, the crack grows in only one of the riveted sheets, while in weldbonded specimens a nugget crack grows into both sheets and into both halves of the sheet.

High-Load Transfer 7075-T6/7075-T6

Effects of Nugget Size on Fatigue Life. The test results under this task are summarized in Table 19. Figure 94 shows the effects of nugget size on the fatigue life of the high-load transfer weldbonded specimens. In this test, the weldbonded specimens with large weld nuggets generally had a better fatigue life, which is opposite to the results for the low-load transfer weldbonded specimens. The fatigue life of the high-load transfer specimens depends primarily upon the nature of the adhesive bond. Because of the location of the weld nugget in the center of the lap joint rather than near the edges of the joint, the weld nugget has only a secondary effect on the fatigue life. However, larger nuggets create a thicker adhesive bondline in these specimens which suggests that the increased adhesive thickness is the reason for the better fatigue behavior of the specimens with large nuggets.

Effects of Manufacturing Defects on Fatigue Life. The effects of two types of defects that can occur with poor weldbond process control were evaluated. Results for these two types of defects (subsurface cracked nuggets and expulsion around nuggets) are summarized in Table 20. In Figure 95, these results are compared to the fatigue results for defect-free high-load transfer specimens. The cracked nugget had no effect on the fatigue life of these high-load transfer specimens because these specimens test primarily the adhesive bond. Expulsion in these specimens did reduce the fatigue properties as compared to specimens without defects. This probably results from two factors: one, due to the severity of expulsion the bond area was reduced, and more importantly, the expulsion destroyed the bond at the more highly stressed edge of the joint (Figure 96). This region is generally the fatigue failure initiation site.

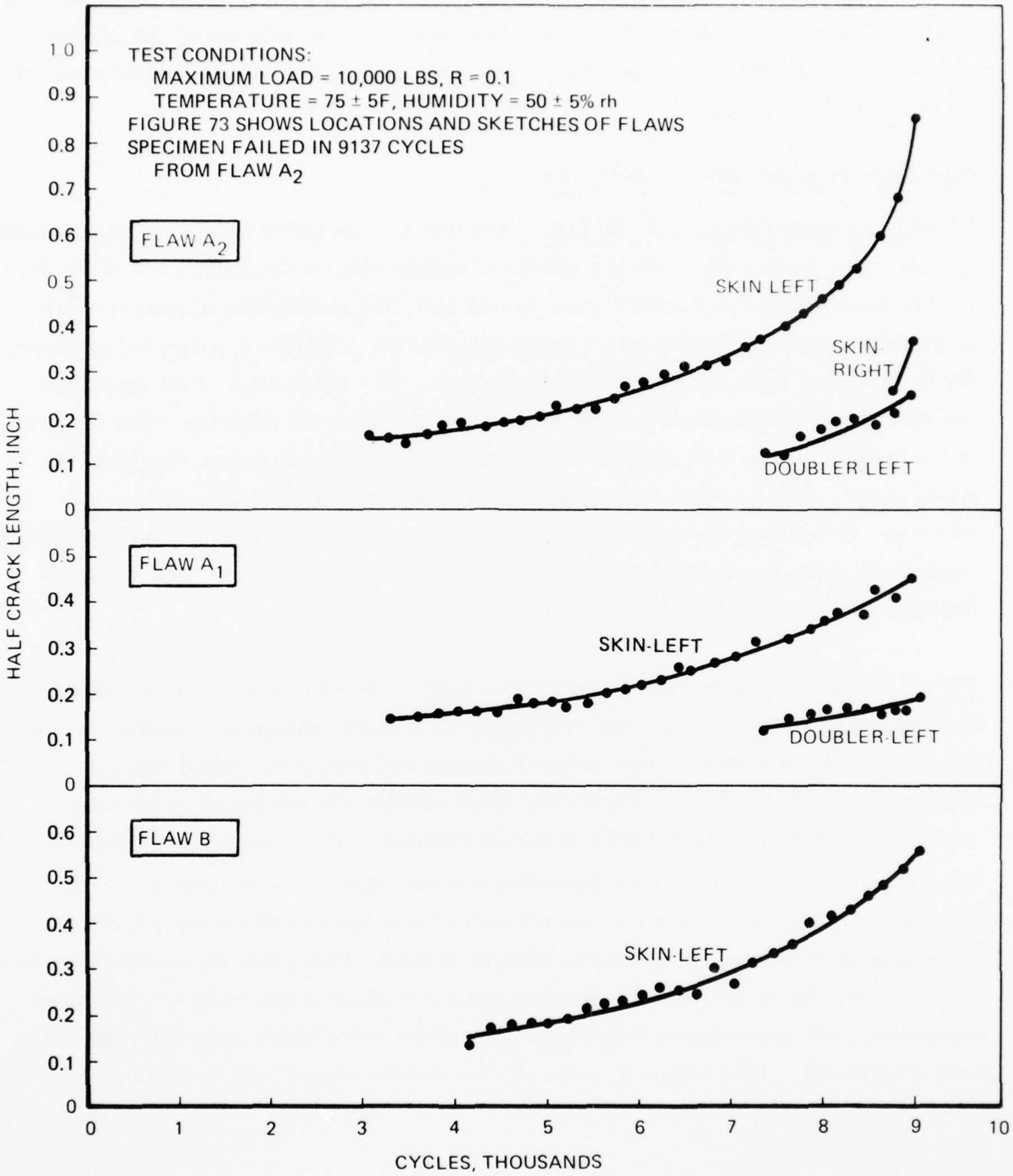


FIGURE 92. FATIGUE CRACK GROWTH IN PREFLAWED RIVETED SPECIMEN NO. LR4

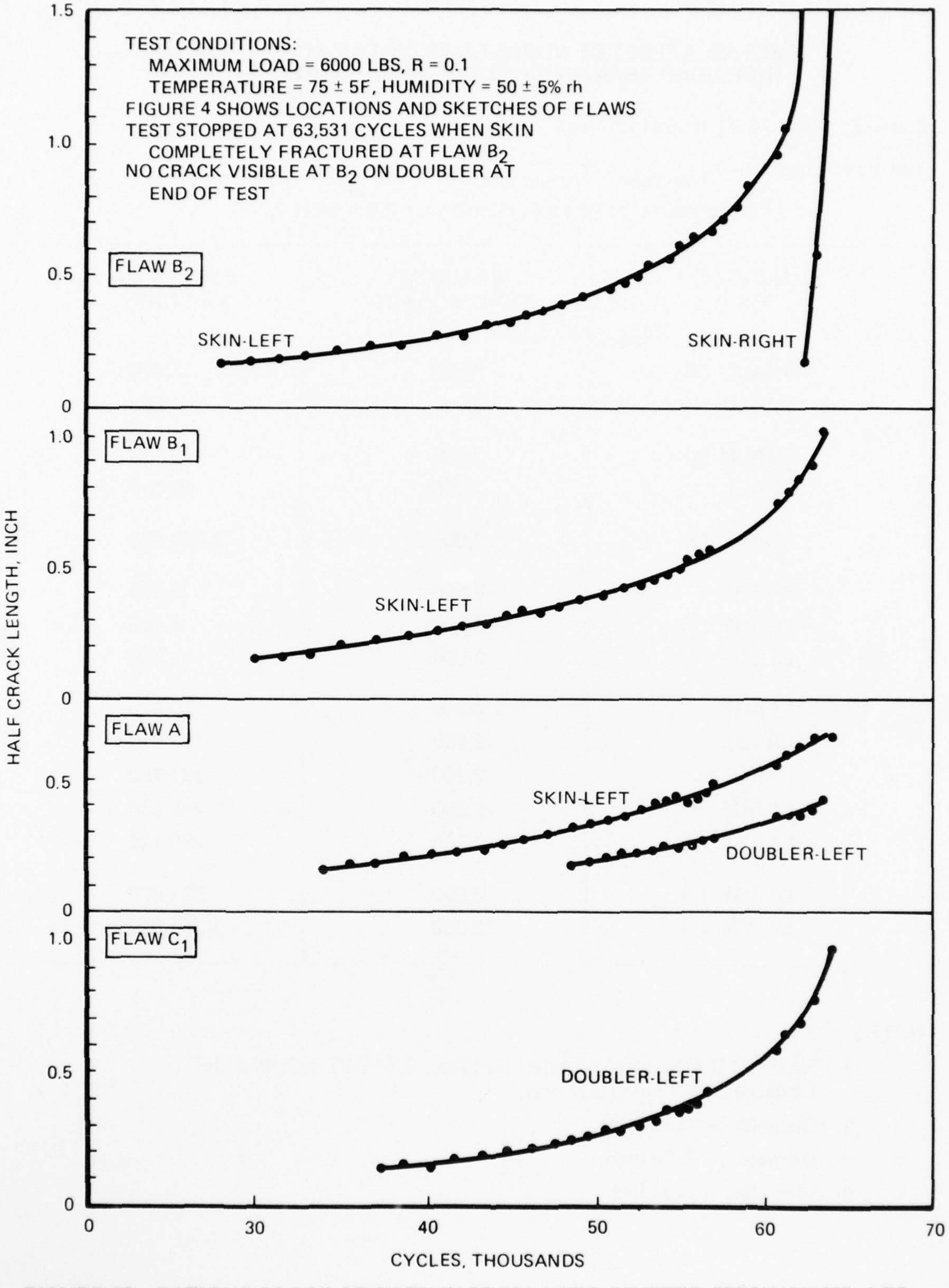


FIGURE 93. FATIGUE CRACK GROWTH IN PREFLAWED RIVETED SPECIMEN NO. LR3

TABLE 19. EFFECT OF NUGGET SIZE ON THE FATIGUE LIFE OF HIGH-LOAD TRANSFER FATIGUE WELDBONDED SPECIMENS

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: $R(\sigma_{\text{minimum}}/\sigma_{\text{maximum}}) = 0.1$, Frequency = 10Hz,
Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

NUGGET SIZE$^{(1)}$	MAXIMUM LOAD, POUNDS	CYCLES TO FAILURE
SMALL (2)	3,500	3,010
SMALL	3,500	4,860
SMALL (2)	2,250	98,560
SMALL	2,250	99,020
SMALL (2)	2,000	1,083,090
LARGE	3,500	5,380
LARGE	3,500	8,450
LARGE	3,500	12,020
LARGE	2,250	130,970
LARGE	2,250	133,670
LARGE	2,250	187,780
LARGE	2,250	235,230
LARGE	2,250	296,120
LARGE (3)	2,000	934,870
LARGE (4)	2,000	1,229,810

NOTES:

1. Small: 0.18-0.22 inch diameter, Medium: 0.23-0.27 inch diameter, Large: 0.28-0.33 inch diameter.
2. Diameter — 0.15 inch
3. Diameter — 0.26 inch
4. Diameter — 0.36 inch

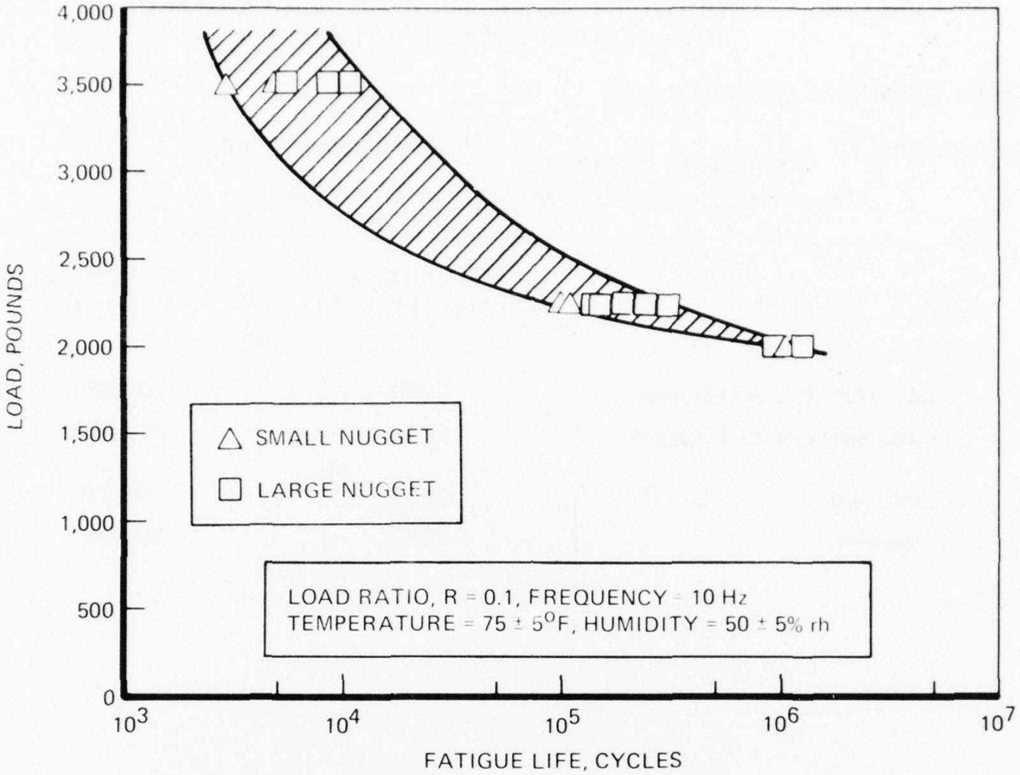


FIGURE 94. EFFECT OF NUGGET SIZE ON FATIGUE LIFE OF HIGH-LOAD TRANSFER 7075-T6/7075-T6 WELDBONDED SPECIMENS

TABLE 20. EFFECTS OF WELDBOND MANUFACTURING DEFECT ON HIGH-LOAD TRANSFER FATIGUE

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: R($\sigma_{minimum}/\ \sigma_{maximum}$) = 0.1, Frequency = 10Hz
Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

DEFECT	MAXIMUM LOAD, POUNDS	CYCLES TO FAILURE
Subsurface Cracked Nugget	2250	207,620
Subsurface Cracked Nugget	2250	283,090
Expulsion	2250	68,930
Expulsion	2250	106,640

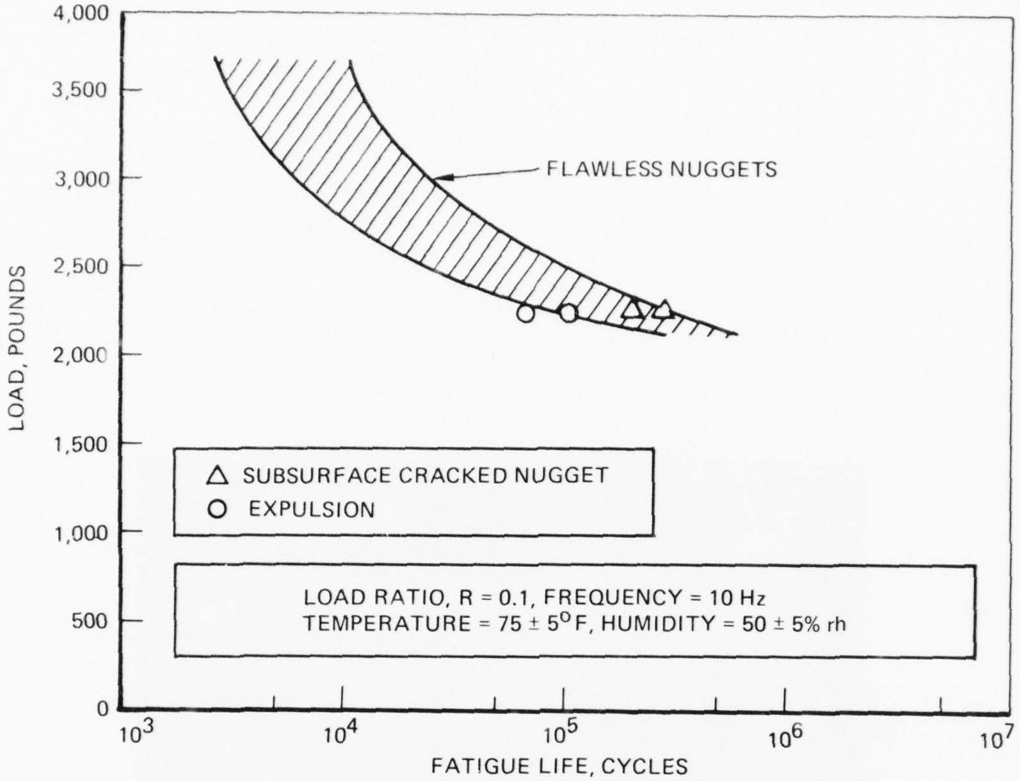


FIGURE 95. EFFECTS OF MANUFACTURING DEFECTS ON THE FATIGUE LIFE OF 7075-T6/7075-T6 HIGH-LOAD TRANSFER SPECIMENS

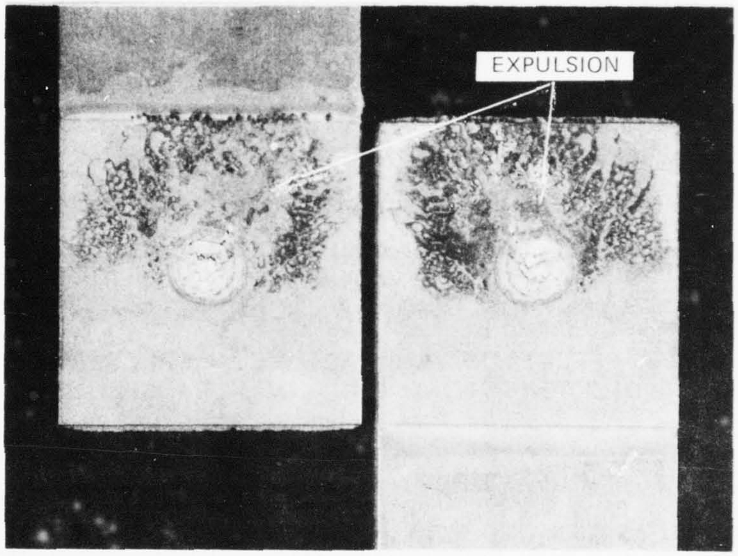


FIGURE 96. EXPULSION IN HIGH-LOAD TRANSFER WELDBONDED FATIGUE SPECIMEN – 7075-T6/7075-T6.

Comparison Tests. The results from the tests on adhesive bonded and riveted high-load transfer specimens are summarized in Table 21. These results are compared to those for weldbonded specimens in Figure 97. This figure shows that adhesive bond specimens have only slightly better fatigue behavior than the weldbonded specimens. As already noted, this similar behavior is expected because this high-load transfer geometry primarily tests the adhesive bond strength at the edge of the joint. The riveted specimen results cannot be directly compared to the adhesive bonded and weldbonded results because of the differences in specimen configuration. However, the significance of these results is that the adhesive system for weldbonding gives excellent fatigue performance relative both to a standard riveted joint and a well developed adhesive system in a high-load transfer fatigue mode.

Table 21 also lists the results for adhesively bonded specimens made with a disbond, centered in the lap, constituting about 25 percent of the area of the lap. The results are essentially the same as the results without disbond. The disbond did not extend to the edges of the lap, the critical area in fatigue, and the remaining area of bond was large enough so that no reduction in fatigue life was seen.

2024-T3 Alclad/7075-T6

Selected fatigue tests were performed on low-load and high-load transfer weldbonded 2024-T3 alclad/7075-T6 specimens. The low-load transfer fatigue results are listed in Table 22 and plotted in Figure 98 with the 7075-T6/7075-T6 results as a reference. Figure 98 shows that the fatigue properties of the 2024-T3 alclad/7075-T6 are slightly below those for the 7075-T6/7075-T6 combination. This difference may be due to the strength of the nugget which has a different metallurgical structure or due to the lower strength 2024-T3 alclad portion of the specimen.

The high-load transfer fatigue results are listed in Table 23. These results are compared with the 7075-T6/7075-T6 results in Figure 99. As seen, the fatigue properties of 7075-T6/7075-T6 and 2024-T3 alclad/7075-T6 high-load transfer specimens are essentially the same. This shows that in high-load transfer geometry, the adhesive bond is being tested, and that the adhesive bonded qualities are similar in fatigue for these two combinations.

TABLE 21. ADHESIVE BONDED AND RIVETED HIGH-LOAD TRANSFER FATIGUE RESULTS

Material: 7075-T6 Al, 0.063 inch thick

Test Conditions: $R(\sigma_{minimum} / \sigma_{maximum}) = 0.1$, Frequency = 10Hz

Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

JOINING SYSTEM	MAXIMUM LOAD, POUNDS	CYCLES TO FAILURE
Adhesive Bond (1)	2250	409,490
Adhesive Bond (1)	2250	457,420
Adhesive Bond (1)	2250	574,210
Riveted (2)	Rivets sheared at approximately 2000 pounds	
Riveted (2)	1500	17,630
Riveted (2)	1000	130,760
Adhesive Bond with Disbond (1, 3)	2250	386,660
Adhesive Bond with Disbond (1, 3)	2250	461,850

NOTES:

1. FPL/BR127/FM123-2 Adhesive System
2. MS 20426-AD5 Rivets
3. Disbond: 0.7" diameter Teflon disc in center of lap

AD-A071 016 NORTHROP CORP HAWTHORNE CA AIRCRAFT GROUP F/G 1/3
ADVANCED WELDBONDING PROCESS ESTABLISHMENT FOR ALUMINUM.(U)
FEB 79 T R CROUCHER F33615-76-C-5412
UNCLASSIFIED NOR-78-185 AFMI -TR-79-4006 NL

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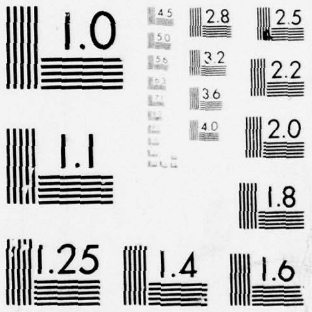


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

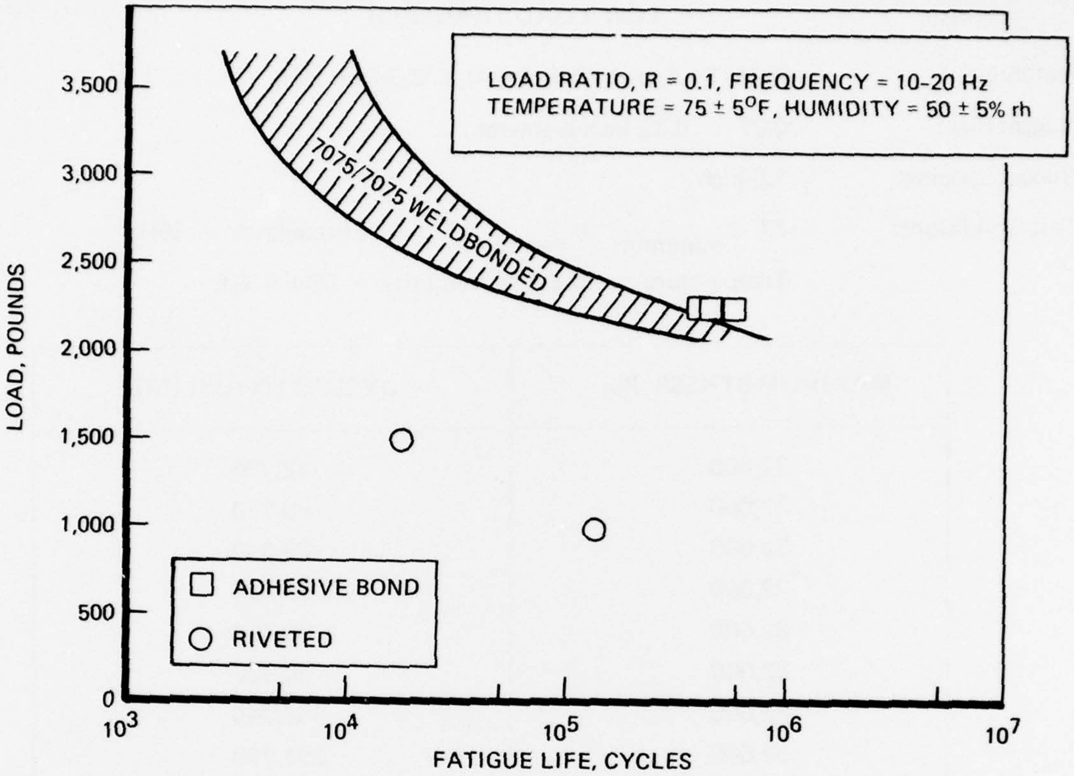


FIGURE 97. COMPARISON OF HIGH-LOAD TRANSFER FATIGUE RESULTS ON 7075-T6/7075-T6 COMBINATIONS

TABLE 22. FATIGUE BEHAVIOR OF 2024-T3 ALCLAD/7075-T6 BARE LOW-LOAD TRANSFER

Material:	2024-T3 Alclad/7075-T6 Al, 0.063 inch thick
Nugget Size:	0.27 – 0.32 inch diameter
Nugget Spacing:	1.5 inch
Test Conditions:	R($\sigma_{minimum}/\sigma_{maximum}$) = 0.1, Frequency = 10Hz Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

MAXIMUM STRESS, PSI	CYCLES TO FAILURE
32,000	42,730
32,000	60,770
32,000	62,040
32,000	66,420
32,000	70,830
32,000	89,630
32,000	152,740
32,000	251,750

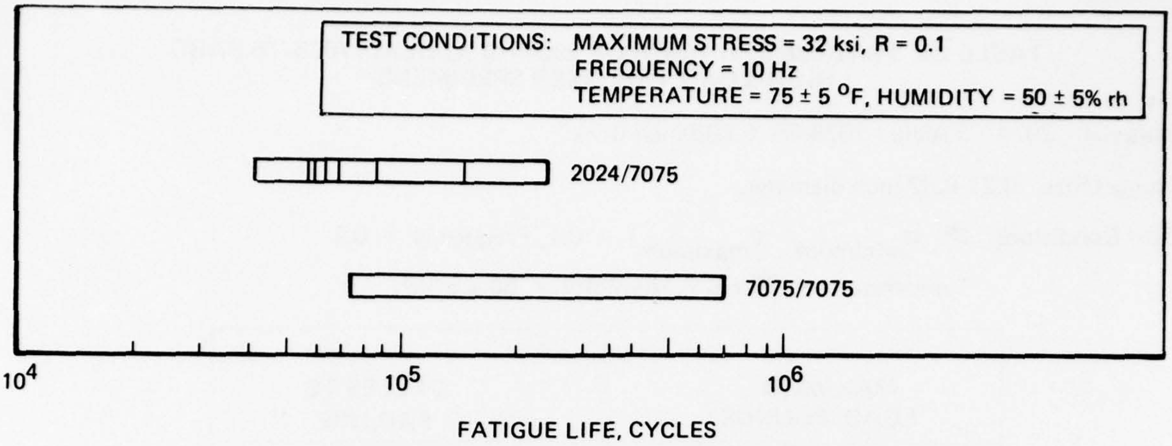


FIGURE 98. FATIGUE BEHAVIOR OF 2024-T3 ALCLAD/7075-T6 LOW-LOAD TRANSFER SPECIMENS

TABLE 23. FATIGUE BEHAVIOR OF 2024-T3 ALCLAD/7075-T6 BARE HIGH-LOAD TRANSFER SPECIMENS

Material: 2024-T3 Alclad/7075-T6, 0.063 inch thick.

Nugget Size: 0.27-0.32 inch diameter.

Test Conditions: R($\sigma_{minimum}$/ $\sigma_{maximum}$) = 0.1, Frequency = 0.1
Temperature = 75 ± 5 F, Humidity = 50 ± 5 %rh

MAXIMUM LOAD, POUNDS	CYCLES TO FAILURE
3,500	6,000
3,500	6,630
3,000	18,360
2,250	148,460
2,250	152,710
2,250	633,110
2,000	637,020
2,000	1,192,500
2,000	1,337,410

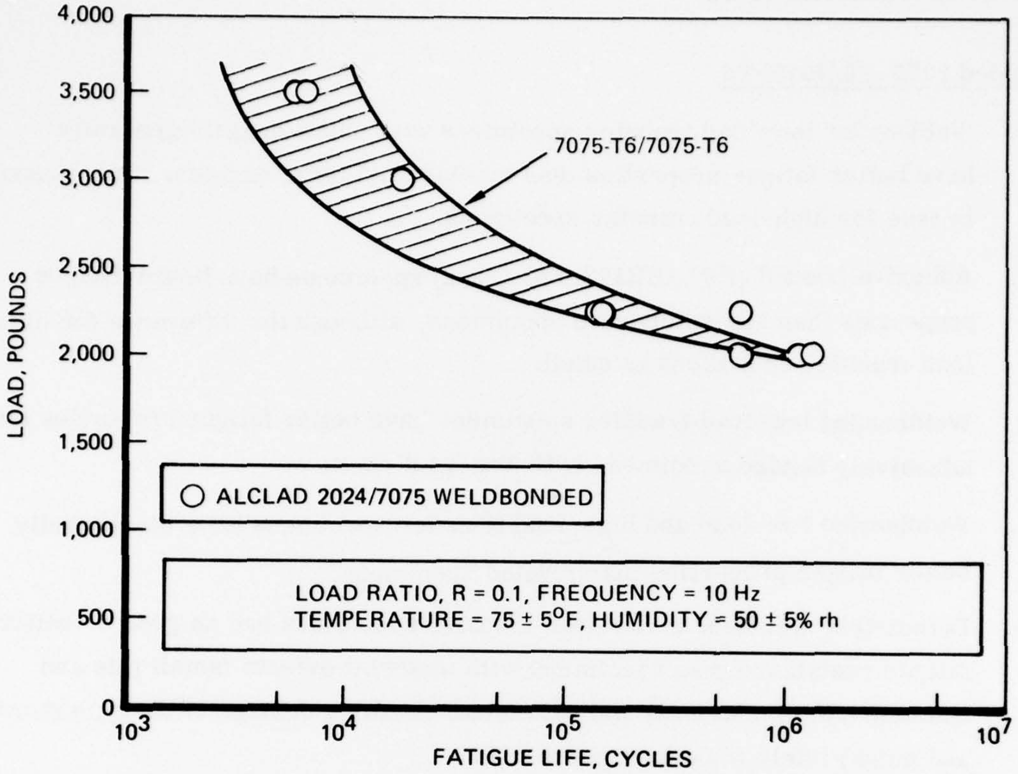


FIGURE 99 FATIGUE BEHAVIOR OF 2024-T3 ALCLAD/7075-T6 HIGH-LOAD TRANSFER SPECIMENS

SUMMARY AND CONCLUSIONS

Weldbonded 7075-T6/7075-T6

1. Weldbonded low-load transfer specimens with small nuggets generally have better fatigue properties than medium and large nuggets. The opposite is true for high-load transfer specimens.
2. Adhesive bonded (FPL/BR127/FM 123-2) specimens have better fatigue properties than the weldbonded specimens, although the difference for high-load transfer specimens is small.
3. Weldbonded low-load transfer specimens have better fatigue properties than adhesively bonded specimens with anti-peel rivets.
4. Weldbonded low-load and high-load transfer specimens have significantly better fatigue properties than riveted specimens.
5. Defect-free weldbonded low-load transfer specimens had as good or better fatigue resistance than specimens with material defects (small pits and titanium-rich inclusions) and with minor handling damage of the type (scratches and nicks) likely to occur in production.
6. Severe cracks in weld nuggets significantly decreased the fatigue life of weldbonded low-load transfer specimens.
7. In weldbonded low-load transfer specimens with cracked nuggets, the cracks became through cracks in both sheets before propagating.
8. In low-load transfer weldbonded specimens with cracked nuggets, when the cracks in the two sheets were nearly equal in length, the cracks propagated as a through crack in a monolithic material. Whenever the cracks in the two sheets were of unequal length, the shorter crack grew faster until the two cracks were of similar length.
9. Cracked weld nuggets did not degrade the fatigue properties of weldbonded high-load transfer specimens.
10. Severe expulsion extending to the edge of the joint slightly lowered the fatigue properties of weldbonded high-load transfer specimens.

11. The scatter in fatigue is reasonable even when the results for various nugget sizes and nugget spacing are considered together, showing good reproducibility of the fatigue behavior of weldbonded joints.
12. A nugget meeting Class A size and strength requirements is not necessary to achieve good fatigue resistance in weldbonded specimens. In fact, better fatigue properties can be obtained with smaller nuggets that may not meet Class A strength requirements.

Weldbonded 2024-T3 Alclad/7075-T6

1. The low-load transfer specimen fatigue results are slightly below those obtained for 7075-T6/7075-T6.
2. The high-load transfer specimen fatigue behavior is essentially the same as that for 7075-T6/7075-T6, as the adhesive bond is the controlling factor.

RELIABILITY EVALUATION

The objective of the reliability evaluation was to determine the reliability and repeatability of the weldbonding process under a range of standard manufacturing variables, and to obtain lap-shear strength design information based on a testing population of at least 300 specimens. The variables considered in this evaluation were aluminum sheet obtained from three different manufacturers, three different lots of adhesive, and specimens that were processed on three different days.

RELIABILITY TEST PLAN

Lap-shear strength for weldbonded joints was obtained for 308 test specimens. Test panels, 5 x 15 inches, were cleaned and anodized and weldbonded according to the weldbond procedures established for this program. Alclad 2024-T3, 0.040-inch thick, was weldbonded to 7075-T6, 0.050-inch thick, using a 1-inch overlap. This combination was selected because it represented the highest load-carrying panels on the A-10 aircraft. After the panels were weldbonded, doublers of 7075-T6, 0.063-inch thick were bonded to the 7075-T6 panel and to the 2024-T3 panel in order to prevent parent material failure and to assure that shear values would be obtained for the weldbond joints.

Paste adhesive A1444B was used for weldbonding the lap joints and for bonding the 7075-T6 doubler panels. These test panels were then cured at 250°F for 1 hour. Twelve lap-shear specimens were cut from each test panel. The test specimen configuration is included in Figure 100.

Each test panel, consisting of 12 lap-shear specimens, represented one of 27 different material/process combinations. These combinations included sheet material obtained from three different aluminum manufacturers; three different lots of A1444B adhesive, and the use of three different process days for surface treatment and weldbonding. The purpose of this test matrix was to determine variability of weldbond lap-shear strength as a function of material supplier, adhesive lots, and variations in process that might occur for different process days.

WELDBOND DESIGN ALLOWABLES

The strength distribution curve for all the lap-shear data (308 tests) is presented in Figure 100. Lap-shear Strength values were rounded up to the nearest 100 lbs., e.g., 5 specimens failed at 4150 to 4200 lbs., and were plotted at 4200 lbs. For a test population of 308 shown in the curve, the lap-shear design allowables, A and B, as defined in MIL-HDBK-5, were determined to be A = 3600 lbs., and B = 4400 lbs. The mean for this data is 5247 lbs. and the standard deviation is 498 lbs.

WELDBOND RELIABILITY

The weldbond lap-shear strength as a function of the aluminum manufacturer, the adhesive batch, and the process day is shown in Figure 101. Each bar represents data from 10, 11, or 12 tests, or a total of 308 tests. The processing used for day 1 was not as good as the processing used for day 2 and for day 3 although no reason was apparent for the differences. The cleaning and anodizing procedures are well established and the process used on day 1 met the process requirements in terms of bath etch rate, bath chemistry, and resulting aluminum surface cleanliness as evaluated by the Scanning Electron Microscope (SEM). However, it is assumed that a minor variation in procedures or bath chemistry occurred which resulted in approximately 11 percent lower average lap-shear strength i.e. 4800 lbs. vs. 5400 lbs. than panels that were processed on day 2 and day 3. This reduced strength is insignificant when considering the design allowables of 3600 and 4400 lbs. described above. In fact, the low value of one test specimen, 3600 lbs., was obtained for material processed on day 2. Also, the minimum lap-shear strength represented for all three process days was approximately the same, 4200 lbs. to 4300 lbs., except for one value at 3600 lbs.

There was no difference in strength as related to adhesive lots E, F, or G. Also, there was no difference in lap-shear strength as related to aluminum manufacturer. In summary, the weldbond process provides high strength lap-joints with excellent process reliability.

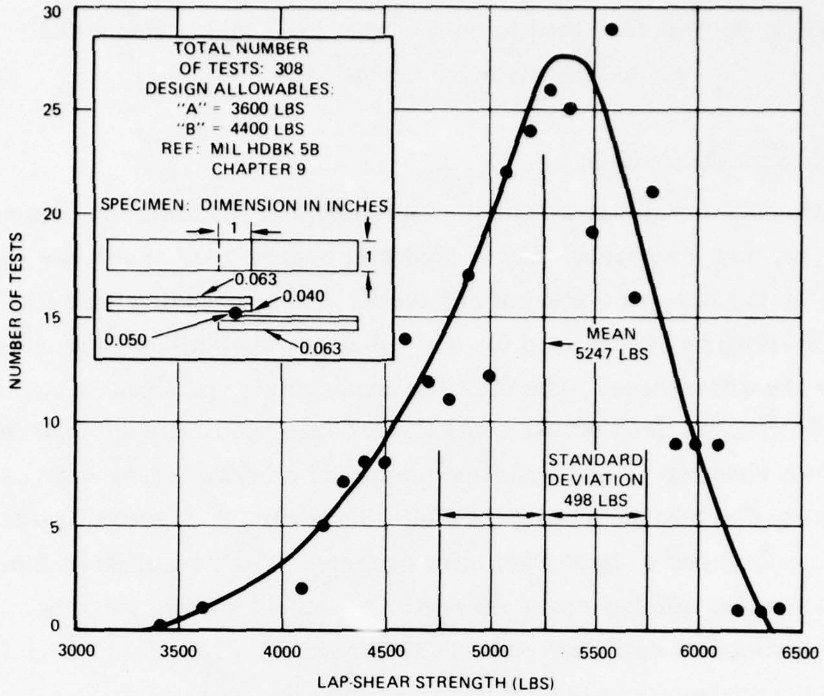
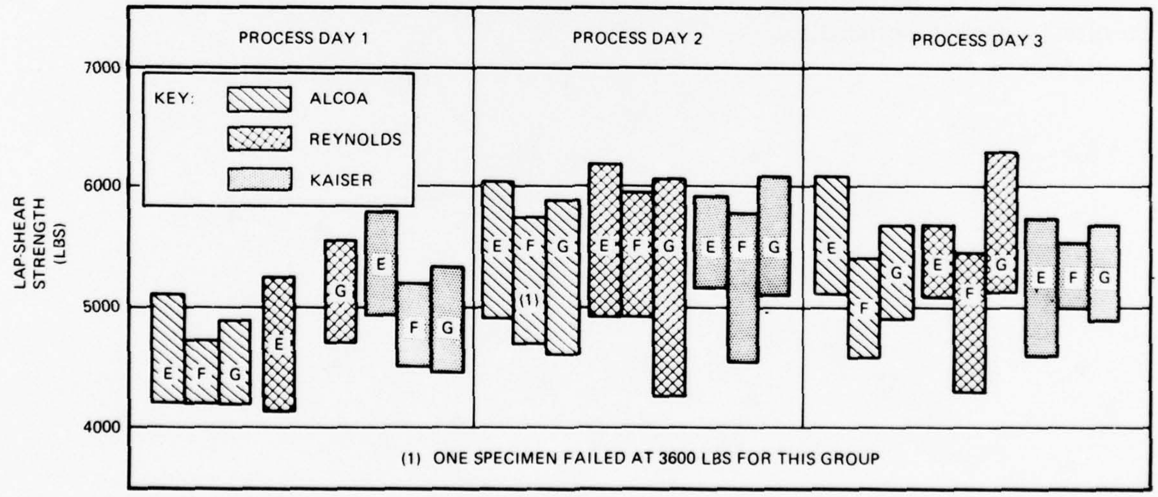


FIGURE 100. WELDBOND LAP-SHEAR STRENGTH DISTRIBUTION CURVE

NOTES: 1. EACH BAR REPRESENTS DATA FOR 10,11, OR 12 TESTS, TOTAL 308 TESTS.
2. ADHESIVE LOT E,F, AND G FOR THE A1444B PASTE.



(1) ONE SPECIMEN FAILED AT 3600 LBS FOR THIS GROUP

FIGURE 101. WELDBOND LAP-SHEAR STRENGTH AS A FUNCTION OF PROCESS DAY' ALUMINUM MANUFACTURER, AND ADHESIVE LOT

DURABILITY EVALUATION

One of the primary concerns in the use of adhesive bonded structures is premature failure due to a time-dependent crack-growth in the bond joint under the combined influence of applied stress and a corrosive environment. This type of failure is commonly termed "environmental stress cracking." Resistance to environmental stress cracking is defined for this program as durability.

In order to compare the durability of the weldbond system with that of the PABST adhesive bonding system and with the standard FPL (Forest Products Laboratory) etch adhesive bonding system, an addendum to the current weldbond contract was funded.

The scope of this program is as follows:

a) Three bonding systems are being evaluated
   (1) FPL/BR127/FM123-2
   (2) Weldbond System
   (3) PABST - Phosphoric Acid/BR127/FM73

b) Four material combinations are being evaluated.
   (1) 2024-T3 alclad to 7075-T6 bare
   (2) 2024-T3 bare to 7075-T6 bare
   (3) 2024-T3 bare to 2024-T3 bare
   (4) 7075-T6 bare to 7075-T6 bare

c) Three testing configurations are being used for this program.
   (1) Wedge test
   (2) Constant load/salt water immersion test
   (3) Surface scratch corrosion test

d) Six different exposure conditions of atmosphere and loads are being used for many exposure times.

In all, 72 different tests are being conducted. The surface/adhesive systems being evaluated are illustrated in Figure 102. The test conditions and specimen types are summarized in Figure 103.

This addendum is still in progress and will be reported in a final addendum report.

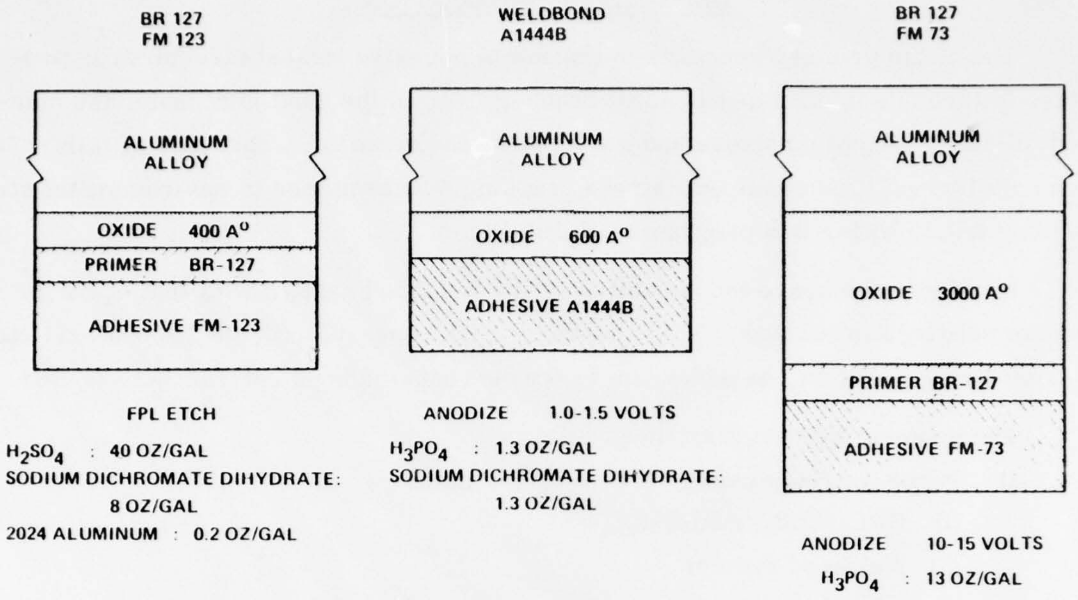


FIGURE 102. SURFACE/ADHESIVE SYSTEMS BEING EVALUATED IN THE ADDENDUM PROGRAM

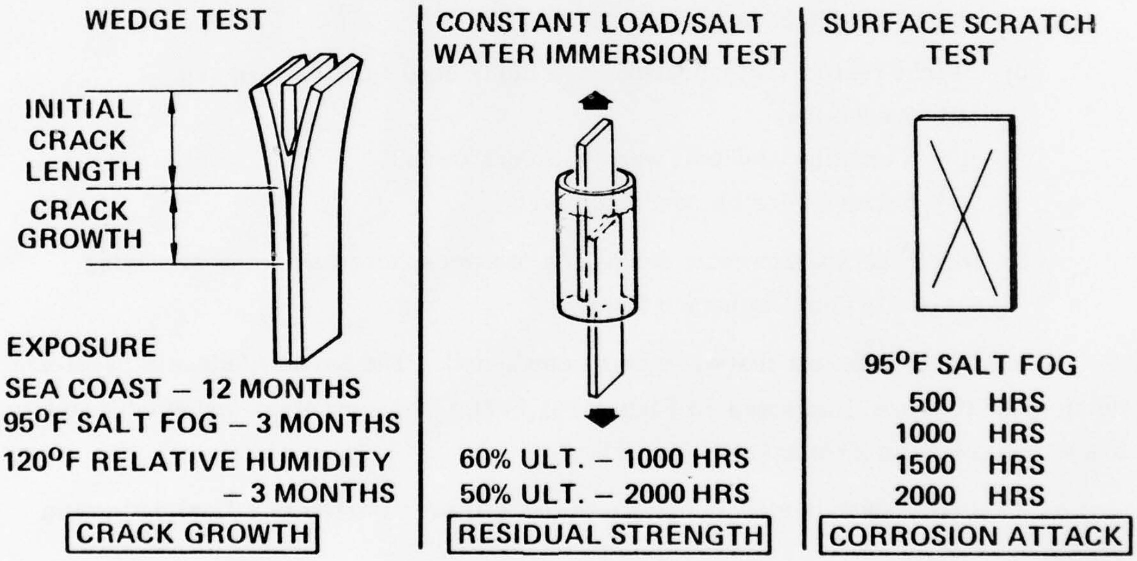


FIGURE 103. TEST CONDITIONS AND CONFIGURATIONS BEING USED IN THE ADDENDUM PROGRAM

MANUFACTURE OF TEST PANELS

Following the selection of the demonstration test panel configuration and the optimization of the cleaning and welding procedures, manufacturing plans for the fabrication of the flat test panels were developed jointly by Northrop and Fairchild. The plans for the different panel combinations were nearly identical. A sample manufacturing plan for the 0.040/0.050 panel combination is contained in Appendix F of this report. The manufacturing plans were used for the fabrication of the flat beaded panels for structural test, as shown in Figure 104, and the curved demonstration panels, as shown in Figure 105. All skin and beaded panel details for both the adhesive bonded and weldbonded configurations were fabricated by Fairchild. Fairchild adhesively bonded all test assemblies while Northrop performed all required weldbonding operations. The processing of the weldbonded details followed the Northrop Process Specification (XPS-WB) which is shown in Appendix A. A description of the individual processing procedures that were followed including observations made during manufacture is contained in the following description.

MANUFACTURE OF PRODUCTION DETAILS

As previously indicated, all skin and beaded pan details for both the adhesive and weldbonded panels were manufactured by Fairchild. The beaded pans supplied to Northrop and Fairchild's bonding facility at Hagerstown were processed together as one batch. A standard production forming block was fabricated out of aluminum for trapped-rubber forming of the beaded pans. The bead depressions for a female forming tool were machined using a formed cutting tool. Bead depths, widths and lengths were identical for all four beads.

All beaded pans and skins were fabricated with 3-inches of excess material on the widths and lengths to provide subsequent test material for SEM evaluations and spot weld process control coupons. Each pan blank was sheared to template, and required tooling holes were added. The blank was then formed in the "O" condition, solution heat treated, quenched in water, straightened and aged to the T6 condition. All heat treat processing was performed according to MIL-H-6088.

