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PRODUCTION ENGINEERING MEASURES PROGRAM
MANUFACTURING METHODS AND TECHNOLOGY

ULTRASONIC WELDING OF HELICOPTER SECONDARY STRUCTURE COMPONENTS

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Final Report
Contract No. DAAJ01-76-C-0913

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Prepared for

US ARMY AVIATION RESEARCH AND DEVELOPMENT COMMAND
St. Louis, Missouri 63166

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Ultrasonic welding was evaluated as a means for assembling helicopter secondary structures. Such welds in several combinations of 2024-and 6061 aluminum alloys demonstrated tensile-shear strengths of more than 2.5 times the strength of resistance spot welds. Inner and outer skins of helicopter doors (0.020-inch 2024-T3 Alclad to 0.025-inch 6061-T6 Alclad aluminum alloys) assembled by this process successfully withstood air loads of

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five to ten times the design loading for the door. Such doors could be ultrasonically assembled in 40 minutes, compared to 2.7 hours assembly time for the adhesive bonding process. Manufacturing labor cost savings of 75 percent and energy cost savings of 99+ percent were anticipated. A process specification for use of ultrasonic welding in nonstructural and secondary structure components for AAH aircraft was prepared for use at Hughes Helicopters. It was recommended that the process be validated for other materials and material combinations and that ultrasonic welding and ultrasonic weld bonding be evaluated for aircraft primary structures.

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SUMMARY

Ultrasonic welding (solid-state bonding) is recognized to offer potential cost savings in the manufacture of nonstructural and secondary structure components for aircraft. Accordingly, a Manufacturing and Methods Technology program was undertaken to develop and validate ultrasonic welding as a viable manufacturing process for the helicopter industry. A corollary of this task was to prepare a process specification that would define the manufacturing requirements for both the ultrasonic joining process and the ultrasonic welding machine.

For implementation of these objectives, multiple ultrasonic welds were made in several combinations of 2024-and 6061 clad aluminum alloys and in several thicknesses of 6Al-4V titanium alloy. Weld coupons were evaluated by tensile-shear tests, fatigue tests, salt-spray tests, and metallographic examination. In addition, four access doors for a YAH-64 helicopter were assembled by ultrasonic welding and subjected to simulated flight testing.

The ultrasonic welds demonstrated ultimate shear strengths of more than 2.5 times the strength of resistance spot welds. For example, of 78 ultrasonic welds between 0.020-inch 2024-T3 Alclad and 0.025-inch 6061-T6 Alclad materials, the average failure load was 617 pounds and the minimum was 543 pounds. For resistance welds in 0.020-inch aluminum alloys, the required minimum average (per MIL-W-6858B) is 140 pounds and the required minimum is 110 pounds. In this case, the ultrasonic weld is about four times stronger.

The weld strengths were confirmed by air load tests on the ultrasonically welded access doors, which sustained loads, without weld failure, of five to ten times the design load of 461 pounds for the door.

Estimated cost savings of about 75 percent in manufacturing labor and 99+ percent in energy were projected for the ultrasonic welding process as a replacement for adhesive bonding. For a production run of 535 YAH-64 aircraft, this was extrapolated to an estimated saving of \$163,000 in labor and \$62,000 in energy costs.

An ultrasonic welding process specification was prepared by Hughes and has been provisionally accepted as a standard for fabrication of such access doors. The process has potential for numerous other types of aircraft secondary structures.

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It was recommended that ultrasonic weld strength data be developed for a range of material and material thickness combinations and that the process be further evaluated for joining aircraft primary structures. Ultrasonic weld bonding (combining ultrasonic welding with adhesive bonding) also merits investigation for this purpose.

PREFACE

This final report was prepared by Sonobond Corporation, West Chester, Pennsylvania, and Hughes Helicopters, Culver City, California, under Army Contract No. DAAJ01-76-C-0913. The work was carried out under the sponsorship of the U. S. Army Aviation Research and Development Command (AVRADCOM), St. Louis, Missouri, with Mr. Robert G. Vollmer of AVRADCOM serving as Contracting Officer's Representative. At Sonobond Corporation, Philip C. Krause was the Program Manager, and Janet Devine, Director of Engineering, was responsible for the technical aspects of the program. At Hughes Helicopters, Gordon K. Dingle was the project engineer in charge of the program.

Hughes provided the materials for the welding of test coupons and fabrication of sample door parts, provided a door assembly welding fixture, conducted static and dynamic tests and other evaluations of the weldments, prepared an ultrasonic welding process specification, and provided other guidance as required to orient the process to end-item use.

Sonobond supplied the ultrasonic welding equipment and tooling, conducted the actual welding of the test coupons and the sample door assemblies, and provided general coordination of the work. Close liaison was maintained between the two companies throughout the program.

This project was accomplished as part of the U. S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U. S. Army Research and Development Command, ATTN: DRDAV-EXT, P. O. Box 209, St. Louis, MO 63166.

TABLE OF CONTENTS

	Page
SUMMARY	iii
PREFACE	v
LIST OF ILLUSTRATIONS	viii
LIST OF TABLES	ix
INTRODUCTION	1
Description of Ultrasonic Welding	2
Current Fabrication Techniques	4
Preliminary Ultrasonic Welding Investigations . . .	5
Selection of Secondary Structure	5
WELDING MACHINE MODIFICATION AND FIXTURE DESIGN	9
Description of Welding Machine	9
Equipment Checkout	10
Welding Fixture for Access Door	16
WELD COUPON FABRICATION AND TESTING	18
Coupon Materials	18
Coupon Preparation	19
Coupon Evaluation	19
COMPONENT FABRICATION AND TESTING	37
Fabrication of First Door Assembly	37
Door Assembly Testing	37
Fabrication of Additional Door Assemblies	41
Tests on Additional Door Assemblies	43
Conclusions from Door Assembly Testing	45

	Page
PROJECTED COST EFFECTIVENESS OF ULTRASONIC WELDING . . .	47
Assembly Sequence	47
Direct Labor Costs	48
Energy Costs	48
Equipment Costs	48
ULTRASONIC WELDING PROCESS SPECIFICATION	49
CONCLUSIONS AND APPLICATIONS	50
RECOMMENDATIONS	54
APPENDIX A. PHOTOMICROGRAPHS OF TYPICAL ULTRASONIC WELDS	55
APPENDIX B. HUGHES PROCESS SPECIFICATION HP 11-9: ULTRASONIC WELDING	63

LIST OF ILLUSTRATIONS

Figure No.		Page
1	Typical Arrangement for Ultrasonic Spot Welding	3
2	Photomicrographs of Resistance and Ultrasonic Welds in 2024-T3 Alclad	3
3	Structure of Ultrasonically Welded 0.050-Inch 2024-T3 Alclad	6
4	Ultrasonic Weld Between 0.032-Inch 2024-T3 Alclad and 0.040-Inch Bare 2024-T3 Alloys	6
5	YAH-64 Access Door Assembly	8
6	M-8000 Ultrasonic Welder with Frequency Converter and Sanborn Recorder	11
7	Indentation Measurements on Representative Welds	12
8	Tensile-Shear Strength Versus Clamping Force	14
9	Strip-Chart Records of Ultrasonic Power Delivery at Various Clamping Forces	14
10	Tensile-Shear Strength Versus Power at 1700-Pound Clamping Force	15
11	Door Skins in Fixture with Hold-Down Bar in Place	17
12	Welding Fixture Showing Holes for Anvil to Penetrate	17
13	Geometry of Weld Coupons After Shearing	21
14	Probability Plot of Strength of Ultrasonic Spot Welds in 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad	24
15	Comparison of Ultrasonic and Resistance Weld Strengths in 2024-T3 Alclad	32
16	Ultrasonic Weld Strength of 0.016-Inch Ti-6Al-4V to Dissimilar Thicknesses of Same Material	33