To prevent unacceptable thinning at the transition of the bead to flat areas, it was necessary to use a two-step forming operation. Rubber shims of approximately half the depth of the beads were used in the center two beads to provide a rough formed

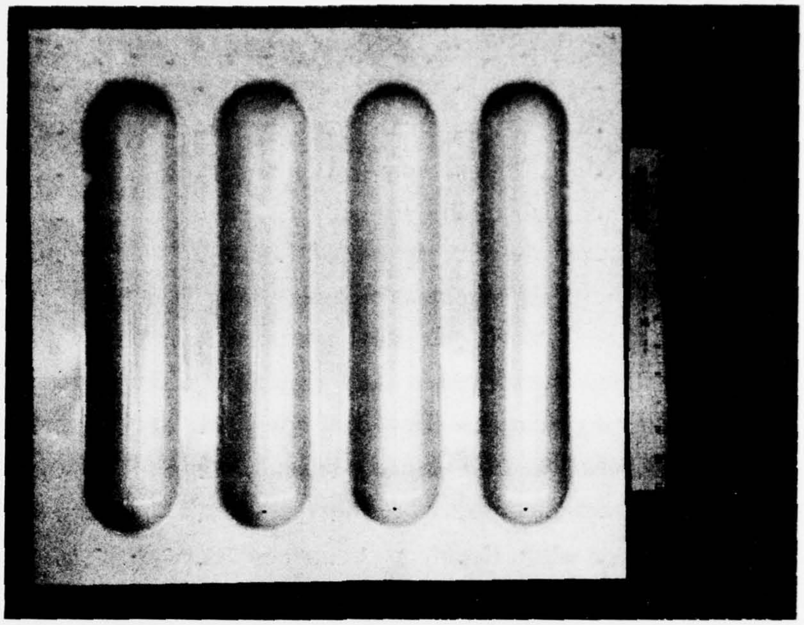


FIGURE 104. FLAT STRUCTURAL WELDBONDED TEST PANEL

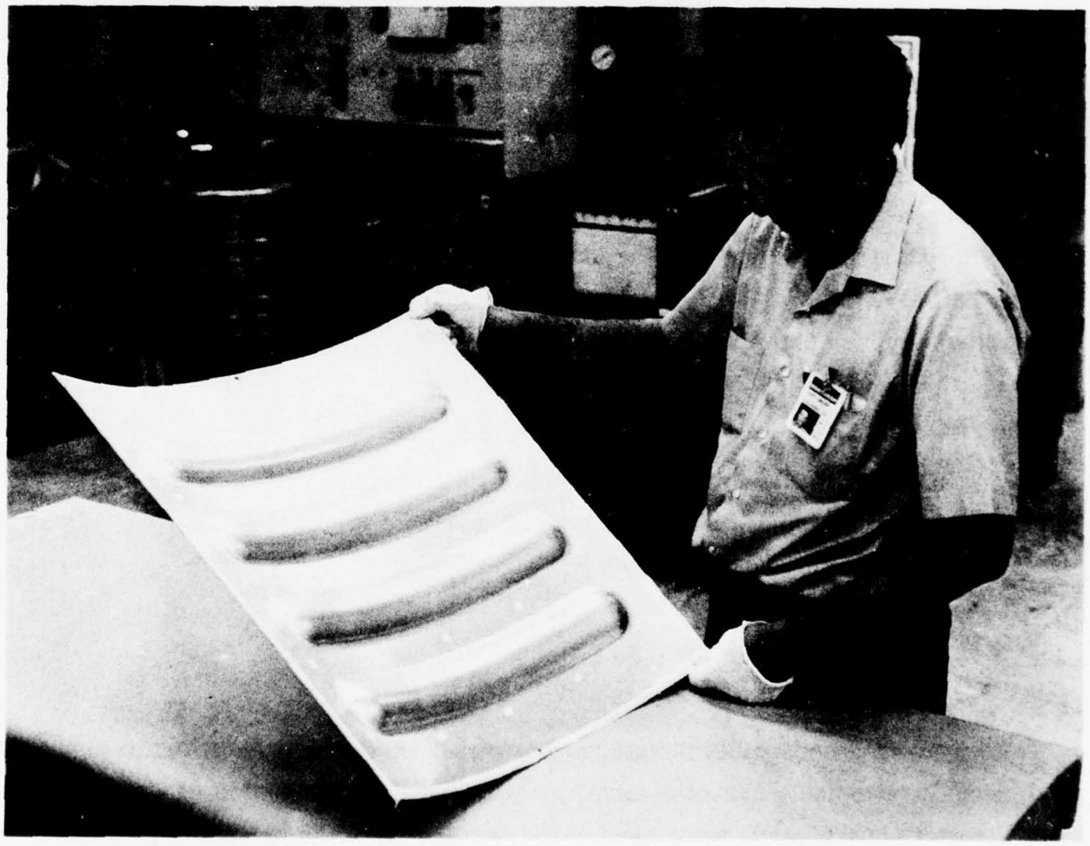


FIGURE 105. CURVED WELDBOND DEMONSTRATION PANEL

pan in the initial forming step. The shims were removed for the second step to finish forming the pans. One tool was used to form both the 0.032-inch thick and 0.050-inch thick 7075-0 aluminum beads.

Thirty-four (34) pans (18 pieces of 0.050-inch and 16 pieces of 0.032-inch 7075-T6 bare) were shipped to Northrop for weldbond processing. Approximately the same number of pans were shipped to Hagerstown for adhesive bonding.

ADHESIVE BONDING ASSEMBLY

Adhesive bonding of the pans to flat 2024-T3 alclad skins was accomplished at Hagerstown with an FPL etch surface preparation, BR-127 adhesive primer and FM-123-2 film adhesive autoclave cured at 250 F for one hour. Details of the process are as follows:

Surface preparation included vapor degreasing and alkaline cleaning (Altrex 1097, 10-20 minutes at 160°F - 190°F), followed by immersion rinsing in water (5 minutes), deoxidizing (sulfuric acid/sodium dichromate 12-15 minutes at 160°F ± 10°F) spray rinsing and drying (at 130°F-150°F). After the details were cleaned the BR-127 adhesive primer was applied by spraying to a thickness of .1 to .4 mils on each adhesive bonding faying surface. The parts were transferred to a controlled clean room environment for film adhesive (FM-123-2) application, layup and leak checking, followed by autoclave curing 250°F for one hour and a final harmonic bond inspection. Assemblies were then shipped to Fairchild Republic, Farmingdale, for drilling the fixture holes to complete the assembly. No bonding difficulties were experienced and acceptable parts were produced.

WELDBOND ASSEMBLY

When the pans were received at Northrop, a problem was encountered in achieving full weld nuggets during weldbonding. It was found that this problem was caused by localized fit-up gaps due to the distortion of the panel. Two types of distortion were observed. The first was an overall slight curve in the panel which was easily corrected by hand-pressure. This distortion is common, normally acceptable, and did not cause a problem for weldbonding. A second type of distortion which appeared as local dimples (approximately 0.005-inch deep) was believed to be caused by local working of the part by the heat treat straightener following the solution heat treatment. This condition is considered acceptable for adhesive bonded assemblies, as autoclave pressure tends to overcome the dimple and the gap is completely filled with adhesive. However, because of the high stiffness of the sheet in the area of the dimple, the gap was too large to allow for adhesive squeeze out and the necessary metal contact for initiating a weld. Tests showed that even with a 4,000 pound weld force (500 pound weld force was normal), it was impossible to squeeze-out the adhesive under the weld. Thus, the absence of metal/metal contact prohibited weld initiation.

In order to meet the program schedule, a special tool was made and the distorted pans were annealed, flattened and re-heat treated by Alum-A-Therm, a Los Angeles heat treating company. To minimize the necessity for any further check and straightening operations after re-solution heat treating, the pans were quenched in a polymer quenchant used by Northrop and other aerospace firms for minimizing heat treat distortion. Utilizing this technique, the distortion was removed and panels were successfully weldbonded. A subsequent series of pans, formed by Fairchild on a hydraulic press, were water quenched and were successfully checked and straightened with no evidence of the dimple condition.

FIGURE 106. PANEL MOUNTED IN SURFACE PREPARATION FIXTURE

It was concluded from this effort that care must be taken to avoid local distortion of the details to be weldbonded. Polymer quenching following the solution heat treatment procedure is recommended. Using this quenching procedure, quenching distortion will be minimized thereby reducing the need for extensive straightening operations which caused the observed local distortion.

SURFACE PREPARATION

After the production beaded pan details were received in the flattened condition from Aluma-A-Therm, they were hardness tested and dimensionally inspected to insure that drawing requirements were met. Each detail was then positioned in a special surface preparation fixture shown in Figure 106 which supported the detail during processing. The fixture contained a main copper supporting bar, aluminum rods which supported the part, and titanium spring clips which were used to position the part against the support rods and to insure electrical contact. The ends of the copper bar were covered with electrical tape to insure that the part was electrically insulated from the deoxidizing/ anodizing tanks. The parts were degreased and alkaline cleaned according to the specification XPS-WB, (Appendix A). After alkaline cleaning, the parts were spray rinsed and deoxidized in the modified Amchem 7/17 deoxidizing bath for 6-8 minutes. They were then immediately transferred to the spray rinse tank and rinsed with a combination of deionized and tap water. As previously discussed, the inclusion of the tap water was found to be necessary in order to eliminate the staining of the 2024 alclad skins. The tap water was applied using a hand-spray technique for the first one minute of rinsing. An adequate flow to insure flooding of the complete part was found necessary in order to achieve effective rinsing. Particular attention was paid to insure that adequate rinsing was achieved around the clip-contact area, as it was this location that was found to be most prone to staining. A deionized water spray rinse was used for the balance of the rinse cycle.

Following the rinse, the part was given a water break test and immediately immersed into the anodizing tank. The electrical connection for the anodizing voltage was connected within 15 seconds after the parts were immersed. Previous studies at Northrop have shown that if connections could be made and current applied within thirty seconds after the parts were immersed into the anodizing bath, effective anodizing would result. The positive pole was then connected with a simple bull-dog clip to the copper contact bar. The negative ground was permanently connected to the tank. This technique is preferrable to connecting electrical leads prior to immersion in the anodizing solution because it eliminates the possibly of high local current densities during the immersion operation.

The required anodizing voltage was applied using two techniques and effective results were achieved using both techniques. Initially an open voltage was applied to the tank using a preset higher value which was predetermined for each specific panel size. The higher than specified applied voltage was necessary due to IR drops in the electrical circuit and the resistance of the solutions being used. The actual voltage applied to the part was maintained within the ± 0.1-volt tolerance and was monitored continually by a digital voltmeter (which was also used to preset the voltage prior to panel processing) and by a recording voltmeter as shown in Figure 107. The continuous voltage recording was used to insure that no stray voltage or current spikes occurred during the anodizing process. Using this technique, it was found that the voltage climbed to the required range within five to ten seconds and thereafter dropped slightly due to the resistance build-up of a surface oxide which resulted during the anodizing process. This technique also resulted in a high current surge initially during formation of the barrier layer followed by a sudden current drop after the oxide barrier layer was formed. A gradual increase in current to a stable value then occurred. The current was continually recorded during the processing of all panels. Typical voltage and current traces for the processing of panels are shown in Figures 108 and 109.

Later in the program, it was found that more consistent results could be achieved by applying the voltage gradually to the maximum value over the first two minutes of anodizing. It is felt that if this technique were to be used in a production environment, it would be desirable to automate this process using a proportional controller recorder to automatically control the rate of voltage application and to insure against voltage spikes. It has been previously shown that even a very short voltage spike can significantly increase the oxide barrier layer thickness and inhibit subsequent welding operations. It is recommended for production usage, that a recording voltmeter be used in the system to insure proper voltage control. The use of current recordings is recommended when the process is being qualified in a new installation to insure that proper anodizing is being achieved. However, continuous current recordings are not necessary in a production situation if adequate voltage control is maintained.

After anodizing, the panel was rinsed for seven minutes using either deionized water or a deionized/tap water mix. It was found that use of tap water was not mandatory following anodizing for the stain control, but could be used as an alternate.

To protect the finished surfaces, following rinsing, the panels were handled only at the edges using white gloves. The panel was removed from the fixture and oven dried at 150°F for thirty minutes in conformance to the process specification. After drying, the panel was removed from the oven and allowed to cool to room temperature. Approximately 1 1/4 inches were then sheared from two sides of the panel

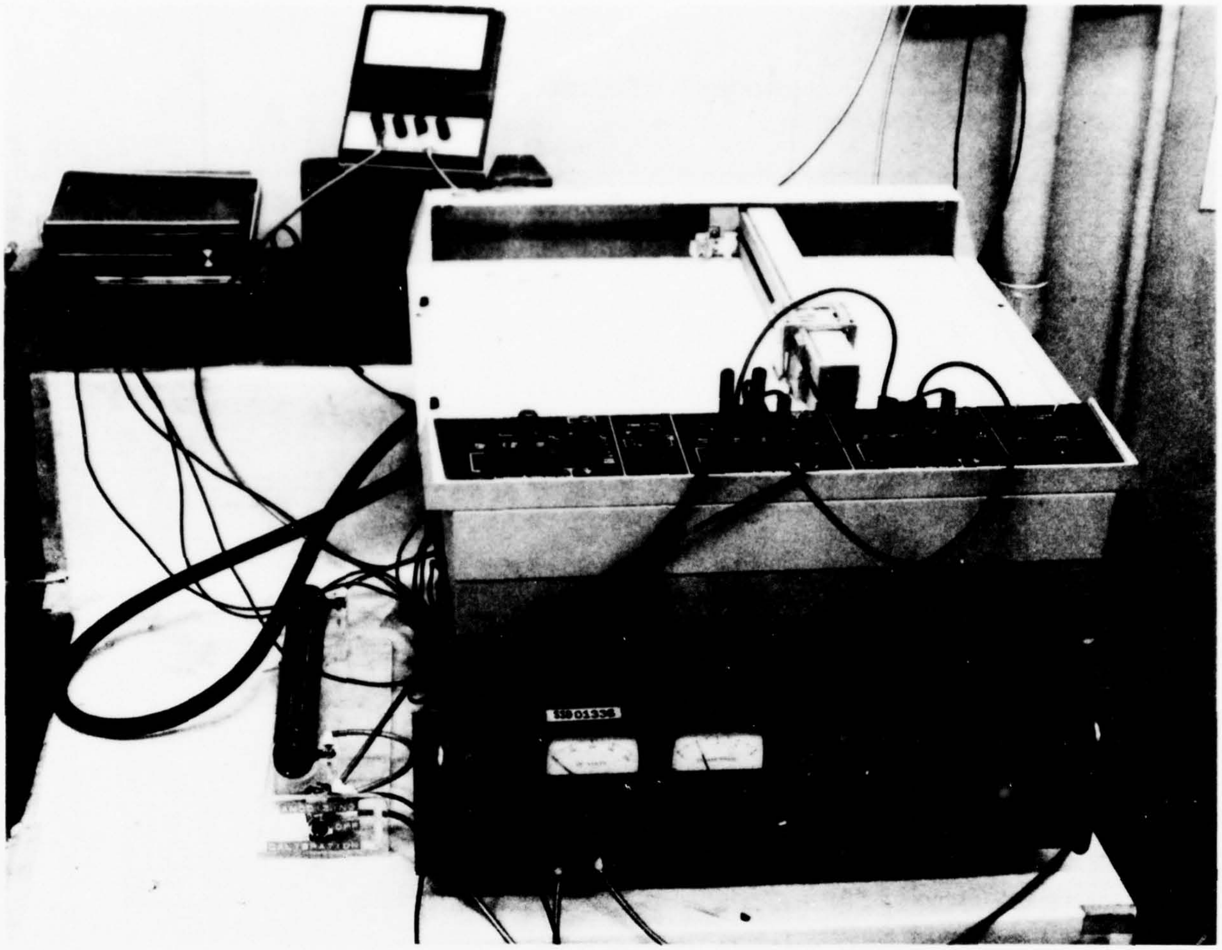


FIGURE 107. VOLTAGE AND CURRENT MONITORING EQUIPMENT

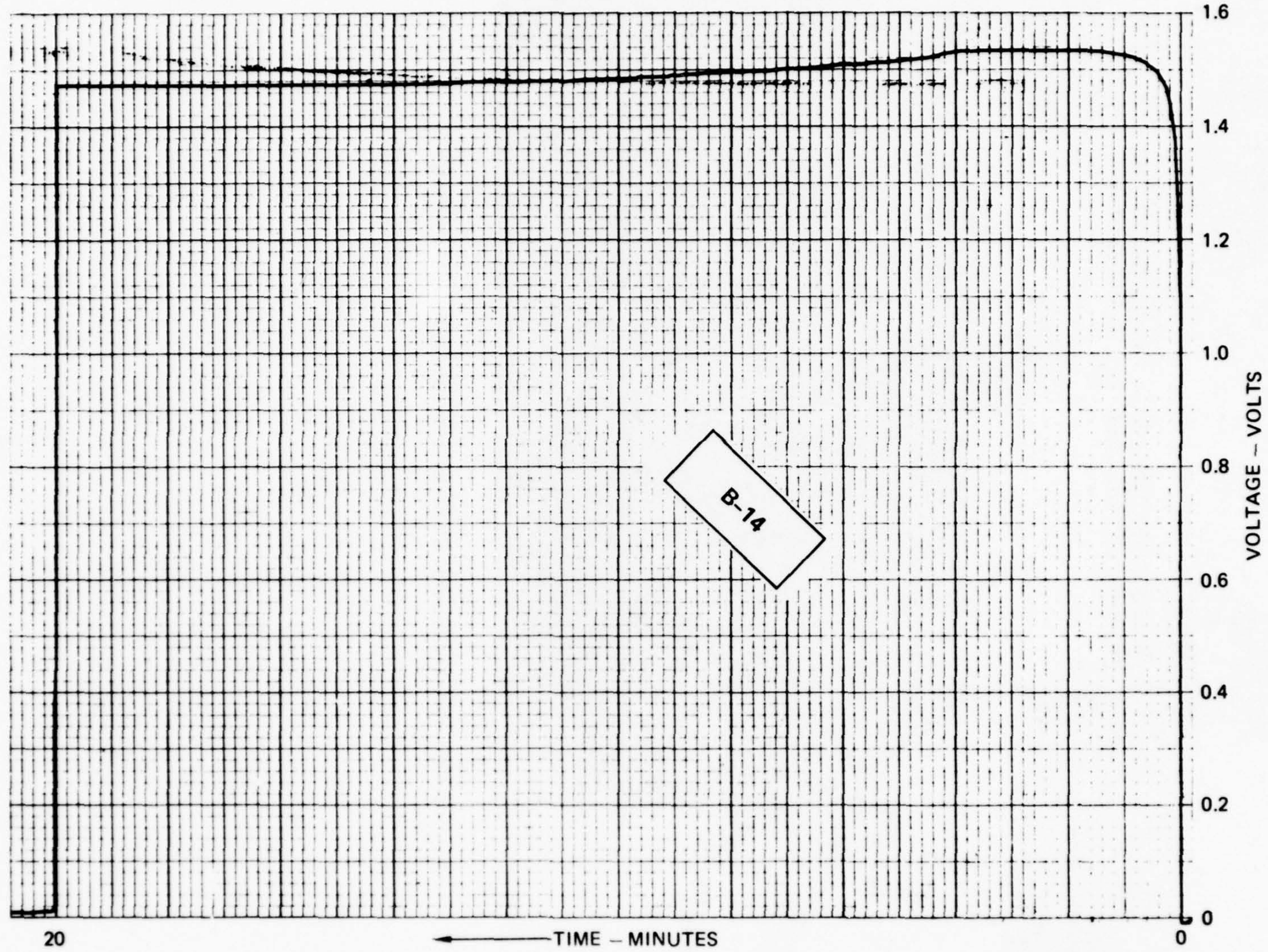
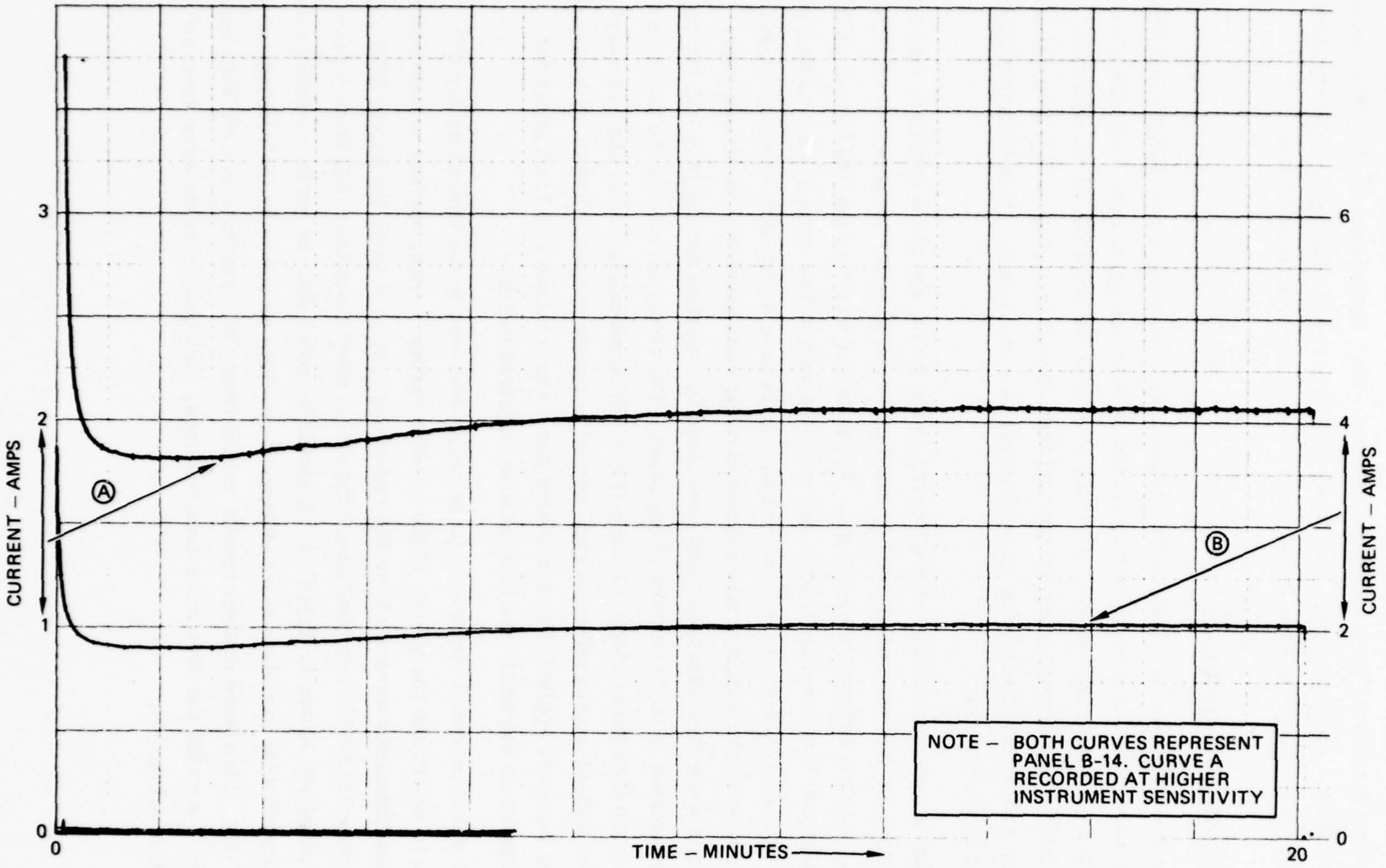


FIGURE 108. VOLTAGE TRACE, PANEL B-14, 7075-T6



NOTE – BOTH CURVES REPRESENT PANEL B-14. CURVE A RECORDED AT HIGHER INSTRUMENT SENSITIVITY

FIGURE 109. CURRENT TRACES, PANEL B-14, 7075-T6

and this was then sheared into 1 1/4 by 2 1/2 inch spot weld control specimens. During the shearing operation, the panel was protected with a kraft paper to avoid damaging the anodized oxide. After shearing, the panel was wrapped in chemically inert blueline kraft bond paper to protect the detail prior to application of the adhesive.

APPLICATION OF ADHESIVE

The A-1444B adhesive used in the program was received in one gallon batch lots starting with batch D and each lot was packed in four one quart cans. All adhesive was stored in a -10F deep freeze box. In order to extend the shelf life of the adhesive, the adhesive was removed from the can and transferred into glass containers which contained sufficient adhesive for approximately two test panels. This adhesive was then returned to the freezer.

Prior to the application of the adhesive on the panel, the glass container was removed from the freezer and allowed to stand unopened at room temperature until the adhesive reached ambient temperature. The adhesive was then applied to both skin and pan details with a wooden applicator and spread evenly with a notched saw-toothed plastic spatula as shown in Figure 110 to a nominal thickness of 0.008-inch on each surface. The thickness of the adhesive was measured using a standard film thickness gage. The details were then assembled and positioned by inserting tooling pins into two tooling holes located in the trim area of the panel. The circumference of the panel was taped using a fiberglass electrical tape (7 mil. thick manufactured by the Permacel Corp.) to control excess adhesive run-out and to insure proper filling of all local areas. After the tape was applied, the assembled panel was wrapped in a kraft paper for transportation to the weld area located in an adjacent facility.

One set of anodized specimens (trim stock) was sent to the laboratory for SEM analysis to determine the quality of the anodize coating. Also, surface contact resistance measurements were made on the remaining trim tabs using the alclad 2024/2024 and the bare 7075/7075 combinations. Typical contact resistance data from a production panel are shown in Table 24. It should be noted that the surface contact measurements showed wide variation in measurement readings as shown by the readings of Panel C-14. Resistance measurements varied from 200 microhms to over 3000 microhms. However, even with the 3000 microhms readings, high quality welds were successfully achieved in all panels.

FIGURE 110. APPLICATION OF ADHESIVE TO PANEL USING SPREADER

TABLE 24. SURFACE CONTACT RESISTANCE OF PANEL C-14

Test Combination	Reading No.	Resistance Micro-ohms	Reading No.	Resistance Micro-ohms
7075 bare to 7075 bare	1	185	7	240
	2	860	8	450
	3	185	9	270
	4	500	10	270
	5	230	11	510
	6	340	12	560
		Average - (12 readings)		383
2024 Alclad to 2024 Alclad	1	290	7	1600
	2	350	8	240
	3	3300	9	1400
	4	2200	10	730
	5	1500	11	900
	6	1600	12	180
		Average - (12 readings)		1190

RESISTANCE SPOT WELDING

Following application of the adhesive, the preassembled panel was taken to the resistance welding area in an adjacent facility. The first step in the welding procedure was to apply an electrode anti-stick solution to the electrode contact areas of the panel to minimize electrode sticking. Further details of this technique are discussed later in this report. A weld locating tool was then attached to the panel as shown in Figure 111 to insure proper locating and spacing of the spot welds.

The welding electrodes were cleaned with a number 320 grit aluminum oxide cloth, wipped with acetone and air dried. Two spot weld samples using the panel set-up material were welded and lap shear tested. If the nugget quality and lap shear strength were satisfactory by the third weld, the welding of the panel was begun. If the third weld was unacceptable, a fourth weld was made and tested. This technique was found necessary due to the characteristics of the anti-stick solution which are described later in this report.

The welding of the panel was begun by making a weld in the trim area adjacent to the center row of welds of the panel. Three different spot weld patterns were evaluated during the course of the program and all resulted in acceptable panels. The weld sequence which gave the best results and which was used on most of the structural test panels is shown in Figure 112. In this sequence, welding was initiated on one end of the panel and progressed continuously across the panel to the opposite end. Approximately 15-16 welds were made between each tip cleaning. Upon completion of each row, a lap shear test specimen was made using the panel trim material to determine the weld quality and strength that would characterize the final weld of the sequence. It was found that lap shear strengths of these final welds were generally higher than the initial welds due to the use of the anti-stick solution. This phenomenon is discussed later in the report. The quality of all welds was excellent with no cracking or expulsion in evidence and the resulting lap shear strengths were well in excess of minimum requirements.

After the completion of each weld sequence, the tip was cleaned and three control welds were made prior to the next sequence of welds. This procedure was repeated until the panel was completely welded after which it was removed from the tooling fixture. Excess adhesive was removed by wiping with a dry Kimwipe. The panel was then wrapped in acid-free kraft paper for transportation to the curing oven.

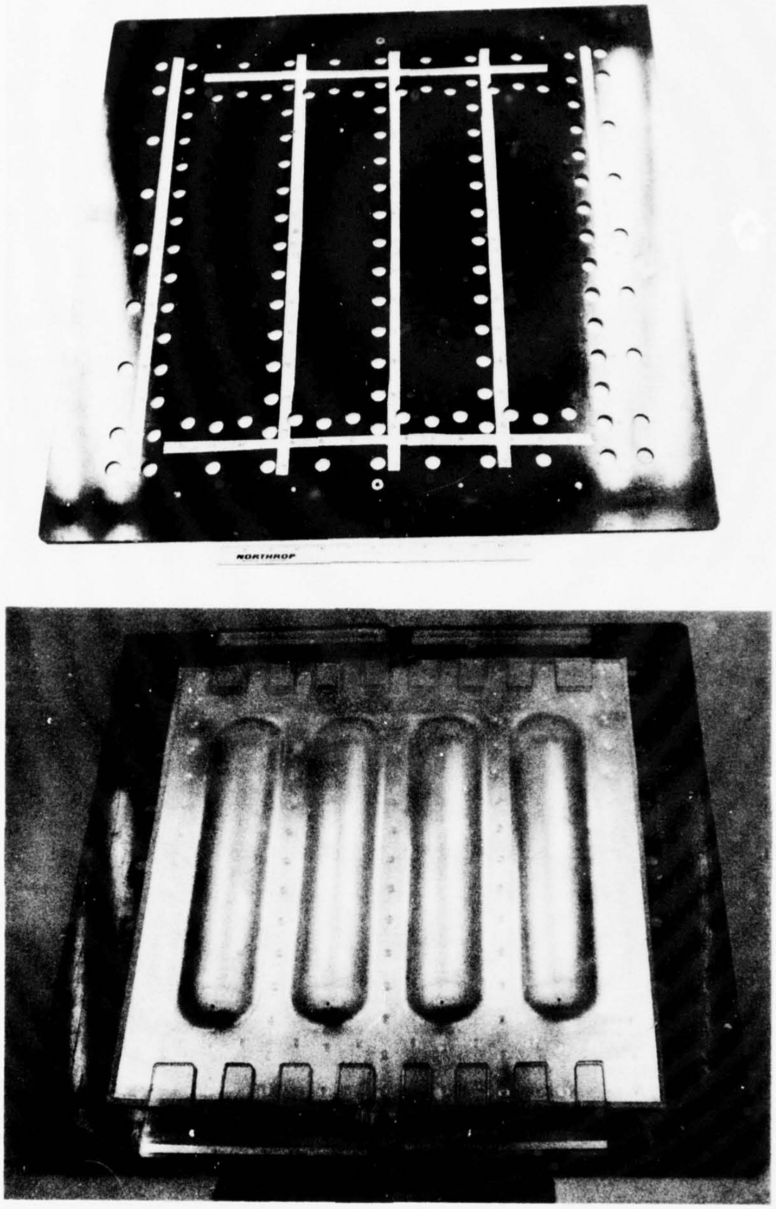


FIGURE 111. PANEL SPOT WELD LOCATING TOOL

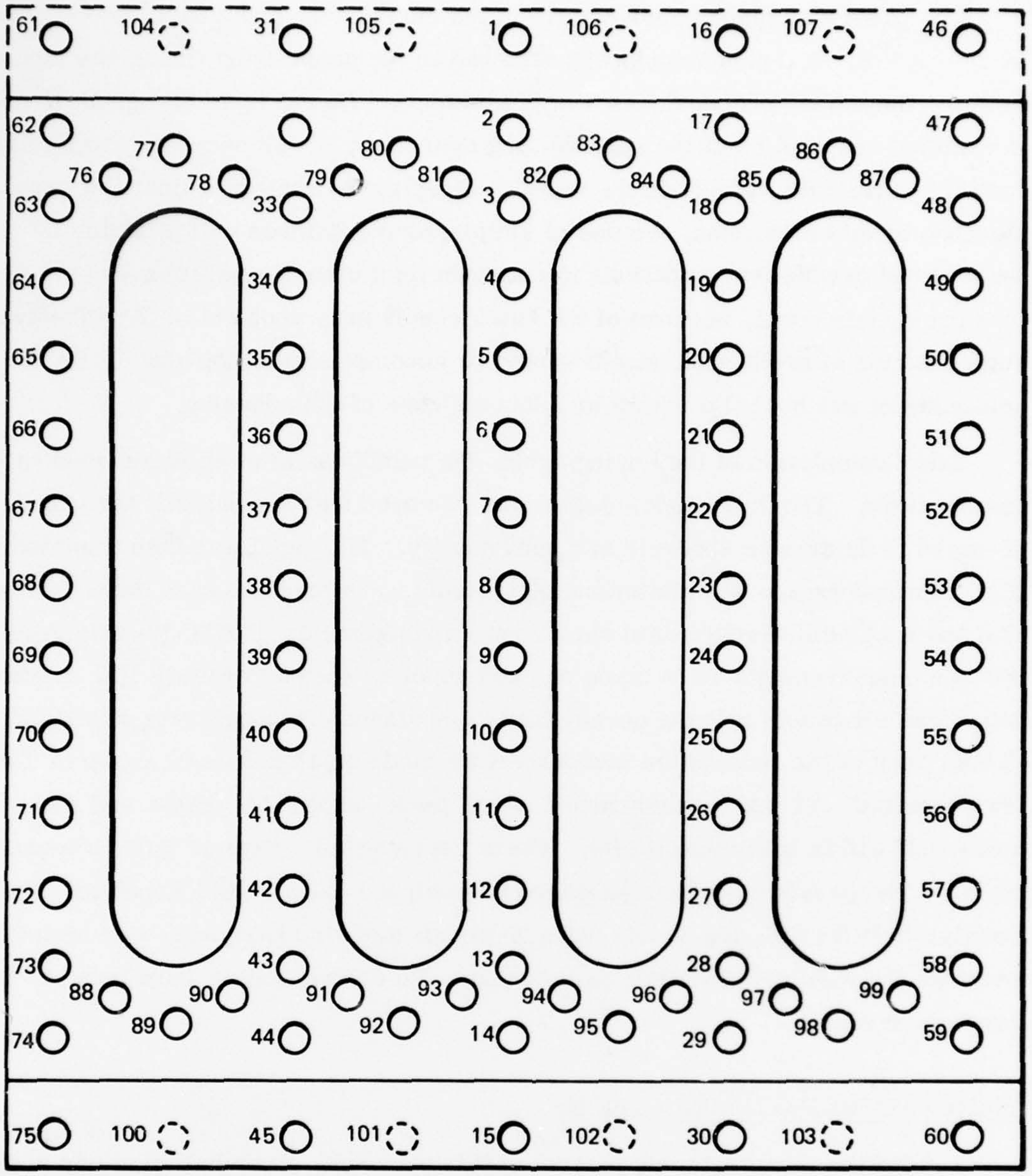


FIGURE 112. PANEL WELD SEQUENCE*

The panel was placed horizontally in the curing oven and cured for one hour at 250-260°F. A thermocouple was attached to the panel using fiberglass tape to monitor the curing process. As a slight distortion (in the form of a gradual curvature) resulted from the spot welding operation, it was necessary to lightly load the panel with weights in the reverse direction to achieve a final flat panel. Because of this distortion, the use of simple curing fixtures will probably be required in production operations to maintain tight dimensional tolerances. Also was previously noted, because of the batch consistency problem of the adhesive, future curing of production panels should be accomplished at 250-260°F for a minimum of two hours to insure an adequate cure of the adhesive.

After completion of the curing cycle, the panel was allowed to air-cool to room temperature. The anti-stick solution was removed with alcohol and the panel was X-rayed to determine spotweld and bond quality. The panel was then trimmed to final dimensions and indentation measurements were made on each panel to confirm that the spot weld aerodynamic smoothness requirements of MIL-W-6858 were met. Fifteen measurements were made on each panel as shown in Figure 113. It was found that all panels met the aerodynamic smoothness requirements of MIL-W-6858. A summary of the indentation measurements made on 14 panels is shown in Table 25. Two hundred and ten measurements were made on the 14 panels and all welds were well within maximum limits. These represented a total of 1498 individual spot welds. The panels were then packaged and shipped to Fairchild Republic. Upon receipt at Fairchild, the panels were X-rayed, and also harmonic bond tested to evaluate the weld and adhesive bond quality. No discrepancies were noted in the production panels.

MANUFACTURING OBSERVATIONS

During the manufacturing portion of this program, a number of minor problems and observations occurred which are worth noting. As each of these problems were solved during the course of this program, discussion and understanding of each is worthwhile to enable a more successful integration of the weldbonding process into new manufacturing environments. Each of these areas are discussed in detail in the sections that follow:

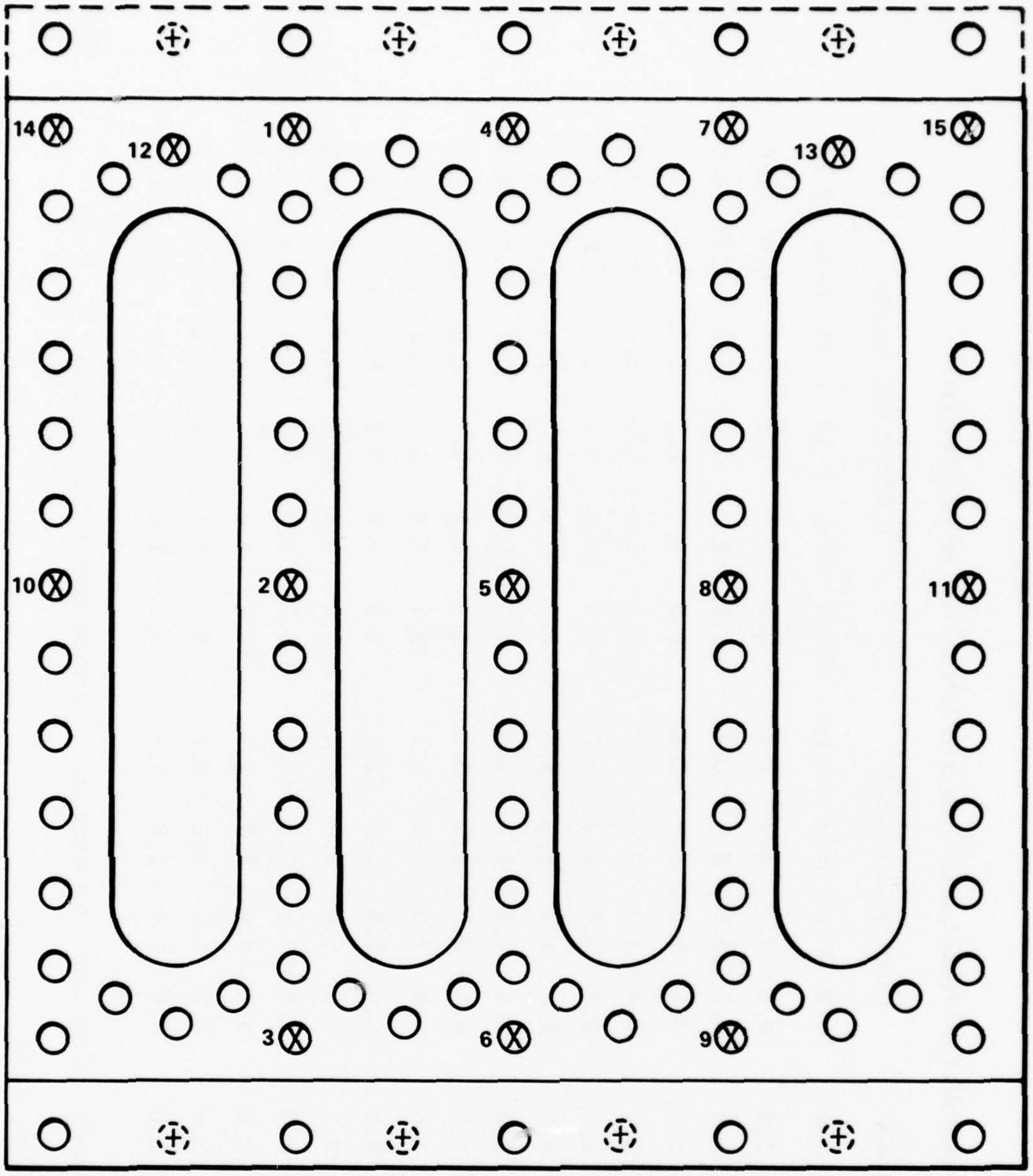


FIGURE 113. LOCATION OF SPOT MEASUREMENTS WELD INDENTATION

TABLE 25. SUMMARY OF PANEL SPOT WELD INDENTATION MEASUREMENT[1]

Location No.[2]	0.071/0.050 Panels				0.040/0.050 Panels				0.025/0.032 Panels					
	A-1	A-2	A-3	A-4	B-10	B-12	B-13	B-15	C-10	C-11	C-13	C-14	C-15	C-16
1	1.7	3.0	1.8	1.3	0.3	0.5	1.0	1.2	3.5	1.4	1.8	2.5	0.0	+1.0
2	1.7	1.9	1.7	1.8	0.1	0.0	2.5	0.8	1.1	+1.3	0.0	+1.2	+1.4	+1.6
3	1.7	3.2	2.0	5.2	0.1	2.8	1.9	3.2	0.5	0.8	1.9	1.2	+1.4	1.1
4	2.1	2.4	1.5	2.5	0.4	1.5	0.5	2.3	1.1	2.0	0.3	2.6	0.7	0.0
5	1.4	1.9	1.4	1.8	+0.7	0.5	2.2	0.2	+0.9	+1.5	0.1	+1.6	+1.2	+1.1
6	3.1	2.5	2.2	4.5	2.3	1.9	2.9	1.4	0.7	0.7	1.4	1.8	1.3	1.1
7	1.8	1.7	1.9	1.5	0.4	0.2	1.3	0.7	1.1	0.6	0.0	0.7	+0.7	+0.2
8	1.1	2.9	1.6	1.2	0.4	0.0	2.0	0.3	1.5	+1.1	+0.7	+1.4	+0.6	+1.2
9	2.2	2.9	1.4	4.8	1.2	0.3	2.1	0.2	2.7	0.9	0.4	1.7	0.5	0.6
10	2.6	2.2	1.9	3.0	1.6	1.4	2.8	1.3	3.3	+0.4	0.9	+0.2	+0.7	+1.7
11	2.6	2.4	2.0	3.1	0.6	1.0	2.7	0.4	+0.2	+0.4	+0.5	+1.7	+0.7	2.3
12	2.0	1.8	1.7	2.8	0.9	3.8	4.8	+0.2	2.3	1.2	5.7	1.3	+0.8	+1.0
13	2.0	2.4	1.5	3.6	1.2	0.9	2.3	1.2	+0.7	1.4	1.1	2.1	+0.4	2.0
14	2.1	2.2	2.0	3.3	2.2	1.7	3.6	0.6	0.6	+0.9	0.2	1.4	+0.2	0.2
15	2.2	2.5	1.9	1.8	0.0	1.0	1.8	1.1	0.2	+1.6	+1.0	1.6	+1.0	+1.1

(1) Measurements in thousandths of an inch. All were below surface except those labeled +.

(2) For location refers to Figure 113.

Effect of Oxide Thickness and Surface Resistivity

Previous weldbond experience at Northrop had indicated that the ideal oxide thickness for welding was in the range of 400-700 angstroms. Experience in this program both at Northrop and Fairchild have indicated, however, that although thickness is a contributing factor for producing a high quality expulsion-free weld, other oxide characteristics are also critical factors. Under certain conditions, the achievement of high quality welds through a much thicker surface oxide (as high as 3,000Å) was possible. Conversely, in some instances, welding was difficult and frequent expulsion resulted when the resulting oxide was within the 400-700Å recommended thickness range. It is believed that this phenomenon was due to some characteristics of the (1) residual oxide left on the part after deoxidation and (2) the barrier layer which was formed during the first 30-60 seconds of anodizing. It is also believed that the oxide character is affected by extraneous particles or contamination in the bath, as bath filtration appeared to produce a thinner (approximately 500Å) and more consistant oxide. Although the scope of this contract effort did not allow investigation into this phenomenon, it can be concluded that the oxide thickness, as measured by the Scanning Electron Microscope (SEM), is not an absolute measure of the weldability of a specific oxide. SEM analysis on a periodic basis is a necessary process control tool for checking the adequacy of the deoxidization, the presence of contamination and the character and thickness of the resulting anodize. However, the oxide thickness as measured by SEM analysis, cannot be used for accepting or rejecting a specific lot of parts without additional information.

In order to more fully understand this phenomenon, additional work must be undertaken to enable a greater understanding of the initiation and growth of the boehmite oxide and the contributing factors that affect weldability. Particular emphasis should be placed on the effect of the barrier layer and particle contamination.

Shape and Alignment of Electrodes

One of the more critical factors in the successful achievement of high quality spot welds through anodized surfaces was found to be the care of the welding electrodes. The condition of the dome radius and the alignment of the electrodes appears to be more critical than for standard resistance spot welding procedures due to the characteristics of the surface oxide. The importance of initiating the nugget near the center of the electrode was discussed previously in this report. To achieve this condition, an accurately shaped electrode of the proper radius is essential. Also the electrode contact area must be accurately centered at the dome tip. A small misalignment of the electrodes (due to improper conditioning) may cause a non-centered nugget initiation point resulting in irregular shaped nuggets and possible expulsion. It was found both at Northrop and Fairchild that the use of a small electrode centering device during electrode-cleaning was extremely helpful in maintaining the proper electrode condition and in lengthening the life of the electrodes. It is recommended that if the condition of the electrodes remain marginal after dressing, they be replaced with a fresh set.

Use of Spot Weld Anti-Stick Solution

In spot welding aluminum alloys through an anodized aluminum surface, sufficient heat is generated at the electrode and between the part interface to cause electrode sticking. It was found that this sticking condition is particularly severe on the 2024-T3 alclad aluminum surface, anodized with the 1.0 V PSD anodize treatment. In order to overcome this sticking problem, an evaluation was made of a commercially available anti-stick solution which, was reported to reduce the sticking problem. The anti-stick solution used in the program was called P-2, and is available from the Swiss Federal Aircraft Factory, Emmen, Switzerland. A second product called Weldeze, available from Farbest Inc., Los Angeles, Calif., was evaluated later in the program and found to give equivalent results. As claimed, the use of the solution greatly reduced the frequency of sticking. It was found that as many as 15 to 100 welds could be made before the first instance of sticking was observed which necessitated cleaning of the electrodes. Without the use of the solution, sticking sometimes occurred in as little as four welds.

Production use of the solution was a simple task. The solution was brush applied to the electrode contact area of the panel to be welded and allowed to air dry. Welding then progressed in a normal manner. The anti-stick solution was left on the panel through the cure, and then was easily removed from the panel by hand wiping with alcohol.

The anti-stick solution was found to be extremely effective in minimizing the number of electrode cleaning operations and aided in the manufacture of Class A welds. An unusual circumstance was noted during the manufacture of the panels, however. The first few welds made after each electrode cleaning were undersize. The exact number of welds needed before full size welds were achieved appeared to be a function of the heat generated in the electrode. Fewer welds were needed on higher heat weld schedules than on lower heat weld schedules. It was also noted that the weld strength tended to progressively increase as an increasing number of welds were made. A production procedure was then initiated for the thin gage material combination so that by the 5th or 6th weld (using dummy material) a weld strength of approximately 350 to 400 pounds was achieved and welding of the panel could begin. As the number of welds increased, however, the strengths progressively increased. Tests conducted on separate test material showed that by the 50th weld, 500 pound lap shear strength was being achieved. This phenomenon appeared to have no detrimental effect on the weld quality except that the weld consistency requirements per MIL-W-6858 may have to be modified when the anti-stick solution is used.

The Welding of Curved Panels

The final effort of this program involved the actual weldbonding of production A-10 curved panels. The panel configuration selected for this demonstration was panel C-5 shown in Figure 105. It is an 0.032-7075-T6 bare pan, 0.025-2024-T3 alclad skin combination located on the top of the aircraft as shown in Figure 3. Three panels were welded both at Fairchild and at Northrop to demonstrate feasibility of applying the weldbonding technique to an actual production panel. These panels were cured and underwent non-destructive inspection to evaluate the weld and bond quality of the panel. It was the intent of this evaluation to determine the feasibility of weldbonding curved panels. It was found that no significant problems were evident as a result of applying the technology up to a curved panel design. For this material thickness and alloy combination, high quality welds were easily obtained.

Summary

The manufacture of the production test panels was overall a successful operation and proved that panels of this type could be manufactured in a production environment with a high level of success and a low reject rate. This program also proved that there is a wide versatility to the process as the first five .050/.040 combination panels were manufactured before the final weld schedules were developed and showed marginal weld quality in regard to nugget roundness and consistency. These panels were included in the test program, however, and all were found to be acceptable. The final twelve weldbonded panels were made according to the complete finalized process. These panels included a total of 1284 spotwelds, and all welds were acceptable as measured by X-ray inspection. Confirming tests conducted at Fairchild substantiated the Northrop results. Fairchild X-ray and harmonic bond inspected all panels made at Northrop and found no rejectable defects in either the weld or bond quality.

The aerodynamic smoothness measurements made on the fourteen panels (210 welds) also demonstrate that using the techniques developed in this program, the application of the process for exterior skin aircraft components will present no problem.

PANEL TEST PROGRAM

TEST PROGRAM APPROACH

The bonded beaded skin panels in the A-10A fuselage center section are in a region of high shear intensity and significant fuel pressurization. The design requirements for these panels include both static strength and fatigue life requirements for shear and normal pressure.

Although a considerable number of panel tests were performed in the design development phase of the A-10 program, these tests were configured to develop design data and to study failure modes for shear and normal pressure loading. Both static and constant amplitude fatigue tests were performed. Structural qualification of these panels was achieved as part of the overall testing of the static and fatigue airframes.

The objective of the test program was to perform, on a one-to-one basis, comparative tests of weldbonded and autoclave bonded beaded skin panels for the A-10 critical loading modes of in-plane shear and normal pressure. The program was designed to investigate relative performance with respect to static strength and fatigue life and to evaluate failure characteristics.

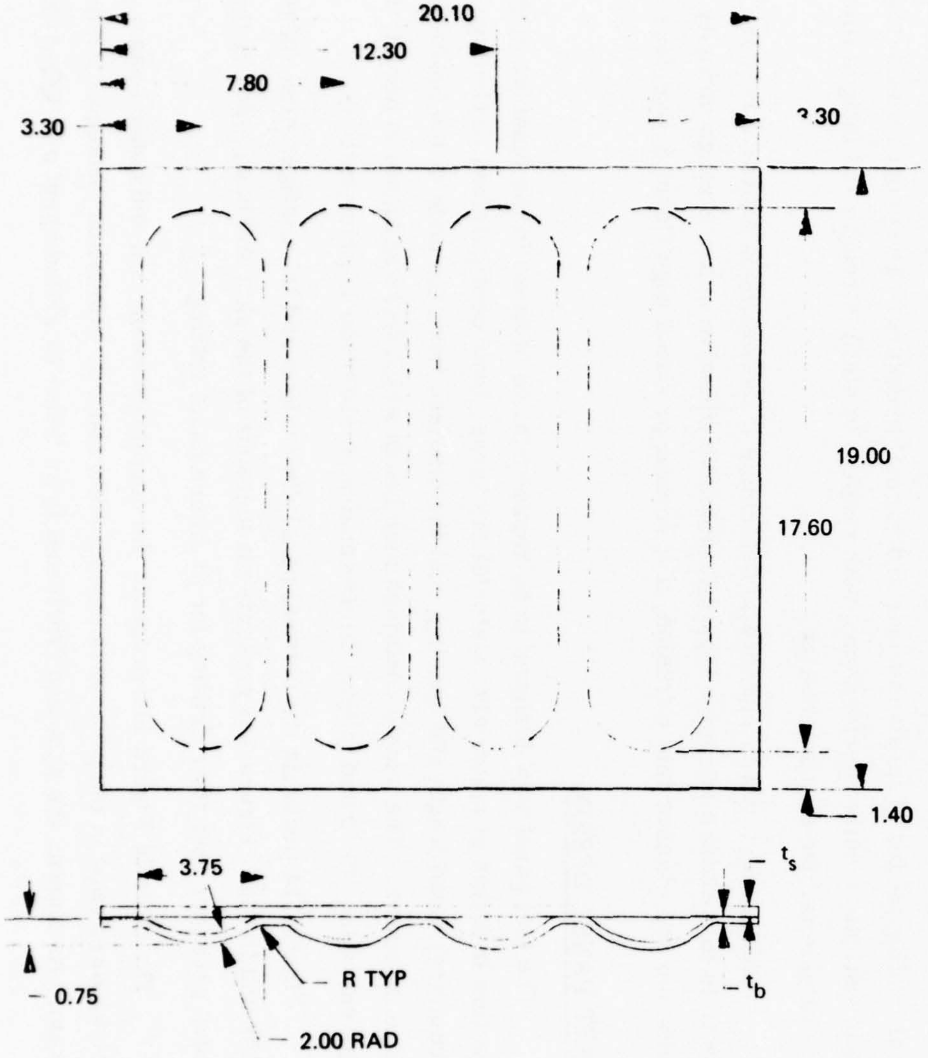
Additionally, it was intended to determine if the weldbond adhesive is more susceptible to moisture intrusion than the autoclave adhesive either through porosity or diffusion and whether this intrusion, if it occurs, produces significant deleterious effects.

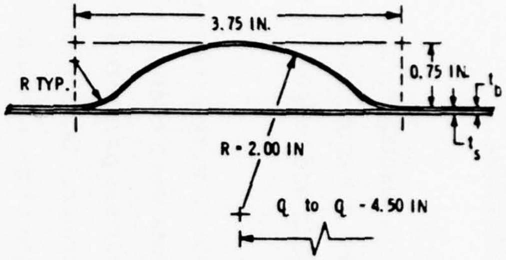
TEST PANEL DESIGN

The test panel was designed to be representative of those in the fuselage midsection in terms of materials, material thickness, bead configuration (including end geometry), bead length and spacing, and the distance from the ends of the beads to edge fasteners. The panels contained four beads which were adequate to permit development of the static and fatigue failure modes as observed in prior testing.

Figure 114 presents the critical panel dimensions and the configuration, of the stiffening beads. Figure 115 presents photographs of the skin and bead sides of the panel pressure test after drilling for pressure panel testing.

The table in Figure 114 presents the combinations of skin and beaded pan thicknesses used in the processes development and test evaluation phases of the program. As shown, the skin was fabricated from 2024-T3 alclad sheet per QQ-A-250/5



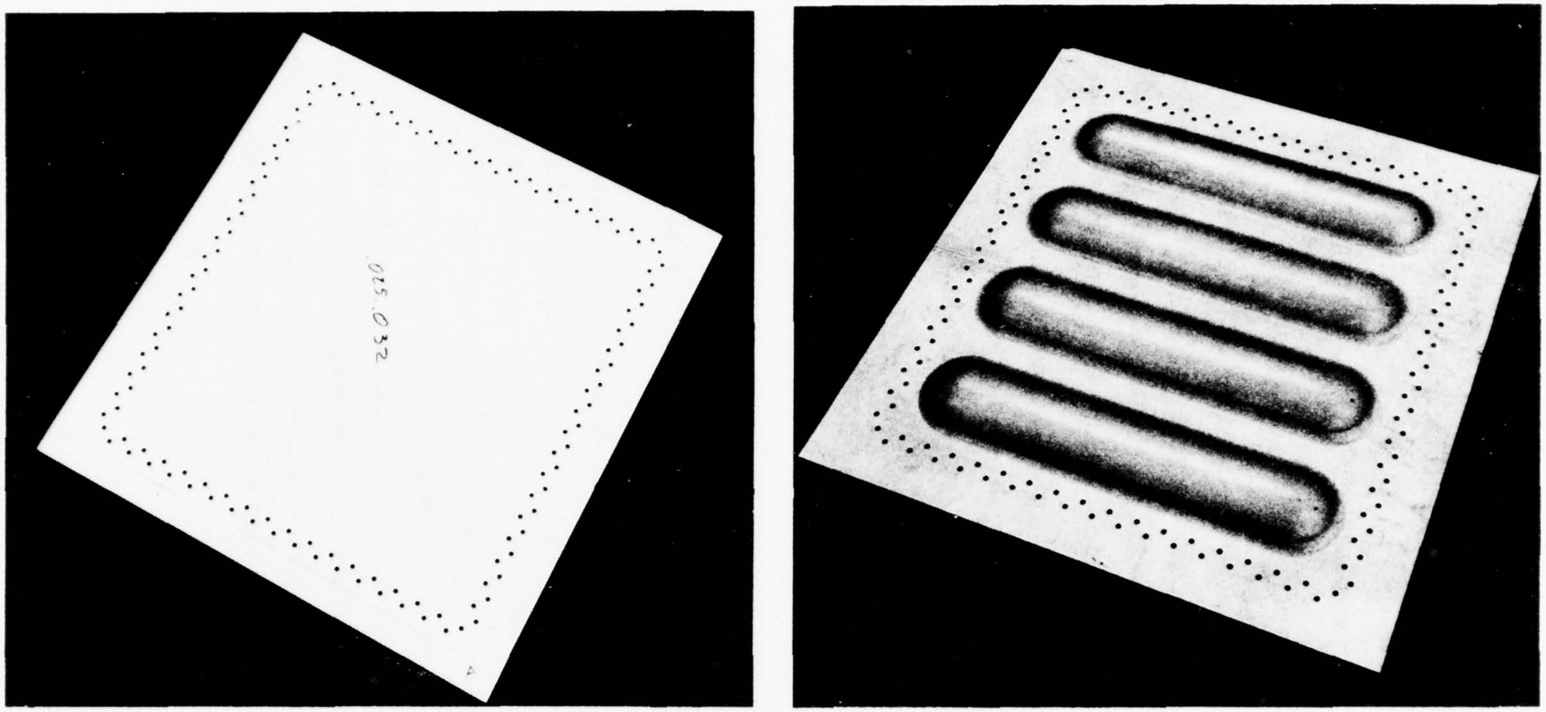


SKIN AND BEAD THICKNESS

	DASH NUMBER	t_s	t_b
AUTOCLAVE	-1	.071	.050
	-3	.040	.050
	-5	.025	.032
WELD BONDED	-7	.071	.050
	-9	.040	.050
	-11	.025	.032

SKIN - 2024-T3 ALCLAD PER QQ-A-250/5
BEAD - 7075-T6 BARE PER QQ-A-250/12

FIGURE 114. TEST PANEL DESIGN



SKIN SIDE BEAD

FIGURE 115. PHOTOGRAPH OF TEST PANEL

and the bead from 7075-T6 bare per QQ-A-250/12. The autoclave bonded and weldbonded panels were fabricated and inspected as described in the previous section. The autoclave bonded panels were prepared using FPL etch, BR 127 corrosion inhibited primer, and FM 123-2 adhesive. The weldbonded panels were prepared with a low voltage phosphoric acid anodize and A-1444B adhesive.

TEST RATIONALE

As discussed previously, autoclave bonded skin panels are used in the A-10 center fuselage in areas of high shear intensity and/or significant fuel pressure. Therefore, the test program was designed to provide the one-to-one test evaluation of panels under static and fatigue conditions for shear and normal pressure loading.

The static shear panel tests included one autoclave bonded and one weldbonded panel in each of the three skin and beaded pan thickness combinations, i.e., 0.025/0.032 inch panel, 0.040/0.050 inch panel and 0.071/0.050 inch panel.

Two approaches were used for the fatigue tests; (1) spectrum load tests for the 0.025/0.032 inch combination and the 0.040/0.050 inch combination, and (2) constant amplitude tests for the 0.071/0.050 inch combination. The spectrum loads and test sequences used in testing of the lighter gage panels were representative of those in the shear critical side fuselage panel. The constant amplitude fatigue load for the heavier gage panel was at 75 percent of the average failing load of the static fuselage panels.

The purpose of the constant amplitude tests was to evaluate the tendency of the bonded lands between beads to "disbond" due to shear buckling of the skin across the bead. Experience with shear buckling beam webs or skin panels, when stiffeners are bonded to the skin, have shown a tendency for local disbonding. This disbonding occurs when free buckling of the sheet is restricted by the stiffener and the buckle wave tends to peel the sheet from the stiffener. It can be expected that the tendency to "disbond" increases with increasing skin thickness of the buckling skin, higher ratios of the applied shear to the sheet buckling shear and decreased adhesive peel strength. Thus the heavier gage, 0.071 in. skin was selected for constant amplitude testing to evaluate the disbonding tendency.

Static pressure panel tests were conducted to determine the failing pressure and the failure mode. Since none of the A-10 fuselage center section panels were critical in the fuel pressure mode of loading, but were critical in shear, and since comparative testing of autoclave bonded and weldbonded panels was being performed, it was unnecessary to reproduce the panel size. Therefore the panel configuration, used for the other static and fatigue tests, as shown in Figure 114, was also used for the pressure panel tests. Pressure fatigue panel tests were run at constant amplitude from zero pressure to 60 percent of the static panel failing pressures. Again, these were comparative tests of the autoclave bonded and weldbonded panels to determine cyclic life and failure mode.

To evaluate possible deleterious effects due to moisture intrusion into the bond lines, one autoclave bonded and one weldbonded panel were subjected to an environment of 95-100 percent relative humidity at 95 F for 120 days. The panels were subsequently sectioned to obtain lap shear test specimens from all metal-to-metal bonded areas within the panel and to examine the interior of the beads for evidence of corrosion or moisture intrusion.

TEST METHOD AND RESULTS

Shear Panel Static Tests

The shear panels, Figure 114, were reinforced around the edges, to prevent inducing panel failure at the edge loading bolts, and in the loading corners, to prevent local compression instability or tension failures as shown in Figure 116. The reinforced panel was then mounted in a loading fixture as shown in Figure 117.

The panel and loading fixture were mounted in a hydraulic test frame as shown in Figure 118 and loaded across the diagonal of the panel. The load was controlled and monitored by a computerized load control system as shown in Figure 119. This loading system was the same as used in the fatigue tests and its function is described later.

The 0.025/0.032 inch panels were loaded in 1250 pound increments to failure and the 0.071/0.050 inch pan panels were loaded in 5000 pound increments. The failure loads for the various panels tested are summarized in Table 26.

The failure mode for all panels was overall panel instability resulting in diagonal shear failure across the beads as shown in Figure 120. In no case was the failure

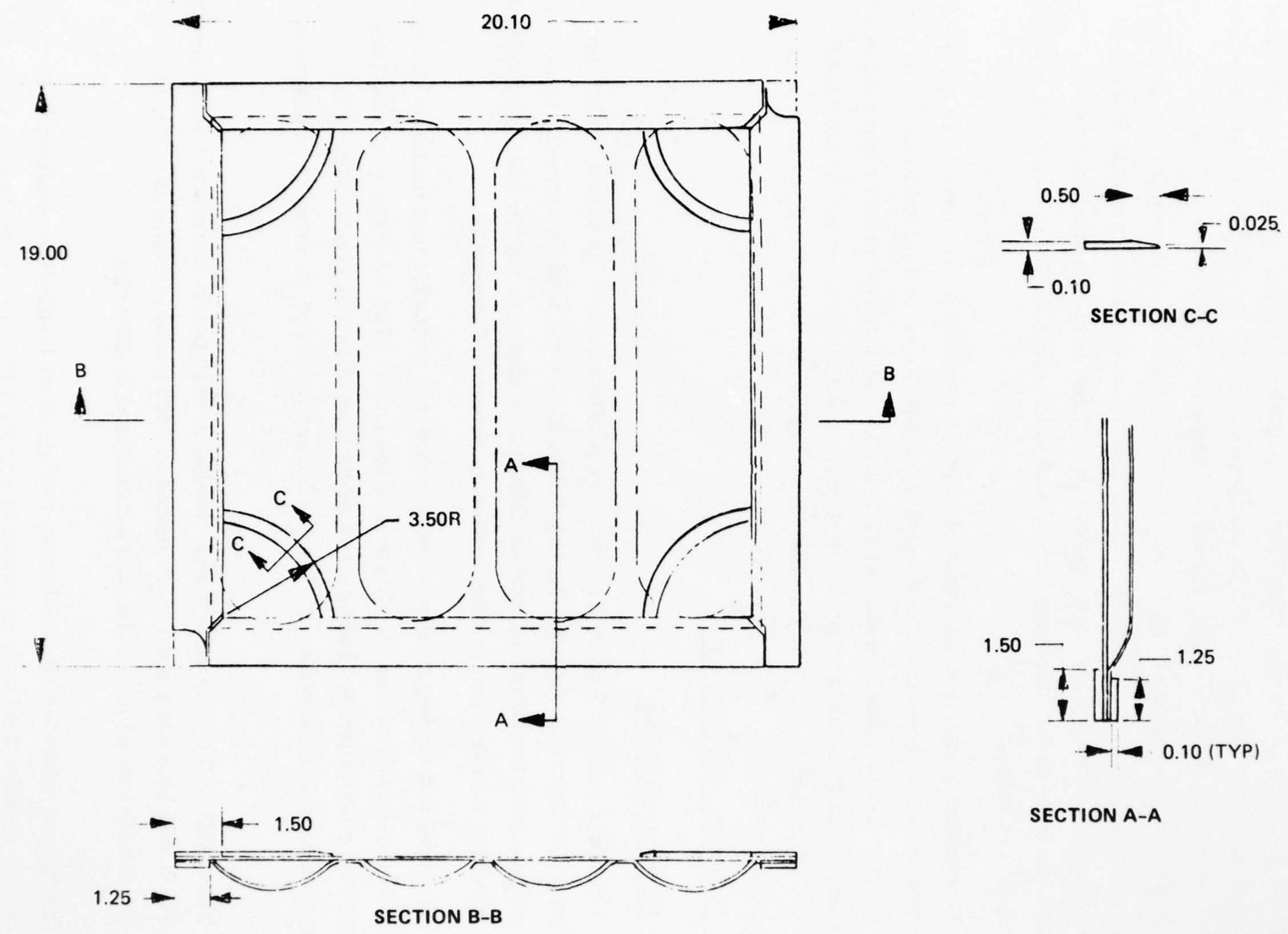


FIGURE 116. SHEAR PANEL REINFORCEMENT

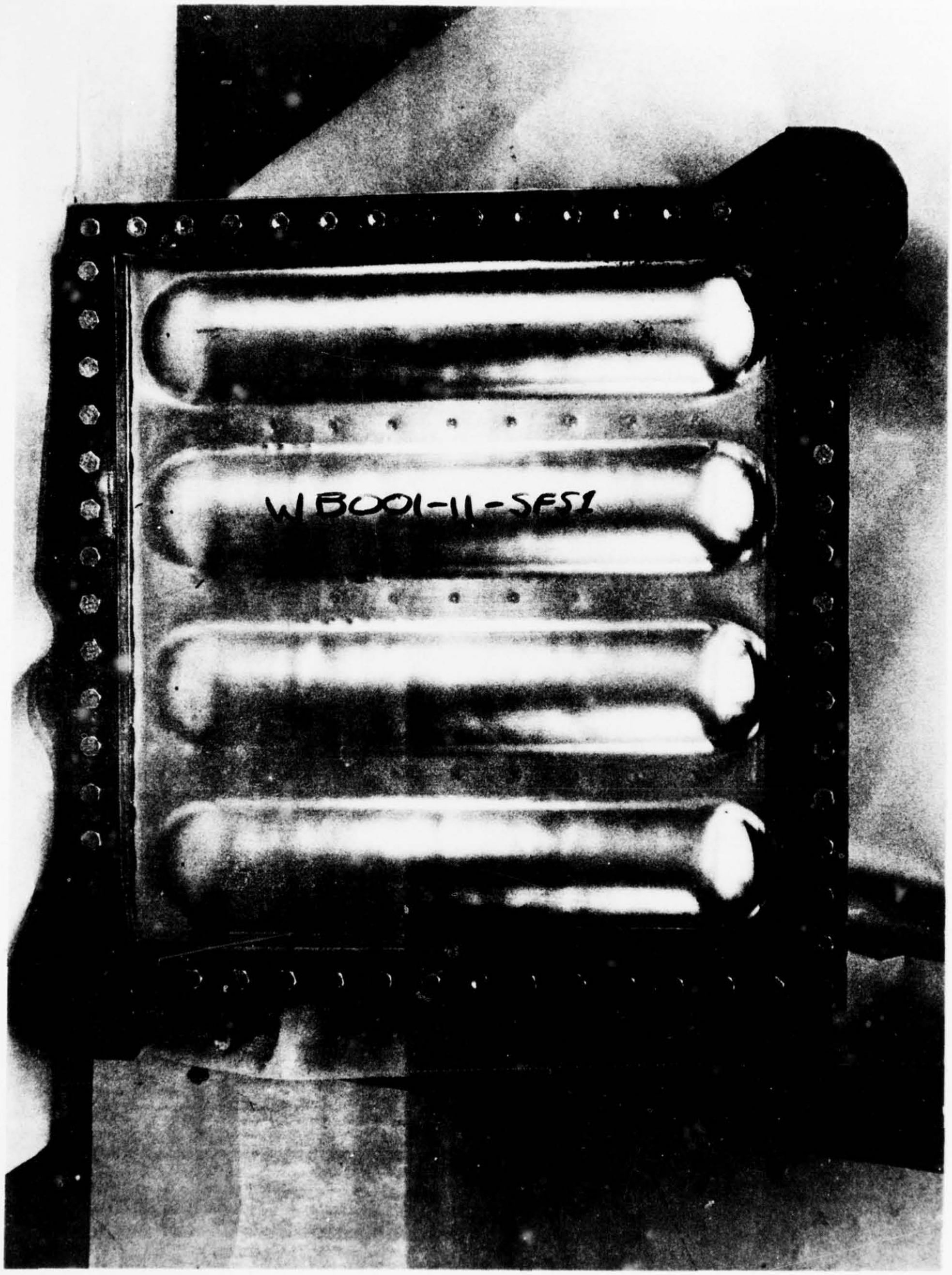


FIGURE 117. SHEAR PANEL LOADING FIXTURE

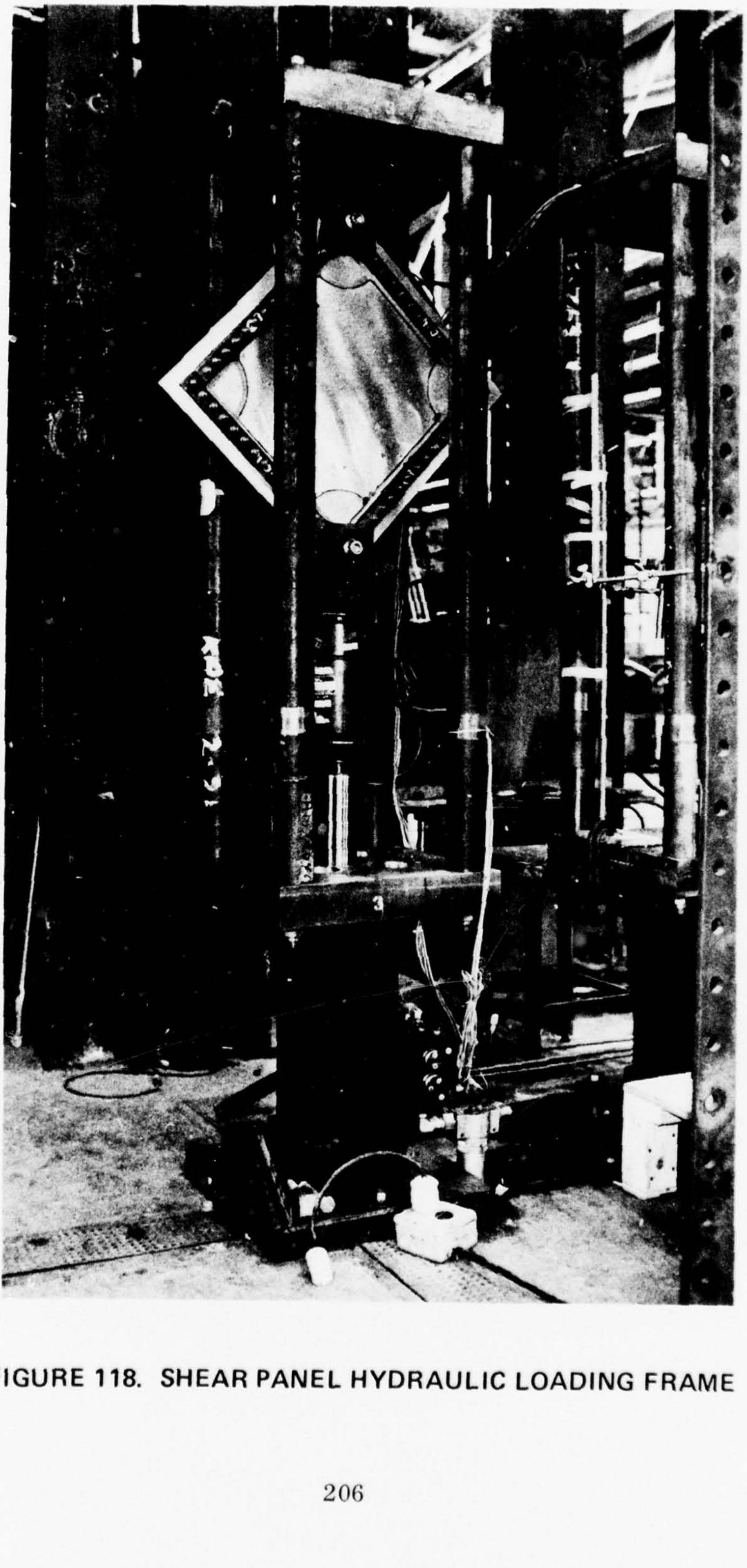


FIGURE 118. SHEAR PANEL HYDRAULIC LOADING FRAME

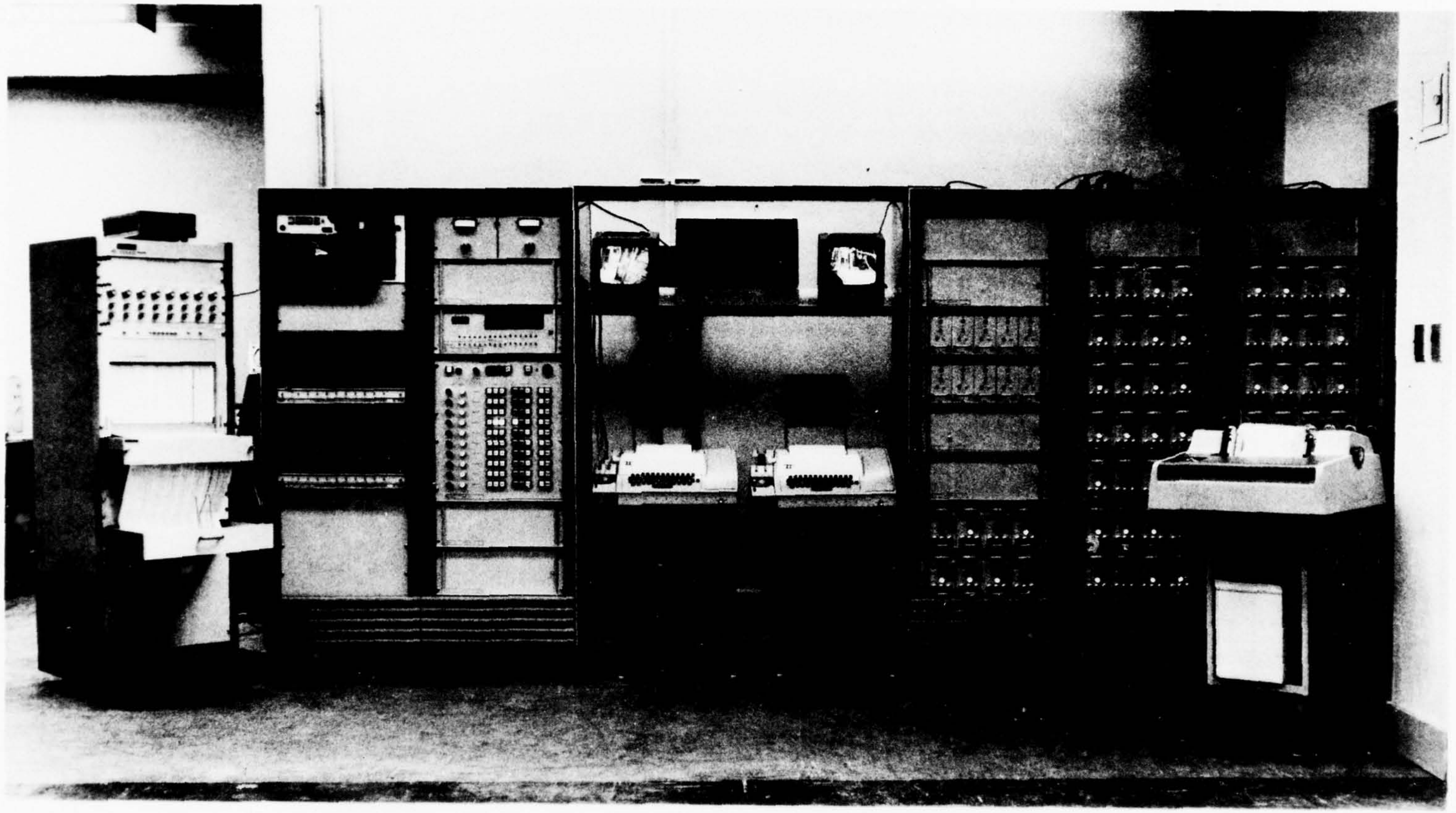


FIGURE 119. COMPUTERIZED LOAD CONTROL SYSTEM

TABLE 26 . SUMMARY OF STATIC SHEAR PANEL TEST RESULTS

SKIN THICKNESS	BEAD THICKNESS	AUTOCLAVE BONDED PANEL FAILING LOAD (LB)	WELD BONDED PANEL FAILING LOAD (LB)	VARIATION (PERCENT)
0.071	0.050	91,500	82,500	11
0.040	0.050	65,000	67,000	3
0.025	0.032	33,000	35,600	8

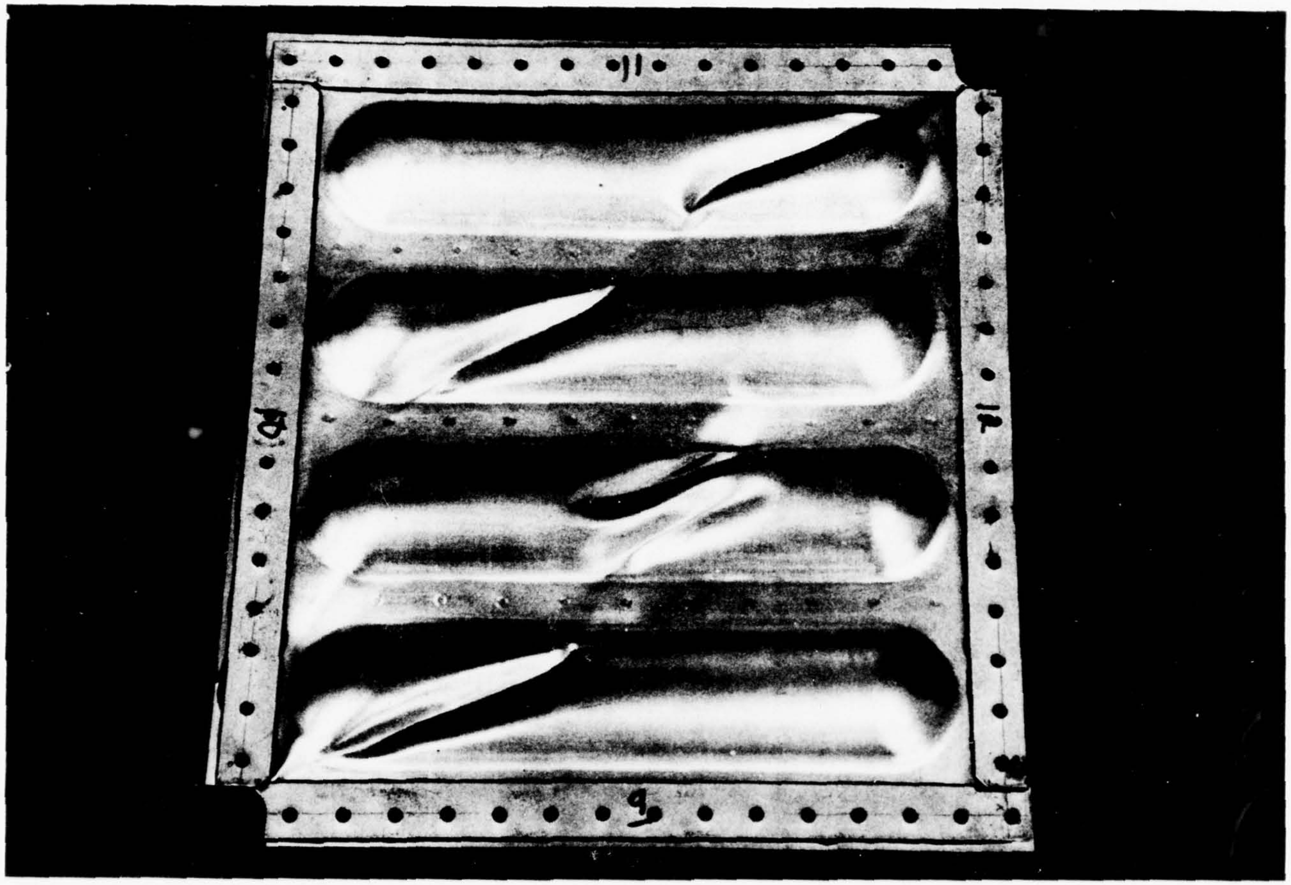


FIGURE 120. TYPICAL STATIC TEST PANEL STABILITY FAILURE

mode a function of the panel adhesive or the spotwelds. Also shown in Table 26 is the difference in load between weldbonded and autoclave bonded panels. The difference is considered to be within normal test scatter.

Shear Panel Fatigue Tests

As described previously, the two lighter gage combination panels, 0.025/0.032 inch and the 0.040/0.050 inch, were tested under spectrum fatigue conditions and the heavier gage combination panel, 0.071/0.050 inch, was tasted in constant amplitude fatigue. For these tests, the edges were reinforced, as shown in Figure 116, and mounted in the same configuration fixture as the static test shear panels, as shown in Figure 117. Testing was performed in the same hydraulic loading frame, and the load controlled and monitored by the same computerized load control system, as used for the static test (Figures 118 and 119).

The fatigue test spectrum used for evaluation of the lighter gage panels was the same as the 6000 flight hour test spectrum used in testing the A-10 fatigue airframe. This spectrum consists of 394,218 cycles of flight, gust, and ground maneuvers. There are 186 loading conditions in the spectrum, 174 flight conditions and 12 ground conditions. The complete flight spectrum is given in Appendix H. The maneuver corresponding to each of these conditions is assumed to be initiated from a flight attitude of $n_z = 0.0$ at the aircraft velocity and gross weight of the maneuver and to return to this condition after the maneuver.

The panel shear intensities corresponding to each of the test conditions were based on the theoretical aircraft internal loads distribution in the structurally critical 0.040/0.050 inch panel as shown in Figure 3.

In addition to definition of the test conditions, the flight spectrum given in Appendix H contains the panel shear intensity for both the maneuver conditions, peak load, and for the 1.0g initiation condition, baseload. The calculated loads were based on the assumption that the door covering the trough area is ineffective in carrying fuselage shear. Strain surveys of the fatigue aircraft revealed that approximately 25 percent of the fuselage shear was carried by the trough doors. Therefore, the experimental shear values for this panel were 33 percent greater than those encountered in the test of the A-10 fatigue airframe.

The basic load sequence was created by randomizing approximately 16,000 loading cycles corresponding to 4 percent of a lifetime of testing. This 4 percent of a lifetime sequence contained 117 simulated flights, 104 of which are at 28,000 pounds gross weight and 13 started at 43,000 pounds gross weight and, as the flight continues, decreased to 28,000 pounds gross weight. Between flights, a series of ground maneuvers occur. This basic sequence is repeated 25 times per lifetime of testing. Since some conditions do not occur 25 times per lifetime or even multiples thereof, and because of their intensity, it is not desirable to overtest for these conditions; they are inserted in the sequence at predetermined discrete locations.

Tables 27 and 28 present the results of the spectrum tests of the 0.040/0.050 inch panels and the 0.025/0.032 inch panels, respectively. The spectrum factor listed in these tables is the factor by which the spectrum loads were multipled in the specific test. As determined by visual and dye penetrant inspection, the crack initiated in the end radius of the beads for all panels, as shown in Figure 121. After detecting and recording the initial crack, the test was continued until the crack grew to approximately a 90° arc, which is also shown in Figure 121. The panel was then tested to failure in a static mode to determine the residual strength.

For these spectrum tests, both the percent of life at which the crack had initiated and propagated to a 90° arc, as shown in Tables 27 and 28, are presented graphically in Figures 122 and 123, for the 0.040/0.050 inch panels and the 0.025/0.032 inch panels, respectively. As noted in Table 27, difficulties were encountered due to the initiation of cracking in scratches in one panel, and at the corner doubler in another panel where the technician had scribed the surface of the skin while cutting the adhesive film used in bonding the corner doubler. The data presented in Figures 122 and 123 exhibits scatter typical of fatigue testing, but shows no trends that would differentiate the weldbonded from the autoclave bonded panels in fatigue life.

There were two modes by which the crack propagated to the 90° arc as shown in Figure 124. Typically, the crack propagated low in the radius, Mode 1, but occasionally propagated high into the spherical end of the bead, Mode 2. The residual panel strength was not dependent on the mode of propagation and Figure 125 is typical of the failure mode which was not an overall panel instability failure, but an extension of the fatigue induced cracks to failure. In this case, cracks were evident at the ends of the beads in three locations by the time the first crack had grown to a 90° arc. Each of these cracks extended significantly at panel failure. One precracked panel did fail in

TABLE 27 . SPECTRUM FATIGUE RESULTS FOR THE 0.040/0.050-INCH PANEL

CONSTRUCTION	TEST CODE	SPECTRUM FACTOR	INITIAL CRACK % LIFE	GROWTH TO 90° ARC % LIFE	*** RESIDUAL STRENGTH LB
AUTOCLAVE BONDED	MB001-3-SFS1	1.75	11.0	14.8	56,300
	-SFS2	1.40	22.0	40.8	49,100
	-SFS3	1.15	52.0	*	–
WELD BONDED	WB001-9-SFS1	1.40	24.5	28.8	60,100
	-SFS2	1.15	**31.5	86.6	58,600
	-SFS3	1.00	108.0	201.0	56,000

*SECOND CRACK INITIATION IN SKIN AT PANEL CORNER DOUBLER.
PROGRESSED TO FAILURE BEFORE 90° ARC GROWTH OF INITIAL CRACK OCCURRED.
**FIRST CRACK INITIATED IN SCRATCH IN RADIUS OF BEAD.
EXHIBITED VERY SLOW CRACK GROWTH IN INITIAL STAGES.
***STATIC PANEL STRENGTH – 66,000-LB AVERAGE.

TABLE 28 . SPECTRUM FATIGUE RESULTS FOR THE 0.025/0.032-INCH PANEL

CONSTRUCTION	TEST CODE	SPECTRUM	INITIAL CRACK % LIFE	GROWTH TO 90° ARC % LIFE	RESIDUAL* STRENGTH LB
AUTOCLAVE BONDED	MB001-5-SFS6	1.11	38.5	82.0	33,500
	-SFS4	1.00	69.0	113.6	33,200
	-SFS5	0.90	72.0	140.0	31,600
WELD BONDED	WB001-11-SFS3	1.11	60.0	120.0	34,000
	-SFS1	1.00	78.0	138.0	36,100
	-SFS2	0.90	72.0	188.0	32,400

*STATIC PANEL STRENGTH – 34,300-LB AVERAGE

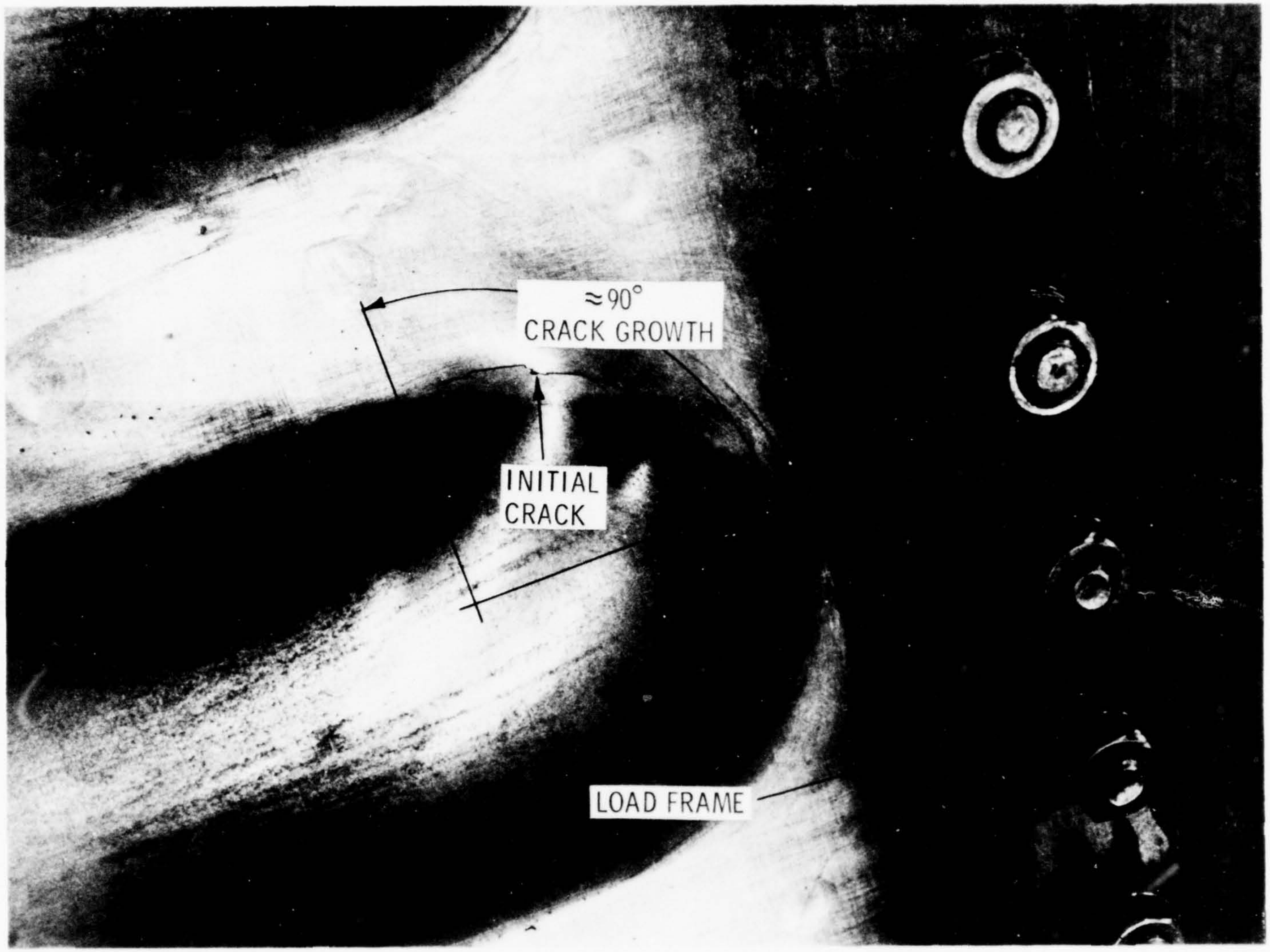


FIGURE 121. CRACK INITIATION AND 90° ARC GROWTH

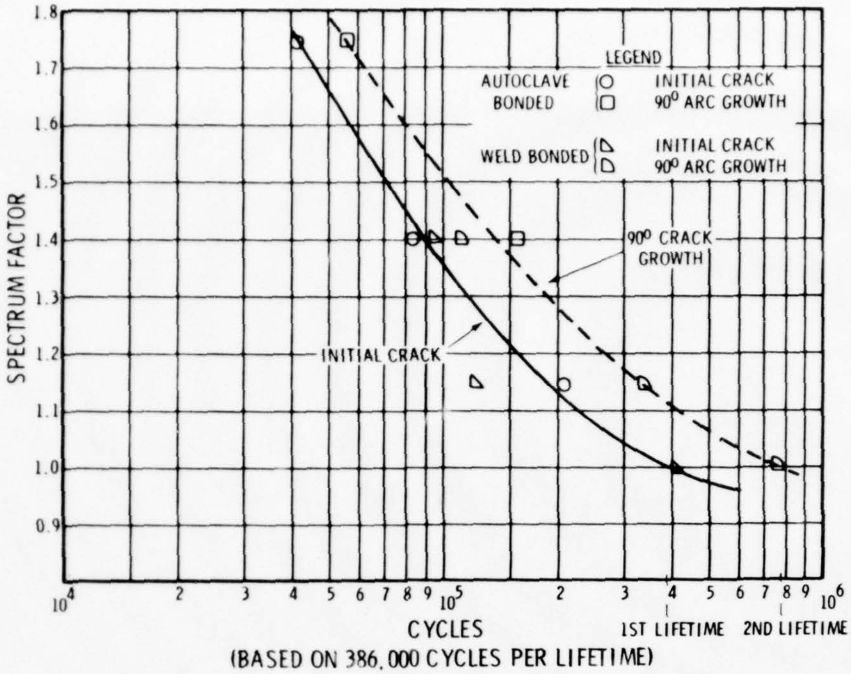


FIGURE 122. SPECTRUM FATIGUE CURVES FOR THE 0.040/0.050-INCH PANEL

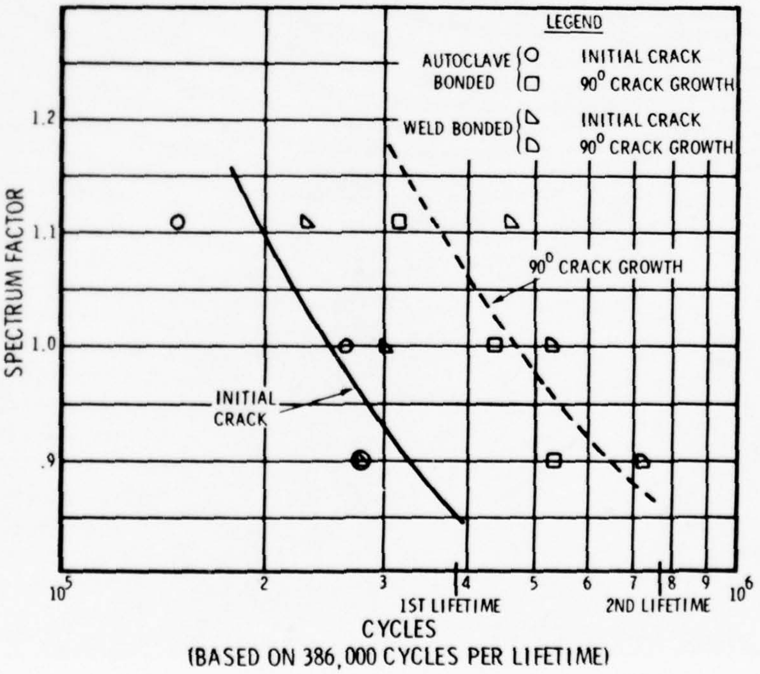
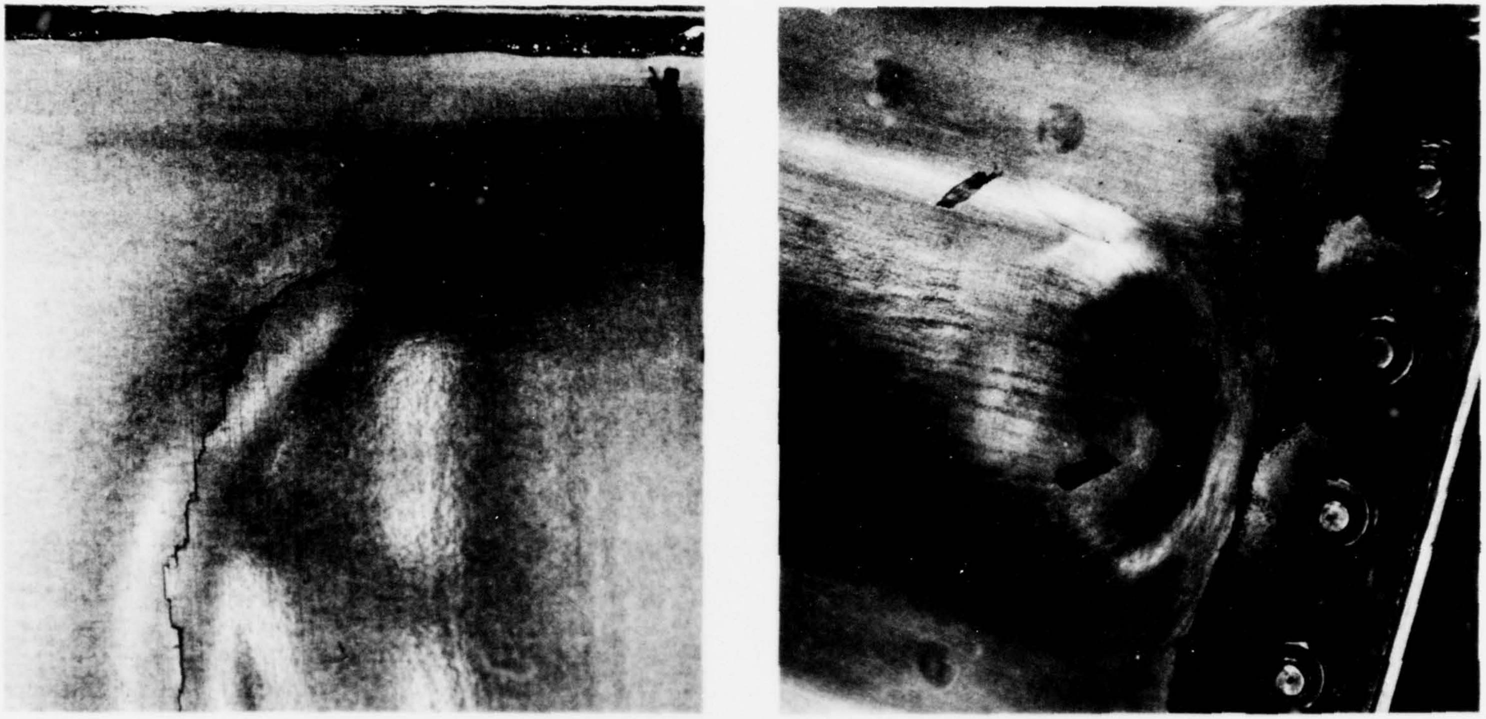


FIGURE 123. SPECTRUM FATIGUE CURVES FOR THE 0.025/0.032-INCH PANEL



MODE 1
PREDOMINANT

MODE 2
OCCASIONAL

FIGURE 124. TYPICAL FATIGUE CRACKS IN SHEAR TEST PANELS

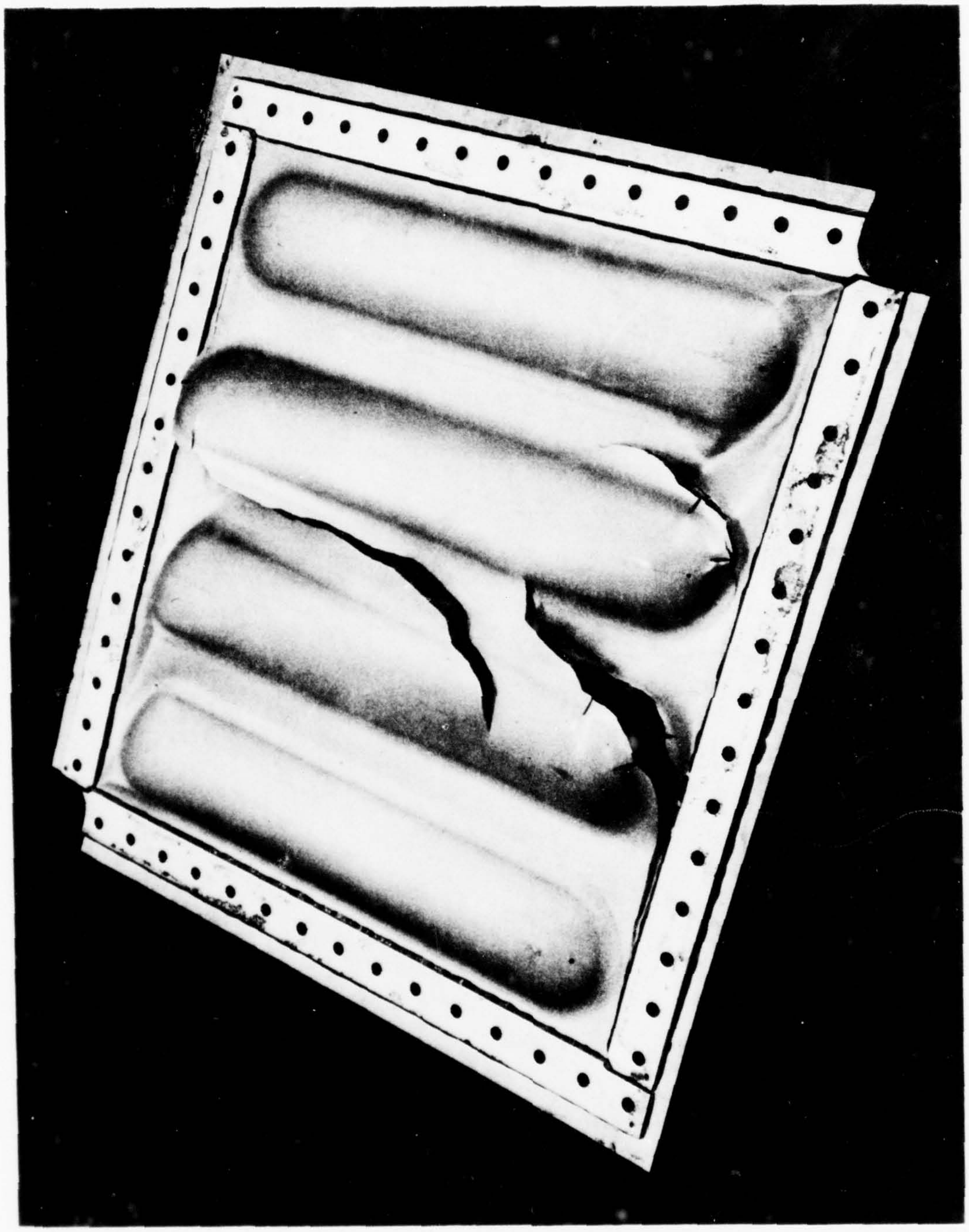


FIGURE 125. TYPICAL RESIDUAL STRENGTH TEST FAILURE FOR A FATIGUE TEST SHEAR PANEL

panel stability. This weldbonded panel, WB001-11-SFS1, as shown in Table 28. failed at 36,100 pounds as compared to an average of 34,300 pounds for the average of the static panels for the thickness combinations from Table 26. The static residual strengths for the 0.040/0.050 inch panels were from 74 percent to 91 percent of the average static test panel strength and the residual strengths for the 0.025/0.032 inch panels were from 92 percent to 105 percent of the average static test panel strength.