Figure No.		Page
17	Fatigue Strength of Ultrasonically Welded Coupons	34
18	Test Setup for Ultrasonically Welded Door Assembly	39
19	Door Assembly No. 1 After Air Load Test . .	39
20	Results of Simulated Flight Test	40
21	Modified Weld Spacing on Door Assemblies .	42
22	Door No. 2 Edge Failure and Weld Failure Locations	44
23	Deflection Data for All Ultrasonically Welded Access Door Assemblies	44
24	Conceptual Design of Portable Ultrasonic Spot Welder for Aircraft Structures	53

LIST OF TABLES

Table No.		Page
1	Coupon Welding Parameters	20
2	Tensile-Shear Test Results for Coupons of 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad Materials	23
3	Miscellaneous Coupon Tensile-Shear Test Results	26
4	Summary of Coupon Test Results	31
5	Fatigue Test Loads	34
6	Possible Applications of Ultrasonic Welding for Aircraft Secondary Structures	52

INTRODUCTION

The objectives of this program were to demonstrate the effectiveness of ultrasonic welding as a high-production, low-cost method of fabricating helicopter secondary structural parts (components) and to develop a process specification for ultrasonic welding of helicopter components.

Helicopter designers in the past have concentrated most of their efforts on the dynamics and performance of the airframe. Only those production processes which would provide well-known and highly reliable results were used. This approach has resulted in the mandatory use of some processes that have proven to be costly and has prohibited the use of other processes which could possibly be more economical. The impact of this approach has been more expensive helicopters and associated systems.

Government and industry personnel are currently striving to achieve lower costs in the manufacture of aircraft components and systems. A recent study program* in ultrasonic manufacturing processes, conducted for AVRADCOM by Sonobond Corporation, indicated that ultrasonic welding would be cost effective when used for the assembly of certain secondary structures of a helicopter.

Ultrasonic welding has been extensively used in various other applications, such as the automotive field, electrical and electronics industries, aluminum foil manufacturing and processing, packaging and encapsulation, and has been found to reduce material and labor costs, to increase production rates, and to provide joints of high strength and integrity.

The process, however, has not heretofore been used in aircraft component fabrication because there are no existing specifications for the process, and structural allowables for design are not readily available. The program described herein was therefore oriented to providing the structural information and the specification, so that helicopter designers and manufacturing process engineers can evaluate and use this new process whenever it offers a potential for lower production cost.

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* Meyer, F. R., "Engineering Feasibility Study of Ultrasonic Applications for Aircraft Manufacture." Research Report 73-15, Aeroprojects Incorporated, Army Contract DAAJ01-72-C-0737(P1G), September 1973. (Since August 1974, Aeroprojects Incorporated has been operating under the name of Sonobond Corporation. The technology and facilities formerly held by Aeroprojects have been retained by Sonobond.)

The work consisted essentially of ultrasonically welding coupons of various combinations of aluminum and titanium alloys and comprehensive evaluation of the welds, followed by the ultrasonic welding and evaluation of actual helicopter access door assemblies. The results of these evaluations were used in preparing the preliminary process specification.

DESCRIPTION OF ULTRASONIC WELDING

The ultrasonic welding process was originated more than 20 years ago at Sonobond Corporation. Since then, the development of its technology has been aggressively pursued. Equipment and techniques have been evolved for ultrasonic spot welding, continuous-seam welding, and ring welding. Activities in this area have included studies in optimization of equipment of each type; investigations in the weldability of a wide variety of metals and alloys; development of techniques and tooling for numerous specific applications; and production engineering and manufacture of welding equipment for industrial use.

Basically the process consists of clamping the parts to be joined under moderate pressure between a welding tip and a supporting anvil, and introducing high-frequency vibratory energy into the material for a brief interval. For spot and ring welds, this interval is usually less than 1 second. A representative arrangement for ultrasonic spot welding is shown in Figure 1.

The welding tip is made to vibrate in the shear mode, i.e., in a plane essentially parallel to the weld interface and perpendicular to the axis of static force application. This lateral or shear vibration breaks up and disperses oxides and other surface films at the interface and introduces dynamic stresses into the metal, producing elastoplastic deformations which in turn create a moderate temperature rise in the weld zone. Despite this temperature rise, ultrasonic welding is actually a solid-state bonding process. Metallographic studies have revealed no evidence of melting in the bond area. There are thus no cast nuggets in the weld zone, as shown in Figure 2, and no intermetallics in dissimilar metal joints that accelerate fatigue failure.

Ultrasonic welding may be used to join a wide variety of similar and dissimilar metals and alloys in a variety of joint geometries. Aluminum and its alloys, including the high-strength structural alloys such as 2014, 2024, 7049, and 7075, are among the most readily weldable materials. Such alloys may be welded in any available form (extruded, rolled, cast, etc.) or with any type of heat treatment (0, T3, T6, etc.), frequently in thicknesses up to 0.100 inch. Sintered aluminum powder can also be welded. Soft aluminum claddings on the surfaces of these metals

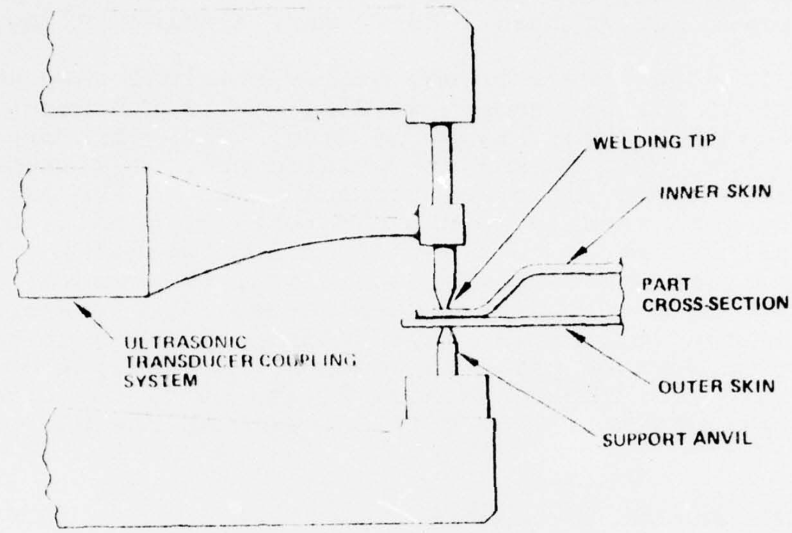
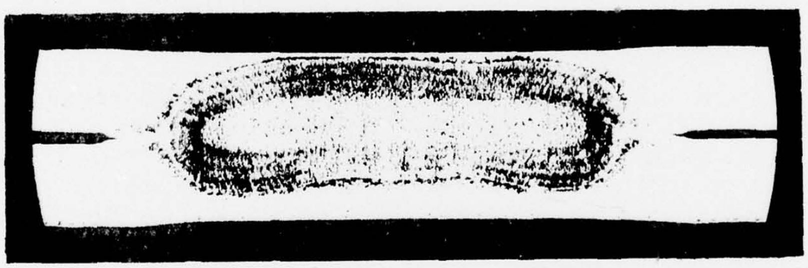
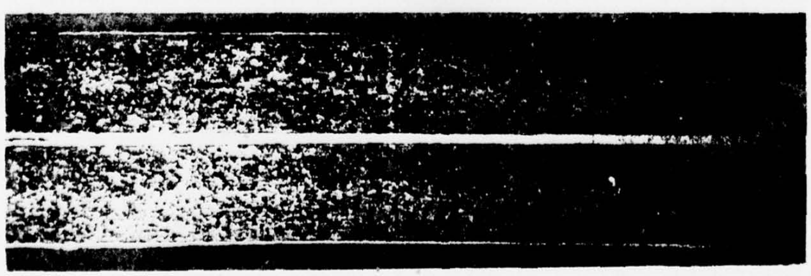


Figure 1. Typical Arrangement for Ultrasonic Spot Welding.