As previously discussed, the heavier panels, 0.070/0.050 inch, were tested in constant amplitude fatigue. The maximum load level was 65,000 pounds, 75 percent of the average static strength, as shown in Table 26, R = +0.1. Table 29 summarizes the results of these tests. As in the case of the lighter gage panels, all fatigue cracks were initiated in the radius at the ends of the beads as shown in Figure 124. In both weldbonded panels, the cracks initiated in the scratches in the bead end radius. Although the cracks in the weldbonded panels initiated at significantly fewer cycles than in the autoclave bonded panels, they were not attributed to the method of panel assembly. The residual strength of the panels after 90° arc grown were from 88 percent to 95 percent of the average static panel strength. Typical mode of failure is shown in Figure 125.

Pressure Panel Tests

Pressure panel static and fatigue tests were performed to evaluate differences in the failure mode, static strength and fatigue life. The panels were mounted in a pressure test fixture, as shown in Figure 126, and positive pressure was applied to the bead side of the panel. The pressurizing medium was air. Instrumentation was provided to adjust, control and cycle the pressure between preset limits, and to count the pressure cycles.

Static tests were run on both autoclave bonded and weldbonded panels for the 0.040/0.050 inch combination and only on the weldbonded panel for the 0.025/0.032 inch combination.

The high pressure cycling switch was set beyond the maximum anticipated static strength of the panel and the pressure increased gradually until failure occurred. Table 30 summarizes the result of these tests. The failure mode was crippling of the bead at approximately mid-span as shown in Figure 127. The autoclave bonded 0.025/-0.032 inch panel was not statically tested since the failure mode

TABLE 29 . CONSTANT AMPLITUDE SHEAR PANEL TEST RESULTS
0.070 SKIN – 0.050 BEAD

CONSTRUCTION	TEST CODE	INITIAL CRACK CYCLES	GROWTH TO 90° ARC CYCLES	** RESIDUAL STRENGTH LB
AUTOCLAVE BONDED	MB001-1-SFC1	16,000	17,300	77,000
	MB001- -SFC2	16,900	19,600	78,400
WELD BONDED	WB001-7-SFC1	7,600*	10,300	77,500
	-SFC2	11,800*	17,600	82,500

*FIRST CRACK INITIATED IN SCRATCH AT RADIUS OF BEAD
**STATIC PANEL STRENGTH – 87,000-LB AVERAGE

TABLE 30 . STATIC PRESSURE PANELS – TEST RESULTS

CONSTRUCTION	SKIN THICKNESS	BEAD THICKNESS	TEST CODE	FAILING PRESSURE PSI
AUTOCLAVE BONDED	0.040	0.050	MB001-3-PS1	56.0
WELD BONDED	0.040	0.050	WB001-9-PS1	76.0
	0.025	0.032	WB001-11-PS1	16.5

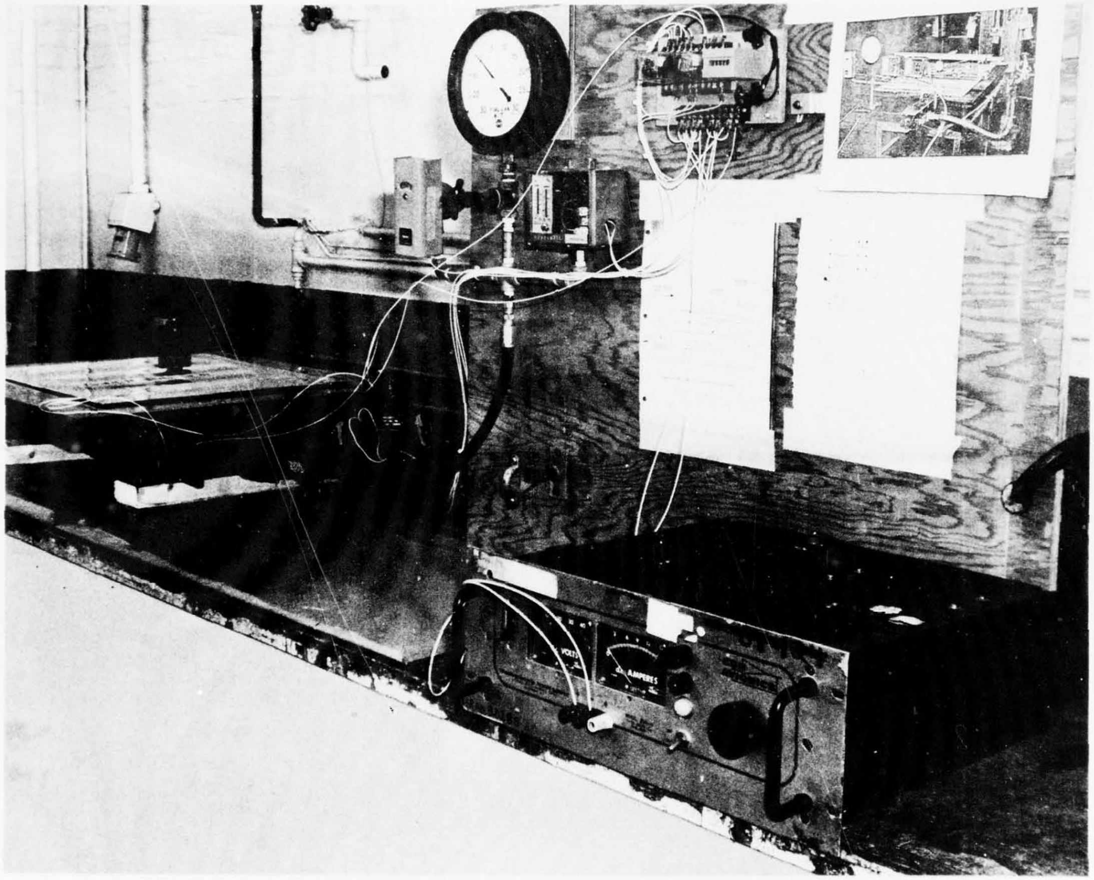


FIGURE 126. PANEL PRESSURE TEST SETUP

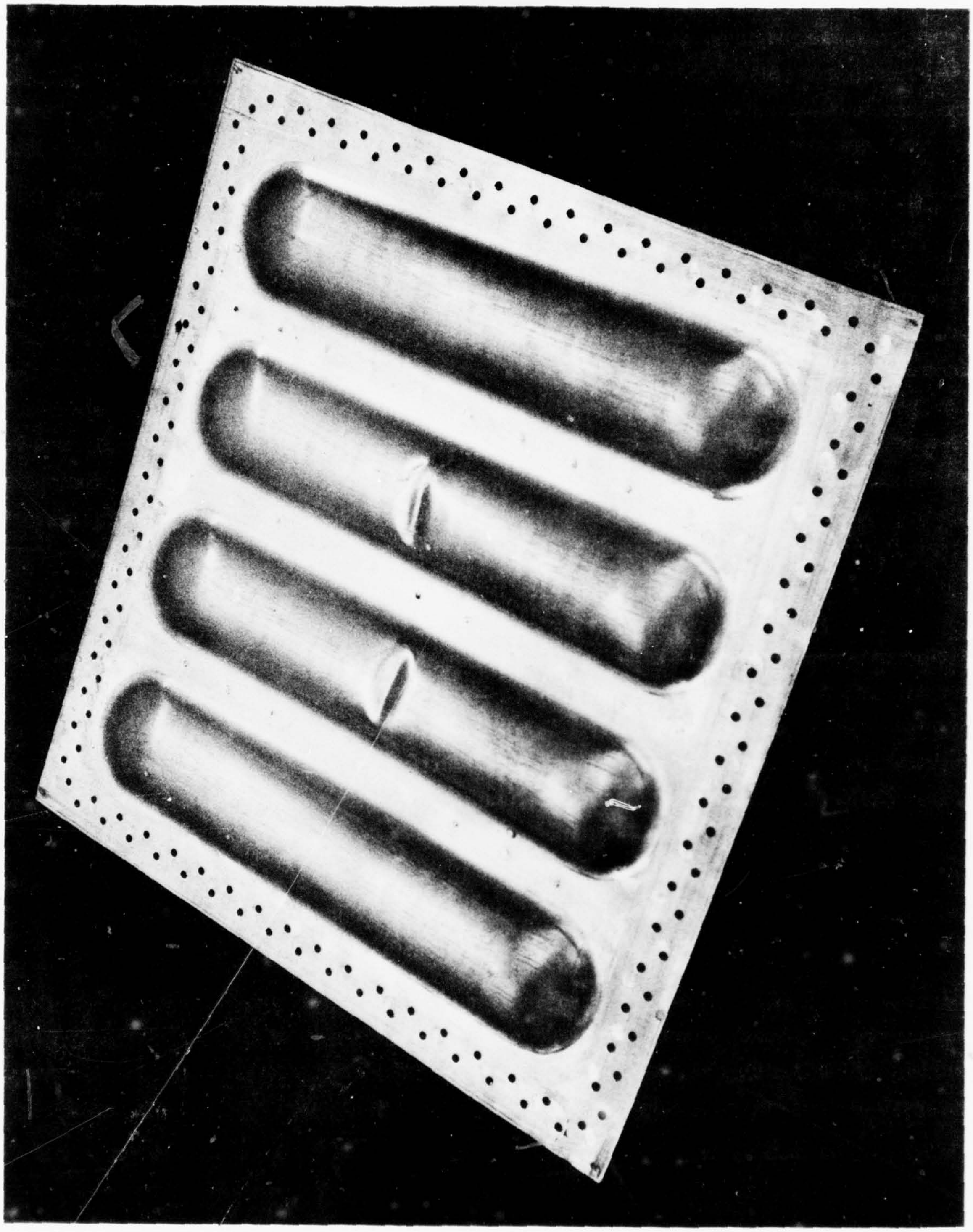


FIGURE 127. TYPICAL PRESSURE PANEL STATIC TEST FAILURE

on the other panels was independent of the method of assembly. A failure analysis subsequent to test revealed no explanation for the difference in the static strength of the 0.040/ 0.50 inch combination. Since the weldbonded panel failed at a higher load than the autoclave bonded panel, the test objective of side-by-side testing proved the weldbonded panel adequate.

The same test setup was used for pressure cycling the panels. The high pressure cycling switch was set at the desired value and the low pressure switch was set as low as possible and still produce cycling. This lower limit was always below 0.5 psi. Table 31 summarizes the results of these tests. The panel pressure was cycled between essentially zero (0.5 psi) and 60 percent of the static panel strength of the weldbonded panels as shown in Table 30 i.e., the 0.04/ 0.050 inch panels were cycled from 0 to 46 psi and the 0.025/ 0.032 inch panel was cycled from 0 to 10 psi. The failure mode was the cracking of the skin along the row of panel fasteners at the ends of the beads, as shown in Figure 128. Also shown in this figure are crack detector wires which were connected to the pressure cycling circuit to stop the test when they were broken. The test of the panel shown in Figure 128 was carried beyond the point where initial cracks were detected to emphasize the mode of failure. Although there were differences in the fatigue life of the weldbonded and autoclave bonded panels, the weldbonded panel life was essentially equivalent to or in excess of the autoclave bonded panel life. The failure mode was independent of the method of assembly.

TABLE 31 . PRESSURE PANEL FATIGUE TEST RESULTS

CONSTRUCTION	SKIN THICKNESS	BEAD THICKNESS	TEST CODE	PRESSURE CYCLES* TO FIRST CRACK
AUTOCLAVE BONDED	0.040 0.025	0.050 0.032	MB001-3-PFC1 MB001-5-PFC1	2,580 7,128
WELD BONDED	0.040 0.025	0.050 0.032	WB001-9-PFC1 WB001-11-PFC1	2,191 23,700

*PRESSURE CYCLED AT 60% OF STATIC STRENGTH
0.040 SKIN – 0.050 BEAD 0-46 PSI
0.025 SKIN – 0.032 BEAD 0-10 PSI

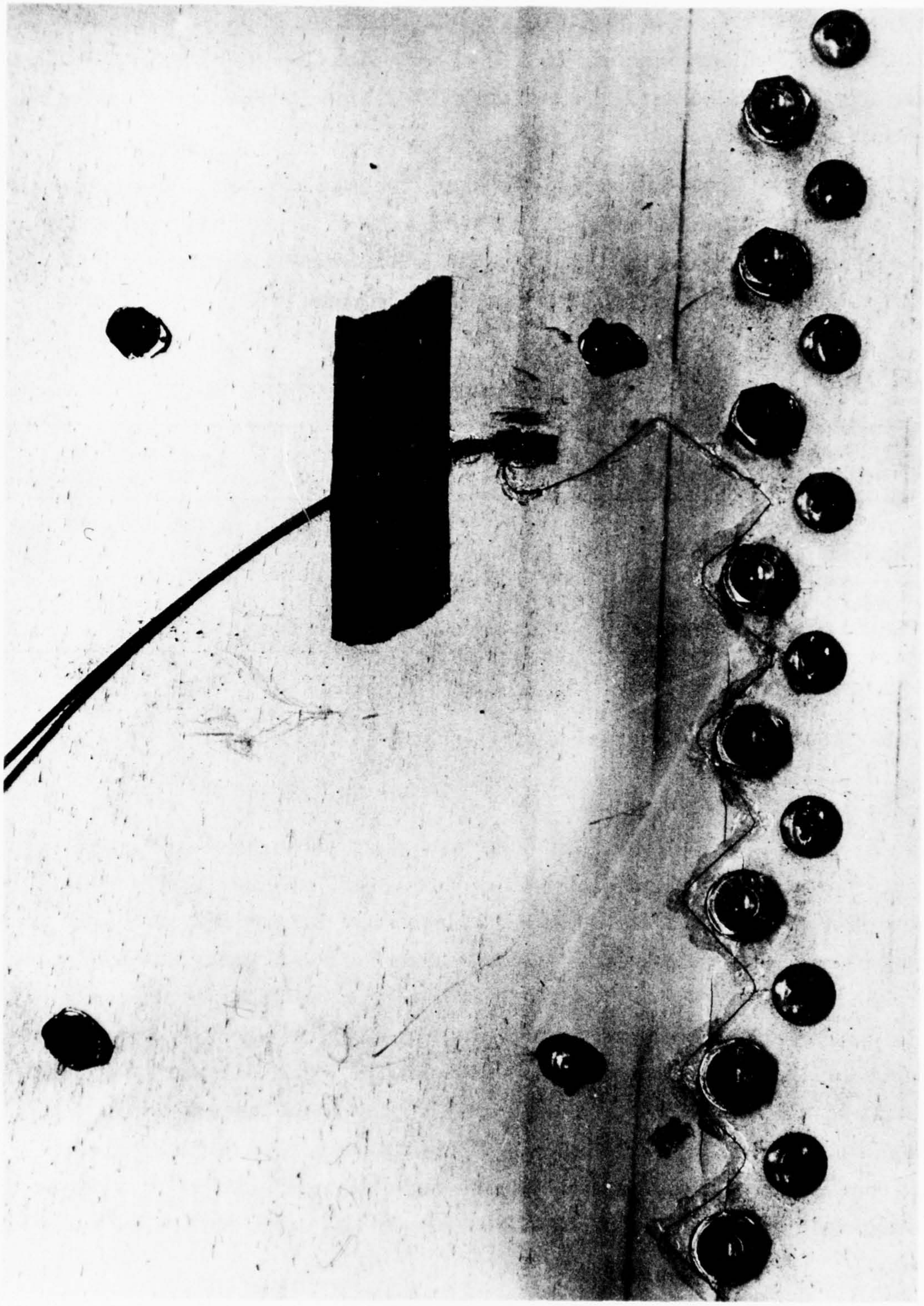


FIGURE 128. TYPICAL PRESSURE PANEL FATIGUE TEST FAILURE

Environmental Panels

One autoclave bonded and one weldbonded panel with 0.040/0.050 inch combination were subjected to a 95 to 100 percent relative humidity at 95 F for 120 days. These panels were prepared by applying an epoxy-polyamide paint primer to all surfaces, then removing it from all edges to expose the bond line. Immediately upon removing the panels from the environmental chamber, an aluminum tape was applied to all edges to seal in any moisture that may have entered the bond line. The panels were then sectioned, first to obtain lap shear specimens, as shown in Figure 129, and second to examine the interior surfaces of the beads for evidence of corrosion or trapped moisture. The edges of all test specimens were covered with the foil tape as soon as the specimens were cut to retain any moisture. This tape remained in place until the time of test.

Visual examination revealed no evidence of corrosion or moisture intrusion in the interior of the beads of either the autoclave bonded or weldbonded panel. Figure 130 presents the test results of the lap shear specimens taken from the autoclave bonded and weldbonded panels. Table 32 presents the mean and standard deviation of the test results for each panel. All failures were cohesive in nature. The weldbond adhesive, A-1444B, average lap shear value was 11 percent greater than that of the autoclave adhesive, FM 123-2, and the standard deviation in both cases was less than 5 percent of the mean. It was anticipated that, if adhesive degradation occurred due to the moisture intrusion, the panel edge specimens would display lower lap shear values than the specimens from the center of the panel, but, to a small degree, the opposite was true. It should be pointed out that the stress level in the 0.040 inch 2024-T3 clad skin exceeded the yield strength, typically 45,000 psi, in all tests, and indeed exceeded the typical ultimate strength, 61,000 psi for some of the weldbonded specimens. Adherend strains above yield can significantly reduce the apparent shear strength of the adhesive since the local strain at the ends of the lap can exceed the limiting strain of the adhesive.

SUMMARY OF TEST RESULTS

In summary, there were not distinguishable differences in static strength or fatigue life that could be attributed to the weldbond process. Test scatter was encountered, particularly in fatigue, but variations in performance occurred as frequently for the autoclave bonded panels as for the weldbonded panels. Static and fatigue failure modes for both the shear and normal pressure panels were not direct functions of the performance of the bond lines.

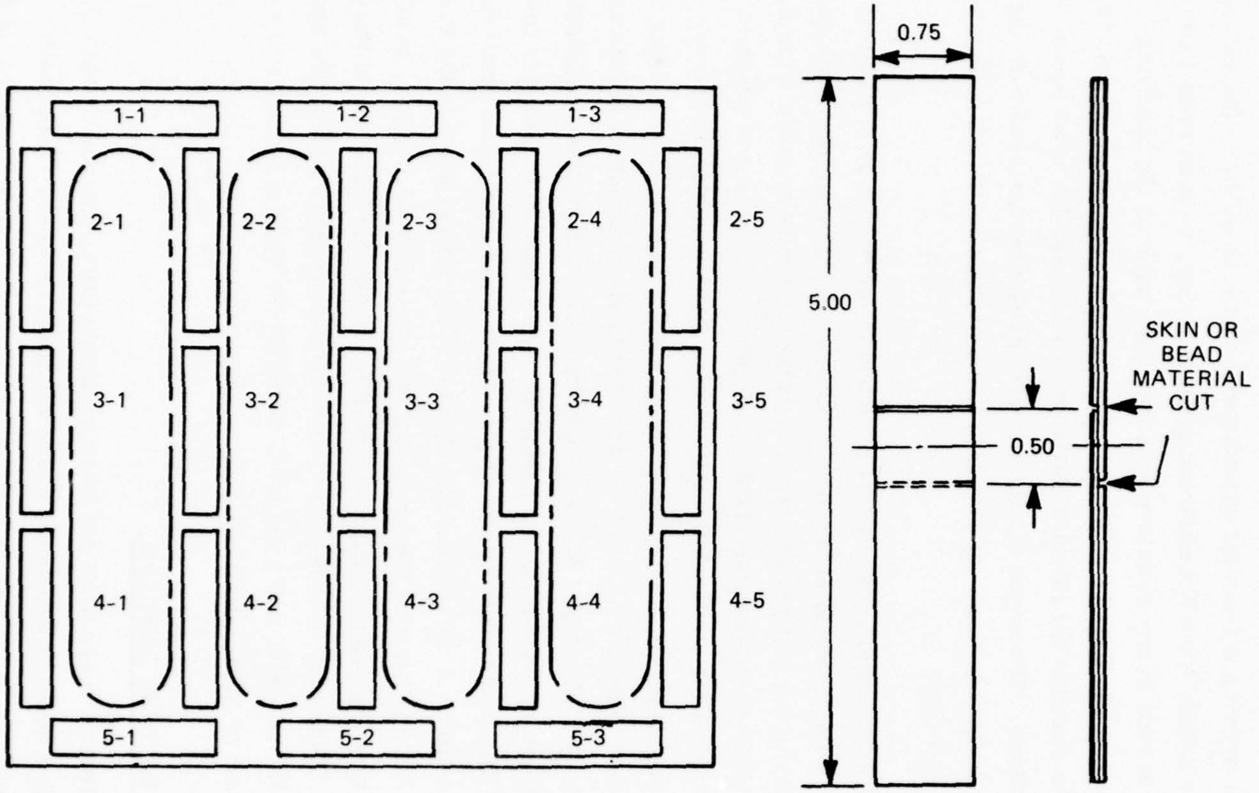
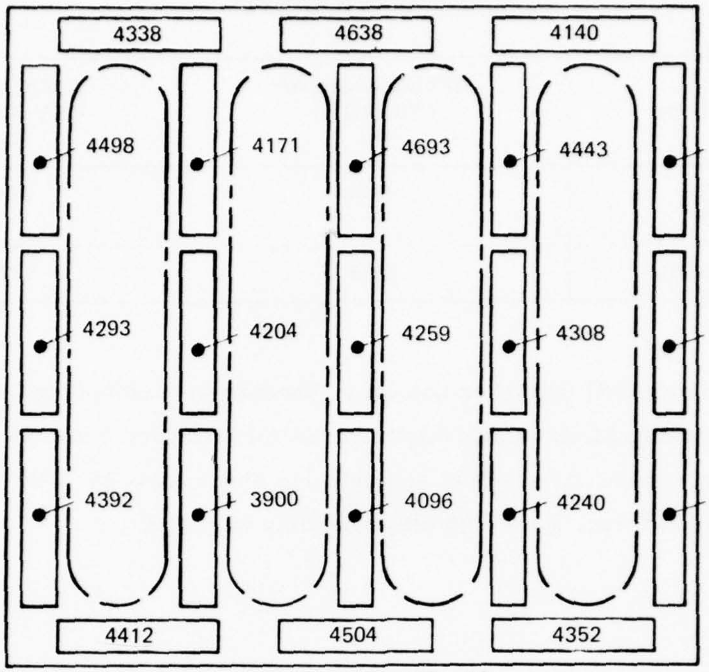


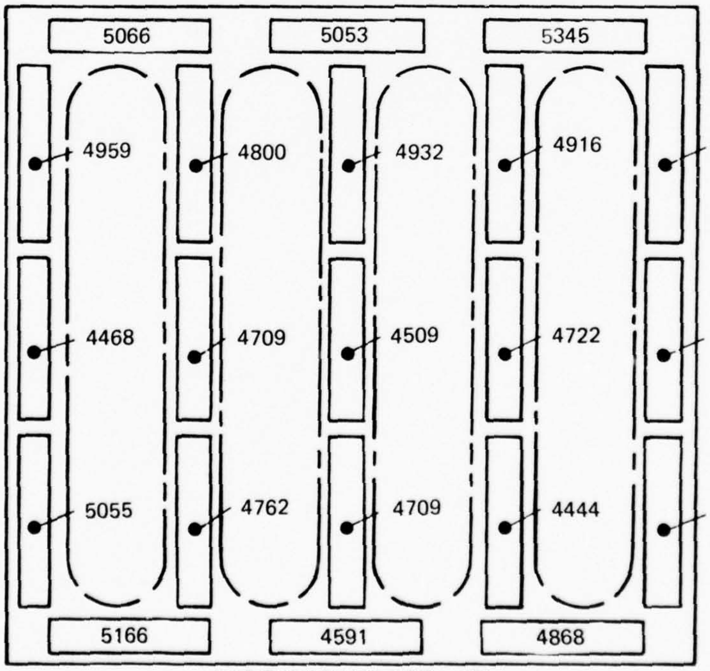
FIGURE 129. ENVIRONMENTAL PANEL LAP SHEAR SPECIMENS

ADHESIVE BONDED PANEL



LAP SHEAR VALUES – PSI

WELDBONDED PANEL



LAP SHEAR VALUES – PSI

FIGURE 130. LAP-SHEAR TEST RESULTS FOR THE ENVIRONMENTAL 0.040/0.050-INCH PANELS

TABLE 32. LAP-SHEAR TEST RESULTS FOR THE ENVIRONMENTAL 0.040/0.050-INCH PANELS

CONSTRUCTION	MEAN LAP SHEAR STRENGTH PSI	STANDARD DEVIATION PSI
AUTOCLAVE BONDED	4340	182
WELDBONDED	4836	232

Test panels assembled by either autoclave bonding or weldbonding subsequent to exposure to high humidity at elevated temperatures for extended time (95 to 100 percent RH, 95 F, 120 days) exhibited excellent residual lap shear strength with the weldbonding adhesive slightly outperforming the autoclave bonding adhesive.

TECHNOLOGY TRANSFER

The objective of this portion of the program was to successfully transfer the aluminum weldbond process, established at Northrop, to the Fairchild manufacturing area. This program involved the establishment of equipment, the transfer of procedures and the effective training of personnel.

The program was carried out in a planned series of transfer steps. Initial contacts were made by Fairchild personnel visiting Northrop on two different occasions to observe the proper process steps involving the fabrication of weldbonded panels and to discuss the requirements for necessary equipment. Also constant phone communication was established between technical personnel to explain details and transmit new information as it was developed. Following the final establishment of the surface preparation, welding, and inspection procedures, and the successful fabrication of the Northrop structural panels, Fairchild installed the required equipment at their Farmingdale, New York facility. Northrop personnel then visited Fairchild and spent approximately two weeks training personnel and assisting with the fabrication of structural panels. During this visit, several curved A-10 panels were successfully fabricated with Fairchild performing the hands-on work.

The following sections describe the equipment and procedures which Fairchild has installed to fabricate weldbond panels per the results of this program. A few of their observations and problems which they encountered during this technology transfer phase are also discussed.

WELDBOND CHEMICAL PROCESSING

Chemical Process Line

The pilot chemical process line for the Northrop weldbond process was established in the Manufacturing Development Laboratory of Fairchild Republic Company. The equipment used in the process line consists of the following:

Water Demineralizer - Permutit, Sybron Corporation, Model No. 1001628
The unit utilizes three cubic feet of M-100 mixed bed resin which is fitted with a Balsbaugh 500 Resistivity Meter.

Spray Rinse Tank

This tank is of polyethylene construction, 48 inches long x 24 inches wide x 30 inches deep, fitted with PVC piping, ball valves and four stainless steel spray heads. The rinse can be either demineralized water, tap water or a mixture of both

Solvent Vapor Degrease

Fairchild Republic Company has a production line, deep well, solvent vapor degrease tank employing 1, 1, 1 trichloroethane as the degreasing solvent. The tank has a lance for clean distillate liquid solvent spray.

Alkaline Clean Tank

This tank is of Type 321 stainless steel welded construction with a volume of 100 gallons. The tank measures 48 inches long x 18 inches wide x 30 inches deep. Heat is supplied to the fiberglass insulated tank by two CLEPCO WSE-6409 6000 watt heaters and a CLEPCO Model C954HT temperature controller.

Deoxidizer Tank

This tank is of Type 321 stainless steel welded construction with a volume of 100 gallons. The tank measures 48 inches long x 18 inches wide x 30 inches deep. The tank is fitted with an exhaust fume hood, filtered air agitation and continuous solution filtration provided by a Sethco ZDX-100B pump motor and filter assembly with a 15-micron polypropylene cartridge filter.

Anodize Tank

This tank is of Type 321 stainless steel welded construction with a volume of 100 gallons. The tank measures 48 inches long x 18 inches wide x 30 inches deep. The tank is electrically isolated from the support frame and house ground and has four polyethylene electrical isolators: two isolators for rack support along the length of the tank and two isolators for short rack support across the width of the tank. The tank has filtered air agitation and continuous solution filtration provided by a Sethco ZDX-100B pump motor and filter assembly with a 15 micron polypropylene cartridge filter.

Electronics Equipment

Power to the anodize tank is controlled by a Harrison Laboratories, Regulated Power Supply, Model 814A with a range of 0-36 volts d.c. and 0-25 amperes. Voltage is monitored by a Weston Model 901 D. C. Voltmeter and current is monitored by a Weston Model 901 D. C. Ammeter. After anodizing, surface resistance is measured with a C. B. Smith Co. Model VT-IIA Surface Resistance Analyzer.

Chemical Surface Preparation

The chemical surface preparation for weldbonding was accomplished in accordance with the Northrop weldbond process specification. The procedure is detailed and clear cut and there were no problems experienced in the chemical processing. Figure 131 shows the rinsed deoxidized beaded pan being lowered into the anodize solution.

Chemical Process Controls

Etch rate determinations on the deoxidizer bath and chemical analyses of the solutions were accomplished at regular intervals. The etch rate at Fairchild during the course of this study was 0.1296g. weight loss, which is higher than the Northrop etch rate of 0.082g. weight loss. The difference in etch rate is due to the fact that the Fairchild pilot line is in a production line environment where the temperature range was 75-85F during the course of this program, while the Northrop process line was in an air conditioned laboratory environment of 68F. Solution temperature differences account for the differences in etch rate. The etch rate determination at Fairchild at 70F was 0.085g. weight loss which is only slightly higher than the 0.082 maximum specified by Northrop.

Chemical analyses of the solutions during the technology transfer showed that no additions were necessary. It should be noted that in the makeup of the original solutions in the process line, the chemical concentrations were used at their uppermost allowable limit. Subsequently, the baths were intentionally heavily loaded with aluminum test specimens and doublers to tax capacity. Chemical analysis then showed that additions of Turco 4215-S to the alkaline cleaner and Amchem 17 to the deoxidizer were necessary. Lap shear and wedge crack extension process control specimens showed 3544 psi for the 1 inch lap shears (FM 123-2 adhesive with BR-127 primer)

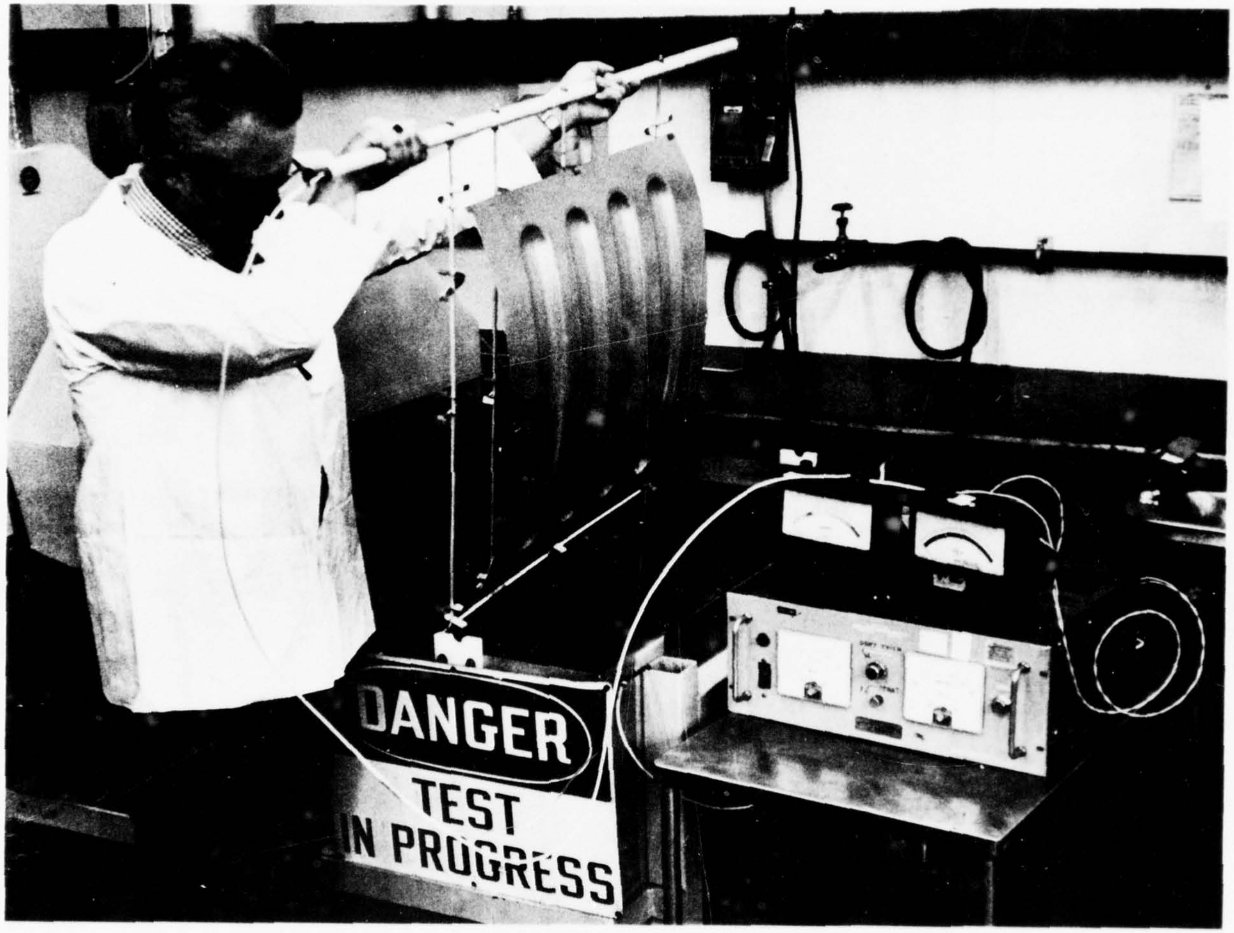


FIGURE 131. SURFACE PREPARATION PILOT PLANT LINE

and a maximum 1/8 inch wedge crack growth in 24 hours at 120F and 95-100% relative humidity. The lap shear failures were cohesive failures. There have been no failures in the adhesive bonded doublers used in the fatigue test program.

Lap Shear and Environmental Process Controls

During the technology transfer, lap shear and wedge crack extension control specimens were processed with their respective skin and beaded panel details. There was an initial difficulty with the wedge crack testing. Tests showed crack extensions up to 1 1/2 inches in the first two hours of environmental exposure. Consultations with Northrop clarified the test techniques as follows which were required to obtain good test results. The method of preparation of the test specimens was changed to add spacers which kept the bondline thickness at 8 mils. Initial specimen preparation resulted in 2-4 mil bondlines. The method of wedge insertion into the crack was changed from a sharp, bottoming hammer blow to a gentle insertion using a vise. In the majority of test specimens, the insertion of the wedge meets some resistance. However, in some specimens, the insertion of the wedge results in a resounding bang. The cause and effects of this anomaly have not been determined.

The process control specimens consisted of two pieces of 6 inch x 6 inch x 0.125 inch 2024-T3 alclad aluminum and two pieces of 6 inch x 6 inch x 0.125 inch 7075-T6 bare aluminum. Specimen fabrication matched one 2024-T3 sheet with one 7075-T6 sheet. The pieces were adhesive bonded with a 5 inch x 6 inch overlap area for the wedge crack extension specimens and a 1 inch x 6 inch overlap area for the lap shear specimens. The wedge crack panel had a 1 inch x 6 inch teflon insert spacer to facilitate crack initiation. Both types of specimens had 8 mil aluminum wire spacers around the periphery to provide constant glue line thickness. The periphery was trimmed off and discarded after curing and the test specimens were cut to 1 inch widths.

Typical test results using the B. F. Goodrich weldbond adhesive A-1444B were 4830 ± 70 psi for the one inch lap shear specimens and 1/8 inch wedge crack extension for twenty-four hour exposure to 120F and 95-100% relative humidity. The lap shear failures were all cohesive failures. Fairchild investigators have never seen adhesive failures with the Northrop weldbond process. Wedge crack growth in test specimens generally occurs in the first hour of environmental exposure.

SCANNING ELECTRON MICROSCOPIC INSPECTION

Fairchild Republic Company has purchased and installed an International Scientific Instruments ISI-60 Scanning Electron Microscope for the examination of aluminum surfaces prepared in accordance with the Northrop weldbond process specification and for in-house fractography investigations. This instrument, shown in Figure 132 processes the following characteristics:

- 60 Angstroms guaranteed resolution
- Magnification from 10X to 200,000X
- Five selectable accelerating voltages to 30KV
- Large specimen handling - 3 inches to 4 inches with flexible externally controlled manipulation controls
- Dual magnification display - lets you observe the sample at different magnifications simulataneously on two viewing screens
- Automatic micron bar display, with alphanumerics video input
- Automatic filament saturation

Fairchild samples aluminum for SEM examination in accordance with instructions from Northrop Corporation. The sample surfaces were prepared for weldbonding in accordance with the Northrop weldbond process specification. The samples were cut into strips 1/4 inch wide x 3/4 inch long, bent with two pairs of pliers to start the angle and then cracked by squeezing gently in a vise. Care is taken not to touch the middle of the sample with the pliers. The cracked specimens are mounted on aluminum SEM planchets using Duco cement. When the mounting cement is dried, a conductive silver-filled cement is used to provide a conductive path from the sample to the planchet.

The sample is placed in a Kinney High Vacuum Evaporator Type 80-3, approximately 4 inches away from a conical tungsten wire filament containing a small quantity of gold wire and arranged so that the crack in the sample extends radially away from the filament. The evaporator is pumped down to a pressure 0.5 microns of mercury at which point an electric current heats the filament to the melting point of the gold. The gold is allowed to evaporate for four seconds. The sample is allowed to cool before the evaporator is shut down and vented to atmospheric air. The samples are examined on the scanning electron microscope. Anodic oxide coatings deposited at Fairchild typically run approximately 400-600 Angstroms.

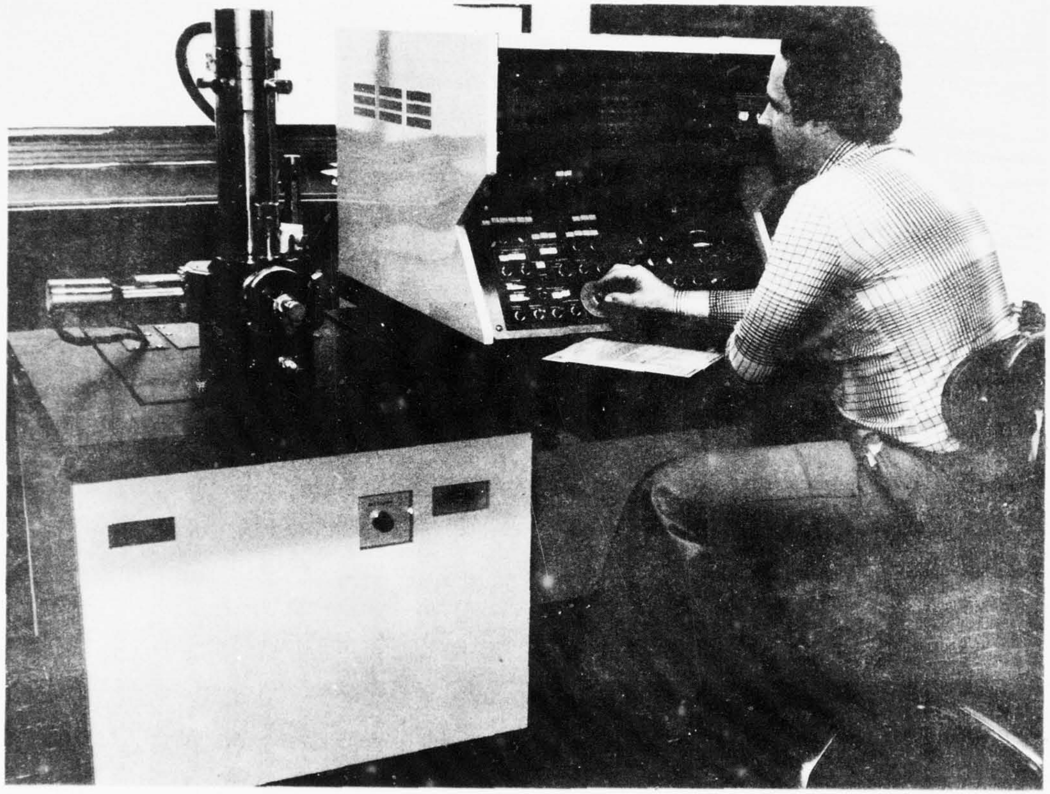


FIGURE 132. SCANNING ELECTRON MICROSCOPE INSPECTION OF PREPARED ALUMINUM SURFACES

Several difficulties have been experienced by Fairchild in the scanning electron microscopy work. In the initial series of runs, chromium was evaporated on the sample surfaces. The chromium film did not provide sufficient secondary electron emission for oxide thickness determinations. Under Northrop's guidance, Fairchild switched to gold for highlighting the oxide coating. The conditions for gold deposition from the evaporator differed from the sputtering technique used at Northrop. Fairchild had to empirically determine the time necessary for coating the oxide in order to get good resolution at the high magnification (20,000 X) required for examination of the oxide thickness. Thick gold coatings tended to spall off on cooling, giving a false indication of no oxide coating. Also, a thick coating which remains on the sample tends to mask the true features of the oxide coating.

The vapor deposition of gold upon weldbond aluminum oxide layers and the examination of these specimens by scanning electron microscopy has become a routine procedure at Fairchild Republic Company.

PASTE ADHESIVE APPLICATION

The B. F. Goodrich A-1444B weldbond adhesive is a one-part epoxy paste adhesive which cures at 250F. The adhesive contains strontium chromate for corrosion inhibition and Cab-O-Sil as a flow control agent. The material is shipped from the manufacturer surrounded by dry ice. At Fairchild Receiving, the adhesive is dated and stored at -5F in sealed plastic containers.

Prior to use, the full can of adhesive is equilibrated to room temperature, the plastic container is removed and the can is wiped dry prior to thorough mixing and division into smaller aliquots. Care is taken not to introduce air into the adhesive during the mixing. The aliquots are transferred to smaller containers, sealed, labeled, dated and stored at -5F. The adhesive viscosity spans the gamut of being easy to spread through being difficult to spread. Indeed, separate cans of the same batch of adhesive having identical out-times may demonstrate wide variance in spreading characteristics. There are no discernible differences in lap shear strength and in wedge crack extension test results from samples showing spreadability differences.

The latest batch of adhesive received (August 1978) showed some slight inhomogeneity in the form of skin-like curds within two cans of a 24-can batch of adhesive. These curds were separated and discarded during adhesive.application, however; one curd apparently got into a weldbonded sample. The material shows up as a connected threadlike radio-opaque series of spots upon the x-ray film. The curd may be a heavy concentration of strontium chromate. Discussion with the supplier indicate that improved process control techniques will be instituted to eliminate the problem in the future.

Aluminum skin-beaded panel detail parts were cleaned, anodized, dried and stored in accordance with the Northrop weldbond process specification. Prior to application of the adhesive, the mylar of the assembly is cleaned and indexed to the skin panel and the inner area's surface in opposition to the beads are traced out. The beaded panel is then indexed to the skin and any mismatches between the perimeters of the details are traced out. These areas are not coated with adhesive. The details are separated and the faying surfaces are coated with adhesive.

The adhesive is applied to the faying surface area with clean wooden tongue depressors or soft aluminum or plexiglas spatulas. The application edge of the tool is a straight line. The easiest application tool to use is a three inch wide plexiglass windshield scraper. Figure 133 shows the application of adhesive to a beaded pan using a plexiglass scraper. The operator, wearing clean white cotton gloves, takes care not to dig into or abrade the aluminum surfaces. The adhesive is applied 8-10 mils thick to each faying surface as measured with a film gage. The time required for adhesive application to eight square feet of faying surface approximates one man hour. Following adhesive application, the beaded panel is carefully placed on the skin so that the indexing holes are aligned. Care must be taken because any skewing or mismatch of parts may require tedious clean up of adhesive. Cleco fasteners are used to clamp the parts. Excess adhesive squeezeout is removed with clean straight edge tongue depressors. Clean cotton gauze or cheesecloth slightly wetted with acetone is used to remove the last traces of adhesive. The edges and any butt joints of the mated assembly are taped to prevent adhesive runout during welding. The cleaned mylar is indexed to the part and the spots for welding are indexed.

During the course of this technology transfer, several problem areas for production application of weldbonding have surfaced in the adhesive and adhesive application area as follows:

- There is no second source for weldbond adhesive. A production hedge is required to guard against (1) work stoppage at the adhesive manufacturer's plant, (2) unavailability of raw material for adhesive compounding, and (3) noncompetitive pricing.

FIGURE 133. APPLYING A-1444B PASTE ADHESIVE TO BEADED PAN DETAIL

- There is inhomogeneity in the adhesive which results in inconsistencies in spreadability and curing time. Discussions with the supplier indicate that tighted controls in the recommended procurement specification should solve this problem.
- The adhesive application time is critical to process cost effectivity; the time must be shortened.
- Thick applications of adhesive are used to provide makeup for slight mismatches in mating part contours. This results in (1) waste due to adhesive squeezeout and runout during cure, (2) heavier part, and (3) repeated cleanup. Removal of cured adhesive runout from parts after the curing operation is a difficult, time consuming chore.
- Provision must be made for alodining the weld spots after welding. Removal of adhesive from surfaces with acetone spreads the adhesive over the oxide layer. After curing, some of the cleaned area has a sheen to it, indicating that there is a thin coat of epoxy on the surface. This coating may not take alodining.
- Judicious sequencing of weldbond manufacturing operations is required for cost effectivity of the process.

ADHESIVE CURING

After the spotwelding operation, the Cleco clamps are removed and the indexing holes are drilled and riveted. The tape along the periphery and any butt joints on the assembly is removed and discarded. All excess adhesive is removed with straight edged clean tongue depressors and cotton gauze or cheesecloth wetted with acetone. Care must be taken to wipe the assembly clean. The edges and any butt joint on the assembly are retaped. Clamping or fixturing of the part may be required in the curing operation. The part is cured in an oven at 260F for two and one-half hours. Skin-panel assemblies are generally cured with the skin side down. If the part is cured with the concave or beaded panel side down, the adhesive runs out into the bead and drips from the hole in the bead.

RESISTANCE WELDING

Fairchild Resistance Welding Machine

A Sciaky 150KVA, 10-cycle spot welder was selected for the transfer of welding technology from Northrop to Fairchild. The machine selected was completely rebuilt by Sciaky in 1977 and updated with a Sciaky solid state control system for resistance welding (through a sealant) production panels for the A-10 close air support aircraft. After rebuilding, the machine was located in Fairchild's Farmingdale, New York production environment, qualified to MIL-W-6858 and modified for accepting the Pertron Microprocessor Control for weldbonding.

This particular machine was selected because of the relatively long cycle time capability, i.e., ten (10) cycles at one hundred (100) percent heat phase. It was necessary to select a ten (10)-cycle machine because of the extended weld and current decay times associated with the developed Northrop weldbond schedules for 0.025/0.032, 0.040/0.050 and 0.071/0.050-inch aluminum sheet material gauges. Conventional resistance welding procedures for gauges within this range normally require five (5) cycle machines.

Pertron Microprocessor Control

A Pertron Model PWC 300 Weldmaster Controller was procured specifically by Fairchild for this weldbond program in accordance with the recommendations from Northrop. The controller consists of a PNE300 programmable nugget expansion feedback unit, a tape recorder, an SCR firing module, a ten (10) position selector switch and the necessary interconnecting cables.

The system was installed by Pertron personnel in such a manner that the unit could be operated either with the Pertron system activated or with the Sciaky solid state system in use, by merely providing two toggle switches in the circuit. This was necessary to provide flexibility between weldbond processing and present A-10 production requirements. Training of personnel in the overall operation of the microprocessor was also provided by Pertron.

Spot Welding Procedures

To effect technology transfer for weldbonding from Northrop to Fairchild, two material thickness combinations and two panel configurations were selected. The two thickness combinations consisted of 0.025-inch 2024-T3 alclad to 0.032-inch 7075-T6 bare and 0.040-inch 2024-T3 alclad to 0.050-inch 7075-T6 bare. For the 0.025-inch and the 0.050-inch gauges, A-10 production details were selected from the production line (P/N 160D215002-41 covers, -43 pans). These details are presently autoclave adhesive bonded to form an assembly located on the top of the mid-fuselage of the A-10. The 0.040-inch and the 0.050-inch aluminum gauges measured 12 inches x 12 inches and were flat. These panels were selected to conduct spacing and possible shunting studies, as well as demonstrating weld nugget qualities resulting from different weld schedules.

All panels were cleaned, deoxidized and anodized in the pilot plant clean line setup previously described. Parts were transferred to a clean room environment where A-1444B paste adhesive was applied, parts were wrapped in neutral paper (MIL-P-17667) and then transferred to the production spot weld area for "weld fixturing."