Resistance Spot Weld in 0.040-Inch Material.



Ultrasonic Spot Weld in 0.050-Inch Material.

Figure 2. Photomicrographs of Resistance and Ultrasonic Welds in 2024-T3 Alclad Aluminum Alloy.

facilitate bonding; for example, 2024-T3 Alclad may be welded at lower power levels than 2024-T3 bare aluminum alloy.

Surface cleanliness is not highly critical when preparing most materials for ultrasonic welding, as is the case with adhesive bonding or resistance welding. The vibratory displacements occurring during the welding process disrupt the normal oxide layers and other surface films on the mating surfaces. The more readily weldable materials, such as clad aluminum alloys, brass, and copper, can be welded in the mill-finish condition and usually require only the removal of surface lubricants with a detergent or degreaser. Other materials, such as titanium and its alloys, may contain a heavy heat-treat scale which must be removed prior to welding. A chemical etch is generally used for this purpose. In any case, the time between cleaning and welding is not critical with ultrasonic welding.

CURRENT FABRICATION TECHNIQUES

Aircraft secondary structures are usually joined by resistance spot welding, riveting, and adhesive bonding. These processes all have limitations with regard to processing techniques, required times, or joint quality.

Resistance Spot Welding

Resistance spot welding is usually avoided because of the unpredictable fatigue qualities inherent in such welds. Resistance welding is accomplished by melting the metal in the weld zone and squeezing the parts together. As in other processes involving elevated temperature, the material in the heated area undergoes grain enlargement or "recasting," due to the rapid melting and cooling. Such changes in the crystalline structure reduce both the strength of the assembly and its life, because the weld-affected area fails in fatigue. The helicopter, with all its cyclic vibrations, is especially susceptible to this type of failure. In addition, spot-welded parts tend to wrinkle and creep due to deformation of the material while the weld zone is molten and under clamping pressure.

Riveting

Riveting has not been widely used in the assembly of secondary structures because of the expense of fabrication, which involves drilling the holes, preparing the sheets, deburring the drilled holes, inserting the rivets, upsetting, etc. In some instances, riveting is accomplished with a Gemcor DRIVMATIC machine, which automatically punches the holes through the sheets, countersinks the holes, inserts the rivets, upsets the rivets, and flush-machines the surface. However, this machine is comparatively slow and expensive. Its cyclic capability, quoted by the manufacturer at approximately 18 rivets per minute, has been established in production at a maximum rate of 7.2 rivets per minute under ideal conditions.

Adhesive Bonding

Adhesive bonding is the most common method of joining secondary structures at Hughes Helicopters. The repetitive strength of bonding is quite predictable, but extreme care must be taken to ensure cleanliness of the assemblies before and during the bonding operation. Access doors used at Hughes typically have compound curves at the faying surfaces, and various clamping pressures are required to correct for contour mismatches between the various parts and for compressing the parts to the required position for bonding. The assembly must be heated to 270° to 300°F and held at that temperature range for 15 to 20 minutes to cure the adhesive. After curing, the assembled door and fixture must be cooled sufficiently to allow handling.

PRELIMINARY ULTRASONIC WELDING INVESTIGATIONS

Ultrasonic welding offered promise of alleviating most of the problems associated with the conventional joining processes. It appeared that high-strength bonds could be obtained in shorter times and without the complications of meticulous surface preparation or use of elevated temperatures.

To confirm the reported benefits prior to undertaking this program, Hughes Helicopters conducted brief exploratory investigations on ultrasonically welded coupons supplied by Sonobond Corporation. The average shear strength proved to be more than 2.5 times the average strength usually demonstrated by resistance spot welds. Fatigue strength was within the upper limits for resistance welds. Metallographic examination of the welded coupons showed that some heat effects, such as recrystallization and grain boundary segregation, may occur. However, the heat was not sufficient to produce a cast nugget (Figure 2), which in turn would result in degradation of the weld. Photomicrographs of typical ultrasonic welds in 2024-T3 aluminum alloy are shown in Figures 3 and 4.

SELECTION OF SECONDARY STRUCTURE

The first part of the program consisted of evaluation of the weldability of several aluminum and titanium alloys in

Figure 3. Structure of Ultrasonically Welded 0.050-Inch 2024-T3 Alclad Aluminum Alloy (150X).

Figure 4. Ultrasonic Weld Between 0.032-Inch 2024-T3 Alclad (top) and 0.040-Inch Bare Aluminum Alloys (150X).

various thickness combinations up to 0.100 inch. Welded coupons of these combinations were evaluated by shear and fatigue strength tests, by salt spray tests, and by metallographic examination. The ultrasonic welding process was then demonstrated in the fabrication of a secondary structure component.

Certain criteria were considered in selecting a secondary structure for this purpose. Because of limitations of available ultrasonic welding equipment, the selected assembly should require a machine throat depth of no more than about 13 inches. In addition, for ease of fabrication, the assembly should be hand-held.

A review of the access doors on the YAH-64 Advance Attack Helicopter (AAH) resulted in the selection of the port electronic access door as a likely candidate. This door assembly (P/N 7-111220115) was initially constructed of an inner skin, outer skin, and 0.75-inch aluminum honeycomb core, and weighed 5.5 pounds. After the door assembly was redesigned to accommodate the ultrasonic welding technique, the calculated weight was 3.3 pounds (a 40 percent reduction in weight). The redesigned door is defined on Hughes Helicopters Drawing 369ASK2043 and is illustrated in the sketch of Figure 5.