Resistance welding schedules were developed for the two thickness combinations, i.e., 0.025-inch/0.032-inch and 0.040-inch/0.050-inch using 1 inch x 7 inches overlapped 2024-T3 alclad and 7075-T6 bare shear specimens. Spot welding parameters were adjusted until shear values and weld nugget diameters met the requirements of MIL-W-6858. Final weld schedules by cycle for both thickness combinations are shown in Figure 134 and 135. Tapes of the welding variables were made on a standard telex machine and entered into the Pertron microprocessor. A Duffers meter was used to indicate maximum current for each weld and a six channel oscillograph was used to record current and electrode pressures. Figure 136 shows the complete monitoring and recording setup to weldbond the technology transfer panels and Figure 137 shows a closeup view of the resistance welding operation.

All panels, flat and curved, were subsequently cured at 250F for one hour and radiographically inspected. The flat 0.040-inch x 12 inches x 12 inches 2024-T3 alclad/0.050-inch 7075-T6 bare panels revealed no weld nugget cracks or expulsion and good adhesive bond coverage. Panels were spotwelded with row to row spacing of one and two inches and spot to spot spacings of one inch and one and one-half inches. The 0.032/0.025 curved A-10 panels revealed acceptable weld nuggets with no evidence of cracks or expulsion with the weld schedule shown in Figure 134. However, some misshaped nuggets were noticed with the thin gauges required in the 0.025/0.032 panel combination indicating that further work was necessary in developing an optimum weld schedule for this combination. It was also believed that the misshaped nuggets for thin gauges (0.032-inch and under) may be associated with the sensitivity of the process towards electrode configuration and electrode alignment requirements, and further effort would be needed in this area.

```
00/401  000  01      TURN ON – APPLY WELD PRESSURE
01/002  000  97      TEST FOOT SWITCH
02/403  030  01      TURN ON BRUSH RECORDER
03/800  060  00      HOLD 60 CYCLES
04/001  000  00      DO NOTHING
05/402  007  01      APPLY FORGE PRESSURE AFTER 7 CYCLES
06/131  001  38      VOLTAGE SPIKE ONE CYCLE – 38%
07/131  005  01      COOL – 5 CYCLES
08/131  001  19  ⎫
09/131  001  33  ⎪
10/131  001  41  ⎬   HEAT UP-SLOPE 5 CYCLES
11/131  001  44  ⎪
12/131  001  49  ⎭
13/131  001  40  ⎫
14/131  005  39  ⎪
15/131  001  32  ⎪
16/131  001  31  ⎪
17/131  001  30  ⎬   HEAT DOWN-SLOPE 10 CYCLES
18/131  001  29  ⎪
19/131  001  28  ⎪
20/131  001  27  ⎪
21/131  001  26  ⎪
22/131  001  25  ⎭
23/403  000  00      TURN OFF BRUSH RECORDER
24/800  180  00      HOLD 180 CYCLES
25/003  000  00      FINISH WELD, RETURN TO STEP 00
```

0.032/0.025 PANEL WELDS, FAIRCHILD SCHEDULES		
0.032	0.025	GAGE
7075-T6	2024-T3	ALLOY
BARE	ALCLAD	CLAD/BARE
1.5V PSD	1.0V PSD	SURFACE PREP
5/8″	5/8″	ELECT – DIA
10″	10″	TIP RADII
1	1	CLASS
500 LBS. /	2000 LBS.	WELD/FORGE

FIGURE 134. RESISTANCE WELDING SCHEDULE FOR 0.025-INCH 2024-T3 ALCLAD AND 0.032-INCH 7075-T6 BARE ALUMINUM ALLOYS

```
00 401  000  01     TURN ON — APPLY WELD PRESSURE
01 002  000  97     TEST FOOT SWITCH
02 403  090  01     TURN ON BRUSH RECORDER
03 800  120  00     HOLD — 120 CYCLES
04 900  065  00     JUMP TO STEP 65
05 613  000  00     INITIATE FEEDBACK EXPANSION
06 404  009  01     RE-ZERO FEEDBACK ENCODER AFTER 9 CYCLES
07 404  009  00     START READING FEEDBACK ENCODER
08 402  004  01     APPLY FORGE PRESSURE — AFTER 4 CYCLES

09 191  025  40     VOLTAGE SPIKE, 1 CYCLE AT 40%
11 000  000  01     ONE CYCLE COOL
13 000  000  09
15 000  000  19
17 000  000  27
19 000  000  31     HEAT UP-SLOPE — 7 CYCLES
21 000  000  35
23 000  000  49
25 000  000  50
27 000  000  47
29 000  000  48
31 000  000  42
33 000  000  42
35 000  000  41
37 000  000  39
39 000  000  37
41 000  000  34
43 000  000  30     HEAT DOWN-SLOPE — 16 CYCLES
45 000  000  29
47 000  000  28
49 000  000  27
51 000  000  26
53 000  000  25
55 000  000  24
57 000  000  24

10 255  000  00
12 255  000  00
14 255  000  00
16 255  000  00
18 255  000  00
20 255  000  00
22 255  000  00
24 255  000  00
26 255  000  00
28 255  000  00
30 255  000  00
32 255  000  00
34 255  000  00     EXPANSION MONITORING
36 255  000  00
38 255  000  00
40 255  000  00
42 255  000  00
44 255  000  00
46 255  000  00
48 255  000  00
50 255  000  00
52 255  000  00
54 255  000  00
56 255  000  00

58 403  000  00     TURN OFF BRUSH RECORDER
59 800  120  00     HOLD 120 CYCLES
60 404  000  01     RESET FEEDBACK ENCODER
61 001  000  00     DO NOTHING
62 001  000  00     DO NOTHING
63 003  000  00     FINISH WELD, RETURN TO STEP 00

65 941  248  05     CHECK SELECTOR SWITCH, IF NO. 1, JUMP TO STEP 5
66 941  240  70     CHECK SELECTOR SWITCH, IF NO. 2, JUMP TO STEP 70
67 900  059  00     JUMP TO STEP 59

70 402  002  01     APPLY FORGE IN TWO CYCLES
71 111  040  25     DEGAUSS, 40 CYCLES AT 25% HEAT
73 003  000  00     FINISH WELD, RETURN TO STEP 00
```

0.050/0.040 PANEL WELDS		
0.050	0.040	GAGE
7075-T6	2024-T3	ALLOY
BARE	ALCLAD	CLAD/BARE
1.5V PSD	1.0V PSD	SURFACE PREP
5/8"	5/8"	ELECT — DIA
10"	10"	TIP RADII
1	1	CLASS
500 /	3000	WELD/FORGE

FIGURE 135. WELDING SCHEDULE FOR 0.040-INCH 2024-T3 ALCLAD TO 0.050-INCH 7075-T6 BARE ALUMINUM ALLOY

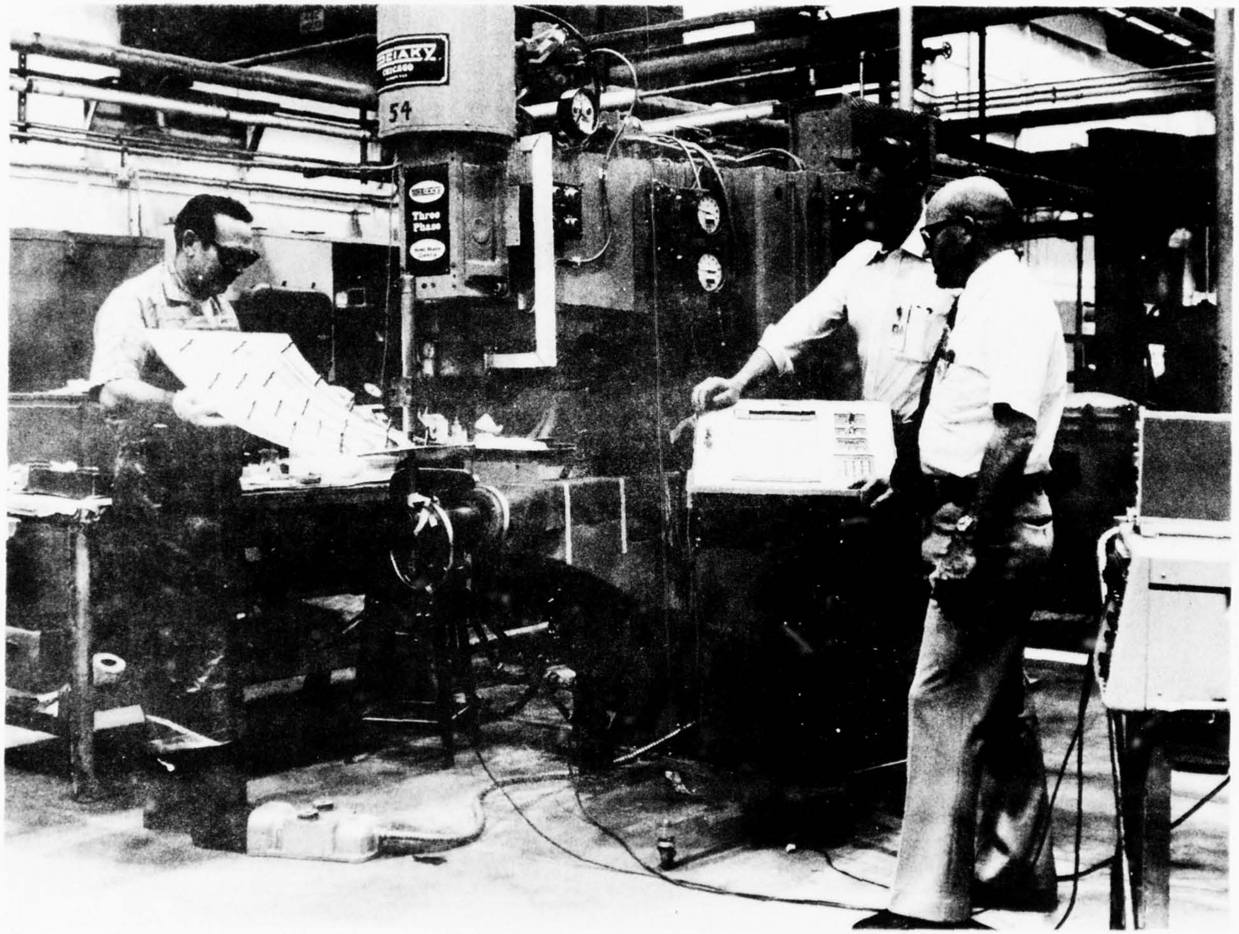


FIGURE 136. RESISTANCE WELDING MACHINE, PERTRON MICROPROCESSOR AND MONITORING/RECORDING EQUIPMENT

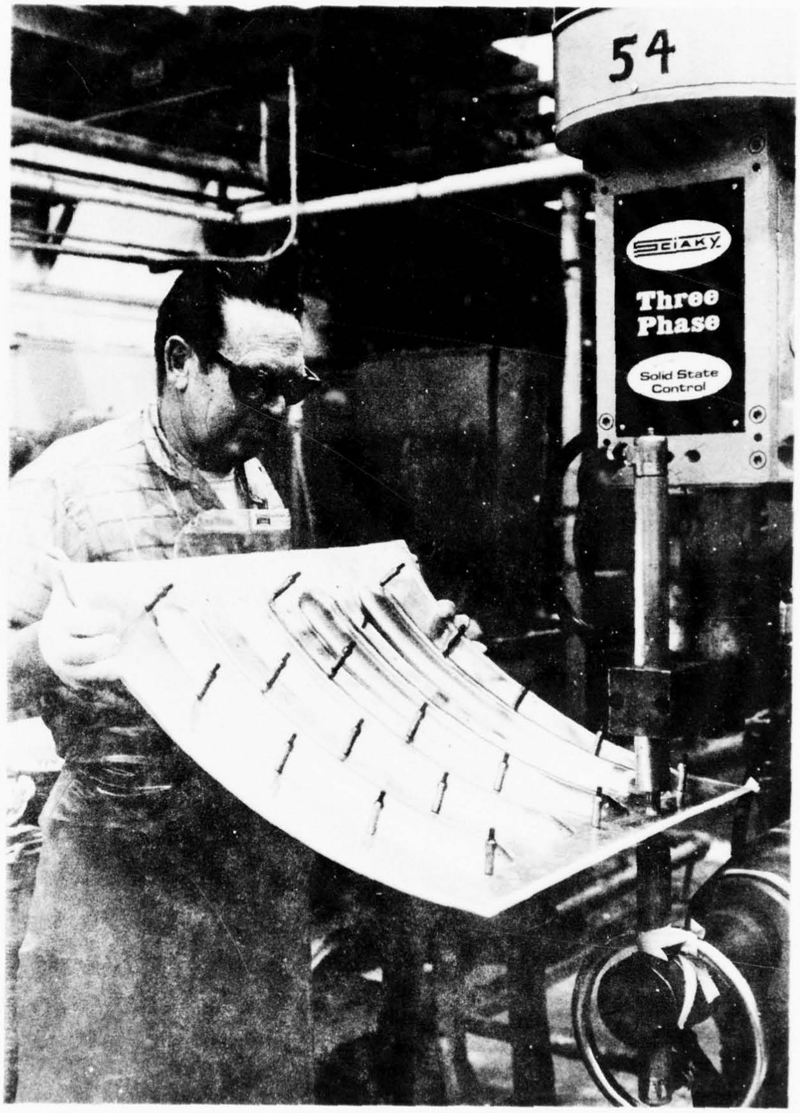


FIGURE 137. A-10 SKIN/BEADED PAN DETAILS P/N 160D215002-41 COVER, -43 PAN BEING WELDBONDED

COST ANALYSIS

A cost analysis was conducted at both Northrop and Fairchild Republic to compare the end item manufacturing cost of weldbond fuselage panels with the more conventional adhesive bonded panels and to determine the major cost drivers of the weldbond process. To obtain the most realistic values regarding the potential savings in applying weldbond methodology to a skin and beaded pan assembly, independent cost analyses were conducted at both Northrop and Fairchild. Complete integration of the results could not be achieved due to the different cost analysis techniques and cost collection systems employed at each company. However, a comparison of the final cost figures was made.

The cost studies conducted in this program did not take into account the nonrecurring cost, including tooling, required for the various processes. The cost analysis was conducted in this manner because the weldbonding process was to be integrated into an existing manufacturing system and maximum cost savings could not be realized, as the autoclave tooling already existed. However, in considering the application of aluminum weldbonding for new aircraft systems, cost savings would be higher, as the expensive tooling cost associated with autoclave curing for conventional adhesive bonding processes would not be necessary.

COST STUDIES AT NORTHROP

Introduction

The cost analysis activities conducted at Northrop included the generation of cost estimates to fabricate the skin and beaded pan details as well as the assembly of these details using both adhesive bonding and weldbonding assembly techniques. A discussion of Northrop's cost estimating methodology and the results of the cost analysis activities are presented in the following paragraphs.

Cost Estimating Methodology

Northrop's detail estimating process was employed to generate the cost estimates for the fabrication of the detail parts and the assembly of these details into the final component panel. This process utilizes Industrial Engineering Time Standards to calculate the "pure" labor hours associated with detail fabrication and assembly operations. Figure 138 presents a generalized detail estimating process.

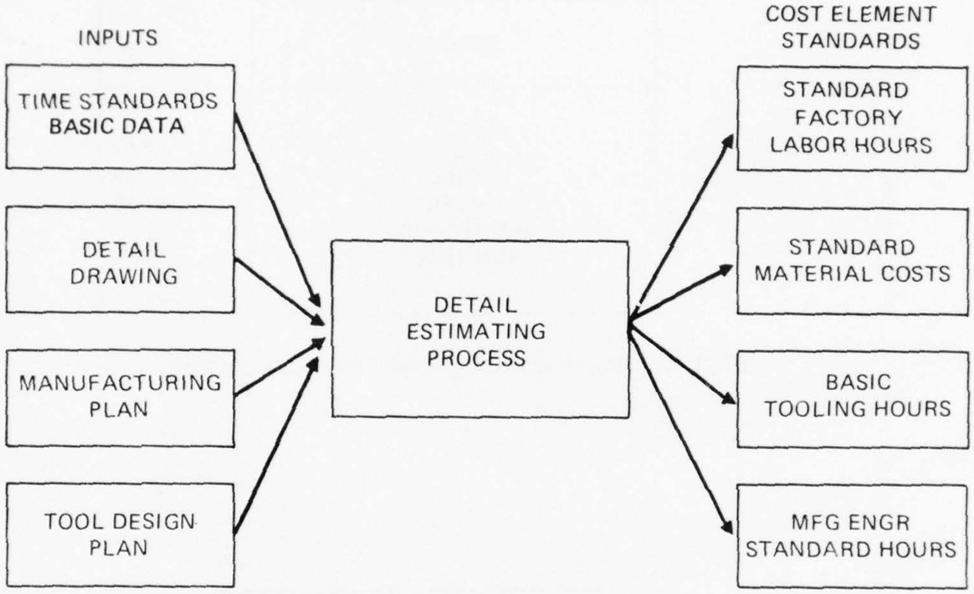


FIGURE 138. GENERALIZED DETAIL ESTIMATING PROCESS

In developing Industrial Engineering Time Standards, basic stop watch time studies were performed at Northrop for operations that are involved in the production of a particular item. The time standards that have been developed account only for the basic work content of a task and do not allow for other elements which are part of factory labor as experienced in a real production environment, e.g., fatigue, waiting time for tools and materials, attention to personal needs, etc. Figure 139 depicts the total work content of factory labor. These time standards have been incorporated into Northrop's Time Standards Basic Data Manual. Once these standards have been established, the production cost elements are projected using suitable labor rates, improvement curves, variance factors and other economic factors to arrive at the projected recurring production costs as shown in Figure 140.

In this program cost estimates were made for two different assembly techniques, adhesive bonding and weldbonding. The estimates for the adhesive bonding process

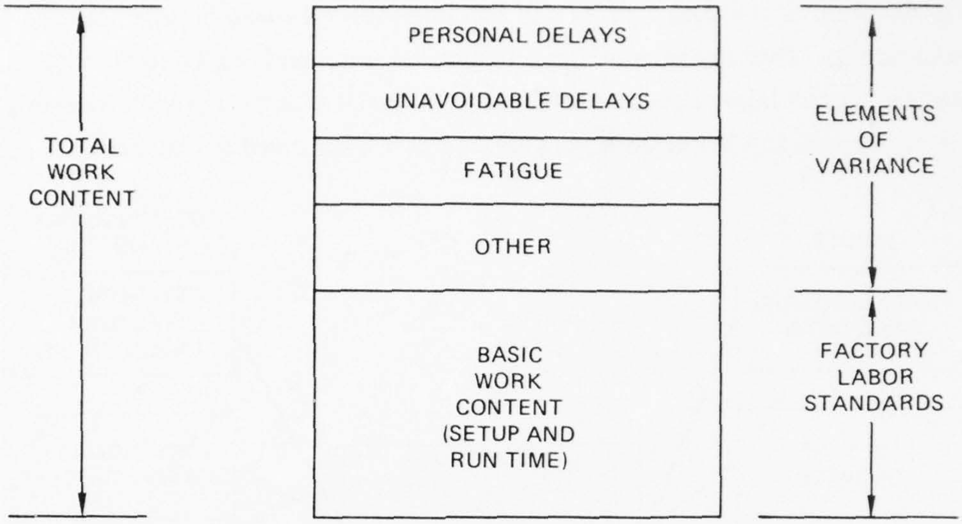


FIGURE 139. FACTORY LABOR BREAKDOWN

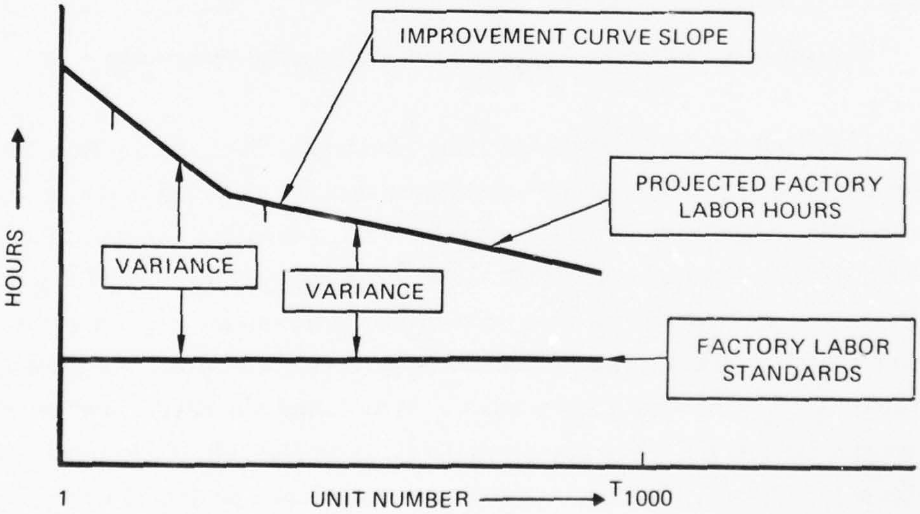


FIGURE 140. PROJECTION OF FACTORY LABOR STANDARDS

were made from the previously developed Industrial Engineering Time Standards. The cost estimates for the weldbond process were made by combining stop-watch time studies made in this program while assembling four different (two 0.040/0.050 and two 0.025/0.032 material combinations) panels following the manufacturing plan, shown in Appendix F, with prior Industrial Time Standards for the fabrication of the skin and beaded panel details.

The WeldBond Learning Curve

Cost element standards are projected from the "pure" (factory labor hour standards) to reflect realistic production conditions through the application of various cost projection factors such as variances, improvement curve slopes, and material and labor rates. These factors are established on the basis of a careful evaluation of related historical data. Figure 140 illustrates Northrop's cost projection procedure. A variance factor is first applied to the factory labor standards at T_{1000}. From this point a projection is made to the first unit following a predetermined improvement curve slope. Unit factory labor hours are read off of the resulting unit curve.

This procedure, presented above, reflects operations that are primarily accomplished manually (hands on labor) in the shop where learning can take place. It does not take into account limitations that can be imposed on either the equipment or the operator, that some type of integration of men and machine may present. In the spotwelding segment of the weldbond assembly procedure such limiting factors may appear. For example, there is a maximum speed in which the operator can move and position the fuselage panel under the electrode to insure high quality welds. In addition, there may be a minimum spotweld schedule which produces the optimum weld in terms of the fatigue environment. This scenario implies that the operator will undergo learning in manually moving and positioning the panel, but at some point (say T_N) any further increase in learning is inhibited by the weld schedule of the machine. This analysis is illustrated graphically in Figure 141.

Conversely, if the weld cycle time was capable of being reduced to allow for a shorter weld to weld time, assuming acceptable welds, the operator would now become the inhibiting factor in the procedure since he has an optimum speed in which he can move and position the panel. This case is illustrated in Figure 142.

This scenario would require that the weld schedule cycle time be reduced to be compatible with the speed of the operator.

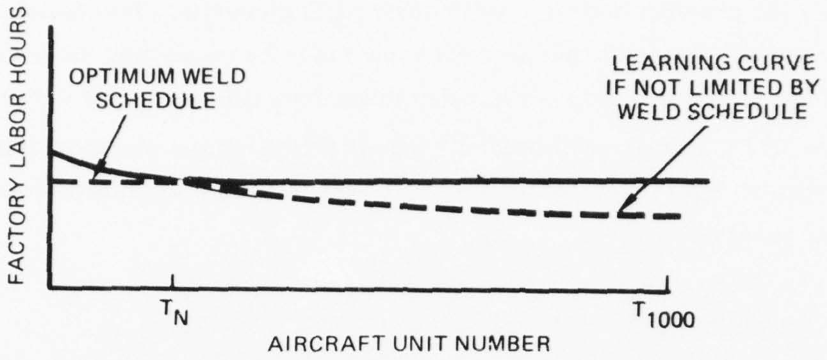


FIGURE 141. ANTICIPATED WELDBOND LEARNING CURVE ASSUMING WELD SCHEDULE AS LIMITING FACTOR

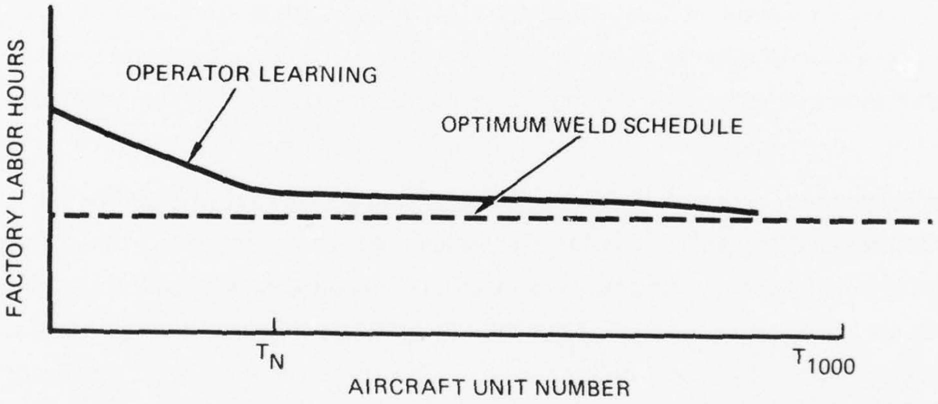


FIGURE 142. WELDBOND LEARNING CURVE ASSUMING OPERATOR AS LIMITING FACTOR

As indicated previously, only four panels were observed by the cost analyst during this program. This is not a sufficient number of observations to generate highly accurate cost data but it was sufficient to make reasonable projections. Subsequently, it was not possible to develop variance factors and improvement curve slopes that would be unique to the weldbond assembly procedure. However, Northrop does have experience in adhesive bonding and the variance and improvement curves employed for this operation were used to develop the cost projections for weldbonding. (It should be noted, that a majority of the operations required to adhesively bond and weldbond were common to both.)

When the weldbonding procedure is moved into a production environment, cost data will become available and a more formalized analysis of variance and improvement curves can be accomplished. At this time, an optimized weld schedule should also be available to insure man/machine optimization.

Results at Northrop

Tradeoff analysis between the adhesively bonded panel and the weldbonded panel reveal that the total fabrication and assembly costs of the weldbond panel is 4.1 percent lower than the adhesively bonded panel for Tu_{500} (where Tu_{500} is defined as the actual cost of the 500th unit), as shown in Figure 143.

By removing the estimated cost of fabricating the skin and the beaded pan of the panel, which is common to both assembly techniques, and just isolating the assembly procedures, the cost savings of weldbonding over adhesive bonding is then 7.0 percent, as shown in Figure 144 for Tu_{500}.

The level of detail at which Northrop develops the cost estimates enables the cost analyst to identify the significant cost drivers in both assembly techniques. The cost savings exhibited in Figure 144 is achieved through the reduction in factory labor hours required to spotweld the panel vs the floor time to autoclave cure the adhesively bonded panels. Figure 145 illustrates that the autoclave time encompasses 65 percent of the time required to assemble the adhesively bonded panel. The adhesive bond autoclave cure time includes discrete elements embodied in the total operating time for the operation. These elements include: Obtain required hand tools, clean as required, position part on tool, prepare vacuum bag, apply zinc chromate, bag and seal, install vacuum fittings and thermocouple leads, apply vacuum, check for leaks, move to autoclave and load, check master controls and install recording documents. (NOTE: The actual autoclave cure time is not included in the factory labor hour estimated, as the Northrop approach for estimating this type of operation is based upon "hands-on" labor only. In the weldbond assembly, the weld cycle time and adhesive application time account for 40 percent and 27 percent of the time respectively. The weld cycle time includes the time to position the panel in the welding machine and the initiation and completion of the spot weld, repeated until the panel is finished. The adhesive application time includes the time to apply adhesive and place the panel in the weld fixture. A summary of the results of the cost study at Northrop is given in Table 33.

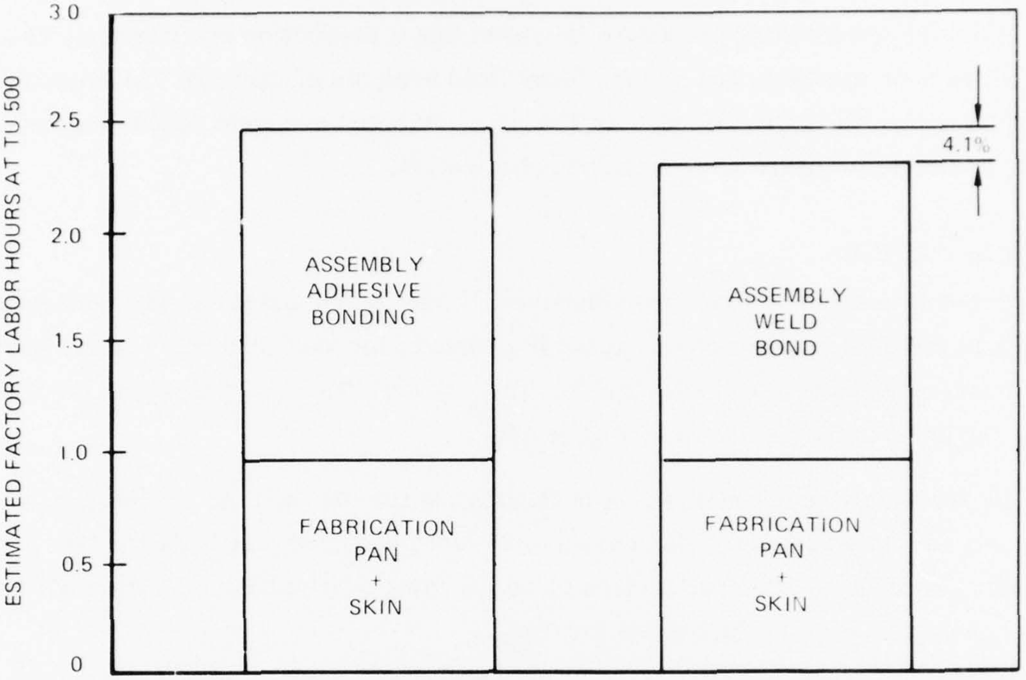


FIGURE 143. COMPARISON OF WELDBOND VS ADHESIVE BOND (FABRICATION & ASSEMBLY)

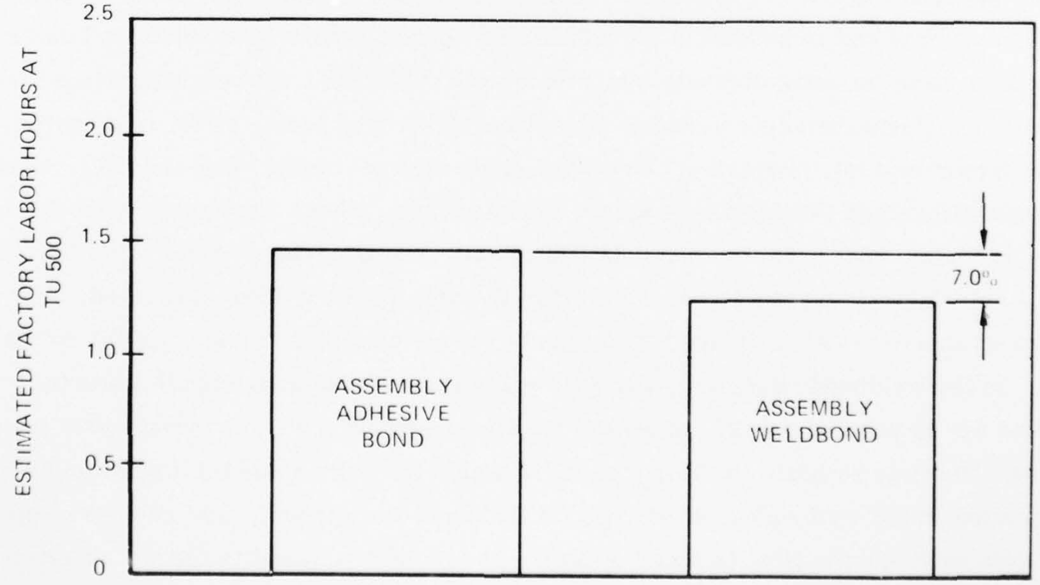


FIGURE 144. COMPARISON OF ASSEMBLY TECHNIQUES ADHESIVE BOND VS WELDBOND

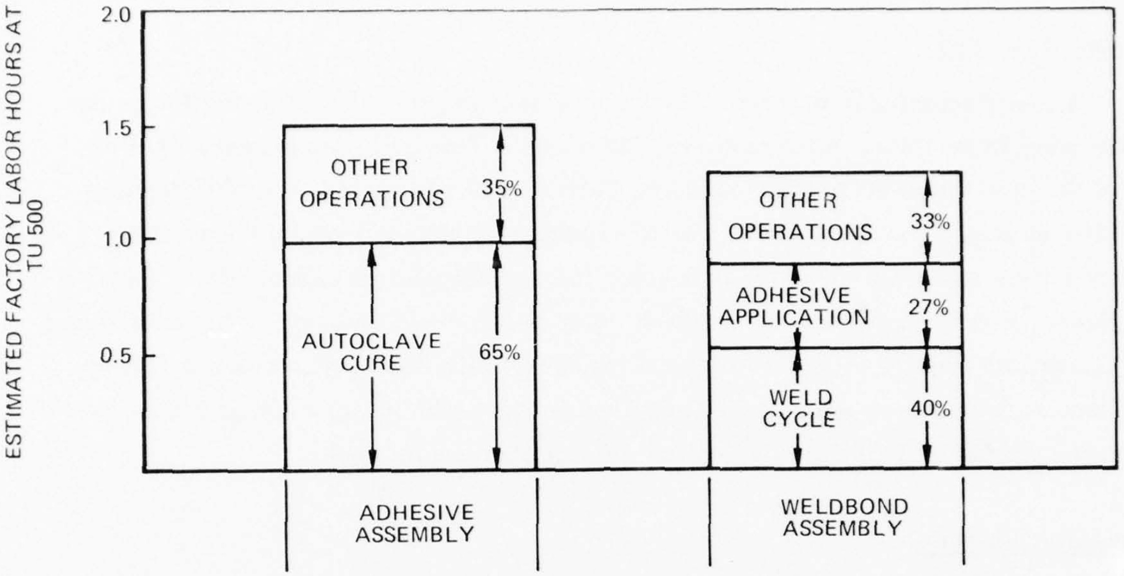


FIGURE 145. SIGNIFICANT COST DRIVERS OF ASSEMBLY TECHNIQUES (ADHESIVE BOND VS WELDBOND)

TABLE 33. RESULTS OF COST STUDIES AT NORTHROP, Tu_{500}

Operation	Adhesive Bond	Weld Bond
1) Prefit	0.0139	0.0139
2) Cleaning & Preparation	0.0619	0.0619
3) Layup & Bag	0.1633	
4) Supply Adhesive & Load		0.3814
5) Spotweld		0.5597
6) Cure	0.9710	0.1661
7) Tear Down	0.0937	0.2119
8) Prepare Test Spec, Handling		
9) Add Tack Rivets	0.1876	
Total average manhours per panel:	1.49	1.39

COST ANALYSIS AT FAIRCHILD

Procedures Used

A manufacturing plan for the Northrop weldbond process was submitted to the Estimating Department in Hagerstown, Maryland. This path was pursued because all of the production adhesive bonding by Fairchild is accomplished in the Bonding Facility at Hagerstown. The Estimating Department has well established set-up and run-time standard hours for producing the skin/beaded pan assemblies, and, therefore, a meaningful one-on-one cost comparison could be made. Table 34 shows the operations required for the weldbond process. Man hour estimates were made for each shop based on information supplied to Fairchild by Northrop and from experience gained by Fairchild during the technology transfer task.

Results at Fairchild

Recurring cost comparison studies between adhesive bonding and weldbonding the skin/beaded pan assembly for Tu_{500} is shown in Table 34. This table reveals that a cost savings of seven percent (which agreed with the Northrop cost analysis) can be realized through use of weldbonding over adhesive bonding using current weldbonding processing techniques. It is further shown that the principal cost drivers are the application of the A-1444B paste adhesive and the relatively long spotwelding cycles required for the weldbond process. Based on experience with similar processes, cost projections were made on an "optimized weldbonding process." Assumptions in developing this philosophy were made regarding potential process improvement, i.e., improving the time for applying the paste adhesive and shortening the weld times to below ten seconds per spot weld. This analysis shows a very respectful cost savings of 47 percent. When one combines this cost savings with the savings realized by precision lay-up adhesive bonding tooling versus simplified spot welding fixtures, then the cost effectiveness of weldbonding becomes even more attractive.

Additional benefits to be derived from the application of the weldbond process to the A-10 include: (1) production experience with weldbonding, and (2) service experience to verify durability. These benefits coupled with the reduction in the two previously mentioned cost drivers (paste applications and spot weld times) represent the two major areas for attention during the follow-on weldbond contract - "Production Application of Weldbonding to A-10" Contract Number F33615-78-C-5121.

TABLE 34. RECURRING COST ANALYSIS (MAN-HOURS) AUTOCLAVE VS WELDBONDING UNIT 500

Operation	Autoclave Bonding	Current Weld Bonding	Optimized Weld Bonding
1. Prefit	.25	.13	.13
2. Cleaning and Preparation	.15	.13	.13
3. Layup and Bag	.67	--	--
4. Apply Adhesive and Load	--	.50	.15
5. Spotweld	--	.67	.39
6. Cure	.46	.25	.15
7. Tear Down	.20	--	--
8. Prepare Additional Test Specimens	--	.16	.10
9. Add Tack Rivets	.25	--	--
Total-Avg. Manhours/Panel	1.98	1.84	1.05
Cost Saving		-7%	-47%

COST ANALYSIS DISCUSSION

The cost analysis activities conducted both at Northrop and at Fairchild Republic showed that the selected structural panel used in this program provides a seven percent cost saving compared to adhesively bonded panels. This cost saving is significant when viewing the potential application of weldbonding to future aircraft systems for the following reasons:

a. The results of the studies both at Northrop and Fairchild revealed that the major cost drivers were (see Table 35): (1) the time necessary for the application of the paste adhesive, (2) the relatively long spot welding cycles.

As both of these factors were unexpected and identified late in the program, significant effort to revise procedures to lower their impact was not possible. As previously indicated, Fairchild will focus attention, as described below

TABLE 35. COST DRIVER IDENTIFICATION,* (Tu_{500}) WELDBONDED ASSEMBLY

Operation	Fairchild	Northrop
1) Prefit	.13	.0139
2) Cleaning & Preparation	.13	.0619
3) Supply Adhesive & Load	.50	.3814
4) Spotweld	.67	.5597
5) Cure	.25	.1661
6) Prepare Additional Test Spec. and Handling	.16	.2119
Total Manhours per panel:	1.84	1.3949

*This table demonstrates that through independent cost analysis activities at Fairchild and Northrop, both companies were able to identify the same significant cost drivers of the weldbond process, i.e., adhesive application and the spotwelding of the panels.

on these areas in the follow-on program.

Application of Adhesive

At the beginning of the current program, it was felt that it was adequate to apply the adhesive by hand using a spatula, as is shown in Figure 110. Fairchild will investigate other techniques for improved application of adhesive, such as rolling techniques or air pressurized applicators, which are current state-of-art for other paste adhesives and sealants. Adoption of such techniques should significantly reduce the time necessary for adhesive application.

Weld Cycle Times

The time necessary for the spot welding of the panel was "time studied" using earlier panel weld schedules which contained a number of "time holds" due to the current spike, the speed of the welding head, and the long current down-slope. These hold times were successfully reduced later in the program during the technology transfer phase after the initial time studies were completed. It is felt that with further effort in optimizing weld schedules, additional time reductions can be achieved. This possibility was considered by Fairchild in the "optimized weld bonding" cost study, shown in Table 34, in which it was assumed that (based on experience with production of assemblies involving weld-through-sealants) these cost drivers could be reduced to the values shown.

The significance of reducing these two major cost drivers is evident since the results of the cost study for the optimized process showed that the cost savings of the weldbonding process over the adhesive bonding process for fabricating these panels is a significant 47 percent.

b. As was previously indicated, the fuselage panel selected for this program showed only a moderate cost savings compared to other A-10 candidates in the original Fairchild analysis. It is possible that the cost savings to be realized when applying the optimized approach to these types of components should be even greater than was shown in this study if these parts were used on the first production aircraft.

c. It is also anticipated that additional savings can be realized when a design philosophy for utilization of the weldbond process is properly developed. To date, aluminum weldbonding has only been applied to existing designs that were previously assembled using other techniques, i.e., adhesives or rivets. To take optimum advantage of the higher fatigue properties of the weldbonding process and to maximize cost savings, a design philosophy must be developed for the weldbonding process. Using this design philosophy, optimum designs can be achieved which not only would show significant cost savings, but could also show reductions in the detail piece count of built up structure. This could also show a potential weight savings due to the fatigue advantage of weldbonded joints versus riveted structure.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The following general conclusions and recommendations regarding the overall performance of the aluminum weldbonding process have resulted from this program. Detailed conclusions regarding the specific individual aspects of this program are contained in appropriate sections of the report.

1. Weldbonding is now ready for implementation on airframe structures.
2. Aluminum weldbonded panels can be successfully fabricated in an aircraft production environment.
3. The aluminum weldbonding process is an effective manufacturing technique for the assembly of aircraft structural components such as A-10 panel assemblies which were shown to be structurally equivalent to those made by the adhesive bonding process.
4. Significant cost savings can be realized while using aluminum weldbonding for the manufacture of aircraft structural components. Using optimized procedures, assembly cost savings as high as 47% were possible by direct substitution of weldbonding for adhesive bonding.
5. Under conditions of low-load transfer, aluminum weldbonded components exhibit significantly superior fatigue performance than structures assembled by rivets.
6. For optimum low-load transfer fatigue results, the necessity of achieving weld nuggets which meet the MIL-W-6858 Class A size requirement is not critical. In contrast to standard spot welding criteria, optimum fatigue performance was achieved with the use of subsize, defect free, and round spotweld nuggets.
7. The surface treatment procedure used for weldbonding provides a more stable surface than spot weld etching and may be an attractive cleaning procedure for standard spot welding operations.

8. The use of in-process monitors and welding controls based on the principal of nugget expansion can be a powerful manufacturing tool for insuring high-quality spot welds. Future work should be undertaken to further understand and develop the metallurgical aspects of spot weld nugget expansion and the potential of microprocessor welding controls to take maximum advantage of this potential.

9. Work should be instituted to qualify additional adhesives, including both paste and film types, to provide further process cost reductions.

10. Improved paste adhesive application techniques need to be developed to provide additional cost reductions.

11. Since the welding cycle time has a significant cost impact on the weldbond process, effort needs to be undertaken to gain further understanding of the mechanisms of weld nugget growth through oxide coated surfaces so that spot weld schedules can be shortened further to provide additional cost reductions.

APPENDIX A

PROCESS SPECIFICATION

This specification, prepared in Northrop Company format, is intended to be a basis for an industry wide specification or individual company specifications to effectively use the aluminum weldbonding process. The procedures and specification limits outlined herein represent the results of the optimum manufacturing techniques which have been proven in this program to achieve acceptable results. However, this specification is not intended to limit potential users from expanding this technical base or further improving the process to achieve successful integration into their own manufacturing operations. As further development is undertaken and as production experience is gained, it is anticipated that many of the process parameters, i.e., temperatures, times, voltages, weld schedules, etc. will be modified to fit specific situations and some of the current production control requirements can be relaxed. These modifications will not only improve the technical base and confidence in the process, but should permit further reductions in manufacturing costs.

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RESPONSIBLE ENGINEER Tom Crowder AIRCRAFT DIVISION SPECIFICATION CONTROL QUALITY CONTROL ENGINEER PROJECT OFFICE	**NORTHROP** Northrop Corporation Aircraft Group - Aircraft Division PROCESS SPECIFICATION	**XPS-WB** **DATE** 23 March 1979 **RELEASE EO** CODE IDENT NO 76823

TITLE: MANUFACTURE OF ALUMINUM WELDBONDED ASSEMBLIES

(PROPOSED COMPANY SPECIFICATION)

1. SCOPE

1.1 This specification establishes the requirements and procedures for the manufacture of metal-to-metal structural weldbonded assemblies for continuous operation in the temperature range of from -67 to +180 F (-55 to +82 C), using a 250 F (121 C) curing adhesive system.

1.2 The requirements of this specification are applicable only when specified on the Engineering drawing.

1.3 Weldbonding performed under this specification is limited to 7075-T6 bare and 2024-T3 bare sheet with a thickness range of from 0.025 to 0.090 inch (0.64 to 2.29 mm), and 2024-T3 alclad sheet with a thickness range of 0.025 to 0.071 inch (0.64 to 1.80 mm). Other combinations shall not be weldbonded without the approval of the procuring activity.

1.4 The customary units of measurement used herein are followed by converted metric units (and when applicable, calculated equivalent metric ratios), using International System (SI) units. Where appropriate in this specification, conversions are practical approximations.

2. APPLICABLE DOCUMENTS

2.1 The following publications of the issue in effect on the date of invitation for bids or request for proposal form a part of this specification to the extent specified herein.

2.1.1	MIL-W-6858	Welding, Resistance; Spot and Seam

2.2 The following specifications identify materials required by this specification. Use of these specifications is not required to perform the tasks described herein.

2.2.1	O-N-350	Nitric Acid, Technical
2.2.2	O-S-595	Sodium Dichromate, Dihydrate, Technical
2.2.3	QQ-A-250/12	Aluminum Alloy Sheet and Plate, 7075-T6
2.2.4	CCC-C-440	Cloth, Cheesecloth, Cotton, Bleached and Unbleached
2.2.5	MIL-P-17667	Paper, Wrapping, Chemically Neutral
2.2.6	XMS-WBA	Adhesive, Aluminum Weldbond, Service Range -67 to 180 F (-55 to 82 C)

3. REQUIREMENTS

3.1 Materials

3.1.1 Metals

3.1.1.1 Aluminum Alloy Sheet, 7075-T6	QQ-A-250/12

3.1.2 Adhesive

3.1.2.1 Weldbond Adhesive	XMS-WBA

3.1.3 Chemical Additions

3.1.3.1 Sodium Dichromate, Dihydrate, Technical	O-S-595
3.1.3.2 Alodine 45	Amchem Products

3.1.3.3	Alodine 1200E	Amchem Products
3.1.3.4	Amchem 7	Amchem Products
3.1.3.5	Amchem 17	Amchem Products
3.1.4	Acid	
3.1.4.1	Acid, Nitric, Technical	O-N-350
3.1.4.2	Acid, Phosphoric, 85 percent	Commercial
3.1.5	Miscellaneous	
3.1.5.1	Cheesecloth, Type I, Class 2	CCC-C-440
3.1.5.2	Paper, Chemically Neutral, Type I	MIL-P-17667
3.1.5.3	Gloves, White Cotton	Commercial
3.1.5.4	Electrode Anti-Stick Solution	Commercial

3.2 Equipment

3.2.1 Welding Machine - The spot welding machine shall be a three phase machine equipped with a computer-type microprocessor welding controller capable of cycle-by-cycle heat control. The machine shall also be capable of controlling the weld and forge force within ± 50 pounds (222 N).

3.2.2 Welding Electrodes - The electrodes shall be water cooled RWMA, Class I or Class II.

3.2.3 Cleaning and Surface Treatment Equipment

3.2.3.1 Deoxidizer Tank - The deoxidizer tank shall be constructed of PVC, CPVC, polyethylene, Koroseal rubber, or 300 series CRES steel material. If CRES steel is used, means shall be provided to ensure complete electrical insulation of the work piece from the tank. The tank shall contain a means of agitation either by air or by circulation with a submerged impeller or circulation pump. The pump and filter housing shall be made of PVC or CPVC material with polypropylene filter cartridges.

3.2.3.2 Anodizing Tanks - The anodizing tanks shall be constructed from Type 300 CRES steel. Provisions shall be made so that the tank is electrically insulated from the holding fixtures and the parts being processed. The tank shall be provided with air agitation and continuous filtration by means of a pump and filter housing made of either PVC or CPVC material with polypropylene filter cartridges. The electrical power supply for the anodizing operation shall produce ripple-free DC (± 2 percent of anodizing voltage).

3.2.3.3 Rinsing Equipment - The equipment shall have provisions for spray rinsing with either tap water or deionized water, either separately or simultaneously.

3.2.4 Tensile Testing Machine - The tensile machine shall be capable of achieving an accuracy of ± 2 percent of the full scale reading.

3.2.5 Surface Resistance Indicators - The surface resistance indicating equipment shall be capable of achieving an accuracy of ± 10 percent of the full scale reading.

3.2.6 Tooling - Tooling required to locate welds or assist in assembly shall be made from nonmagnetic material and shall be so designed that welding current is not shunted through the tool.

3.3 Process Synopsis - Flow Chart - The processing sequence shall be as specified in Figure 1.

3.4 Storage and Handling Adhesive

3.4.1 The adhesive shall be stored as specified in Table 1.

3.4.2 Storage shall be provided to protect the material from moisture, direct sunlight, and exposure to elevated temperature.

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ADVANCED WELDBONDING PROCESS ESTABLISHMENT FOR ALUMINUM.(U)
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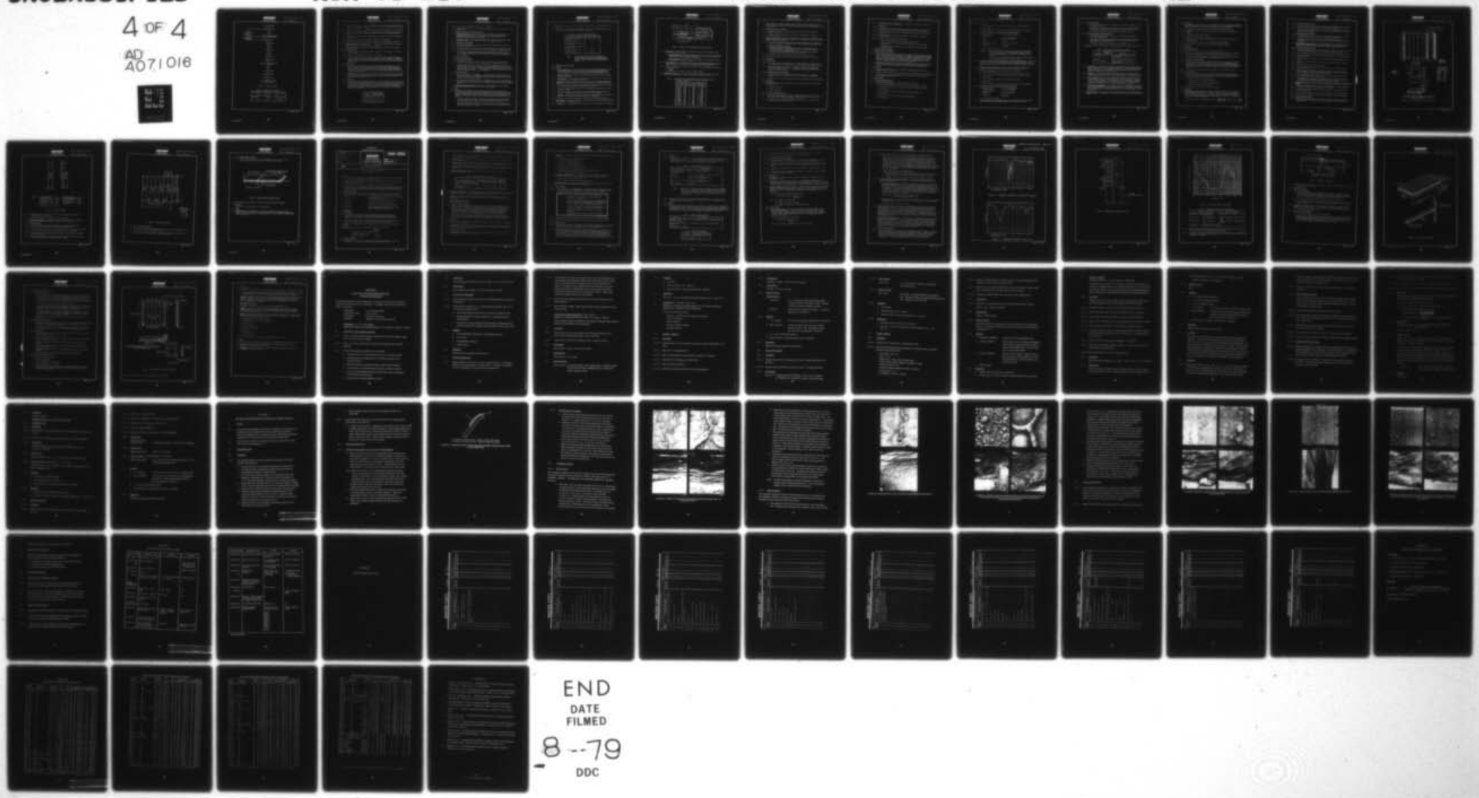

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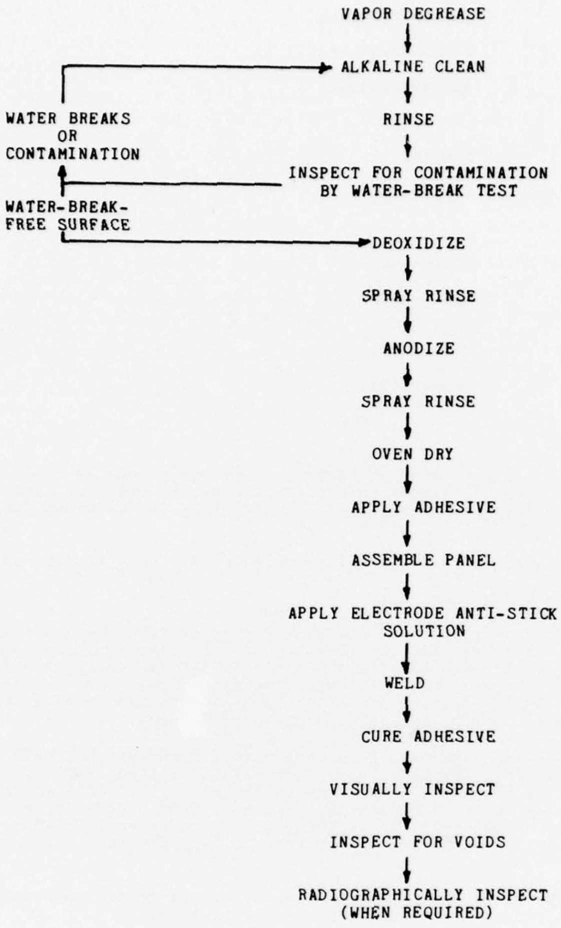


FIGURE 1. PROCESS FLOW CHART

TABLE 1. STORAGE TIME FOR ADHESIVE

Material	Storage Temperature, F (C) Maximum	Storage Time
XMS-WBA	0 (-18)	6 months
	80 (27)	7 days

3.4.3 The material manufacturer's data or instructions on handling and storage shall form a part of the requirements of this specification. In event of conflict, the requirements of this specification shall govern.

3.4.4 Materials shall be used on a sequential basis; the oldest material shall be used first.

3.4.5 Containers removed from storage shall be identified with the removal time and date and with the time and date of return to storage. The total out time shall not exceed 7 days.

3.4.6 The container removed from cold storage shall not be opened until it has reached room temperature.

3.4.7 The unused portion shall be returned to storage as soon as possible.

3.4.8 Materials not being used shall be kept in sealed or closed packages or containers.

3.5 Surface Preparation - All surfaces of all parts and test specimens shall be cleaned and anodized in accordance with the following procedure.

3.5.1 Vapor Degreasing - All parts shall be vapor degreased to remove all oil or grease.

3.5.2 Alkaline Cleaning

3.5.2.1 Immerse parts in a nonsilicated alkaline cleaner at 125 to 165 F (52 to 74 C) for 12 to 15 minutes.

3.5.2.2 Spray rinse with deionized water for 5 to 7 minutes.

3.5.2.3 Inspect for water-break-free surface. If parts are not water break free, repeat 3.5.2.1 through 3.5.2.3 until a water-break-free surface is obtained. Parts shall be considered to pass the water-break inspection if, after completion of rinsing, the surface of the parts will maintain a continuous film of water for 30 seconds without sudden flashout.

3.5.3 Deoxidizing

3.5.3.1 Immerse alkaline cleaned parts in an agitated deoxidizer solution (4.3.1.1) at 70 to 80 F (21 to 27 C) for 6 to 8 minutes. Higher deoxidizing temperatures may be used if reduced times are employed which achieve equivalent results. The solution shall be certified in accordance with 3.14. Parts and hanging brackets shall be suspended in the tank so that they do not make metal-to-metal contact with the tank if CRES steel tanks are used.

3.5.3.2 Immediately spray rinse with ambient temperature deionized water for 5 to 7 minutes. The inclusion of tap water for the first 1 to 2 minutes of rinse to minimize staining on alclad material is acceptable. No drying of the part shall be evident prior to immersion into the anodizing solution.

3.5.4 Anodizing

3.5.4.1 Immediately immerse in anodize solution (4.3.1.5) at 70 to 80 F (21 to 27 C) for 18 to 22 minutes at the voltages shown in Table 2. The solution shall be certified as part of the system in accordance with 3.14. The electrical connection must be made and the current applied within 30 seconds after the parts are immersed in the anodizing solution. Electrical connections made to the parts below solution level must be made with aluminum or titanium electrical connectors. The use of copper or CRES steel connectors is prohibited.

TABLE 2. ANODIZING VOLTAGES

Alloy	Voltage Range
2024-T3 bare	1.4 to 1.6
7075-T6 bare	1.4 to 1.6
2024-T3 alclad	0.9 to 1.1

3.5.4.2 Spray rinse with deionized water for 5 to 7 minutes.

3.5.5 Drying - Oven dry parts in a recirculating air oven at 150 to 160 F (66 to 71 C) for 30 to 60 minutes.

3.6 Acceptance Criteria for Surface Preparation

3.6.1 Anodize Thickness - The cleaned and anodized surface shall have minimum anodized thickness of 400 angstroms (A°) when tested in accordance with 4.6.3. The recommended maximum thickness is 800 angstroms (A°), but thicker oxides are acceptable if acceptable welds are achieved.

3.6.2 Surface Resistance - The cleaned and anodized surface shall have an average surface resistance of 200 to 1200 microhms when tested in accordance with 4.6.4.

3.6.3 Provisions for Recleaning

3.6.3.1 Parts may be recleaned if they become contaminated, are misprocessed, or fail to meet the requirements of 3.6.

3.6.3.2 If an error occurs in the anodizing process, the part may be reprocessed by rinsing, deoxidizing for 3 to 4 minutes, and then continuing through the normal procedure.

3.6.3.3 If parts become contaminated after anodizing or fail to meet the requirements of 3.6, they may be processed starting with the vapor degreasing in accordance with 3.5.1. However, deoxidizing times in accordance with 3.5.3 shall be reduced to three to four minutes.

3.7 Preparation for Welding

3.7.1 Part Handling and Storage

3.7.1.1 The cleaned and anodized parts shall be handled with clean cotton gloves. The surfaces to be bonded shall not be touched, even with the clean cotton gloves.

3.7.1.2 The paste adhesive shall be applied to the cleaned and anodized parts within 120 hours from the time they are anodized. Parts shall be maintained in a clean room atmosphere until the adhesive is applied. If transportation through any contaminated area is required prior to applying the adhesive, the parts shall be wrapped in acid-free kraft paper or placed in a protective container. The wrapped parts shall not be stacked and shall be handled only at the edges.

3.7.2 Adhesive Application

3.7.2.1 The adhesive, warmed to room temperature, shall be applied to both surfaces of the part to a sufficient film thickness to achieve a final glue line thickness of from 0.005 to 0.012 inch (0.13 to 0.30 mm). The adhesive shall be applied to the areas specified on the Engineering drawing.

3.7.2.2 The parts with adhesive applied shall be assembled within 4 hours of the application of the adhesive. If transportation of the assembled part to any contaminated area is required, the parts shall be wrapped in acid-free kraft paper or placed in a protective container.

3.7.3 Electrode Anti-Stick Application - Apply electrode anti-stick solution to exterior surfaces of assembled parts in the area that is to be welded.

3.8 Welding

3.8.1 Welding shall be performed using a certified weld schedule for the material and thicknesses being joined. The thickness combination of the production parts may vary from the certified weld schedule within the limits noted below, provided the certified nugget size average can be reproduced with a weld heat (current) setting that is within ± 10 percent for each cycle of the certified value, all other conditions being the same.

a. For outer sheets up 0.040 inch (1.02 mm) inclusive, the variation in thickness of either outer sheet is within ± 0.004 inch (0.10 mm) and the variation in the summed thickness of the combination is within ± 0.006 inch (± 0.16 mm).

b. For outer sheets over 0.040 inch (1.02 mm), the variation in thickness of either outer sheet is within ± 10 percent and the variation in the summed thickness of the combination is within ± 10 percent.

3.8.2 Welding shall be performed within 96 hours of the application of the adhesive to the parts.

3.8.3 Welding shall be discontinued and electrodes recleaned when electrode sticking occurs or when tip pickup exceeds the requirements of Table 3.

TABLE 3. VISIBLE EXTERNAL IMPERFECTIONS

Nature of Weld Imperfection	Acceptance Factor (1)
Cracks open to surface	0
Edge bulge cracks	0
Surface pits over 0.063 inch (1.60 mm) dia	0
Surface pits under 0.063 inch (1.60 mm) dia	0.03
Flash and surface fusion	0.03
Electrode pickup	0.02

NOTE: 1. The number of allowable visible imperfections is calculated by multiplying the acceptance factor times the number of welds inspected and raising any fractional number product to the next higher whole number.

3.9 Acceptance Criteria for Welds

3.9.1 Visual

3.9.1.1 Surface Indentation - The surface indentation shall not exceed 0.004 inch (0.10 mm) on aerodynamic surfaces and 0.10t (thickness of outer member) or 0.005 inch (0.13 mm), whichever is greater, for all other surfaces when measured on the surface of the part or determined by metallographic methods specified in 4.6.7.

3.9.1.2 External Imperfections - Other external imperfections shall not exceed the limits specified in Table 3.

3.9.1.3 Weld Location - All welds shall be located within ± 0.060 inch or ± 1.52 mm of the location specified on the Engineering drawing.

3.9.2 Radiographic - Certification welds, first article part welds, and when specified on the Engineering drawing, production part welds shall meet the following requirements:

3.9.2.1 Welds shall be free of cracks and cladding inclusions, and the fused zone of the weld shall be generally consistant in size and regular in shape.

3.9.2.2 No pore or incomplete fusion shall have a linear dimension greater than 0.15 times the nugget diameter.

3.9.2.3 Porosity or incomplete fusion shall not have an aggregate area of greater than 5 percent of the nugget area when seen in the plane of the radiograph.

3.9.2.4 Expulsion - Three percent of the welds may contain expulsion that does not exceed 50 percent of the area of the nugget, as viewed in the radiograph.

3.9.2.5 There shall be a weld at every location specified on the Engineering drawing.

3.9.3 Metallographic - The internal quality of the weld shall meet the following requirements, when tested in accordance with 4.6.7.

3.9.3.1 Nugget Size - The minimum nugget size shall be 0.100 inch (2.54 mm); see Sm, Figure 2.

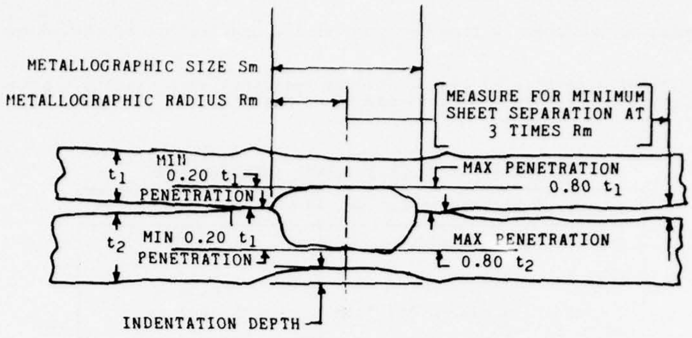


FIGURE 2. NOMENCLATURE FOR METALLOGRAPHIC SPOT WELD SECTIONS

3.9.3.2 Penetration - Penetration shall be measured at the center of the nugget and shall meet the following requirements:

a. Minimum Penetration - The minimum penetration shall be 0.20 times the thickness of the sheet for equal thickness combinations or 0.20 times the thickness of the thinner sheet for unequal thickness combinations.

b. Maximum Penetration - Penetration into each member shall not exceed 0.80 times the thickness of that member (Figure 2).

3.9.3.3 Sheet Separation - The separation of the sheet after welding shall not be less than 0.005 inch (0.127 mm) nor greater than 0.012 inch (0.305 mm) when measured at a distance (radius) of three (3) times the nugget diameter. See Figure 2.

3.9.3.4 Internal Imperfections - Welds shall be free of the following internal imperfections:

a. No nugget
b. Cracks
c. Imperfections exceeding 0.10 times the nugget diameter.

3.9.4 Mechanical Properties - The individual spot welds shall have a minimum weld strength exceeding the values given in Table 4, when tested in accordance with 4.6.6.

TABLE 4. MECHANICAL PROPERTY REQUIREMENTS FOR SPOT WELD SHEET SPECIMENS

Nominal Thickness of Thinner Sheet,		lb per spot	N per spot
inch	millimetres	minimum	minimum
0.020	0.50	140	625
0.022	0.55	160	710
0.025	0.65	185	825
0.028	0.70	215	955
0.032	0.80	260	1,155
0.036	0.90	305	1,355
0.040	1.00	345	1,535
0.045	1.10	405	1,800
0.050	1.30	465	2,070
0.050	1.40	555	2,470
0.063	1.60	670	2,980
0.071	1.80	825	3,670
0.080	2.00	1000	4,450
0.090	2.30	1000	4,450
0.100	2.50	1000	4,450
0.112	2.80	1000	4,450
0.125	3.20	1000	4,450

3.10 Adhesive Curing - The welded assembly shall be cured in an oven at 255 F ± 5 (124 C ± 3) for 2 to 3 hours. Thermocouples shall be used to verify that the proper curing temperature has been achieved. The cured part may be oven cooled or removed from the oven and air cooled.

3.11 Acceptance Criteria for Adhesive

3.11.1 The adhesive shall have a minimum strength of 4500 psi (31 MPa) when tested in accordance with 4.6.9.

3.11.2 The void and nonvoid (acceptable bond) areas shall be determined by testing in accordance with 4.6.10.

3.12 Facility Requirements - Subsequent to anodizing, all detail parts, test specimens, and assembled details shall be stored or assembled in an environmental controlled room that meets the following requirements.

3.12.1 The area shall be maintained under positive pressure differential at all times by a continuously operating air handling system. The following conditions shall apply:

a. Regular maintenance of filters
b. No eating or smoking in the area
c. Maintain records of the temperature and humidity of the controlled area
d. Vehicles permitted in the controlled area must be nonpolluting in operation, such as electrically or hand propelled
e. No process or operation which produces uncontrolled spray, dust, fumes, or particulate matter is permitted in the controlled area.

3.12.2 The temperature in the controlled area shall be 65 to 85 F (18 to 29 C).

3.12.3 The relative humidity in the controlled area shall be a maximum of 60 percent.

3.13 Qualification

3.13.1 Weld Machine

3.13.1.1 All welding machines used for welding to the requirements of this specification shall be qualified in accordance with 4.4.1 prior to performing production welding.

3.13.1.2 Requalification shall be required if the machine is rebuilt or if significant operational changes are made in it. A change of location within a plant, not involving a change in power source, or maintenance, or parts replacement does not necessitate requalification.

3.13.2 Weldbonding Process Qualification

3.13.2.1 Qualification shall be accomplished by making and testing the first assembly in accordance with the requirements of this specification and the Engineering drawing.

3.13.2.2 Requalification shall be performed when any of the processing procedures are changed.

3.14 Certification

3.14.1 Deoxidizer Solution - Each new deoxidizer solution shall be certified in accordance with 4.5 for:

a. Agitation - Etch rate

b. Surface cleanliness

c. Degree of etching.

3.14.2 Surface Prepartion Durability

3.14.2.1 The surface preparation system shall be certified to ensure that when the individual solutions are used together as a system, a surface will result that is cleaned, etched, and anodized to the requirements specified herein.

3.14.2.2 The certification of the surface preparation system shall be by performance of a durability test in accordance with 4.6.5.

3.14.2.3 Certification shall be performed prior to placing a new deoxidizer solution or anodize solution into production.

3.14.3 Weld Schedule

3.14.3.1 A weld schedule shall be established in accordance with 4.5.3 for each material combination and for each thickness combination to be welded in production.

3.14.3.2 A certified weld schedule shall be established by meeting all the requirements specified in 3.9.

3.14.3.3 The certified weld schedule shall be posted near the machine for which the schedule applies.

3.14.3.4 The weld schedule shall be recertified when:

a. Machine location change involves a change in power source

b. When the machine is rebuilt excluding replacement of parts and general maintenance

c. Process controls indicate machine is no longer meeting the requirements specified herein.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection

4.1.1 Unless otherwise specified on the contract or purchase order, the processing supplier shall be responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or purchase order, the supplier may use his own facilities or any commercial laboratory acceptable to the procuring activity. The procuring activity reserves the right to perform any or all of the inspections set forth herein where such inspections are deemed necessary to assure that the processing conforms to the prescribed requirements.

4.1.2 Inspection records shall be kept complete and available to the procuring activity in accordance with contract or purchase order. These records shall contain all data necessary to determine compliance with the requirements of this specification.

4.2 Inspection

4.2.1 Inspection shall verify that all the cleaning and anodizing tanks are within the requirements specified herein.

4.2.2 Inspection shall verify that all welding is performed using certified welding schedules.

4.2.3 All weldbonded parts shall be visually inspected to assure the parts are free of surface defects specified in 3.9.1.

4.3 Process Control

4.3.1 Solution Makeup and Control

4.3.1.1 Deoxidizer Solution Makeup - For each 100 gallons (378.5 litres)

a. Put approximately 50 gallons (189 litres) of deionized water in the tank.

b. Slowly add 13.0 gallons (49.1 litres) of nitric acid with gentle agitation.

c. Mix thoroughly.

d. Slowly add 19 pounds (8.6 kg) of Amchem 7 with gentle agitation.

e. Mix thoroughly.

f. Slowly add 1.13 litre of Alodine 45 with gentle agitation.

g. Mix thoroughly

4.3.1.1 (Continued)

h. Slowly add 1.33 litres of Alodine 1200E activator with gentle agitation.

i. Mix thoroughly.

j. Adjust solution to operating level with deionized water and mix thoroughly.

4.3.1.2 Control the Deoxidizer Solution Within the Following Limits:

a.	Nitric Acid Be 42 (70% HNO_3)	11 to 14 percent by volume
b.	Amchem 7	2.9 to 3.3 wt oz/gallon 21.7 to 24.7 g/litre
c.	Copper	2 ppm max
d.	Unagitated etch rate	0.2 to 0.3 mil/side/hour
e.	Temperature	70 to 80 F (21 to 27 C)

f. Provide constant filtering.

NOTES: 1. When chemical addition is required to maintain solution strength, Amchem 17 shall be added to maintain specific solution strength and etch rate requirements. Alodine 45 may be added as necessary to maintain required etch rate if Amchem 17 additions are not sufficient.

2. A higher deoxidizer temperature bath may be used if reduced immersion times are employed to achieve equivalent results.

4.3.1.3 Chemical Analysis and Etch Rate Determination of the Deoxidizer Solution - The chemical analysis of the deoxidizer solution shall be determined every other day or when chemical additions are made. The etch-rate shall be determined weekly. Necessary additions shall be made to the solution to maintain the solution within the limits of 4.3.1.2.

4.3.1.4 Deoxidizer Surface Cleanliness - The cleanliness and degree of etching of the deoxidized surface shall be determined each week in accordance with 4.6.2.

4.3.1.5 Anodize Solution Makeup - For each 100 gallons (378.5 litres)

a. Put approximately 50 gallons (189 litres) of deionized water in the tank.

b. Slowly add 135 fl oz (3.99 litres) of phosphoric acid (85 percent H_3PO_4).

c. Mix thoroughly.

d. Slowly add 140 oz (3.97 kg) of sodium dichromate dihydrate.

e. Mix thoroughly.

f. Adjust solution to operating level with deionized water and mix thoroughly.

4.3.1.6 Control the Anodize Solution Within the Following Limits:

a.	Phosphoric Acid (85 percent H_3PO_4)	1.2 to 1.5 fl oz/gallon (9.4 to 11.7 ml/litre)
b.	Sodium Dichromate Dihydrate	1.3 to 1.5 oz/gallon (9.7 to 11.2 g/litre)
c.	Temperature	70 to 80 F (21 to 27 C)

d. Provide constant filtering.

4.3.1.7 Chemical Analysis of the Anodizer Solution - The chemical analysis of the anodize solution shall be determined weekly or when chemical additions are made.

4.3.1.8 Anodize Thickness

a. The anodize thickness shall be determined on a test specimen processed in each new anodize solution.

b. The anodize thickness shall be determined each week on a separately processed test specimen or a sample taken from excess trim from a production part.

c. The anodize thickness shall be determined in accordance with 4.6.3.

4.3.1.9 Surface Resistance of Anodized Surface

a. The surface resistance shall be measured on a test specimen processed in each new anodize solution.

b. The surface resistance shall be measured on a test specimen processed with each production lot of anodized parts or on one production part from each production lot of anodized parts.

c. The surface resistance shall be measured in accordance with 4.6.4.

4.3.2 Welding - Production weld process control, as shown in Table 5, shall be as follows:

TABLE 5. PRODUCTION WELD PROCESS CONTROL SPECIMENS

Schedule	Number of Specimens	Examination
Preproduction	4	Visual, mechanical property, and metallography
Production	3	Visual and mechanical property
Post Production	4	Visual, mechanical property, and metallography

4.3.2.1 Preproduction - Four preproduction weld specimens shall be welded at the start of each work day or before a new production lot is welded or before welding is resumed after a machine shut down. The specimens shall be visually inspected and then 3 specimens tested for lap shear strength in accordance with 4.6.6 and one metallographically inspected in accordance with 4.6.7.

4.3.2.2 Production - Three production weld specimens shall be welded after an electrode change or other equipment change or at one hour intervals. The specimens shall be visually inspected and then tested for lap shear strength in accordance with 4.6.6.

4.3.2.3 Post Production - Four post production weld specimens shall be welded at the end of each production work day or after completion of a production lot if more than 1/2 hour has elapsed since the last production test was performed. The specimens shall be visually inspected. Three specimens shall then be tested for lap shear strength in accordance with 4.6.6. The remaining one shall be examined metallographically in accordance with 4.6.7 after the adhesive has been cured.

4.3.2.4 Welding Control Adjustment - The welding machine control settings may be varied from the certification settings by ± 6 percent on any one or a combination of more than one current settings. Air pressure settings may be varied ± 10 percent. Production specimens welded after the setting changes shall meet all the requirements of this specification.

4.3.3 Bond Verification - A minimum of one bond verification panel shall accompany each cure load during curing of the adhesive. The cured panel shall be tested in accordance with 4.6.9.

4.4 Qualification

4.4.1 Welding Machine - Qualification of the welding machine shall be performed in accordance with the qualification requirements of MIL-W-6858. Qualification may be performed using standard procedures that do not include the requirements for weldbonding.

4.4.2 First Assembly - The first assembly fabricated shall be examined as follows:

4.4.2.1 Visually inspect entire part to the requirements herein and on the Engineering drawing.

4.4.2.2 Radiographic inspect all the welds.

4.4.2.3 Inspect part for void areas in adhesive.

4.4.2.4 Dissect the part to obtain metallurgical sections through at least 5 percent of welds and examine.

4.4.2.5 Dissect the part to obtain at least 10 adhesive strength specimens.

4.4.2.6 Dissect the part to obtain at least two anodize thickness specimens.

4.5 Certification

4.5.1 Deoxidizer Solution

4.5.1.1 Determine the unagitated etch rate in accordance with 4.6.1.

4.5.1.2 Agitate the solution such that the agitated etch rate is between 2 and 3 times the etch rate of the unagitated solution. Fix the agitation at this rate.

4.5.1.3 Process two cleanliness samples in the agitated solution subsequent to degreasing and alkaline cleaning and examine in accordance with 4.6.2.

4.5.2 Surface Preparation Durability

4.5.2.1 Process two surface preparation durability assemblies (four detail parts) in each new deoxidizer solution or new anodize solution. Locate the assemblies on the process rack in such a position that they will represent the maximum upper and lower solution levels to which the production load details are exposed. The assemblies shall accompany the production details through all steps of the surface preparation process.

4.5.2.2 Test the surface preparation durability assemblies in accordance with 4.6.5.

4.5.3 Weld Certification

4.5.3.1 Weld certification shall consist of preparing 25 mechanical property specimens (50 details) using the same techniques as will be used on production parts, including cleaning, anodizing, adhesive application, and anti-stick material application.

4.5.3.2 Weld the 25 specimens and test as follows:

a. Visually inspect all 25 welded specimens.

b. Radiographically inspect all 25 welded specimens.

c. Lap shear test 20 of the specimens.

4.5.3.3 Metallographically examine the 5 remaining specimens.

4.6 Test Methods

4.6.1 Etch Rate - Deoxidize Solution - To determine the metal removal rate, use 7075-T6 bare aluminum specimens of at least 9 square inches (58 cm^2) in area (one side), and a gage of 0.020 to 0.063 inch (0.51 to 1.60 mm). Measure this gage with a micrometer, and weigh specimens before and after a measured immersion time (about 15 minutes) in the solution. Metal removal rate is determined with the solution in an unagitated condition. Calculate rate as follows:

$$\text{Metal removal rate, inches (mm)/surface/hour} = \frac{\text{weight loss}}{\text{original weight}} \times \text{gage-in. (mm)} \times \frac{30}{\text{minutes}}$$

4.6.2 Deoxidizer Surface Cleanliness

4.6.2.1 The material shall be the same nominal composition and thickness as the production part and shall be of convenient size for processing and examination.

4.6.2.2 The surface cleanliness and degree of etching shall be determined using a technique approved by the procuring activity. The use of the scanning electron microscope (SEM) has proven successful.

4.6.3 Anodize Thickness Measurement

4.6.3.1 The material shall be the same nominal composition and thickness as the production part and shall be of convenient size for processing and examination.

4.6.3.2 The anodize thickness shall be measured using a technique approved by the procuring activity. The use of the scanning electron microscope (SEM) has proven successful.

4.6.4 Surface Resistance Measurement - The surface resistance of the anodized parts shall be measured using surface resistance measuring equipment that is acceptable to the procuring activity and by the techniques specified by the equipment supplier.

4.6.5 Surface Preparation Durability

4.6.5.1 The surface preparation durability specimens shall be made from 0.125 inch (3.18 mm) thick 7075-T6 aluminum and shall have the configuration shown in Figure 3.

4.6.5.2 Clean and anodize the details using the same techniques used on production parts.

4.6.5.3 Apply adhesive and oven cure to achieve a bondline thickness of 0.005 to 0.012 inch (0.13 to 0.30 mm).

4.6.5.4 Machine or saw cut test panels into five one-inch (25.4 mm) wide specimens; see Figure 3.

4.6.5.5 Precrack the end containing the separator film by inserting a wedge as shown in Figure 3.

4.6.5.6 Locate and mark the tip of the initial crack.

4.6.5.7 Expose the wedged open specimens to 5 percent salt fog, in a chamber maintained at 95 F ± 5 (35 C ± 3).

4.6.5.8 After exposure for 24 hours ± 1, measure the increase in crack length resulting from the exposure. The crack shall not exceed 0.10 inch (2.5 mm) or the baths shall be termed unacceptable for further processing.

4.6.5.9 If the crack length does not exceed 0.10 inch (2.5 mm), re-install specimens in salt atmosphere for an additional 9 days.

4.6.5.10 After exposure for the additional 9 days, measure the increase in crack length resulting from the exposure. The crack shall not exceed 0.50 inch (12.7 mm) or the baths shall be termed unacceptable for further processing.

4.6.6 Mechanical Properties of Weld Certification, Preproduction, Production, Postproduction Specimens

4.6.6.1 Fabricate the specimens as shown in Figure 4 from material of the same composition and nominal thickness as the production parts to be welded.

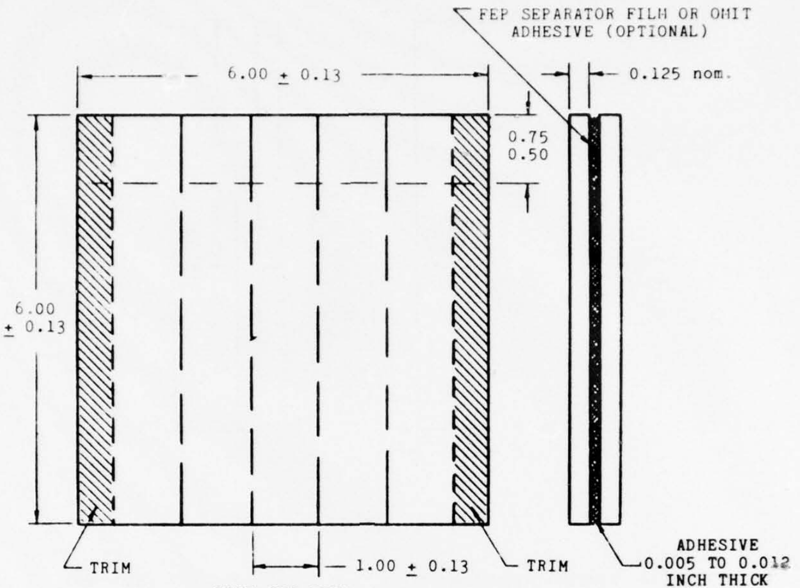
4.6.6.2 Clean, anodize, apply adhesive and anti-stick material using the same techniques as on production parts.

4.6.6.3 Weld the specimens together to form a lap shear specimen. Do not cure adhesive.

4.6.6.4 Tension test the lap shear specimens to failure and obtain a spot weld strength.

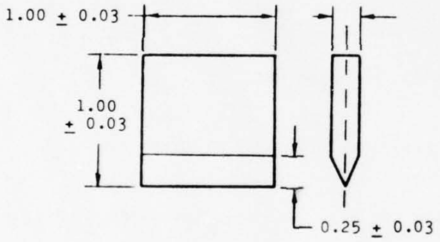
4.6.7 Weld Metallography Specimen

4.6.7.1 Fabricate the weld metallographic specimens by the same techniques and procedures used to fabricate the weld mechanical property specimens (4.6.6) except do not tension test.



FIVE ONE INCH
WIDE SPECIMENS

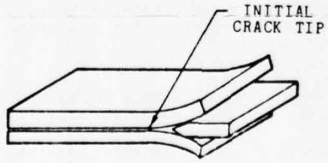
NOTE: ALL DIMENSIONS IN INCHES.



ALUMINUM OR CRES STEEL WEDGE

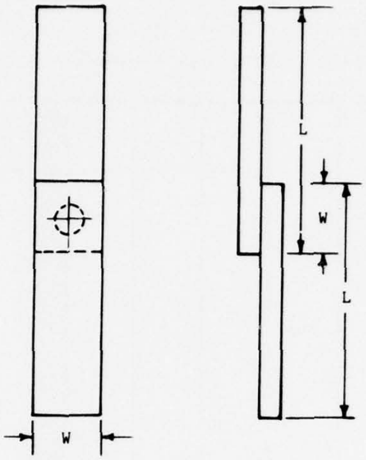
Conversion Key

inch	millimetre
0.005	0.13
0.012	0.30
0.03	0.8
0.13	3.3
0.25	6.4
0.50	12.7
0.75	19.0
1.00	25.4
6.00	152.4



WEDGED CRACK EXTENSION SPECIMEN - THE END AND SIDES
OF THE WEDGE SHALL BE APPROXIMATELY FLUSH WITH
SPECIMEN END AND SIDES

FIGURE 3. SURFACE DURABILITY SPECIMEN CONFIGURATION



NOTES: 1.

Nominal Thickness of Thinner Sheet, in.	W in., min	Nominal Thickness of Thinner Sheet, mm	W mm, min
Over 0.008 to 0.030,	0.68	Over 0.20 to 0.75,	17.0
Over 0.030 to 0.100,	1.00	Over 0.75 to 2.50,	25.0
Over 0.100 to 0.130,	1.25	Over 0.50 to 3.20,	32.0
Over 0.130	1.50	Over 3.20	38.0

2. L shall be not less than 4W.

FIGURE 4. SPOTWELD SPECIMEN

4.6.7.2 Metallographically section the weld such that the surface being examined is through the center of the weld.

4.6.7.3 Etch the metallographic specimen to reveal the weld nugget.

4.6.8 Radiographic Inspection - Radiographic inspection of the welds shall be performed using standard accepted techniques approved by the procuring activity.

4.6.9 Bond Verification

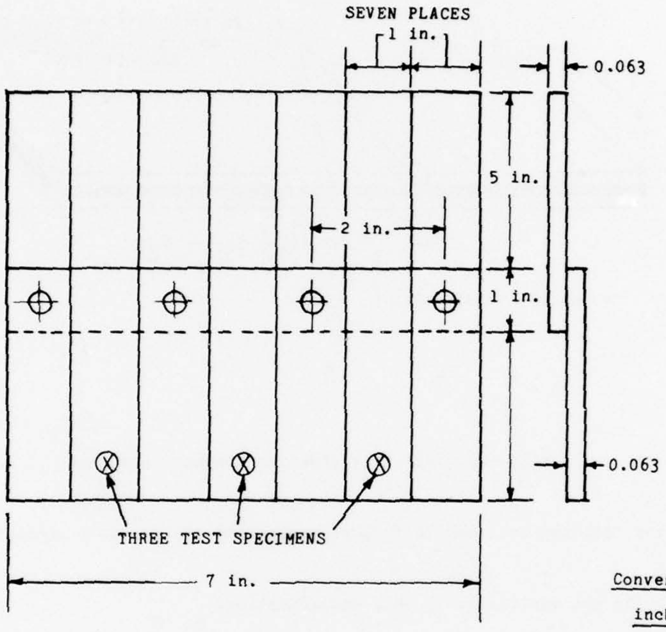
4.6.9.1 The bond verification panels shall be made from 0.063 inch (1.60 mm) thick 7075-T6 aluminum and shall have the configuration shown in Figure 5.

4.6.9.2 Clean, anodize, and apply adhesive using the same techniques used on production parts.

4.6.9.3 Cure the adhesive at the same time as the production part it represents.

4.6.9.4 Saw cut test panels into 3 adhesive bonded specimens. Testing of the weldbonded specimens is optional.

4.6.9.5 Tension test the specimens to failure at a rate of 0.030 to 0.035 inch per minute (0.76 to 0.89 mm per minute) and obtain adhesive strength.



Conversion Key

inches	mm
0.063	1.60
1	25
2	51
5	127
7	178

FIGURE 5. BOND VERIFICATION PANEL

4.6.10 Adhesive Void Determination

4.6.10.1 Use a technique that is normally used for inspection of adhesive bonded panels and that is approved by the procuring activity.

4.6.10.2 The levels of inspection of the bond, the probes to be used, and the acceptance readings shall be established for each specific assembly.

4.6.11 Assembly Adhesive Strength

4.6.11.1 Prepare the assembly adhesive strength specimen in accordance with Figure 6. There shall be no welds in the section of adhesive to be tested.

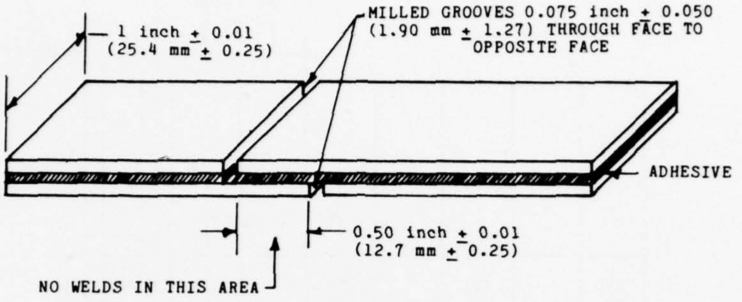


FIGURE 6. ASSEMBLY ADHESIVE STRENGTH SPECIMEN

4.6.11.2 Tension test the specimen to failure and obtain the adhesive strength.

5. PACKAGING

This section is not applicable to this specification.

6. NOTES

6.1 Intended Use - This specification is intended to establish the basic controlling factors in the weldbonding process through certification of weld schedules, designation of material combinations, methods of preparing materials, and for methods of process control in the weldbonding.

APPENDIX B

ADHESIVE SPECIFICATION

RESPONSIBLE ENGINEER
AIRCRAFT DIVISION
SPECIFICATION CONTROL
QUALITY CONTROL ENGINEER
PROJECT OFFICE

NORTHROP
Northrop Corporation
Aircraft Group - Aircraft Division
MATERIAL SPECIFICATION

XMS-WBA

DATE 23 February 1979
RELEASE EO ____________
CODE IDENT. NO 76823

TITLE: ADHESIVE, ALUMINUM WELDBOND
SERVICE RANGE -67 TO 180 F (-55 to 82 C)

(PROPOSED COMPANY SPECIFICATION)

1. SCOPE

1.1 This specification establishes the requirements for a modified epoxy adhesive to be used in conjunction with an aluminum spot-welding operation.

1.2 The modified adhesive system shall consist of a catalyzed one-part epoxy adhesive system containing selected fillers.

1.3 The service temperature of the cured material shall be -67 to 180 F (-55 to 82 C).

1.4 The customary units of measurement used herein are followed by converted metric units (and when applicable, calculated equivalent metric ratios), using International System (SI) units. Where appropriate in this specification, conversions are practical approximations.

2. APPLICABLE DOCUMENTS

2.1 The following publications of the issue in effect on the date of invitation for bids or request for proposal form a part of this specification to the extent specified herein.

2.1.1	ASTM D1002	Strength Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)
2.1.2	ASTM D1876	Peel Resistance of Adhesives (T-Peel Test)
2.1.3	QQ-A-250/12	Aluminum Alloy 7075, Plate and Sheet
2.1.4	QQ-A-250/5	Aluminum Alloy 2024 Alclad, Plate and Sheet
2.1.5	MIL-S-5002	Surface Treatments and Inorganic Coatings for Metallic Surfaces of Weapon Systems

3. REQUIREMENTS

3.1 Qualification

3.1.1 The adhesive furnished under this specification shall be a product that has been tested and has passed the qualification tests specified herein, and has been listed or approved for listing on the applicable Qualified Products List (QPL).

3.1.2 Subsequent to qualification, any change in the chemical make-up of the adhesive or method of manufacture shall require requalification of the adhesive.

3.2 Quality - The adhesive shall be of uniform quality and free from lumps and foreign matter.

3.3 Composition - The composition of the adhesive shall be as follows:

	Percent
Base Epoxy Resin (1-part system)	90 ± 0.8
Strontium Chromate (filler)	3 ± 0.3
Cab-O-Sil (filler)	7 ± 0.5

3.4 Physical Properties

3.4.1 Viscosity - The viscosity of the adhesive system shall be a maximum of 2,000,000 centipoises at room temperature, when tested in accordance with 4.5.2.

3.4.2 Volatile Content - The volatile content of the resin system shall not exceed 0.2 percent when tested in accordance with 4.5.3.

3.4.3 Filler Content - The filler content shall meet the requirements of 3.3 when tested in accordance with 4.5.4.

3.4.4 Adhesive Flow - The adhesive shall exhibit flow characteristics of a minimum of 1 inch (25 mm) and a maximum of 3 inches (76 mm) when tested in accordance with 4.5.5.

3.4.5 Degree of Cure - The adhesive shall fully cure when heated to 255 F ± 5 (124 C ± 3) for sixty minutes in a preheated recirculating air oven when tested in accordance with 4.5.6.

3.5 Mechanical Properties - The adhesive shall conform to the mechanical property requirements listed in Table 1.

TABLE 1. MECHANICAL PROPERTY REQUIREMENTS

Test Identification	Requirement, Room Temperature	Test Method
Lap Shear Strength, adhesive bond or weldbond, RT, psi (MPa)	4500 (31.0) minimum	4.5.7
T-Peel Strength, RT, P/IW (N/m)	20 (3502) minimum	4.5.8

3.6 Durability of Adhesive - The maximum crack extension after 24 hours exposure to a 5 percent salt fog solution at 95 F (35 C) shall be 0.1 inch (2.5 mm) and after 10 days exposure shall be 0.5 inch (12.7 mm) when tested in accordance with 4.5.9.

3.7 Storage - The adhesive shall meet the requirements of this specification when stored in its original unopened container at 0 F (-18 C), or lower, for 6 months from date of manufacture.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility For Inspection

4.1.1 Unless otherwise specified on the contract or purchase order, the supplier of the material shall be responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or purchase order, the supplier may use his own facilities or any commercial laboratory acceptable to the procuring activity. The procuring activity reserves the right to perform any or all of the inspections set forth herein where such inspections are deemed necessary to assure that the material conforms to the prescribed requirements.

4.1.2 Inspection records shall be kept complete and available to the procuring activity in accordance with the contract or purchase order. These records shall contain all data necessary to determine compliance with the requirements of the specification.

4.2 Sampling

4.2.1 Lot - A lot is defined as all the material produced in a single production run submitted for delivery at one time.

4.2.2 Sample Size - Three samples shall be taken, one from each of 3 containers selected at random from each lot. Each sample shall comprise sufficient material for performance of the tests specified in 4.5.

4.3 Classification Of Tests

4.3.1 Qualification - Qualification shall include all examination and testing necessary to determine compliance with 3.2 through 3.6.

4.3.2 Acceptance - Standard acceptance tests for each lot of adhesive shall consist of the following:

a. Visual examination in accordance with 4.5.1

b. Viscosity in accordance with 4.5.2

c. Volatiles in accordance with 4.5.3

d. Filler content in accordance with 4.5.4

e. Adhesive flow in accordance with 4.5.5

f. Room temperature lap shear strength in accordance with 4.5.7

g. T-peel strength in accordance with 4.5.8.

4.3.3 Additional Acceptance Tests - The following additional acceptance tests shall be required when specified on the purchase order by the procuring activity:

a. Degree of cure in accordance with 4.5.6

b. Wedge crack extension test in accordance with 4.5.9.

4.4 Surface Preparation - All aluminum parts used for tests in 4.5 shall be cleaned and anodized in accordance with the following procedure.

4.4.1 Vapor Degrease

4.4.1.1 Vapor degrease in 1,1,1 trichloroethane vapor (MIL-S-5002). Suspend the parts in the vapor zone of the degreaser for a minimum of 60 seconds followed by spray rinse of condensed trichloroethane fluid for an additional 60 seconds.

CAUTION: The following shall be observed in vapor degreasing:

1. Parts shall be completely free of moisture before immersion in the degreaser.
2. The rate of immersion and withdrawal from the degreaser shall be slow enough to prevent vapors from rising above the cooling coils. The immersion and withdrawal rate shall not exceed 11 feet (3.35 metres) per minute.
3. The end of the spray nozzle shall be used only below the surface of the vapors. Never spray above the tank.
4. Never use compressed air to dry parts in the vapor degreaser.
5. Maintain solvent acid range from 0.03 to 0.17 percent by weight.

4.4.1.2 Remove the parts from the degreaser and allow to cool for 2 minutes, minimum.

4.4.1.3 Repeat the degreasing process once in accordance with 4.4.1.1 and 4.4.1.2.

4.4.2 Alkaline Clean

4.4.2.1 Immerse degreased parts in an alkaline cleaning solution consisting of 6 to 8 ounces per gallon (45 to 60 g/litre) of Turco 4215-S. Immersion shall be for 12 to 15 minutes with the solution temperature at 145 to 165 F (63 to 74 C).

4.4.2.2 Immediately spray rinse in a cold deionized water spray for 5 to 7 minutes. The parts shall be positioned so that all surfaces are exposed to the spray and are sufficiently flushed. The parts shall pass a water-break inspection after the rinsing operation. Parts shall be considered to pass the water-break inspection if, after completion of rinsing, the surface will maintain a continuous film of water for 30 seconds. Parts which fail the water-break inspection shall be reprocessed in accordance with 4.4.2 until the parts pass the water-break inspection.

4.4.3 Deoxidize

4.4.3.1 Immerse alkaline cleaned parts in a deoxidizer solution prepared in accordance with the instructions of Table 2. Immersion shall be for 6 to 8 minutes in a room temperature agitated solution. Parts and hanging brackets shall be suspended in the tank so that they do not make metal-to-metal contact with the tank.

TABLE 2. DEOXIDIZER MAKE-UP SOLUTION (1)

Material	Concentration
Nitric Acid, 42 Be' 70 percent HNO_3	11 to 14 percent by volume
Amchem 7	2.9 to 3.3 wt oz/gallon (21.7 to 24.7 g/litre)
Alodine 45	11.2 to 11.5 ml/gallon solution (2.95 to 3.03 ml/litre)
Alodine 1200E Activator	13.2 to 13.4 ml/gallon solution (3.47 to 3.53 ml/litre)
Deionized Water	Balance

NOTE: 1. When chemical addition is required to maintain solution strength, Amchem 17 shall be added to maintain specified solution strength, and etch rate requirements. Alodine 45 may be added as necessary to maintain required etch rate at the required level of 0.20 to 0.30 mils/side/hour (unagitated bath) if Amchem 17 additions are not sufficient.

4.4.3.2 Immediately spray rinse in cold deionized water spray for 5 to 7 minutes. The inclusion of tap water for the first 1 to 2 minutes of rinse to minimize staining on alclad material is acceptable.

4.4.4 Anodize

4.4.4.1 Immediately immerse and anodize for 20 ± 2 minutes in an anodizing solution prepared in accordance with the instructions shown in Table 3. Anodizing shall be conducted in a room temperature solution using a "ripple-free" DC power supply using the anodize voltages listed in Table 4. Neither the part nor the hanging bracket shall make metal-to-metal contact with anodizing tank (voltage will read zero if this occurs).

TABLE 3. ANODIZING MAKE-UP SOLUTION

Material	Concentration
Phosphoric Acid, 85 percent H_3PO_4	1.2 to 1.5 fl oz/gallon (9.4 to 11.7 ml/litre) solution
Sodium Dichromate Dihydrate	1.3 to 1.5 oz/gallon (9.7 to 11.2 g/litre) solution
Deionized Water	Balance

TABLE 4. ANODIZING REQUIREMENTS

Alloy	Voltage	Time, minutes
7075-T6 Bare	1.5 ± 0.1	20 ± 2
2024-T3 Alclad	1.0 + 0.1	

4.4.4.2 Immediately spray rinse in cold deionized water spray for 5 to 7 minutes.

4.4.4.3 Oven dry for 30 to 60 minutes at 150 to 160 F (66 to 71 C).

4.4.5 Handling After Surface Preparation

4.4.5.1 Cleaned parts shall be handled only with clean white cotton gloves. The surface to be bonded shall not be touched even with clean white cotton gloves.

4.4.5.2 Cleaned and dried parts may be stored in an environmentally controlled area for periods of up to 14 days prior to bonding by wrapping them in chemically neutral paper.

4.4.5.3 Parts shall be wrapped with clean brown Kraft paper for transportation to other areas.

4.4.5.4 No reworking or metal removal shall be permitted of cleaned or anodized surfaces without provisions for recleaning.

4.5 Test Methods

4.5.1 Examination - The material shall be visually inspected for compliance with the requirements of 3.2.

4.5.2 Viscosity - The adhesive viscosity shall be determined with a Brookfield RVT Viscosimeter, No. 6 spindle at 10 RPM (or equal equipment) and at 75 F ± 2 (24 C ± 1) after stabilization at this temperature for a minimum period of 2 hours. The average of three readings from one sample shall be reported and meet the requirements of 3.4.1.