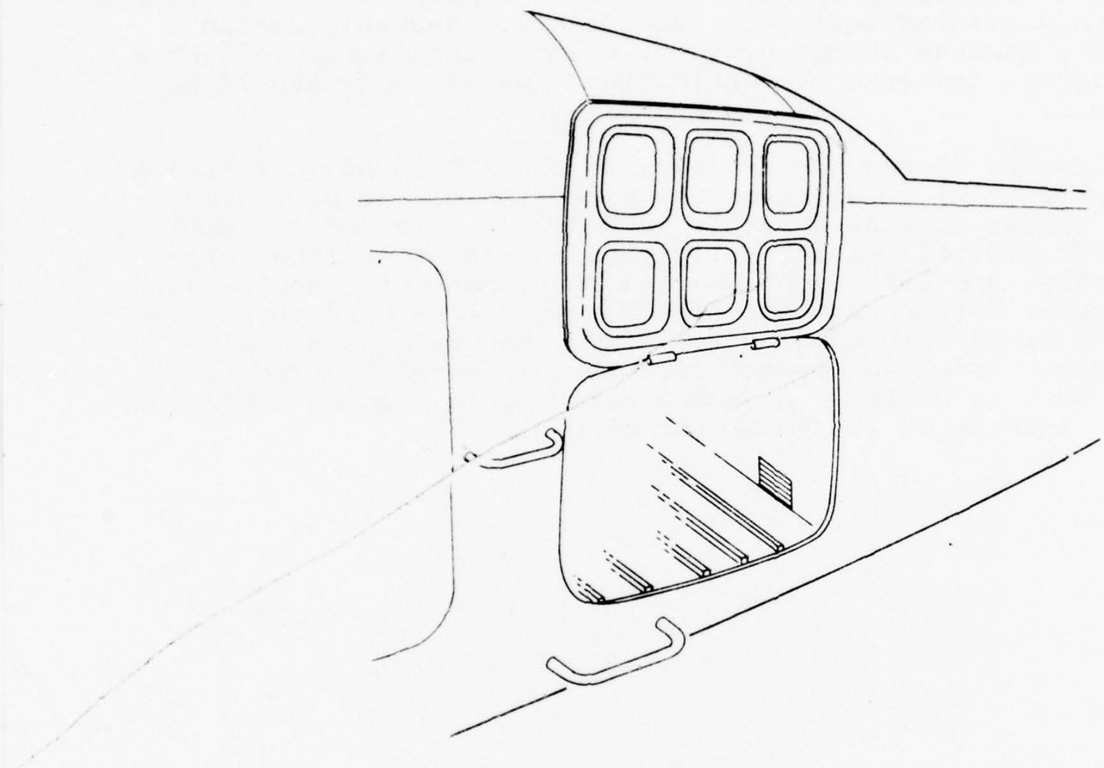


Figure 5. YAH-64 Access Door Assembly

WELDING MACHINE MODIFICATION AND FIXTURE DESIGN

DESCRIPTION OF WELDING MACHINE

All welding for the program was carried out on a Sonobond Model M-8000 ultrasonic spot welder. This welder was equipped with a standard wedge-reed transducer-coupling system (shown schematically in Figure 1) in which the transducer transmits lateral vibrations through a wedge coupler, inducing flexural vibration of the perpendicular reed member attached to it, so that the welding tip at the lower end of the reed executes shear vibration on the surface of the weldment. The transducer consisted of piezoelectric ceramic elements enclosed in a tension-shell assembly and operated at a nominal frequency of 15 kilohertz. It was capable of accepting 4.2 kilowatts of radio-frequency (RF) power when operating on an intermittent 50-percent duty cycle. Standard tooling consisted of a screw-on tip with a 3-inch spherical radius and a screw-on flat anvil tip, both of which had an electro-discharge machined (EDM) surface finish equivalent to 300 grit.

The standard frame of the M-8000 welder had a useful throat depth of 11 inches. This frame was modified to provide a 13-inch throat depth to obtain the clearance required for the interior welds of the selected access door.

The welding machine was driven by a solid-state frequency converter with a transistor hybrid-junction amplifier. The converter operated at a nominal frequency of 15 kilohertz, with provisions for tuning to the precise operating frequency of the welder. The power output was variable up to about 4000 rms RF watts.

The frequency converter incorporated a wide-band RF power measuring circuit, which sampled the output power and detected the forward power and the load power based upon the principle of directional coupling in a transmission line. The signal was processed electronically to provide true rms values, which were selectively displayed on a LED panel meter as either the forward power or the load power. Forward power is the output of the frequency converter delivered to the transducer in the welding head. Load power is the transducer drive power that is acoustically absorbed by the anvil. The difference between forward and load power readings represents the reflected power induced by the load impedance mismatch, and is minimized during welding operations by impedance matching techniques.

In addition to the load power readout displayed on the frequency converter panel, the output of the power meter was monitored by a Sanborn Model 150 strip-chart recorder calibrated for these measurements. The welding clamping force was similarly monitored. A strain gage pressure transducer was installed in the hydraulic system of the welder, and this signal was recorded as a third channel on the Sanborn recorder.

Thus, the principal welding machine settings--power, clamping force, and weld time interval (obtained via chart speed)--were recorded for each weld of both coupons and doors. The experimental welder setup is shown in Figure 6.

EQUIPMENT CHECKOUT

Preliminary welding tests were made with the modified welder for checkout and qualification of its performance, instrument calibration, and determination of welding and anvil tip contours for most effective welding. These checkout tests were made using a 0.020-inch/0.020-inch 2024-T3 Alclad aluminum alloy combination in order to conserve the certified material supplied by Hughes Helicopters for the test coupon welding.

Sonotrode tip contour was investigated in an effort to (1) minimize weld spot indentation and distortion (cupping) of the material and (2) minimize surface cladding expulsion in the area of the weld. The investigation encompassed tips with spherical radii of 1, 2, and 3 inches. All tips were roughened by EDM, using a suitably contoured electrode to provide a "toothed" surface for welding. The flat-faced anvil tips were similarly roughened. The tips were provided with surface roughnesses equivalent to 200 and 300 grit finish.

Evaluation of welds made with various tip combinations indicated minimum indentation, distortion, and cladding damage with 2-inch and 3-inch radius tips and EDM 300 tip finish. Differences in weld quality between the 2-inch and 3-inch tips at the welding conditions investigated were minimal. These results were confirmed with the material combination 0.020-inch 2024-T3 Alclad/0.025-inch 6061-T6 Alclad, which was the combination selected for the access door. The 3-inch-radius, EDM 300 welding tip finish contour was selected for use in the welding program.

Indentation measurements on coupons of 0.020-inch 2024-T3 Alclad to 0.025-inch 6061-T6 Alclad welded at 1100 watts power, 1700 pounds clamping force, and 0.5 second weld time showed a maximum indentation of 0.002 inch for the 2-inch and 3-inch spherical radius tips. A series of measurements taken on a plane through the weld center is shown in Figure 7.