4.5.3 Volatile Content - Weigh three samples of 1 gram ± 0.2 each in three dry tared ceramic crucibles. Weighing accuracy shall be ± 0.001 gram. The crucibles shall then be placed in a forced air circulating oven at 250 F ± 5 (121 C ± 3) for 1 hour. Remove from the oven, cool in a desiccator, and reweigh when the specimens are at room temperature.

Calculate the percent volatile content as follows:

$$\text{Percent Volatile Content} = \frac{W_2 - W_3}{W_2 - W_1} \times 100$$

Where: W_1 = Weight of crucible (dry)

W_2 = Weight of crucible plus sample

W_3 = Weight of crucible plus sample after drying

4.5.4 Filler Content

4.5.4.1 Total Filler Content - Use the samples from the determination made in 4.5.3. Heat crucibles and samples in a muffle furnace for 2 hours at 1500 F (816 C). The resin will be burned off and the residue will be Cab-O-Sil and strontium chromate. Remove crucibles from furnace, let cool in air until they reach 200 F (93 C) or below. Place in desiccator and cool to room temperature. Weigh crucibles and contents.

Calculate the percent filler as follows:

$$\text{Percent filler} = \frac{W_4 - W_1}{W_2 - W_1} \times 100$$

Where: W_4 = Weight of crucible plus contents after burnoff

4.5.4.2 Identification of Cab-O-Sil and Strontium Chromate by Infrared Spectrometry

a. Mix 0.8 mg of the inorganic solids residue from one of the crucibles from 4.5.4.1 with 250 mg of dried infrared grade potassium bromide powder in a mortar and pestle until the sample is evenly mixed throughout the potassium bromide [an agate mortar about 2 inch (51 mm) diameter and an agate pestle about 0.75 inch (19.0 mm) diameter is adequate]. Pour the total mixture into a potassium bromide pellet press (Perkin-Elmer Model No. 1, Part Number 186-0025). Press the mixture to a clear disc by applying 8 to 20 tons per square inch (110 to 276 MPa) for five minutes at room temperature. Place the pellet in the infrared pellet holder and insert into the infrared spectrophotometer (Perkin-Elmer Model No. 457). Determine the infrared absorption over the wavelength region from 1400 to 300 wavenumbers.

b. Infrared Characteristics of Inorganic Solids

1. Strontium Chromate - A multiple of sharp peaks in the 930 to 840 wavenumber region. Pronounced peaks appear at 908 and 840 wavenumbers (Figure 1).

2. Cab-O-Sil - Strong broad bands at 1100 and 465 wavenumbers (Figure 2).

4.5.4.3 Strontium Chromate and Cab-O-Sil Content - The strontium chromate and Cab-O-Sil contents shall be determined by either the following or other equivalent chemical analytical techniques.

a. Strontium Chromate Content - Transfer the solids from each of the two remaining crucibles referenced in 4.5.4.1 into two 250 millilitre beakers. Add 50 millilitres distilled water and 20 millilitres of concentrated hydrochloric acid. Swirl or stir until the colored solids dissolve; colloidal Cab-O-Sil should remain suspended but not dissolved. Add 5 millilitres of potassium iodide solution (250 grams KI per litre), swirl and allow to stand for 3 minutes. Titrate with 0.1 N sodium thiosulfate to a straw color. Add 3 millilitres of starch indicator. Continue the titration until the blue color just disappears. Calculate the percent strontium chromate as follows:

$$\text{Percent } SrCrO_4 = \frac{0.00678 \times \text{ml of } 0.1 \text{ N } Na_2S_2O_3 \times 100}{W_2 - W_1}$$

b. Cab-O-Sil Content - The Cab-O-Sil content is determined as the difference between the percent total inorganic solids (4.5.4.1) and the percent strontium chromate (4.5.4.3a).

Percent Cab-O-Sil = % Filler - % $SrCrO_4$

4.5.5 Adhesive Flow - The adhesive flow shall be determined by fabricating test specimens to the configuration shown in Figure 3. The specimens shall be cleaned and anodized in accordance with 4.4. Four spot welds shall be placed in the sample thereby controlling the adhesive bond line thickness to 0.010 inch ± 0.002 (0.25 mm ± 0.05). The specimen shall be cured by placing the specimen in a vertical position in a cold recirculating air oven and heating to 255 F ± 5 (124 C ± 3) within 30 minutes [use a heating rate of 8 to 10 F per minute (4 to 6 C per minute)]. Adhesive flow shall be measured on the specimen using a scale readable to ± 0.1 inch (2.5 mm) and shall meet the requirements of 3.4.4.

4.5.6 Determination of Degree of Cure - The degree of cure of the adhesive using the standard cure cycle of 1 hour at 255 F ± 5 (124 C ± 3) will be determined by differential scanning calorimetry (DSC). A 20 to 30 mg sample is placed in the aluminum cup and cured in an oven for 1 hour at 255 F ± 5 (124 C ± 3). The cup is then placed in the DSC cell and analysed. If complete cure has been obtained, there will be no peaks between 248 and 356 F [(120 and 180 C) Figure 4]. The maximum peak allowed between 248 and 356 F (120 and 180 C) shall be 0.10 millicalories/second. The experimental conditions of the DSC analysis are summarized in Table 5.

4.5.7 Lap-Shear Strength Test

4.5.7.1 Test specimens shall be fabricated to the configuration shown in Figure 5. Specimens may be fabricated either by weldbonding or by adhesive bonding. Material shall be 0.063 inch (1.60 mm) 7075-T6 bare aluminum (QQ-A-250). Five specimens shall be machined for test from a bonded panel made from two 5 by 6 inch (127 by 152 mm) sheets. The 5 inch (127 mm) dimension shall be in the roll direction of the aluminum sheet. The surface preparation shall be in accordance with 4.4.

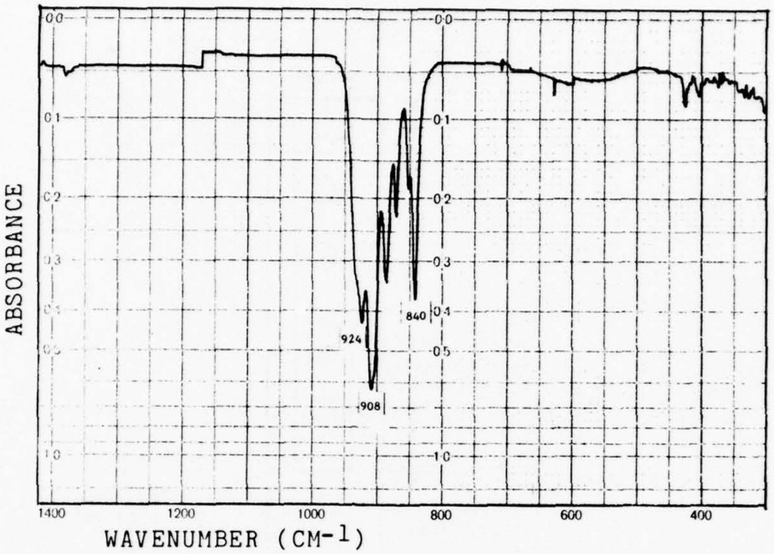


FIGURE 1. INFRARED SPECTRUM OF STRONTIUM CHROMATE

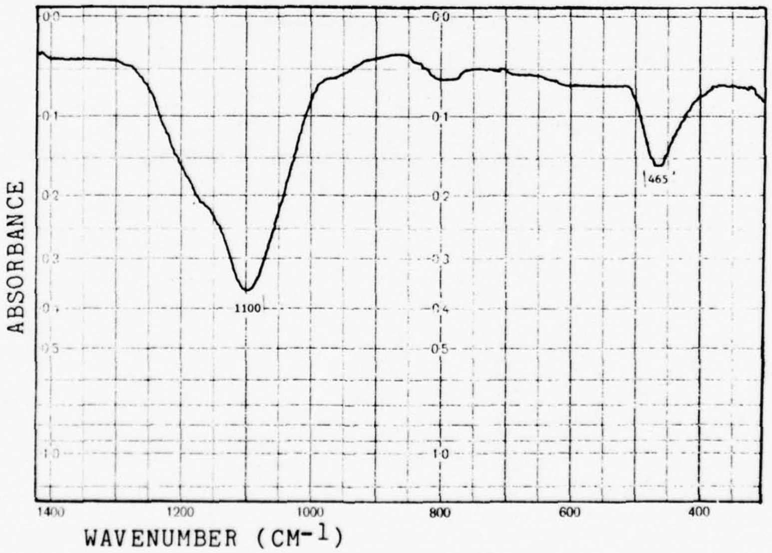


FIGURE 2. INFRARED SPECTRUM OF CAB-O-SIL

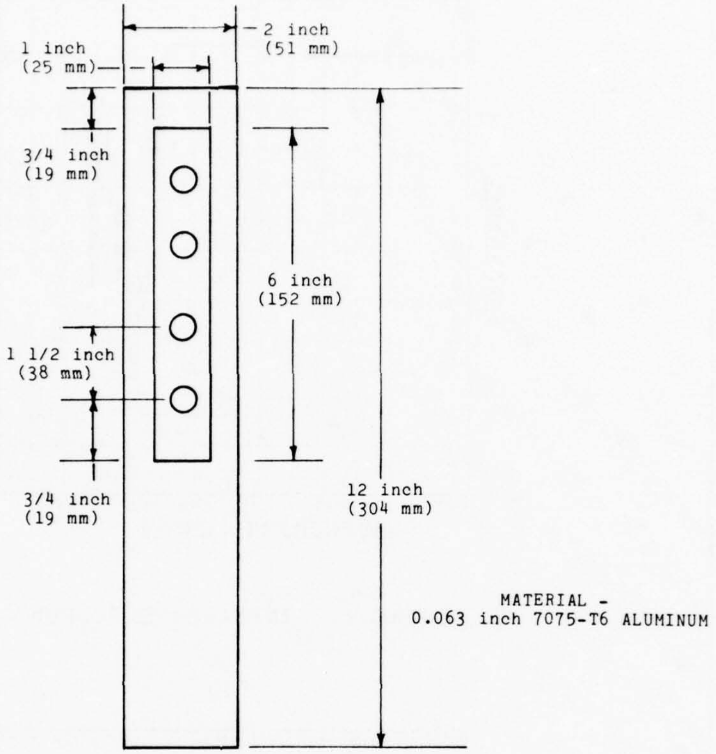


FIGURE 3. CONFIGURATION OF ADHESIVE FLOW TEST

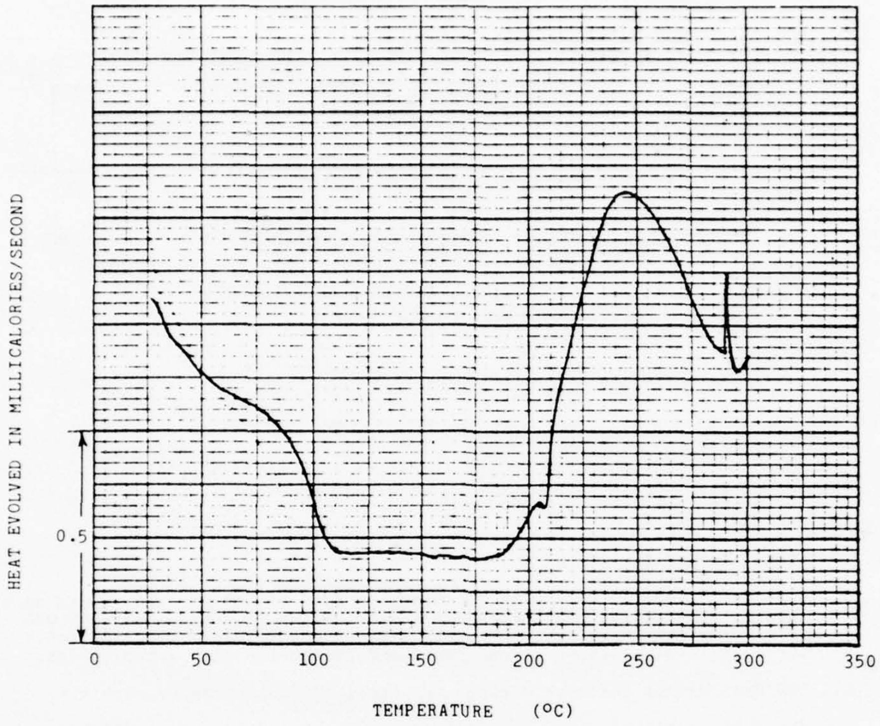


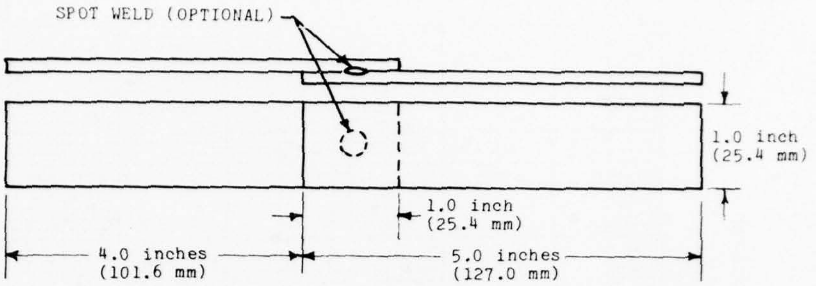
FIGURE 4. DSC CURVE FOR CURED A1444B ADHESIVE

TABLE 5. EXPERIMENTAL CONDITIONS OF DSC ANALYSIS

Instrument Parameters		Sample Requirements
Temperature Range	RT to 300 C (RT to 572 F)	Sample size: 20 to 30 mg
Heat up rate	10 degrees/minute	Sample container: open aluminum cup
Dial Setting	0.5 mcal/sec-in.	Sample reference: empty aluminum cups
Gas Flow	Nitrogen-0.4 ml/minute	

4.5.7.2 When welding, specimens shall be welded on 1.1 inch (27.9 mm) centers to form five 1 by 9 inch (25.4 by 229 mm) lap-shear test specimens when cut.

4.5.7.3 Place panel in a hot circulating air oven at 255 F ± 5 (124 C ± 3). Cure panel for 60 minutes. Cool panel to room temperature and cut panel into one inch (25.4 mm) wide lap shear test specimens.



7075-T6 BARE ALUMINUM ALLOY SHEET
THICKNESS - 0.063 inch (1.60 mm)

FIGURE 5. LAP-SHEAR TEST SPECIMEN

4.5.7.4 Specimens shall be tested at room temperature as specified in ASTM D1002 for adhesive-bond lap-shear tensile strength.

4.5.8 T-Peel Strength Test

4.5.8.1 Test Panel Preparation

a. Test panels shall conform to the dimensions of Figure 6. They shall be made from 2024-T3 Alclad aluminum sheet (QQ-A-250), 6.750 by 12.000 by 0.020 inches (171.45 by 304.80 by 0.51 millimetres). Five specimens, one inch (25.4 mm) wide, shall be prepared as one panel and tested for each adhesive lot.

b. The test panels shall be cleaned and anodized in accordance with 4.4.

c. No primer shall be used. The adhesive shall be applied by roller or by spatula to both sheets making up a panel. Adhesive thickness shall be 0.008 inch ± 0.002 (0.20 mm ± 0.05).

4.5.8.2 Cure Panel - Specimens shall be cured in an oven with contact pressure of 0.5 psi (3.45 kPa) at 255 F ± 5 (124 C ± 3). Heating rate of panel in oven shall be 8 to 10 F (4.4 to 5.6 C) per minute. The panel will be cured for 60 minutes after 255 F (124 C) oven temperature is achieved.

4.5.8.3 Test Procedure (ASTM D1876)

a. All peel testing shall be done at room temperature.

b. Clamp the bent, unbonded ends of the test specimen into the jaws of a test machine with self-aligning jaws and apply the load at a rate of 3 inches (76 mm) per minute; separation of the bond will then be 1.5 inch (38 mm) per minute. Record the load versus distance peeled and determine the "T" peel strength over at least a 5 inch (127 mm) length of bondline after the initial peak.

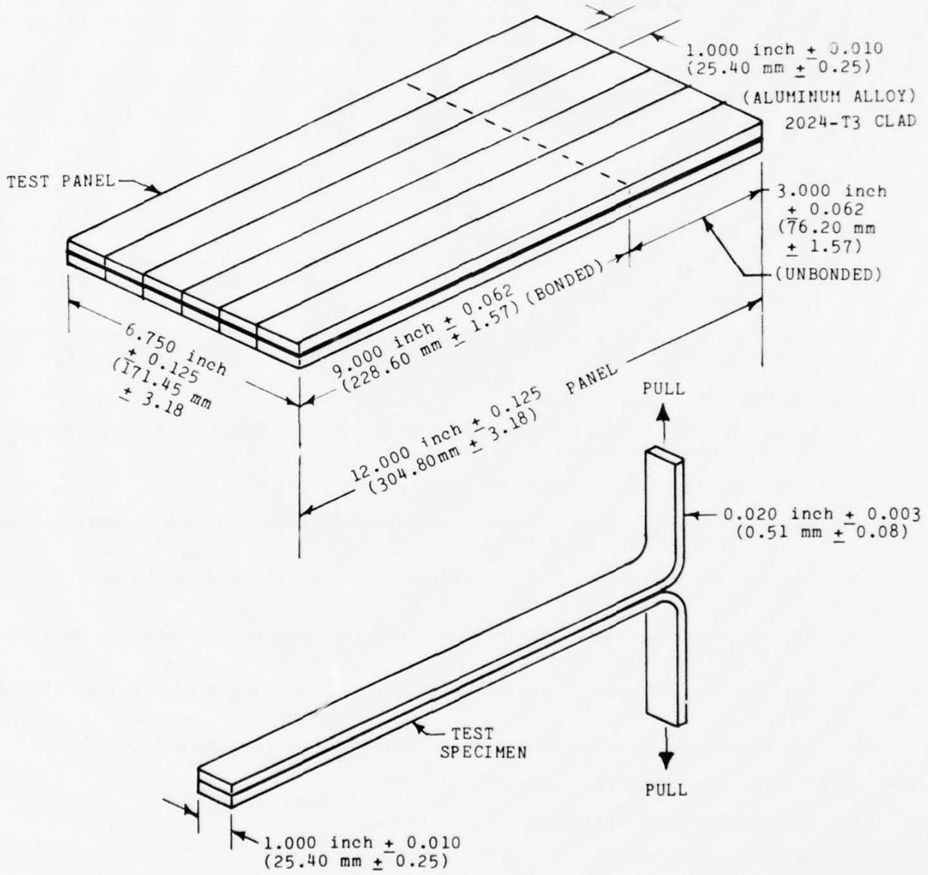


FIGURE 6. T-PEEL PANEL AND SPECIMENS

4.5.9 Wedge Crack Extension Test

4.5.9.1 Test Panel Preparation

a. The test panel shall be prepared from two 0.125 by 6 by 6 inch (3.18 by 152 by 152 mm) 7075-T6 bare aluminum sheets (QQ-A-250). Wedges shall be machined from 0.125 inch (3.18 mm) 7075-T6 bare aluminum sheet. Both items shall conform to the basic dimensions of Figure 7. Five individual test specimens, 1 by 6 inch (25.4 by 152 mm), shall be machined from the bonded test panel for evaluation. The edges of all test specimens shall be milled; shear edges are not acceptable.

b. The test panel shall be cleaned in accordance with 4.4.

c. The adhesive shall be applied to a thickness of 0.008 inch ± 0.002 (0.20 mm ± 0.05) by roller or spatula to each surface of the test panel. Control the adhesive thickness by the insertion of aluminum shims along the trim part of the test panel. Do not extend the shim beyond the trim (Figure 7).

d. The test panel shall be cured in an oven using a contact pressure of 0.5 psi (3.45 kPa) at 255 F ± 5 (124 C ± 3). Heating rate of panel in oven shall be 8 to 10 F (4.4 to 5.$\bar{6}$ C) per minute. The panel will be cured for 60 minutes after 255 F (124 C) oven temperature is achieved.

e. The cured adhesive shall have a thickness of 0.005 to 0.012 inch (0.13 to 0.30 mm).

4.5.9.2 Specimens from Test Panel

a. Machine or saw cut test panel into five one inch (25.4 mm) wide specimens as shown in Figure 7. Identify all test specimens and their location in the original 6 by 6 inch (152 by 152 mm) test panel.

b. Use a table saw with sharp blade to cut specimens and exercise extreme care in sawing to avoid chatter or overheating which could damage the adhesive bond.

4.5.9.3 Test Procedure

a. Precrack the end of each specimen containing the separator film by inserting a wedge as shown in Figure 7.

b. Locate and mark the tip of the initial crack.

c. Expose the wedged open specimens to 5 percent salt fog in a chamber maintained at 95 F (35 C) for 24 hours.

d. Measure the increase in length of the crack resulting from the salt-fog exposure.

e. Return the wedged open specimens to salt fog chamber and continue exposure for an additional 9 days.

f. Measure the increase in length of the crack resulting from the total 10 day exposure.

g. Split the specimens apart and observe mode of failure in bondline.

4.5.9.4 Record the information as follows:

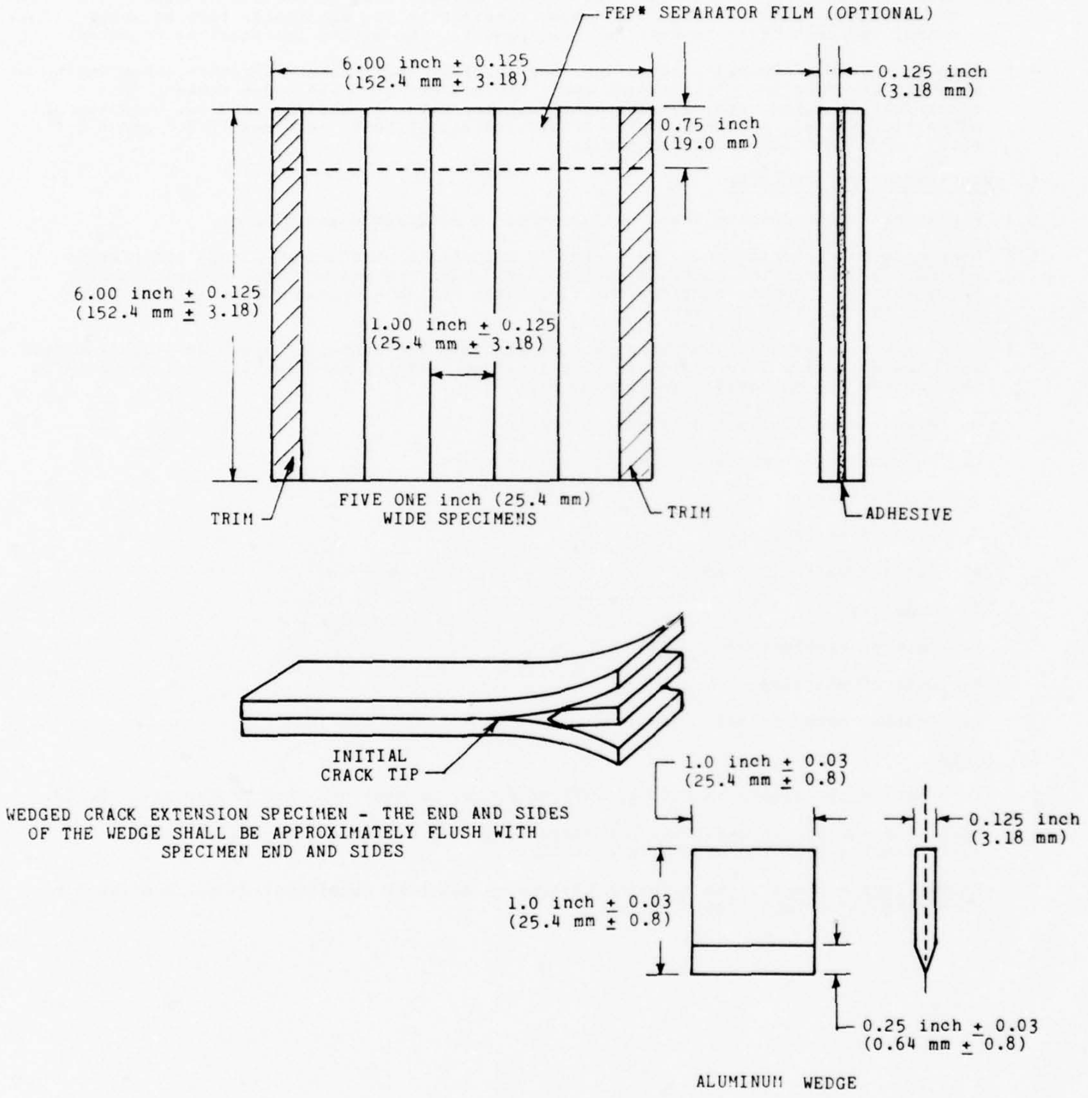
a. Average bondline thickness

b. Initial crack length

c. Crack length after 24 hour exposure

d. Crack length after 10 day exposure

e. Estimate percent and mode of failure, such as cohesive (failure within the adhesive), adhesive (adhesive separation from metal surface), or void (lack of contact during bonding).



WEDGED CRACK EXTENSION SPECIMEN - THE END AND SIDES OF THE WEDGE SHALL BE APPROXIMATELY FLUSH WITH SPECIMEN END AND SIDES

ALUMINUM WEDGE

FIGURE 7. STANDARD WEDGE TEST PANEL AND COUPON

*FEP - Fluorinated Ethylene Propylene Release film or equivalent.

4.6 Rejection

4.6.1 Any material not conforming to the requirements of this specification shall be rejected.

4.6.2 Material rejected in accordance with 4.6.1 may be retested once. For retest, the number of specimens shall be twice the number required by the applicable test methods. If any retest specimen fails to meet the requirements, the entire lot shall be rejected.

4.7 Reports - Unless otherwise specified, the supplier shall submit a report accompanying each shipment of adhesive. This report shall include the purchase order number, this specification number and revision, the supplier material designation, the quantity of material supplied, and the results of all individual tests required in 3.4 and 3.5 for each lot of material in the shipment.

5. PREPARATION FOR DELIVERY

5.1 Packaging - The adhesive shall be furnished in reclosable metal cans.

5.2 Packing - The material shall be packed in shipping containers of a type which shall adequately protect the contents during normal handling and meet the minimum packing requirements of common carriers for acceptance and safe transportation at the lowest rate to the point of delivery.

5.3 Marking - Each exterior shipping package and interior container shall be legibly marked with the following information in such a manner that the markings will not smear or be obliterated during normal handling or use:

a. Procuring activity specification number

b. Purchase order number (exterior package only)

c. Manufacturer

d. Product designation

e. Lot (or batch) number

f. Quantity

g. Date of manufacture

h. Date of shipping

i. Caution note (in red): Ship and store at or below 0 F (-18 C)

6. NOTES

6.1 Information pertaining to this specification may be obtained from procuring activity.

6.2 Suppliers may obtain information pertaining to, or additional copies of, this specification from the procuring activity.

6.3 Equivalency - There is no existing Government material specification which meets the requirements of this specification.

APPENDIX C

ANALYTICAL CONTROL PROCEDURES FOR SURFACE PREPARATION

The following laboratory test procedures were developed to control the cleaning and anodizing of aluminum parts for weldbonding. Procedures are given for the following steps in the process:

DEGREASE	1,1,1-Trichloroethane
ALKALINE CLEAN	Turco 4215-S
DEOXIDIZE	Amchem 7/nitric acid
ANODIZE	Phosphoric acid/sodium dichromate

1. DEGREASE - 1,1,1-Trichloroethane
(Reference Northrop; Process Specification; C-15, Revision B, page 4, 1/24/75)

1.1 Procedure - Acid Acceptance Analysis

1.1.1 The 1,1,1-trichloroethane shall be maintained with an acid acceptance range of 0.03 to 0.27 percent by weight.

1.1.2 The 1,1,1-trichloroethane shall be analyzed and maintained in the range specified.

1.1.3 The following analysis procedure is recommended:

a. Pipette exactly 15 ml of the sample into a 125 ml Erlenmeyer flask.

b. Add exactly 35 ml of standard (0.03 ± 0.002N) hydrochloric acid/ methanol solution.

c. Reflux the mixture for 5 minutes under a water-cooled condenser.

d. Cool and add 25 ml of distilled water through the reflux condenser.

e. Add 1 ml of phenolphtalein indicator solution and titrate with standard 0.1N-NaOH to a pink end point.

f. Calculate percent acid acceptance as NaOH.

1.2 Calculation

Acid acceptance (as NaOH): percent by weight = 0.02 x ml of 0.1N-NaOH.

1.3 Specification

Acid acceptance (as NaOH): 0.03 to 0.27 percent by weight.

1.4 Control of the Degreaser

1.4.1 Drain the water separator at least once a day and assure that it is functioning properly.

1.4.2 Clean out and recharge the 1,1,1-trichloroethane degreaser when any of the following conditions occur:

a. The acid acceptance drops below 0.03 percent by weight of NaOH.

b. The temperature in the sump exceeds 175F, indicating excessive contamination.

c. The solvent in the sump does not boil vigorously indicating excessive resinous residue on the heating coils or excessive metal chips or fines.

1.5 Reagents

1. 0.03 ±0.002N-HCl, Hydrochloric acid/methanol solution.
2. 0.1N-NaOH.
3. Phenolphthalein indicator.
4. Distilled water.

1.6 Equipment

Standard laboratory glassware and stirrers.

1.7 Cleaning of Degreaser

1.7.1 Begin distillation of solvent from sump or boiling chamber, collecting the distillate in the storage tank or in clean drums. Continue the distillation until the temperature of the boiling solvent reaches 183F.

1.7.2 In cases where cleaning of the degreaser unit has been initiated due to an acid condition (decomposition) of the solvent, add a large excess of soda ash to the boiling chamber to neutralize the acid before distillation is started. In addition, after distillation has been completed, all interior portions of the unit, including tank, sump, lines, and valves shall be cleaned and neutralized with 5 percent soda ash solution. These areas shall be thoroughly dried prior to recharging.

1.7.3 Remove the remaining solvent and discard in a manner approved by the Safety Engineer.

1.7.4 Remove all dirt, sludge, metal chips and other foreign materials from the tank and sump.

2. ALKALINE CLEANER ANALYSIS - Turco 4215-S

(Reference, Northrop Lab Test Procedure 7.10, page 1, 6/26/69)

This procedure is used to control the concentration of the alkaline processing solution by determination of total alkalinity.

2.1 Procedure

2.1.1 Pipette exactly 25 ml of the sample of the Turco 4215-S solution into a 250 ml beaker and add approximately 50 ml of DI water.

2.1.2 Titrate with 0.5N HCl to an end-point of pH 5.4 using a pH meter.

2.2 Calculations

Turco 4215-S: oz/gal = 0.522 x ml 0.5N-HCl

2.3 Specifications

Turco 4215-S: 6 to 8 oz/gal

2.4 Solution Control

Turco 4215-S: (8-(current oz/gal)) x tank capacity (gal) = number of ounces of Turco 4215-S to add. Multiply by 28.35 to obtain the number of grams to add.

2.5 Reagents

1. 0.5N-HCl
2. Buffer solutions: pH = 4 and pH = 7
3. Deionized water, resistivity greater than 1 megohm.

2.6 Equipment

pH meter - any type (calibrate with standard buffers at pH = 4 and pH = 7).

3. DEOXIDIZER - Amchem 7/Nitric Acid

(Reference, Northrop Lab Test Procedure 7.47, 6/26/69 and Amchem Deoxidizer 17, Technical Service Data Sheet)

Perform the following analyses:

Amchem 7 Analysis (same as sodium dichromate)
Nitric Acid Analysis
Copper Analysis
Reaction Products Analysis
Etch Rate Analysis

3.1 Amchem 7 Analysis

3.1.1 Procedure

3.1.1.1 Pipette exactly 5 ml of the sample into a 250 ml beaker and add 50 ml of DI water.

3.1.1.2 Add 10 ml of concentrated HCl.

3.1.1.3 Add 5 ml of KI solution, swirl and allow to stand for 3 minutes.

3.1.1.4 Titrate with 0.1N-$Na_2S_2O_3$ to a straw color.

3.1.1.5 Add 2 ml of starch solution.

3.1.1.6 Continue the titration until the blue color just disappears.

3.1.2 Calculations

Amchem 7: oz/gal = $0.174 \times$ ml $0.1N\text{-}Na_2S_2O_3$

3.1.3 Specification

Amchem 7: 2.9 to 3.3 oz/gal.

3.1.4 Solution Control

Initial Make-Up

Amchem 7:	(3.2 - (current oz/gal)) x tank capacity (gal) = number of ounces of Amchem 7 to add. Multiply by 28.35 to obtain the number of grams.
Replenish:	Use Amchem 17 instead of Amchem 7. Calculate quantity as for Amchem 7.

3.1.5 Reagents

1.	$0.1N\text{-}Na_2S_2O_3$	24.819 grams $Na_2S_2O_3 \cdot 5H_2O$ per liter of solution.
2.	Starch Indicator	To 100 ml boiling water add 1 gram soluble starch as a paste. Stir thoroughly and while still hot, add 1 mg HgI_2 and 0.4 grams KI.

3. C. P. HCl (concentrated reagent)

4. Deionized water, resistivity greater than 1.0 megohm.

3.1.6 Equipment

Standard laboratory glassware and stirrers.

3.2 Nitric Acid Analysis

3.2.1 Procedure

3.2.1.1 Pipette exactly 10 ml of the sample into a 250 ml beaker and add 50 ml of DI water.

3.2.1.2 Titrate with 1.0N-NaOH to an end-point of pH = 3.8 using a pH meter.

3.2.2 Calculations

Nitric Acid: Volume percent 42 ^{o}Bé HNO_3 = $0.665 \times$ ml 1.0N-NaOH
(42 ^{o}Bé HNO_3 is concentrated reagent, 69 percent assay)

3.2.3 Specifications

Nitric Acid:	11 to 14 percent by volume (of concentrated 69 percent HNO_3)

3.2.4 Solution Control

Nitric Acid:	(13 percent - (current percent)) x tank capacity (gal) = number of gallons of concentrated HNO_3 (70%) to add. Multiply by 3785 to find ml.

3.2.5 Reagents

1. 1.0N-NaOH
2. Buffer Solutions, pH = 4 and pH = 7
3. Deionized water, resistivity greater than 1.0 megohm.

3.2.6 Equipment

1. Standard laboratory glassware and stirrers.
2. pH meter - any type (calibrate with standard buffers at pH = 4 and pH = 7).

3.3 Copper Analysis

3.3.1 Procedure

3.3.1.1 Transfer a 50 ml sample into a clean plastic bottle.

3.3.1.2 Set the following instrumental parameters on the Perkin Elmer 370 atomic absorption spectrophotometer.

Wavelength: 324.1 nm
Slit: 0.7 mm
Light Source: Copper hollow cathode lamp.
Nitrous Oxide Cylinder Regulator Pressure: 60 psig.
Nitrous Oxide Flow: 45
Acetylene Cylinder Regulator Pressure: 12 psig
Acetylene Flow: 25
Air Regulator Pressure: 60 psig

3.3.1.3 Adjust the spectrophotometer burner height for maximum absorption while aspirating a 5 ppm copper standard solution.

3.3.1.4 Adjust the meter with the EXPANSION control until the meter display reads the concentration of the 1.0 ppm copper standard solution.

3.3.1.5 Aspirate the sample solution and record the meter reading in ppm.

3.3.2 Calculations

3.3.2.1 The ppm Cu is directly obtained from the instrumental meter reading.

Copper: ppm = instrument reading

3.3.3 Specifications

Copper: 2 ppm maximum

3.3.4 Solution Control

Add Alodine 1200E in increments of 5 ml/gal of deoxidizer until the copper analysis is within the specification limits of 2 ppm maximum as determined by paragraph 3.4.1.

3.3.5 Reagents

1.	1000 ppm Cu standard	Purchase from chemical supply house.
2.	5 ppm Cu standard	Pipette exactly 5 ml of 1000 ppm Cu standard into a 1000 ml volumetric flask and dilute to volume with distilled water. Store the solution in a polyethylene bottle.
3.	1 ppm Cu standard	Pipette 100 ml of 5 ppm Cu standard into a 500 ml volumetric flask and dilute to volume with distilled water. Store the solution in a polyethylene bottle.
4.	Distilled water.	

3.3.6 Equipment

1. Standard laboratory glassware and stirrers.
2. Perkin-Elmer 370 Atomic Absorption Spectrophotometer or Equivalent.

3.4 Reaction Products:

(Amchem Deoxidizer 17, Technical Service Data Sheet)

As aluminum is processed in the Amchem 7 bath, reaction products will gradually accumulate unless there is sufficient drag-out of the bath during processing. When the reaction products reach the concentration specified below, the Amchem 7 bath should be discarded and a fresh bath made up.

3.4.1 Procedure

Pipette exactly 5 ml of the sample of the Amchem Deoxidizer bath into a iodimetric flask and dilute to approximately 100 ml with DI water.

3.4.1.2 Add approximately 1.0 grams (1/2 teaspoonful) of sodium peroxide.

3.4.1.3 Add several glass beads to the flask and bring to boil on a hot plate.

3.4.1.4 Boil for approximately 20 minutes, then cool to room temperature.

3.4.1.5 Add 15 ml of concentrated HCl in three equal portions to the lip of the flask.

3.4.1.6 Rinse the lip several times with DI water and replace the stopper.

3.4.1.7 Add approximately 2 grams (1 teaspoonful) of potassium iodide and agitate the solution until the potassium iodide is dissolved. Let sample settle for about 1 minute.

3.4.1.8 Titrate with 0.1N-$Na_2S_2O_3$ until a straw color is obtained.

3.4.1.9 Add 2 ml of soluble starch indicator solution: continue the titration until the blue-black color disappears.

3.4.1.10 Record the number of ml of 0.1N-$Na_2S_2O_3$ used.

3.4.2 Calculation

Reaction products (as $Na_2Cr_2O_7 \cdot 2H_2O$): oz/gal = 0.133 x ml 0.1N-$Na_2S_2O_3$

3.4.3 Specification

When the Reaction Products titration reaches a value of 90.0 ml or above, discard the Amchem 7 bath. This is equivalent to a total reduced oxidized chromium content of 0.133 x 90 = 12.0 oz/gal of $Na_2Cr_2O_7 \cdot 2H_2O$.

Reaction Products: 90 ml maximum.

3.4.4 Solution Control

None.

3.4.5 Reagents

1. C.P. Na_2O_2, Sodium Peroxide.
2. C.P. HCl (concentrated reagent).
3. C.P. KI, potassium iodide.
4. 0.1N-$Na_2S_2O_3$ — 24.819 grams per liter of solution, $Na_2S_2O_3 \cdot 5H_2O$
5. Starch Indicator — To 100 ml boiling water add 1 gram soluble starch as a paste. Stir thoroughly and while still hot, add 1 mg HgI_2 and 0.4 grams KI.
6. Deionized water, resistivity greater than 1.0 megohm.

3.4.6 Equipment

Standard laboratory glassware and stirrers.

3.5 Etch Rate

Etch rate is to be determined on a new bath both in the still and agitated conditions. The etch rate of the still bath is a measure of the fluoride level of the tank. The etch rate of the agitated bath is mainly used to measure the effect of the agitation on the etch rate of the bath. The etch rate of the agitated bath should be 2 to 3 times that of the still bath. After the characteristics of a specific tank have been determined, the etching characteristics and fluoride level of the bath may be controlled by measuring the etch rate resulting from an exposure of a sample in the agitated bath.

3.5.1 Procedure

3.5.1.1 Test Coupon: Shear two (2) 3.0 in. x 3.0 in. x 0.063 in. aluminum coupons of 7075-T6 bare aluminum sheet. Drill a 1/8-inch hole in one corner of each coupon (or use titanium clips or other technique) to hold the aluminum coupon in the processing and test tanks. Clean the test coupons using standard weldbond cleaning process consisting of degreasing, alkaline cleaning, and Amchem 7/nitric acid deoxidizing. Dry coupons for 30 minutes at 150-160F in a hot air circulating oven.

3.5.1.2 Weigh each aluminum test coupon on an analytical balance to the nearest milligram.

3.5.1.3 Still Etch Rate Procedure

Etch rate determination may be made on a 1000 ml sample of the Amchem 7/nitric acid processing solution or in the actual production tank. In the 1000 ml sample technique, glass containers should not be used. Fluoride in the solution will attack glass.

3.5.1.3.1 Turn off agitation and let solution settle for 30 minutes.

3.5.1.3.2 Immerse the test coupons without agitation or filtration for exactly 20 minutes. Ensure that individual coupons do not rest on the bottom of the tank or touch each other.

3.5.1.3.3 After 20 minutes, quickly remove the test coupons and spray rinse with deionized water for 5 to 7 minutes.

3.5.1.3.4 Dry coupons for 30 minutes in a hot air circulating oven at 150-160F.

3.5.1.3.5 Cool and weigh the coupons on an analytical balance to the nearest milligram.

3.5.1.4 Agitated Etch Rate Procedure

3.5.1.4.1 Agitate the bath either through a pump or air agitation (preferred) to give a moderate agitation in the deoxidizer. Start the filter pump. Continue filtration and agitation for a period of 10-20 minutes to insure complete mixing of solution and complete removal of all contamination particles.

3.5.1.4.2 Continue agitation and filtration. Immerse the test coupons for exactly 20 minutes. Ensure that individual coupons do not rest on the bottom of the tank or touch each other.

3.5.1.4.3 After 20 minutes, quickly remove the test coupons and spray rinse with deionized water for 5 to 7 minutes.

3.5.1.4.4 Dry coupons for 30 minutes in a hot air circulating oven at 150-160F.

3.5.1.4.5 Cool and weigh the coupons on an analytical balance to the nearest milligram.

3.5.2 Calculations

Etch rate is the grams lost by an 18 sq inch surface exposed for 20 minutes in a still bath or an agitated and filtered bath.

(a) = grams, initial weight of coupon (3.5.1.2)

(b) = grams, final weight of coupon (3.5.1.3.5) (3.5.1.4.7)

1. Etch rate: grams lost/20 min = (a) - (b)
2. Agitation Factor = $\frac{\text{Etch Rate (agitated)}}{\text{Etch Rate (still)}}$
3. Conversion Factor = $\frac{\text{gms lost}}{\text{20 min.}}$ x 3.67 = etch rate (mils/side/hr)

3.5.3 Specification

Etch Rate (still bath): 0.52 to 0.080 grams lost/20 min (0.20 to 0.30 mils/side/hr)

Agitation Factor: 2.0 to 3.0

3.5.4 Solution Control

Measure etch rate on the solution only after it has been adjusted or replenished for Amchem 7 content and for nitric acid content. Correct bath with Alodine 45 solution as follows:

One ml of Alodine 45 per gallon of deoxidizer raises the "still" etch rate by approximately 0.010 grams, depending on how many square feet of aluminum per gallon of deoxidizer have been processed. However, it is recommended that half the required amount of Alodine 45 be added, and etch rate checked per paragraph 3.5.1.3. Additional Alodine 45 should be added in small increments until the maximum etch rate of 0.080 grams is reached.

Alodine 45: (0.080 - Still Etch Rate) x 10,000 = number of ml of Alodine 45 to be added to 100 gallon tank.

3.5.5 Reagents

None required.

3.5.6 Equipment

Analytical Balance.

4. ANODIZE (phosphoric acid/sodium dichromate)

4.1 Phosphoric Acid

4.1.1 Procedure

4.1.1.1 Pipette exactly 25 ml of the sample into a 250 ml beaker and add 50 ml of DI water.

4.1.1.2 Titrate with 1.0N-NaOH to an end point of pH = 4.5 using a pH meter.

4.1.2 Calculations

Current Phosphoric Acid (85% Assay) concentration (fl oz/gal) = 0.345 x ml 1.0N NaOH

4.1.3 Specification

Phosphoric Acid: 1.2 to 1.5 fl oz/gal H_3PO_4 (85.4 percent Assay).

4.1.4 Solution Control (Northrop target = 1.4 fl oz/gal)

Phosphoric Acid = (1.4 - current fl oz/gal) x tank capacity (gal) x 29.57 = ml of 85% H_3PO_4 to add.

4.1.5 Reagents

1. 1.0N-NaOH - Sodium hydroxide.
2. Buffer Solutions, pH = 4 and pH = 7.
3. Deionized water, resistivity greater than 1.0 megohm.

4.1.6 Equipment

1. Standard laboratory glassware and stirrers.
2. pH meter - any type (calibrate with standard buffers at pH = 4 and pH = 7).

4.2 Sodium Dichromate

4.2.1 Procedure

4.2.1.1 Pipette exactly 2 ml of the sample into a 250 ml beaker and add 50 ml of DI water.

4.2.1.2 Add 10 ml of concentrated HCl.

4.2.1.3 Add 5 ml of KI solution, swirl and allow to stand 3 minutes.

4.2.1.4 Titrate with 0.1N-$Na_2S_2O_3$ to a straw color.

4.2.1.5 Add 2 ml of starch indicator.

4.2.1.6 Continue the titration until the blue color just disappears.

4.2.2 Calculations

Sodium dichromate current oz/gal: oz/gal $Na_2Cr_2O_7 \cdot 2H_2O = 0.332 \times$ ml 0.1N $Na_2S_2O_3$

4.2.3 Specifications

Sodium dichromate: 1.30 to 1.50 wt oz/gal

4.2.4 Solution Control - Northrop targets to 1.40 oz/gal

Sodium dichromate: (1.40 - current oz/gal) x tank capacity (gal) = no. of oz of $Na_2Cr_2O_7 \cdot 2H_2O$ to add.

4.2.5 Reagents

1.	0.1N-$Na_2S_2O_3$	24.819 grams per liter of solution, $Na_2S_2O_3 \cdot 5H_2O$
2.	Starch Indicator	To 100 ml boiling water add 1 gram soluble starch as a paste. Stir thoroughly and while still hot, add 1 mg HgI_2 and 0.4 grams KI.
3.	C.P. HCl (concentrated reagent)	
4.	Deionized water, resistivity greater than 1.0 megohm.	

4.2.6 Equipment

Standard laboratory glassware and stirrers.

APPENDIX D

SEM PROCEDURES FOR QUALITY CONTROL OF ANODIC COATINGS

1. SCOPE:

1.1 This procedure establishes the equipment, standards, and techniques for verification of the acceptability of surface preparation procedures following deoxidation and low voltage phosphoric acid/sodium dichromate anodizing of 7075-T6 bare and 2024-T3 alclad aluminum alloys.

1.2 The acceptance criteria for the anodized surfaces of bare 7075-T6 and clad 2024-T3 are specified in 2.3.

2. REQUIREMENTS

2.1 Equipment

2.1.1 The scanning electron microscope (SEM) shall consist of, but not be limited to the following:

a. An electron source with accelerating potential of at least 15 KV.

b. Pre-aligned electro-magnetic lens system with coarse and fine objective lens controls for image focusing.

c. Enclosed vacuum column evacuated by an oil diffusion pump and backed by a roughing pump. Pump-down time to a pressure of 1×10^{-4} torr after specimen insertion shall not exceed two minutes.

d. Double deflection scanning coils with two secondary electron scanning modes: one for visual observation and one for photographic recording

e. Display screen (CRT) for viewing and photographic documentation.

f. Specimen stage capable of handling anodized specimens, with a minimum sample diameter of 0.75 inch and a minimum sample height of 0.50-inch, X- and Y-translation, and manual or electronic rotation and tilt from 0^{o} to greater than 45^{o}.

g. Stepwise variable, direct reading magnification control from not less than 100X to at least 20,000X.

h. Electron-optical performance with a guaranteed resolution of at least 150Å.

2.1.2 The equipment for preparation of the specimens prior to SEM inspection shall consist of the following:

a. A vacuum system capable of depositing a clean, uniform layer of gold, 100Å to 200Å in thickness, on the anodized surface. The coating process may include, but not be limited to, either vapor deposition or sputter-coating. A rotary/tilting coater sample holder should be used to provide complete exposure of the gold coating. This provides a rotation and tilting motion of the specimen during the deposition process.

2.2 Process Requirements

2.2.1 Specimen Preparation Procedure Prior to SEM Inspection

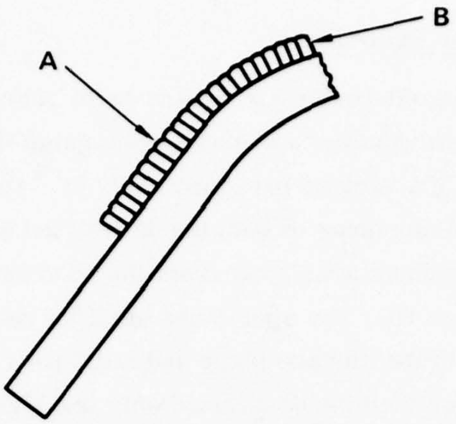
a. Specimens shall be removed from panels both after deoxidation and after phosphoric acid/sodium dichromate anodizing. The specimen size shall not exceed 0.125-inch by 1.0-inch by 0.125-inch in thickness, unless it is determined to be compatible with the size of the SEM specimen stage, as specified in 2.1.1.f. The specimens are to be representative of the anodic surface character of the larger panels.

Note: Specimen surfaces to be inspected shall be kept clean and free from all contaminants that may alter the character of the anodic coating. This includes, but is not limited to, grease, oils, vapors, and fingerprints. The "deoxidized only" specimen must be gold coated for SEM analysis in less than 24 hours after processing.

b. Manually break or bend the specimens in order to view the anodic coating at the radius (see Figure D1).

c. Mount the cracked specimens on a SEM mount (specimen stub) using a conductive paste, paint, or colloidal suspension. These may contain either silver or carbon as the conductive medium.

d. Apply a thin, uniform coating of high purity gold (about 100Å - 200Å thick) on the mounted cracked specimens by vapor deposition or sputtering.