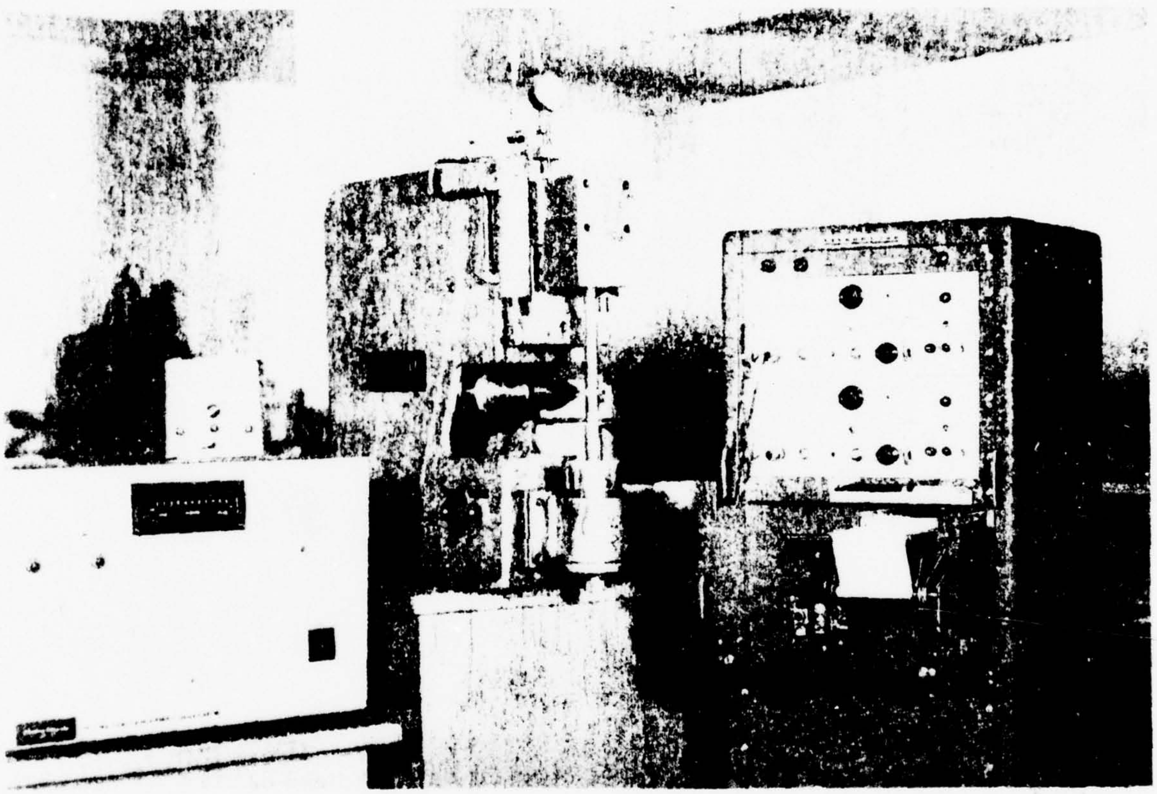


Figure 6. M-8000 Ultrasonic Welder (center) with Frequency Converter (left) and Sanborn Recorder (right).

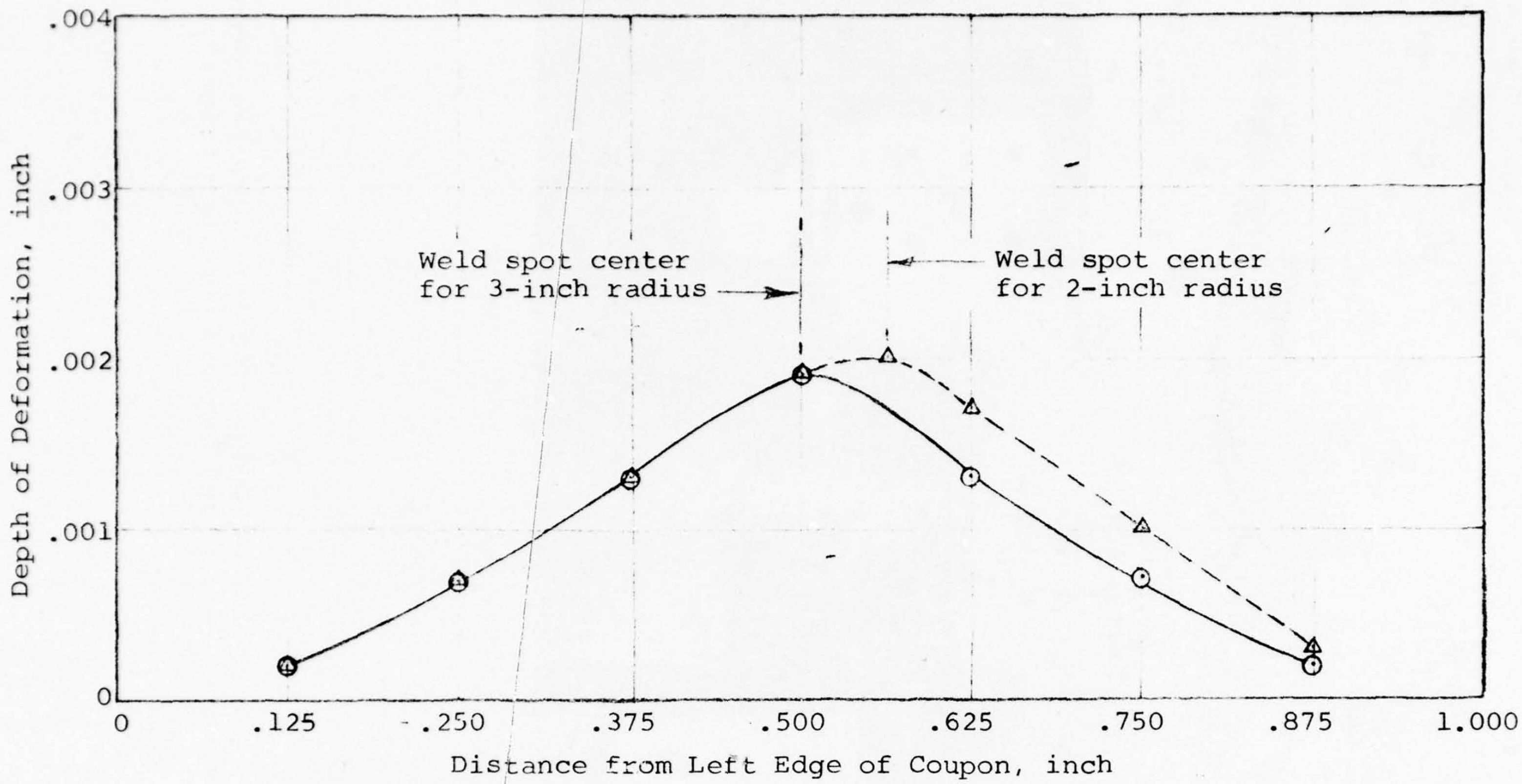


Figure 7. Indentation Measurements on Representative Welds - 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.

For each material combination to be ultrasonically welded, there is an optimum combination of the three variables of power, clamping force, and weld time which produces the best welds. The method of selecting these optimum settings is illustrated by the data presented in Figures 8, 9, and 10. In this case, the material combination was 0.025-inch 6061-T6 Alclad/ 0.020-inch 2024-T3 Alclad. Welding was performed with the 6061-T6 material adjacent to the spherical welding tip (the orientation to be used with the selected access door assembly). The data for Figures 8 and 10 were derived from tensile-shear tests, conducted on an Instron Model TT-C-L testing machine, on 1-inch-wide, overlapped, single-weld test coupons.

Figure 8 shows the variation of tensile-shear strength with clamping force at two power input levels and constant weld time. Maximum weld strength was obtained at the clamping force which provided the best load impedance match and maximum energy delivery into the workpiece. The influence of clamping force (CF) on power delivery is shown by the strip-chart records of load power in Figure 9. The optimum clamping force (in this case, 1700 pounds) resulted in a more constant load impedance condition and maximized energy delivery. These power response traces, obtained from the strip-chart oscillograph, verified the optimum clamping force obtained by the tensile-shear tests (Figure 8), thus offering a simplified approach to selection of an optimum clamping force.

Tensile-shear strength data obtained at increasing load power levels at the optimum clamping force of 1700 pounds are shown in Figure 10. The curve shows that input power levels higher than those associated with nugget tear-out failure of the coupon produce a diminishing strength increase. Growth of the weld area (weld spot size) at the higher power levels results in slightly higher strength values (in this case at approximately 1100 watts), but the increased scatter in the values at significantly higher power levels (1300 watts) signals the onset of degradation due to overwelding.