A – NORMAL TO SURFACE PLANE – INSPECT AT 2000X, AND 10,000X
B – PARALLEL TO SURFACE PLANE – INSPECT AT 4000X AND 20,000X

FIGURE D1. REPRESENTATION OF BENT ANODIZED SPECIMEN SHOWING DIRECTIONS OF SEM INSPECTION

2.2.2 SEM Inspection Procedures

a. Insert the gold-coated specimens (with stub) into the scanning electron microscope and execute the pump-down and start-up sequence. A vacuum pressure of 1×10^{-4} torr is required.

b. Inspect the surfaces of both the deoxidized only and anodized specimens in an area away from the bend radius as indicated by A in Figure D1. The specimens shall be viewed at right angles (normal) to the surface plane and must pass the acceptance criteria for both the deoxidized only and phosphoric acid/sodium dichromate anodize at each of the following magnifications. 2000X and 10,000X in accordance with 2.3.1 a, c, and d for bare 7075-T6 and 2.3.2, a, c, and d for clad 2024-T3.

c. Inspect the surfaces of both the deoxidized only and anodized specimens along a direction normal to the cross section of the oxide, as indicated by B in Figure D1. Both surfaces must pass the acceptance criteria at each of the following magnifications: 4000X and 20,000X as specified in 2.3.1 b and e for bare 7075-T6, and 2.3.2 b and e for clad 2024-T3.

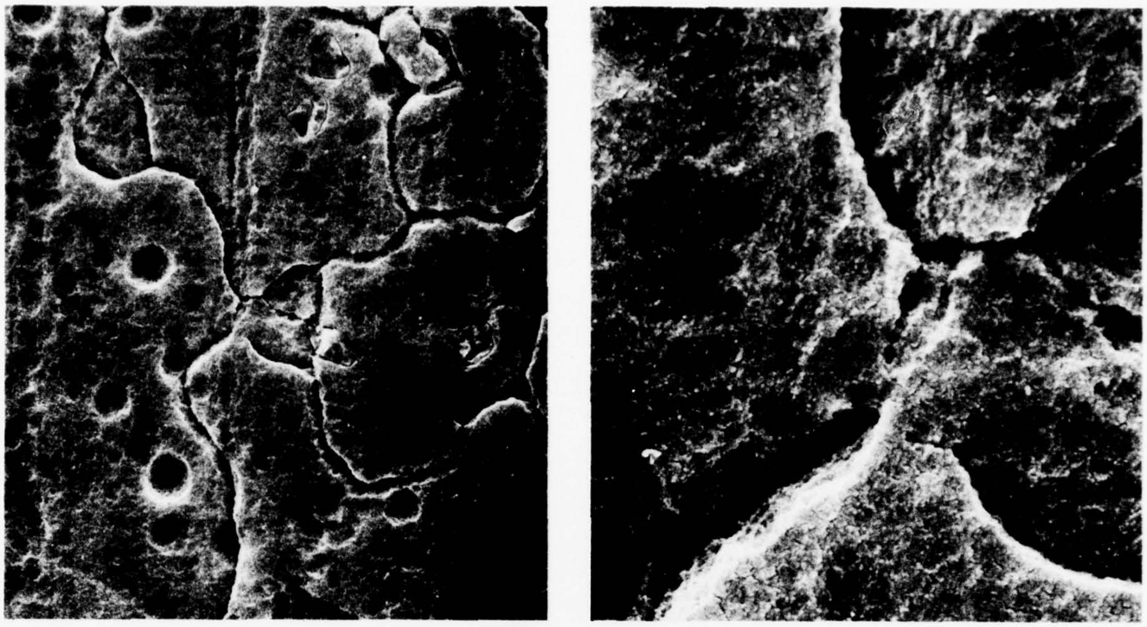
2.3 Acceptance Criteria

2.3.1 7075-T6 Bare

The acceptance criteria for 7075-T6 bare consists of two sets of SEM photographs showing the acceptable surface character in both the "deoxidized only" and "anodized" conditions. The appearance and acceptable conditions are specified as follows:

a. Specimens which have been "deoxidized only" are to be viewed along a direction normal to the surface plane (see Figure D1) and inspected at magnifications of 2000X and 10,000X. The appearance must be similar to that shown in the SEM photomicrographs in Figure D2. Large particles that contaminate the surface as shown in Figure D3 at 2000X are unacceptable, and etched grain boundaries must be visible. The absence of grain boundary etching indicates that a deoxidizing bath is out of specification limits. Surface defects, such as holes and pits in the surface are acceptable.

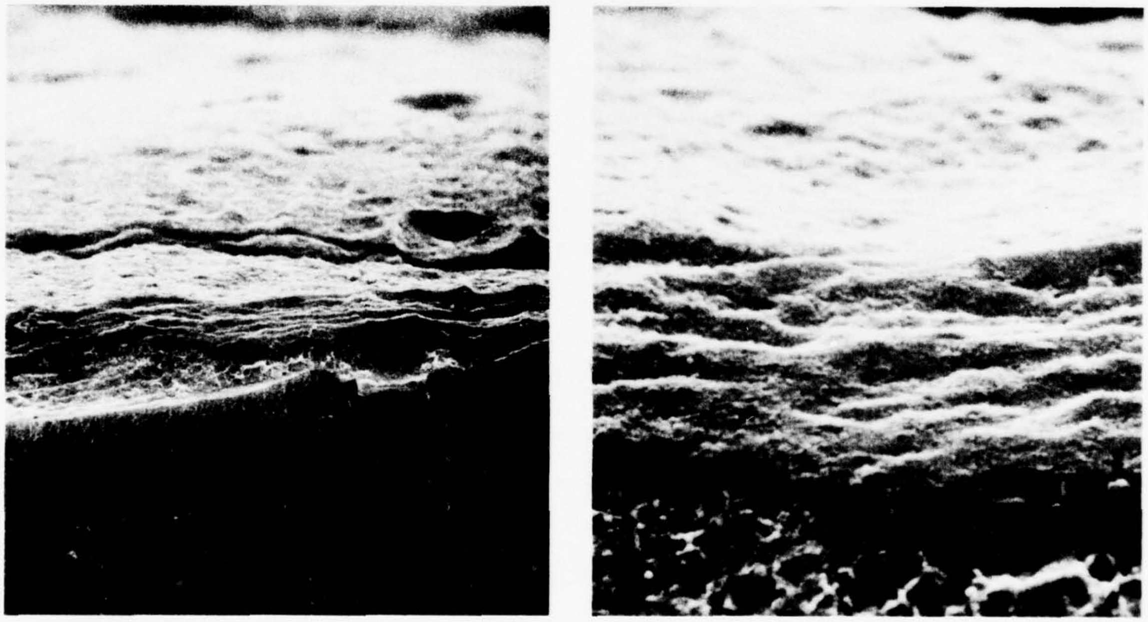
NORMAL VIEW



2000X

10,000X

PARALLEL VIEW



4,000X

20,000X

FIGURE D2. GENERAL CHARACTER OF STANDARD SURFACE OF BARE 7075-T6 "DEOXIDIZED ONLY"

b. Inspection of the "deoxidized only" surface through its cross section will be performed at magnifications of 4000X and 20,000X and shall reveal images similar to those shown in Figure D2 (edge view). The surface shall appear clean with no surface contamination. Contamination of the surface as shown in Figure D3 at 20,000X, where the "deoxidized only" surfaces give the appearance of an anodized surface, is unacceptable. The presence of the light mud cracked amorphous oxide is acceptable, but should not exceed 3000Å in thickness.

c. The appearance of the phosphoric acid/sodium dichromate anodized surface of bare 7075-T6 when inspected along a direction normal to the surface plane (see Figure D1) at a magnification of 2000X must appear similar to the surface shown in the SEM photomicrograph in Figure D4. Note should be made of the presence of the etched grain boundaries, which must be visible. Absence of grain boundary etching is not acceptable. Surface defects, such as holes and pits are acceptable.

d. Inspection of the anodized surface at a magnification of 10,000X must present an appearance similar to that shown in Figure D4. The grain boundary etching must again be evident and comparable in depth to that shown in D4.

e. Inspection of the anodic coating thickness through its cross-section at a magnification of 4000X and 20,000X shall reveal images similar to those shown in Figure D4. Acceptance of the panel is based on the thickness of the coating measured from the 20,000X image, which must be at least 500Å, but not greater than 1000Å.

Note: A trend toward greater or lesser thicknesses is indicative of changes in the anodizing procedures: i.e., bath concentration, voltage, time, or poor electrical connections.

2.3.2 2024-T3 Alclad

The acceptance criteria for 2024-T3 alclad material both in the "deoxidized only" and "anodized" conditions consists of two sets of SEM photographs shownning the acceptable surface character specified as follows:

a. The appearance of the 2024-T3 alclad aluminum in the "deoxidized only" condition when inspected along a direction normal to the surface

NORMAL VIEW

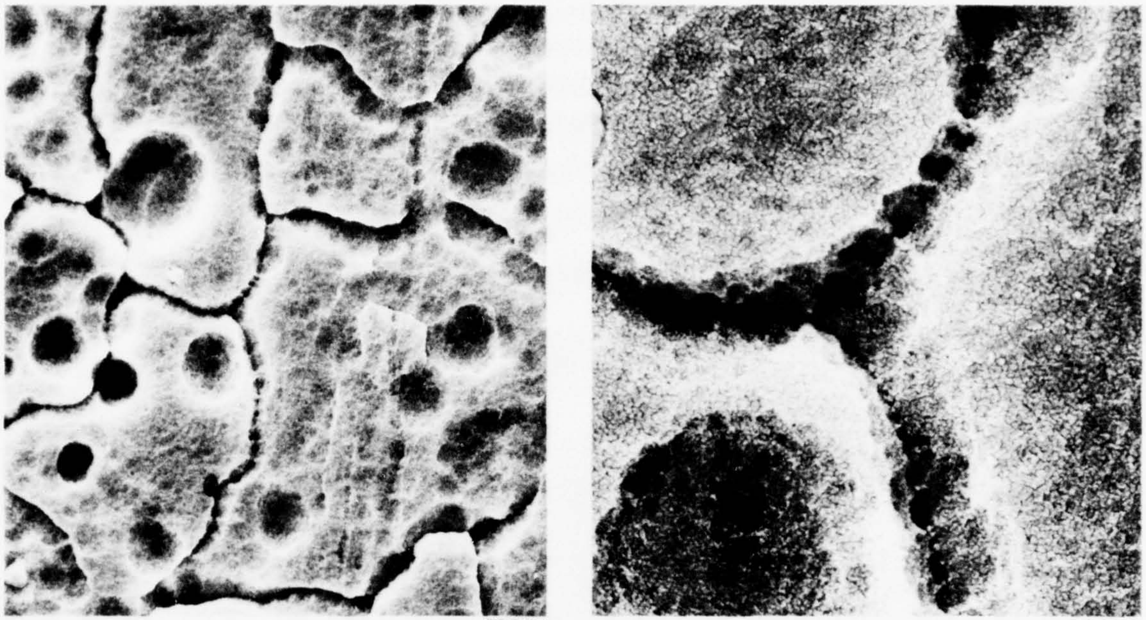
2000 X

PARALLEL VIEW

20,000X

FIGURE D3. UNACCEPTABLE LEVEL OF SURFACE CONTAMINATION OF 7075-T6

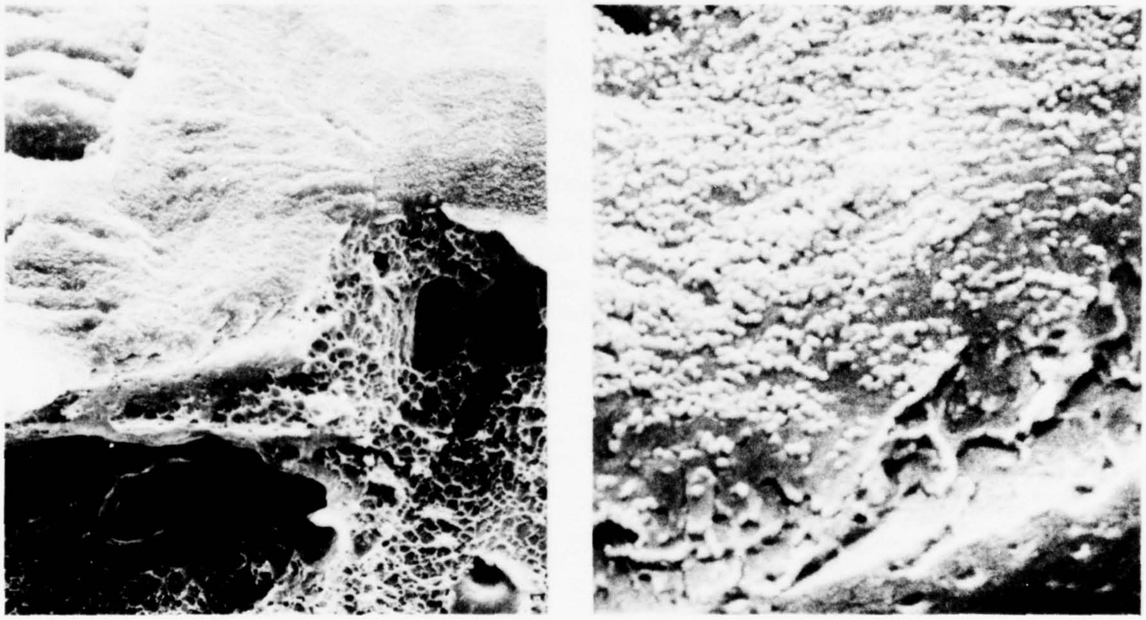
NORMAL VIEW



2000X

10,000X

PARALLEL VIEW



4,000X

20,000X

FIGURE D4. GENERAL SURFACE CHARACTERISTICS OF THE AREA USED FOR OXIDE THICKNESS DETERMINATION OF BARE 7075-T6 ANODIZED IN PHOSPHORIC ACID/SODIUM DICHROMATE

plane (see Figure D1) at magnifications of 2000X and 10,000X must appear similar to the surface shown in the SEM photomicrograph in Figure D5. Note should be made of the absence of etched grain boundaries. Surface defects such as holes and pits are acceptable. Surface contamination as indicated by the appearance of foreign particles (Figure D6) on the material is not acceptable.

b. Inspection of the "deoxidized only" surface through its cross-section at magnifications of 4000X and 20,000X shall reveal images similar to those shown in Figure D5. The surface shall appear clean with no surface contamination such as the large particle that appears on the surface at 20,000X in Figure D6.

c. The appearance of the phosphoric acid/sodium dichromate "anodized" surface of 2024-T3 alclad when inspected along a direction normal to the surface plane (see Figure D1) at a magnification of 2000X must appear similar to the surface shown in the SEM photomicrograph in Figure D7. Note should be made of the absence of etched grain boundaries. Surface defects, such as holes and pits are acceptable. Surface contamination is not acceptable.

d. Inspection of the anodized surface at a magnification of 10,000X must present an appearance similar to that shown in Figure D7.

e. Inspection of the oxide thickness through its cross-section at a magnification of 4000X and 20,000X shall reveal an image similar to that shown in Figure D7. Acceptance of the panel is based on the thickness of the coating measured from the 20,000X image, which must be at least 400Å, but not greater than 800Å.

2.4 Facility Requirements

2.4.1 Locate equipment, specimens, and records in a clean, well-lighted area free of noise and vibration and sufficiently removed from the production facilities to preclude contamination by substances detrimental to both specimens and equipment. This includes, but is not limited to, dusts, acids, oils, greases, solvents, fumes, and vapors.

2.4.2 Optimum performance of the scanning electron microscope is achieved by

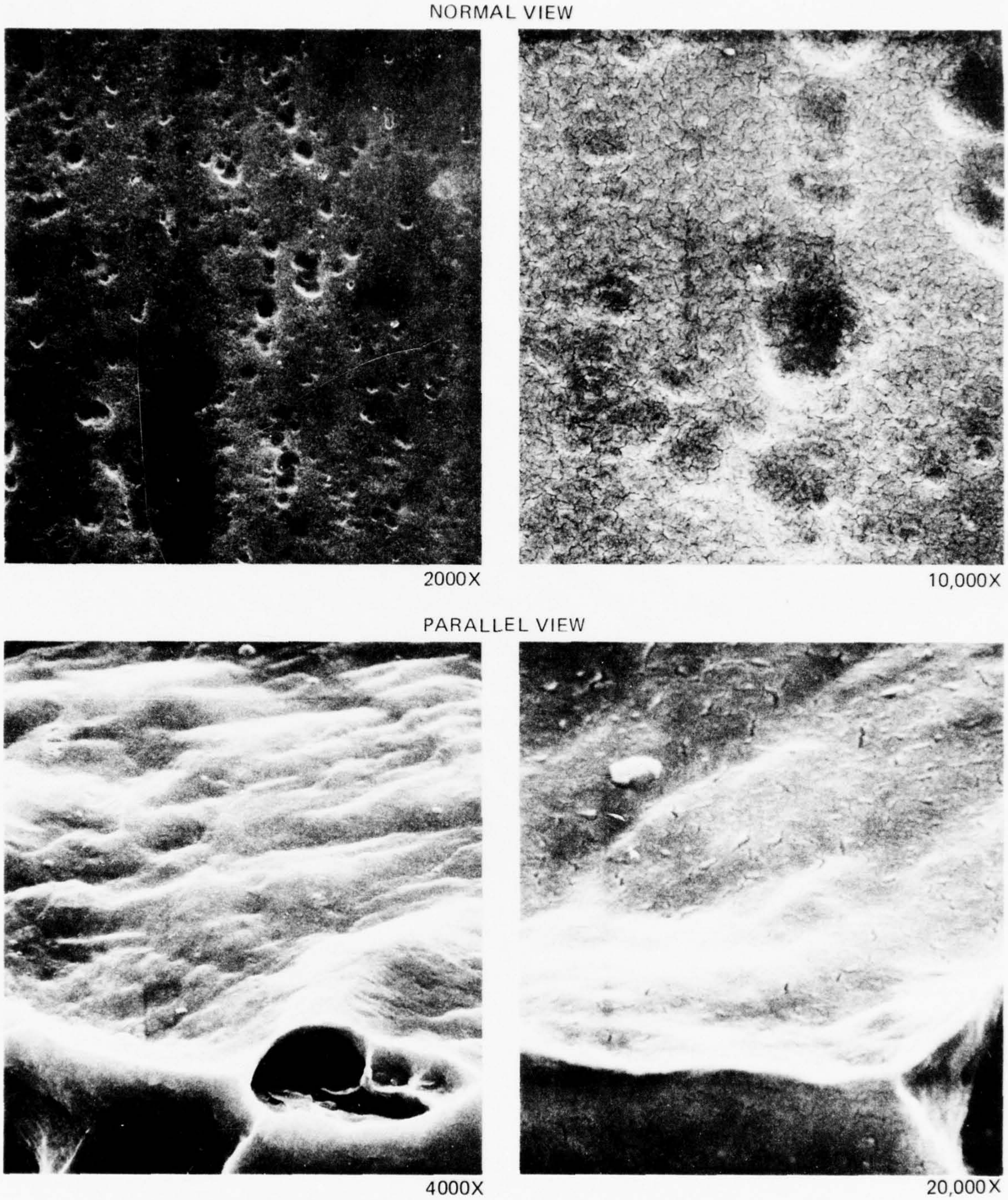
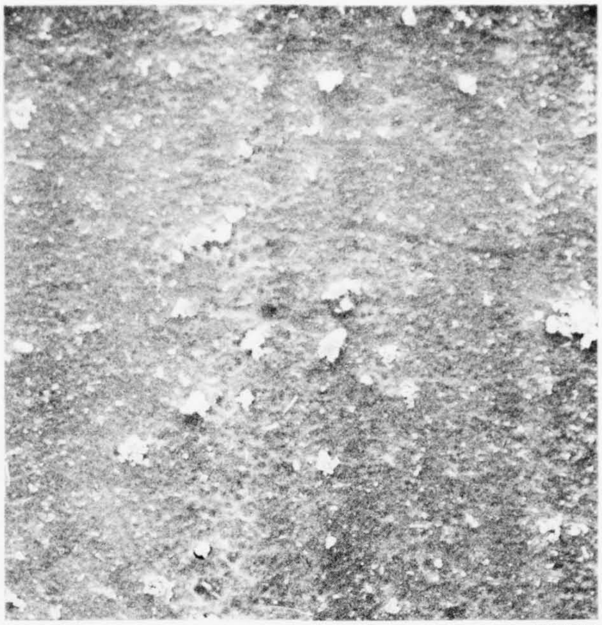


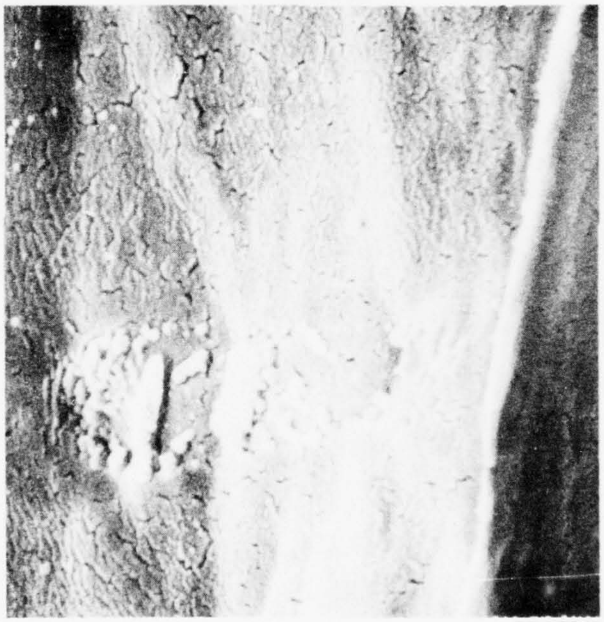
FIGURE D5. GENERAL CHARACTER OF STANDARD SURFACE OF 2024-T3 ALCLAD "DEOXIDIZED ONLY"

NORMAL VIEW



2000X

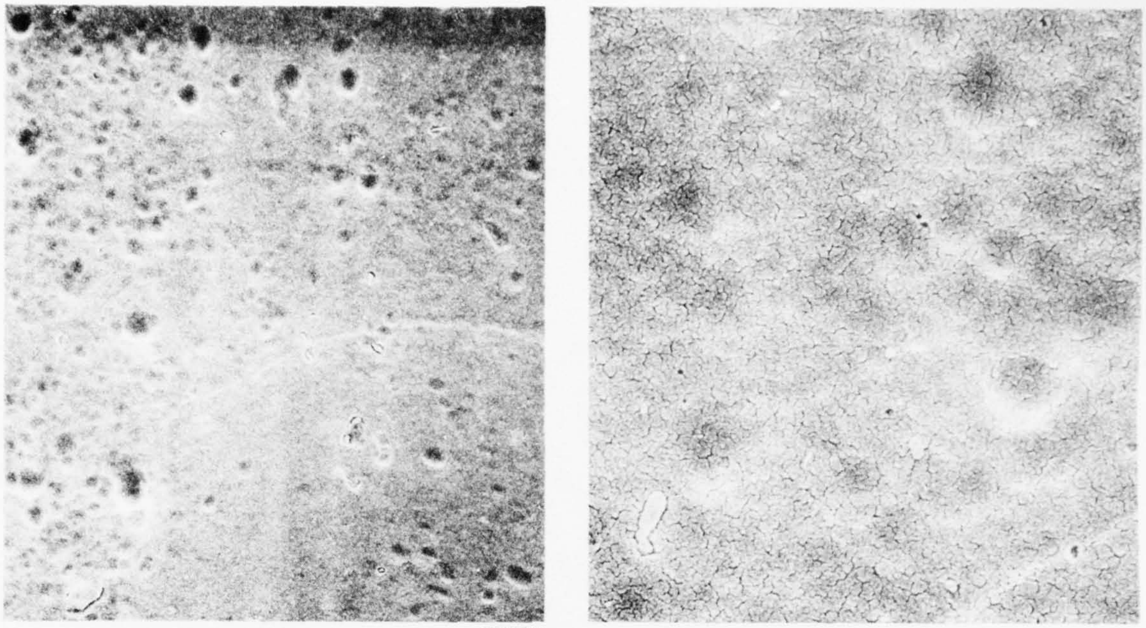
PARALLEL VIEW



20,000X

FIGURE D6. UNACCEPTABLE LEVEL OF SURFACE CONTAMINATION OF 2024-T3

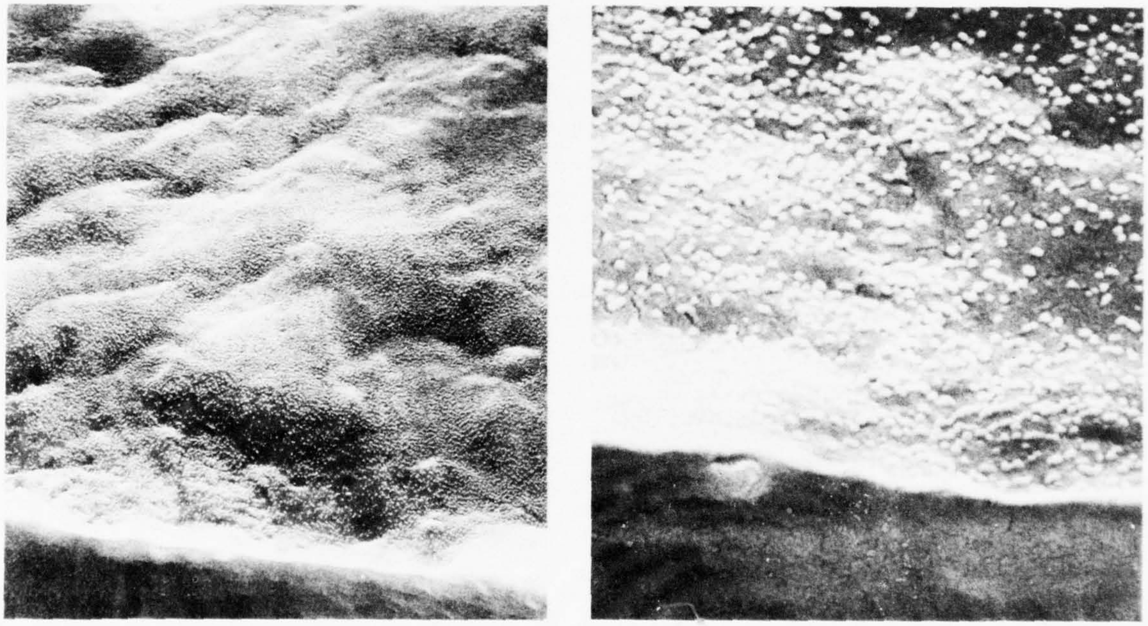
NORMAL VIEW



2000X

10,000X

PARALLEL VIEW



4000X

20,000X

FIGURE D7. GENERAL SURFACE CHARACTERISTICS OF THE AREA USED FOR OXIDE THICKNESS DETERMINATION OF 2024-T3 ANODIZED ON PHOSPHORIC ACID/SODIUM DICHROMATE locating the equipment in an area that can be darkened.

2.5 Qualification of Personnel

2.5.1 All personnel operating the inspection equipment and accepting or rejecting anodized panels shall be certified by:

a. Completion of a training course on the operation of the sample preparation and inspection equipment.

b. On-the-job training by a certified operator.

3.0 QUALITY ASSURANCE

3.1 Manufacturing and Inspection Control

3.1.1 Maintain an inspection procedure that will allow traceability of tab specimen back to the larger anodized panel or batch of panels.

3.1.2 Inspection records shall be kept complete and available on the anodic coating thicknesses of each panel inspected, as well as any comments by the inspector on any abnormalities or deviations from normal that develop in the character of the anodic coating.

3.2 Equipment and Standards

3.2.1 All equipment shall be maintained in working order in accordance with 2.1.

3.2.2 Periodic servicing of the scanning electron microscope shall be required to maintain a minimum working resolution of 150Å.

3.2.3 A reference file shall be maintained of current SEM photographs from representative acceptable and rejectable anodic surfaces.

APPENDIX E

MICROPROCESSOR CONTROL CODES

INPUT CODE	CONTROL CODE	A DATA	B DATA
001-000-00	Do Nothing - one cycle		
002-000-00	Test foot switch		100% heat curve
-97			100% heat curve
-60			60% heat curve
003-000-00	Turn everything off		Return to step 00
004-000-00	Repeat		
-005-04	Repeat - from present step to step in B data	No. of times repeated i.e., 5 times	Return to step 4
HEAT COMMANDS			
111-010-70	Apply Heat - single phase	Ten cycles	70%
131-001-18	Apply Heat - 3-phase	One cycle	18%
181-000-00	Polarity set code sets polarity +		
181-000-00 001-000-00	Sets polarity -		
191-025-14	Apply heat on feedback control mode	Total no. of heat cycles in feedback program	First cycle of Heat - 14%
255-000-00	Feedback monitor to read actual expansion		
302-015-01	Precompression - turns forge on for no. of cycles specified	15 cycles	Must be 01 to turn valve on

INPUT CODE	CONTROL CODE	A DATA	B DATA
401-000-01	Turn weld valve on/off	No. of cycles delay usually 00	ON-01 or OFF-00
402-007-01	Turns forge valve on	7 cycle delay after command step	ON-01 or OFF-00
403-030-01	Turn on oscillograph recorder	30-cycle delay after command step	ON-01 or OFF-00
404-009-00	Sets feedback encoder	After delay of 9 cycles from command step	01-Resets encoder to zero
-01			00-Command to start measuring
613-000-00	Feedback expansion selection command for nugget expansion		
800-025-00	DO NOTHING	for 25 cycles	
-025-06			Check for contact gage
800-000-00	Special - causes polarity reversal when inserted in middle of weld cycle		
900-058-00	Jump to specified step	Step No. 58	00
941-232-19*	Initiate program Select Switch	Code for proper switch No - ie #2 248-0 240-1 232-2 224-3 216-4 208-5 200-6 192-7 184-8 176-9	Jump to Step No. ie 19

*See Attachment

APPENDIX F

MANUFACTURING TEST PLAN

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From File

Part Number
Assembly

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV															SHEET NO. 1 OF 4	PART NO. 180K100001-9

OPER NO	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
		This assembly consists of:								
		(1) 180K100001 - 23A Skin (0.040) S-111								
		(1) 180K100001 - 27A Beaded Pan (0.050) S-111								
		This plan is written to accomplish the manufacturing methods necessary to produce a weldbonded panel assembly.								

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Part Number
Assembly

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV	
SHEET NO.	2 OF 4
PART NO.	180K100001-9

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN SU	NO. MEN RUN	STANDARD HRS. S.U.	STANDARD HRS. PER PIECE	PROD. STAMP	INSP. STAMP	ST/FIM
5		Obtain details for Part Storage								
10		Prefit Details								
15		CK ID TAG								
20		Vapor Degrease both details								
25		Alkaline clean both details per XPS-WB								
30		Spray Rinse, DI water 5-7 min. per XPS-WB								
35		Deoxidize, both details 6-8 min. per spec. XPS-WB								
40		Spray Rinse, DI + tap water, 5-7 min. per spec XPS-WB								
45		Anodize details per XPS-WB for 20 min. 1.5V for bare alloys 1.0V for clad alloys								
50		Spray Rinse DI water, 5-7 min. per XPX-WB								
55		Dry details in air circulated and filtered 140-160F 30-60 minutes								
60		Wrap details in acid-free Kraft paper for transportation to clean room.								

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Part Number
Assembly

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV

SHEET NO.
3 OF 4

PART NO.
18K100001-9

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
65		Inspect, visual and surface contact restance per XPS-WB								
70		Apply Adhesive in Clean Room								
75		Tape edges								
80		Wrap Assembly in acid-Free Kraft paper for transportation to Clean Room								
85		Check ID TAG								
90		Assemble Details in Weld Fixture								
95		Spot Weld Assembly per XPS-WB								
100		Remove Assembly from Weld Fixture								
105		Remove Excess Adhesive per XPS-WB								
110		Check ID TAG								
115		Place Assembly in Curing Fixture								
120		Cure 250-260F for 2-3 hrs.								

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Assembly

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV	
SHEET NO.	4 OF 4
PART NO.	18K100001-9

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
125		Verify Furnace Log								
130		Remove Assembly from Curing Fixture								
135		NDI - Radiography								
140		NDI - Fokker Bond Test								
145		Final Trim to B/P								
150		Hand Deburr								
155		Identify Panel - Rubber Stamp only								

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From File

Part Number
Beaded Pan (0.050)

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV																SHEET NO. 1 OF 3	PART NO. 180K100001-27A

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
		This plan is written to accomplish the fabrication of the 7075-T6 beaded pan detail which is required to be a part of the weldbonded panel assembly P/N 180K10000-9								

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Do Not Remove From File

Part Number
Beaded Pan (0.050)

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV															SHEET NO. 2 OF 3	PART NO. 180K100001-27A

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
5		Shear Material to Template								
10		NOTE: Drill (2) tool holes only and mark for trim								
15		Trim to mark								
20		Rout perimeter								
25		Pin Rout corners								
30		Hand Deburr								
35		Degrease								
40		Form								
45		Finish Form								
50		Identify (TAG)								
55		Clean per XPS-WB								
60		Heat Treat - 7075W, Glycol Quench and refrigerate per MIL-H-6088								
65		Inspect - OP #55 per QAI 9-8 Verify HT Log								

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From File

Part Number
Beaded Pan (0.050)

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV		SHEET NO.	PART NO
		3 OF 3	18K10000-27A

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
70		Check and Straighten								
75		Inspect - OP #10-50 & 65 per QAI 7-3	BP, CPT, PRB, Scale, Visual							
80		Age 7075-T6 per MIL-H-6088								
85		Inspect - OP #75 per QAI 9-9 RB 85-94								
90		Lay-out and trim perimeter of Pan - 2 inches oversize in length and width to B/P dimension								
95		DeBurr GF 101*								
100		Drill (1) #40 Vent Hole per B/P								
105		Degrease GR 302*								
110		Identify Part No. (TAG) ZR 701*								
115		Inspect - OP #85-100 per QAI 7-3 and 14-1	BP, Visual							
120		Store for S-161 ZP 801*								

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Part Number
SKIN-

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV															SHEET NO. 1 OF 2	PART NO. 180K100001-23A

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
		This plan is written to accomplish the fabrication								
		of the Skin detail which is required to be part of								
		a weldbonded panel assembly P/N 180K100001-9.								

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Part Number
SKIN

DETAIL AND/OR ASSEMBLY WORK ORDER-OPERATION SHEET

REV

SHEET NO. 2 OF 2

PART NO. 180K100001-23A

OPER NO.	OPER REV	DESCRIPTION OF OPERATION List all part No's & Sources, going into Ass'bly	TOOL-JIG OR FIXTURE NO.	NO. MEN		STANDARD HRS.		PROD. STAMP	INSP. STAMP	ST/FIN
				SU	RUN	S.U.	PER PIECE			
5		Shear material -- 22 X 23.10	Set-up							
10		Hand Deburr								
15		Degrease								
20		Identify (TAG)								
25		Inspect OP# 5-2 per QAT 7-3 and 14-1	BP, Scale, Visual							
30		Store for S-111 ZP 801								

APPENDIX G

ETCH RATE CONVERSION FACTOR DERIVATION

Assumptions

1. w = total weight loss on 3 inch x 3 inch sample etched for 20 minutes
2. E = Etch rate in/side/hour or mls/side/hour
3. Sample size - 0.062-inch x 3 inch x 3 inch
4. Edge effect negligible = thus total surface area = 3 x 3 = 9 in^2/side
5. Density of 7075 aluminum = 0.10 lbs/in^3

Derivation

$$E \text{ (in/side/in)} = \frac{w \text{ (gms/20 minutes) } 3 \text{ (20 minutes/hour)}}{9 \text{ (in}^2\text{/side) } \times 2 \text{ (sides) } \times 453.6 \text{ (gms/lb) } \times 0.10 \text{ (lb/in}^3\text{)}}$$

E (in/side/hr) = 0.00367 in/side/hour

E (mils/side/hour) = 3.67

APPENDIX H

A-10A TEST SPECTRUM FOR SHEAR PANELS

COND. NO.	CONDITION DESCRIPTION	GROSS WEIGHT (LBS.)	n_z/n_y	V_e KNOTS	CYCLES PER LIFETIME	MANEUVER SHEAR INTENSITY	MANEUVER PANEL* LOAD	BASE SHEAR INTENSITY	BASE PANEL* LOAD
1	Symmetrical Pullout	28000	2.5	200	7475	237	6221	304	7980
2			2.5	300	10000	696	18270	734	19267
3			2.5	340	4375	903	23703	982	25777
4			3.0	200	20325	215	5643	304	7980
5			3.0	300	17100	682	17902	734	19267
6			3.0	340	10425	877	23021	982	25777
7			3.5	200	14625	193	5066	304	7980
8			3.5	300	12400	669	17561	734	19267
9			3.5	340	8275	852	22365	982	25777
10			4.0	200	8750	171	4488	304	7980
11			4.0	300	7375	657	17246	734	19267
12			4.0	340	6025	824	21630	982	25777
13			4.5	200	150	148	3885	304	7980
14			4.5	300	10525	644	16905	734	19267
15			4.5	340	4000	798	20947	982	25777
16			5.0	300	5875	631	16563	734	19267
17			5.0	340	2275	773	20291	982	25777
18			5.5	300	2975	618	16222	734	19267
19			5.5	340	1050	746	19582	982	25777
20			6.0	300	1225	605	15881	734	19267
21			6.0	340	407	721	18926	982	25777
22			6.5	300	458	592	15540	734	19267
23			6.5	340	153	694	18217	982	25777
24			7.0	300	205	579	15198	734	19267
25			7.0	340	38	666	17482	982	25777
26			7.5	300	95	567	14883	734	19267
27			7.5	340	25	641	16826	982	25777
28			8.0	300	51	553	14516	734	19267
29			0	200	7150	350	9187	304	7980
30			0	300	1000	760	19950	734	19267
31			0	340	500	1036	27195	982	25777
32			-0.5	200	550	373	9791	304	7980
33			-0.5	300	50	774	20317	734	19267
34			-0.5	340	25	1062	27877	982	25777
35			-1.0	200	751	395	10368	304	7980
36			-1.5	200	113	417	10946	304	7980
37			-2.0	200	131	441	11576	304	7980
38	Symm Pullout-50% Speed Brake		3.0	300	5075	682	17902	734	19267
39			4.0	300	3575	657	17246	734	19267
40			5.0	300	400	631	16563	734	19267
41	Symm Pullout-80% Speed Brake		3.0	300	2525	683	17928	734	19267
42			4.0	300	1775	658	17272	734	19267
43			5.0	300	200	631	16563	734	19267
44	Dynamic Symmetrical		2.5	200	7325	237	6221	304	7980
45			2.5	300	9975	696	18270	734	19267
46			2.5	340	4350	903	23703	982	25777
47	n_z Roll, n_y = -0.3 Base		3.5/.35	200	6575	193	5066	304	7980
48	n_z Roll, n_y = 0 Base		3.5/.35	300	7925	669	17561	734	19267

*The panel load is the panel diagonal between loading points (26.25 in.) times the shear intensity

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A-10A TEST SPECTRUM FOR SHEAR PANELS (Continued)

COND. NO.	CONDITION DESCRIPTION	GROSS WEIGHT (LBS.)	n_z/n_y	V_e KNOTS	CYCLES PER LIFETIME	MANEUVER		BASE	
						SHEAR INTENSITY	PANEL* LOAD	SHEAR INTENSITY	PANEL* LOAD
49	n_z Roll, n_y = 0 Base	28000	3.5/.35	340	3650	852	22365	982	25777
50			5.5/.35	300	2200	619	16248	734	19267
51			5.5/.35	340	750	746	19582	982	25777
52			6.5/.35	300	175	592	15540	734	19267
53			6.5/.35	340	75	694	18217	982	25777
54	n_z Roll - n_y = -0.3 Base		3.0/.55	200	475	215	5643	304	7980
55			3.0/.55	300	525	683	17928	734	19267
56			3.0/.55	340	225	879	23072	982	25777
57			4.5/.55	300	250	644	16905	734	19267
58			4.5/.55	340	100	798	20947	982	25777
59			6.0/.55	300	75	605	15881	734	19267
60			6.0/.55	340	25	721	18926	982	25777
61	1.0g Roll		1.0/.35	200	6875	304	7980	304	7980
62			1.0/.35	300	30200	734	19267	734	19267
63			1.0/.35	340	14225	982	25777	982	25777
64	1.0g Roll - n_y = -0.3 Base		1.0/.50	200	3000	304	7980	304	7980
65			1.0/.50	300	3925	734	19267	734	19267
66			1.0/.50	340	1825	982	25777	982	25777
67			1.0/.80	200	75	304	7980	304	7980
68			1.0/.80	300	50	734	19267	734	19267
69			1.0/.80	340	25	982	25777	982	25777
70	Symmetrical Pullout	43000	2.5	200	1425	154	4042	307	8058
71			2.5	300	250	665	17456	705	18506
72			3.0	300	1100	519	13623	705	18506
73			3.5	300	575	473	12416	705	18506
74			4.5	300	125	380	9975	705	18506
75			5.0	300	75	334	8767	705	18506
76			5.5	340	50	500	13125	933	24491
77			4.0	300	325	426	11182	705	18506
78			0	300	25	798	20947	705	18506
79	Dynamic Symmetrical		2.5	200	175	156	4095	307	8058
80			2.5	300	250	565	14831	705	18506
81	Symmetrical Pullout	37500	2.5	200	450	206	5407	306	8032
82			2.5	300	1100	600	15750	718	18847
83			2.5	340	875	826	21682	941	24701
84			3.0	200	200	173	4541	306	8032
85			3.0	300	1825	561	14726	718	18847
86			3.0	340	1425	787	20658	941	24701
87			3.5	300	1525	521	13676	718	18847
88			3.5	340	1125	749	19661	941	24701
89			4.0	300	1100	482	12652	718	18847
90			4.0	340	825	709	18611	941	24701
91			4.5	300	700	443	11629	718	18847
92			4.5	340	550	672	17640	941	24701
93			5.0	300	400	405	10631	718	18847
94			5.0	340	300	634	16642	941	24701
95			5.5	300	175	365	9581	718	18847
96			5.5	340	150	595	15618	941	24701
97			6.0	300	75	325	8531	718	18847

*The panel load is the panel diagonal between loading points (26.25 in.) times the shear intensity.

A-10A TEST SPECTRUM FOR SHEAR PANELS (Continued)

COND. NO.	CONDITION DESCRIPTION	GROSS WEIGHT (LBS.)	n_z/n_y	V_e KNOTS	CYCLES PER LIFETIME	MANEUVER		BASE	
						SHEAR INTENSITY	PANEL* LOAD	SHEAR INTENSITY	PANEL* LOAD
98	Symmetrical Pullout	37500	6.0	340	50	555	14568	941	24701
99			6.5	340	50	517	13571	941	24701
100			0	200	750	374	9817	306	8032
101			0	300	100	798	20947	718	18847
102			0	340	75	1019	26748	941	24701
103			-0.5	200	25	407	10683	306	8032
104			-0.5	300	75	796	20895	718	18847
105	Dynamic Symmetrical		2.5	200	75	206	5407	941	8032
106			2.5	300	750	600	15750	718	18847
107			2.5	340	600	826	21682	941	24701
108	n_z Roll - n_y = -0.3 Base		3.5/.35	200	325	140	3675	306	8032
109	n_z Roll		3.5/.35	300	1600	521	13676	718	18847
110			3.5/.35	340	900	749	19661	941	24701
111			5.5/.35	300	250	365	9581	718	18847
112			5.5/.35	340	250	595	15618	941	24701
113	n_z Roll - n_y = -0.3 Base		3.0/.55	200	25	173	4541	306	8032
114			3.0/.55	300	100	561	14726	718	18847
115			3.0/.55	340	50	787	20658	941	24701
116			4.5/.55	300	25	443	11628	718	18847
117			4.5/.55	340	25	672	17640	941	24701
118			6.0/.55	300	25	325	8531	718	18847
119	1.0g Roll		1.0/.35	200	1075	305	8006	306	8032
120			1.0/.35	300	5975	719	18873	718	18847
121			1.0/.35	340	3525	940	24675	941	24701
122	1.0g Roll - n_y = -0.3 Base		1.0/.50	200	125	305	8006	306	8032
123			1.0/.50	300	775	719	18873	718	18847
124			1.0/.50	340	450	940	24675	941	24701
125			1.0/.80	300	25	719	18873	718	18847
126	Symmetrical Pullout	32500	2.5	200	250	232	6090	317	8321
127			2.5	300	1225	650	17062	735	19293
128			2.5	340	700	856	22470	942	24727
129			3.0	200	100	204	5355	317	8321
130			3.0	300	2000	621	16301	739	19293
131			3.0	340	1150	828	21735	942	24727
132			3.5	200	25	176	4620	317	8321
133			3.5	300	1575	593	15566	735	19293
134			3.5	340	900	798	20947	942	24727
135			4.0	300	1175	565	14831	735	19293
136			4.0	340	675	769	20186	942	24727
137			4.5	300	750	537	14096	735	19293
138			4.5	340	450	740	19425	942	24727
139			5.0	300	450	508	13335	735	19293
140			5.0	340	250	711	18663	942	24727
141			5.5	300	175	479	12573	735	19293
142			5.5	340	125	682	17902	942	24727
143			6.0	300	75	451	11838	735	19293
144			6.0	340	50	652	17115	942	24727
145			6.5	300	30	422	11077	735	19293

*The panel load is the panel diagonal between loading points (26.25 in.) times the shear intensity.

A-10A TEST SPECTRUM FOR SHEAR PANELS (Continued)

COND. NO.	CONDITION DESCRIPTION	GROSS WEIGHT (LBS.)	n_z/n_y	V_e KNOTS	CYCLES PER LIFETIME	MANEUVER SHEAR INTENSITY	MANEUVER PANEL* LOAD	BASE SHEAR INTENSITY	BASE PANEL* LOAD
146	Symmetrical Pullout	32500	0	300	100	794	20842	735	19293
147	↓	↓	0	340	25	1001	26276	942	24727
148	↓	↓	-0.5	300	100	820	21525	735	19293
149	↓	↓	-1.0	300	26	849	22286	735	19293
150	Dynamic Symmetrical	↓	2.5	200	50	232	6090	317	8321
151	↓	↓	2.5	300	825	650	17062	735	19293
152	↓	↓	2.5	340	475	856	22470	942	24727
153	δ_F = 20° - 1.0g Ground Base	28000	2.5	200	3700	237	6221	50	1312
154	δ_F = 30° - 1.0g Ground Base	↓	2.5	200	3625	237	6221	50	1312
155	δ_F - 20°	↓	2.5	200	7325	237	6221	304	7980
156	1.0g Roll - n_y = -0.3 Base	↓	1.0/.35	200	16300	304	7980	304	7980
157	Symmetrical Pullout	↓	8.0	340	1	614	16117	982	25777
158	↓	↓	8.5	340	12	588	15435	982	25777
159	↓	↓	9.0	340	6	562	14752	982	25777
160	↓	↓	9.5	340	3	537	14096	982	25777
161	↓	↓	10.0	340	2	509	13361	982	25777
162	↓	32500	7.0	300	10	394	10342	735	19293
163	↓	↓	6.5	340	17	623	16353	942	24727
164	↓	↓	7.0	340	6	596	15646	942	24727
165	↓	↓	7.5	340	15	566	14857	942	24727
166	↓	↓	8.0	340	5	536	14070	942	24727
167	↓	↓	8.5	340	1	507	13308	942	24727
168	↓	37500	7.0	340	20	477	12521	941	24701
169	↓	43000	6.0	340	6	453	11891	734	19267
170	↓	28000	-1.5	300	1	800	21000	734	19267
171	↓	↓	-2.0	300	1	812	21315	734	19267
172	↓	↓	-1.5	340	1	1112	29190	982	25777
173	↓	↓	-2.0	340	1	1140	29925	982	25777
174	↓	37500	-1.0	200	1	438	11495	306	8032
175	Land-Sink Speed 9 ft/sec	25000			12	50	1312	50	1312
176	-Sink Speed 6 ft/sec	↓			411				
177	-Sink Speed 3 ft/sec	↓			1525				
178	-Sink Speed 1 ft/sec	↓			1725				
179	Hard Brake	↓			7100				
180	Hard Brake	45522			900				
181	Medium Brake	45522			1125				
182	Turning	25000			12575				
183	Turning	45522			1125				
184	1 ± .45g Taxi	45522			50				
185	1 ± .45g Taxi	25000			300				
186	1 ± .45g Taxi	25000			25				

*The panel load is the panel diagonal between loading points (26.25 in.) times the shear intensity.

REFERENCES

1. Gasko, J.J. and Kizer, J.A., "Weldbond Flight Component Design/Manufacturing Program," AFML-TR-74-179, AD B002 822L.

2. Bowen, B.B., et al., "Development of Corrosion-Resistant Surface Treatments for Aluminum Alloys for Spot-Weld Bonding," AFML-TR-75-69, AD B008 190L.

3. Wu, K.C. and Bowen, B.B., "Aluminum Weldbond Manufacturing Methods Development," AFML-TR-76-131, AD B016 865L.

4. Fairchild Republic Corporation Report GT160R0011, dated 19 October 1973 - A-10 Component Test Report - Beaded Panel Design Allowable Test Program.

5. Szabo, R. L., "Feedback Controlled Spotwelding," AFML-TR-76-35, AD B014 690L.

6. Bowen, B.B., et al., "Improved Surface Treatment for Weldbonding Aluminum," AFML-TR-76-159.

7. Ratwani, M.M., "Characterization of Fatigue Crack Growth in Bonded Structures - Crack Growth Predication in Bonded Structures," AFFDL-TR-77-31, Volume 1, AD A046 280, June 1977.

8. Ratwani, M.M., "Characterization of Fatigue Crack Growth in Bonded Structures - Analysis of Cracked Bonded Structures," AFFDL-TR-77-31, Volume II, AD A046 179, June 1977.

9. Chanani, G.R., "Fundamental Investigation of Fatigue Crack Growth Retardation of Aluminum Alloys," AFML-76-156, AD A037 184, September 1976.

10. Remmel, T.P., "Characterization of Surfaces Prior to Adhesive Bonding," AFML-TR-76-118, AD A034 826.

☆U.S. Government Printing Office: 1979 — 657-002/652