Analysis of these data indicated that the 0.025-inch 6061-T6/0.020-inch 2024-T3 material combination should be welded using the following machine settings:

Power:	1100 watts
Clamping force:	1700 pounds
Time interval:	0.5 second.

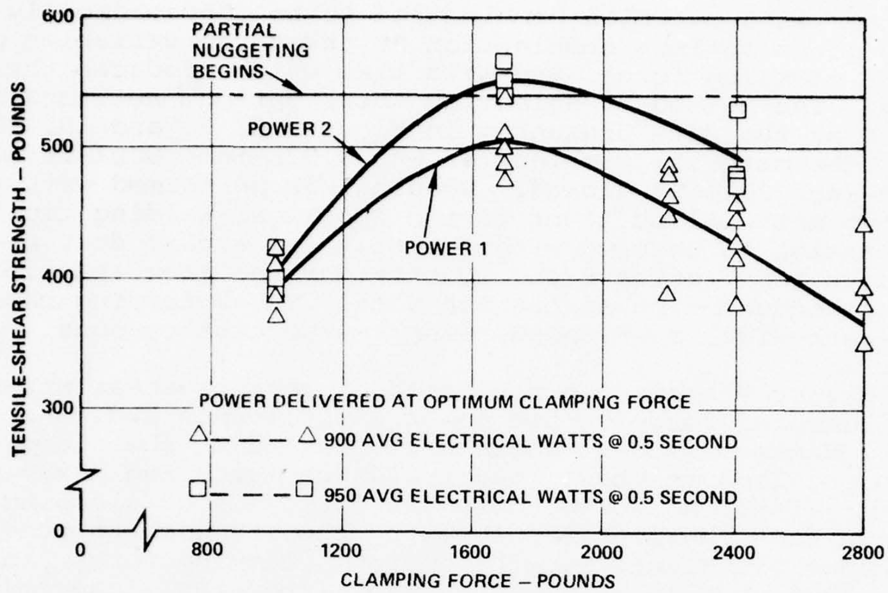


Figure 8. Tensile-Shear Strength Versus Clamping Force - 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.

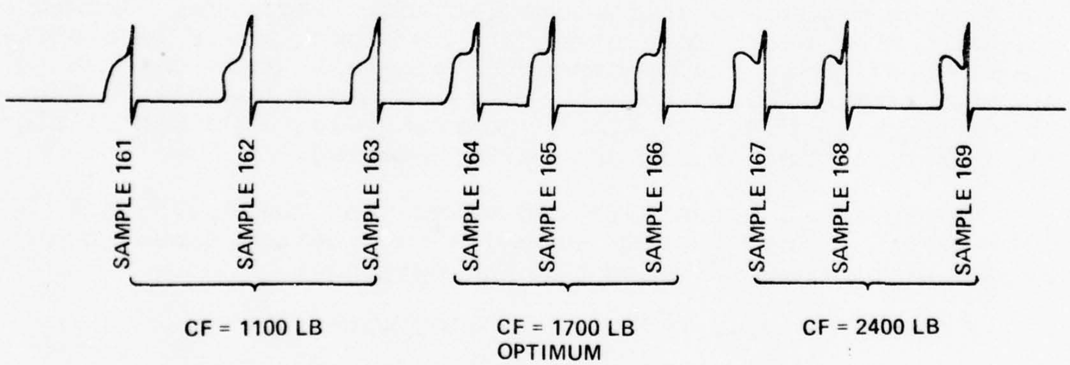


Figure 9. Strip-Chart Records of Ultrasonic Power Delivery at Various Clamping Forces.

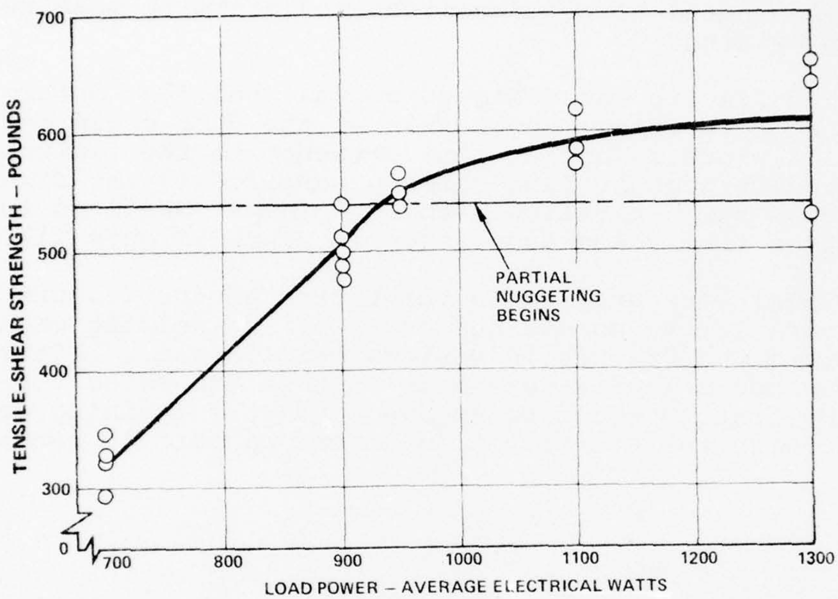


Figure 10. Tensile-Shear Strength Versus Power at 1700-Pound Clamping Force - 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.

WELDING FIXTURE FOR ACCESS DOOR

Hughes Helicopters designed and fabricated a fixture to support the selected access door assembly during ultrasonic welding. The fixture design, depicted on Hughes Helicopters Drawing 369ASK2044 and in Figures 11 and 12, was coordinated with Sonobond Corporation for compatibility of fixture and welding machine. The fixture was fabricated of epoxy fiberglass laminates to reduce weight and minimize mass resonance during welding.

The fixture was designed so that the flat outer skin and the formed (waffled) inner skin of the door could be nestled in the fixture. Tooling pins attached to the fixture were inserted through tooling holes predrilled in the skins. A hold-down bar, installed with "C" clamps, was used to hold the skins firmly and accurately in place (Figure 11).

Holes were drilled in the bottom of the fixture, as shown in Figure 12, to permit the anvil of the welding machine to penetrate the fixture in various weld locales. After a suitable number of welds were made to hold the skins together, the welding fixture could be removed and the remaining welds completed with the assembly held in the operator's hands.

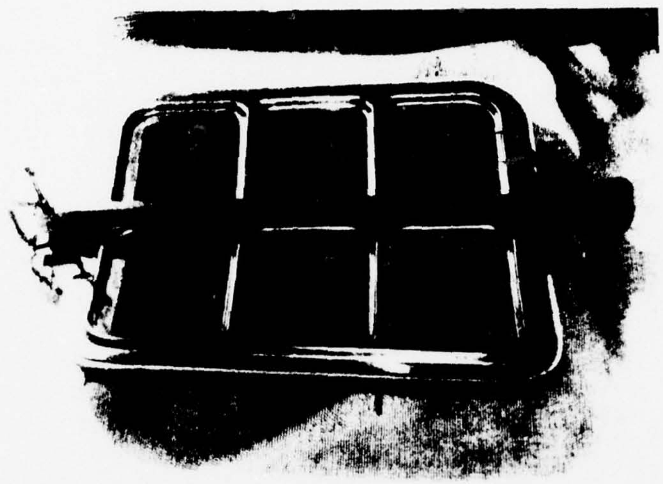


Figure 11. Door Skins in Fixture with Hold-Down Bar in Place.

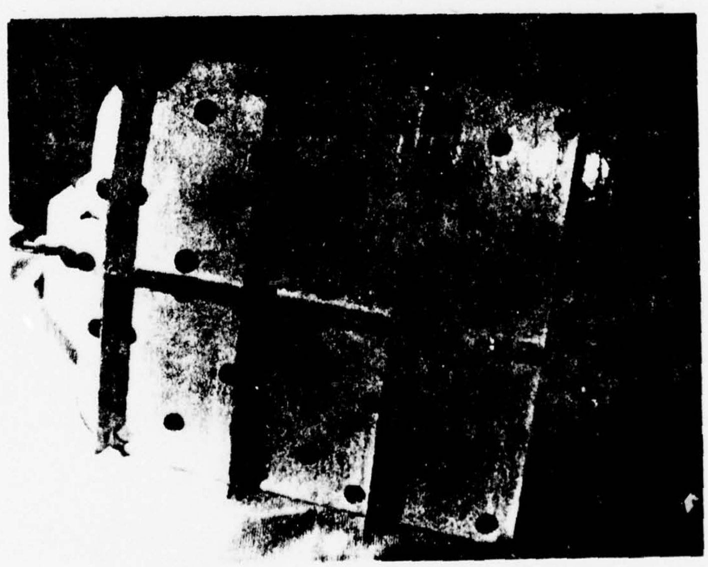


Figure 12. Welding Fixture Showing Holes for Anvil to Penetrate.

WELD COUPON FABRICATION AND TESTING

Welded coupons of various aluminum and titanium alloy combinations were fabricated and tested in order to establish satisfactory welding machine settings for these combinations, to bracket the weld strengths, and to verify the repeatability of the welding machine.

COUPON MATERIALS

Weld coupons were prepared from the material combinations listed below. All materials were supplied by Hughes Helicopters and were certified to conform to military specifications. For combination a, the materials were supplied in sheets 5 feet long by 5 inches wide. Sheets for all other materials were 25 inches long by 5 inches wide. The combinations were:

a. 0.020-inch 2024-T3 Alclad to 0.025-inch 6061-T6 Alclad

b. 0.020-inch 2024-T3 Alclad to 0.025-inch 6061-0 Alclad

c. 0.016-inch 2024-T3 Alclad to 0.016-inch 2024-T3 Alclad

d. 0.016-inch 2024-T3 Alclad to 0.040-inch 2024-T3 Alclad

e. 0.016-inch 2024-T3 Alclad to 0.063-inch 2024-T3 Alclad

f. 0.016-inch 2024-T3 Alclad to 0.100-inch 2024-T3 Alclad

g. 0.016-inch 6Al-4V titanium to 0.020-inch 6Al-4V titanium

h. 0.016-inch 6Al-4V titanium to 0.040-inch 6Al-4V titanium

i. 0.016-inch 6Al-4V titanium to 0.063-inch 6Al-4V titanium

j. 0.032-inch 2024-T3 Alclad to 0.032-inch 2024-T3 Alclad

k. 0.040-inch 2024-T3 Alclad to 0.040-inch 2024-T3 Alclad

l. 0.063-inch 2024-T3 Alclad to 0.063-inch 2024-T3 Alclad

m. 0.100-inch 2024-T3 Alclad to 0.100-inch 2024-T3 Alclad.

The above list reflects several changes from the scope of work originally specified for the program:

1. The thickness of the 6061-T6 and 6061-0 Alclad materials (combinations a and b) was increased from 0.020 inch to 0.025 inch to reflect the door assembly final design.

2. The thicker material combinations of 2024-T3 Alclad (combinations j, k, l, and m) were added to provide additional weldability data.

3. Additional coupons of the 0.040-inch 2024-T3 Alclad (combination k) were welded with minimum overlap to established the effect of edge distance of an ultrasonic weld.

COUPON PREPARATION

For each material combination, the long dimensions of the sheets were overlapped by approximately 2 inches, and ultrasonic spot welds were spaced at intervals of 1.00 ± 0.06 inch along the center of the overlap. In each case, optimum welding machine parameters were selected based on oscillograph traces of the energy delivery into the workpiece, as described in Figure 9. The final parameters selected for each combination are shown in Table 1.

After welding, each assembly was sheared into single-weld coupons, approximately 8 inches long by 1 inch wide, as shown in Figure 13a. A backup sheet was used when the panels were sheared to preclude notch effects which would compromise the validity of the fatigue and tensile-shear tests.

For the minimum-overlap coupons of combination k, the panels were overlapped a minimum amount and ultrasonically welded on 1-inch centers to provide an edge distance (distance from edge of weld spot to edge of sheet) which varied from 0 to 1/8 inch (Figure 13b).

For material combination a (the combination intended for the access door assembly), a minimum of 100 welds were prepared for evaluation. Twenty-five welds each were prepared for all other combinations.

COUPON EVALUATION

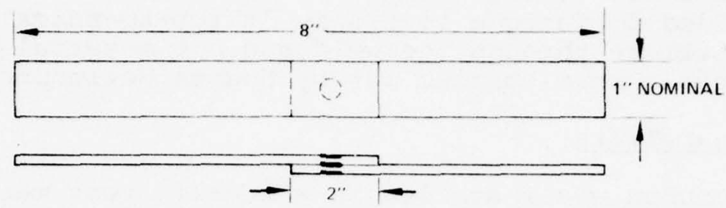
The welded coupons were evaluated by tensile-shear tests, fatigue tests, and metallographic examination to establish that surface cladding expulsion and metal distortion were minimal and that the ultrasonic weld strength was within the access door specification requirements.

Of the coupon samples prepared from material combination a, 96 were tensile-shear tested, one was metallographically evaluated, and 18 were scrapped because the welds were excessively off-center. Of the 25 each coupons prepared from the

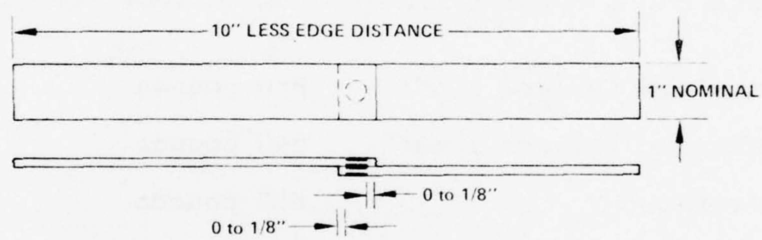
Table 1. Coupon Welding Parameters

Material Combination Welding Tip Side/ Anvil Side	Welding Conditions			Expected Tensile-Shear Strength* (lb)
	Power (Average RF Watts)	Clamping Force (lb)	Welding Time (sec)	
a. 0.025-inch 6061-T6 Alclad/ 0.020-inch 2024-T3 Alclad	1000-1100	1700	0.5	607
b. 0.025-inch 6061-0 Alclad/ 0.020-inch 2024-T3 Alclad	1400-1500	420	0.5	340
c. 0.016-inch 2024-T3 Alclad/ 0.016-inch 2024-T3 Alclad	950-1000	800	0.5	500
d. 0.016-inch 2024-T3 Alclad/ 0.040-inch 2024-T3 Alclad	1100	1200	0.5	500
e. 0.016-inch 2024-T3 Alclad/ 0.063-inch 2024-T3 Alclad	900-950	1300	0.5	450
f. 0.016-inch 2024-T3 Alclad/ 0.100-inch 2024-T3 Alclad	1050-1150	880	0.5	525
g. 0.016-inch 6Al-4V Titanium/ 0.020-inch 6Al-4V Titanium	3000	600	1.5	-
h. 0.016-inch 6Al-4V Titanium/ 0.040-inch 6Al-4V Titanium	3200	1100	1.5	-
i. 0.016-inch 6Al-4V Titanium/ 0.063-inch 6Al-4V Titanium	3500	1100	1.5	-
j. 0.032-inch 2024-T3 Alclad/ 0.032-inch 2024-T3 Alclad	3500	1400	0.75	-
k. 0.040-inch 2024-T3 Alclad/ 0.040-inch 2024-T3 Alclad	3700-4000	1750	1.25	-
l. 0.063-inch 2024-T3 Alclad/ 0.063-inch 2024-T3 Alclad	3900	2200	1.5	-
m. 0.100-inch 2024-T3 Alclad/ 0.100-inch 2024-T3 Alclad	4000	2200	1.5	-

* Test values obtained by Sonobond.



a. Standard Coupons with 2-Inch Overlap.



b. Coupons with Minimum Edge Distance Overlap.

Figure 13. Geometry of Weld Coupons After Shearing.

remaining combinations (b through m), 10 to 20 were tensile-shear tested and 1 to 5 were metallographically examined (depending on variation in properties). For combinations k and m, 10 coupons each were subjected to fatigue test. Combination b was to be fatigue-tested; however, this test was cancelled when it was decided to fatigue test only "thick-to-thick" coupons, to assure failure through the weld and not material failure. All evaluations were carried out by Hughes Helicopters.

Tensile-Shear Tests

Each coupon was installed in a tensile test machine (Tinius Olsen) and subjected to a gradually increasing tension load until failure occurred. The failure load gives an indication either of the ultimate strength of the weld or the strength of the material surrounding the weld.

The results of the 96 tensile-shear tests for material combination a are presented in Table 2. As noted, 18 of the coupons were less than 1.0 inch wide, and test data for these were not included in the repeatability calculations. Analysis of the data for the remaining 78 coupons shows the following results:

Maximum failure load:	660 pounds
Minimum failure load:	543 pounds
Average:	617 pounds
Mean:	617.2 pounds
Variance:	636.2
Standard Deviation (SD):	25.2 pounds
SD/Mean:	4 percent
Percent variation:	$\frac{660 - 543}{617} \times 100 = 19$ percent.

The standard deviation divided by the mean (4 percent) compares very favorably with the SD/mean for the yield strength of structural metals, which is typically 6 percent.

A probability plot of the failure loads is presented in Figure 14. Based on this curve, secondary structures would probably be designed using a tensile-shear load value per weld of 568 pounds. For primary structures, the value would probably drop to 530 pounds, which checks closely with the FAA procedure of subtracting three SD's from the mean value:

Table 2. Tensile-Shear Test Results for Coupons of 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad Materials

Coupon No.	Failure Load (lb)	Coupon No.	Failure Load (lb)	Coupon No.	Failure Load (lb)
393	627	426	616	460	648
394	622	427	637	461 (0.60)	552
395	590	428	632(F)	462	545
396	602	429	524	463	593
397	602	430	628	467	578
398	605	431	615	468 (0.60)	509
399	647	432	591	469	682
400	610	433	630	470 (0.60)	518
401	637	434	616	471	603
402	625	435	637	472	594
403	640	436	629	473	595
404	600	437	627	475	625
405	660	438 (0.80)	609	476 (0.58)	532
406	595	439	573	477 (0.75)	567(F)
407	660	440 (0.80)	555	478 (0.60)	549
408	630	441	610	483 (0.73)	590
409	660	444	630	484	560
410	645	445	627	485 (0.75)	595
411	645	446	598	488	556
412	635	447	625	489	628
413	640	448 (0.60)	562	491	634
414	630	449	615	493	632
415	631	450	605	495	630
416	623	451	642	479 (0.80)	610
417	610	452 (0.60)	557	499	630
418	625	453	571(F)	501	600
419	600	454 (0.75)	596	502	543
421	635	455 (0.70)	599	503	635
422	636	456 (0.83)	562(F)	507	637
423	650	457	615	509	616
424	617	458	580	510 (0.60)	540
425	640	459	612	511	621

Notes:

(1) Coupon width was 1.0 inch unless coupon number has value in parentheses.

(2) F = Failure across the weld; remaining coupons failed through the material next to the weld

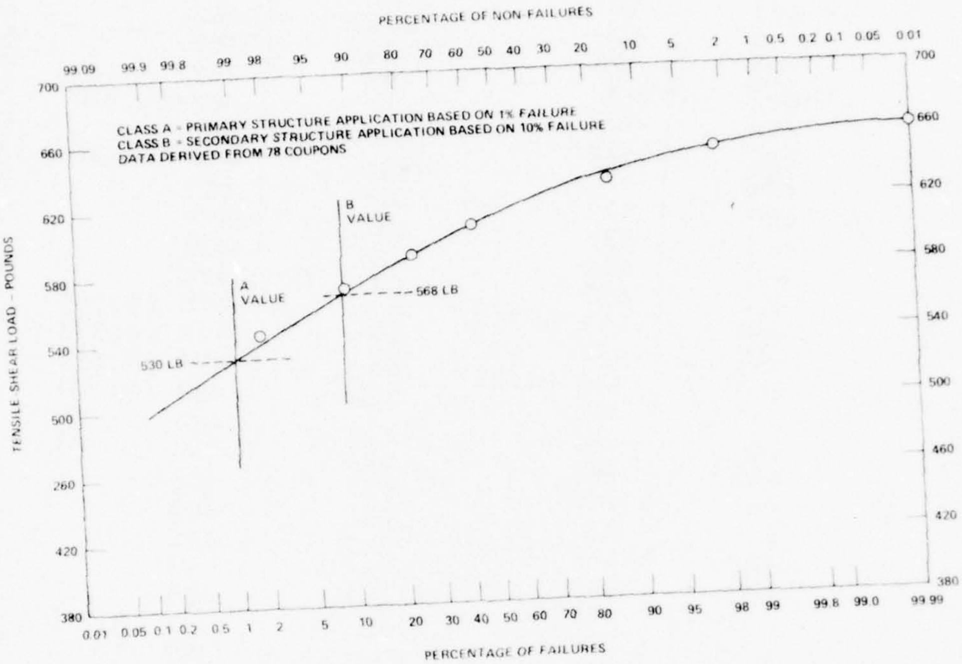


Figure 14. Probability Plot of Strength of Ultrasonically Spot Welded 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.

$$617.2 - 3(25.2) = 541.6 \text{ pounds.}$$

Test data for the remaining coupons (material combinations b through m) are presented in Table 3. In general, the data show consistent weld strength repeatability, except for the two thickest aluminum material combinations (l and m). For these coupons, the full power of the Model M-8000 welder was used, and the weld time was increased, as shown in Table 1, to provide higher weld energies. The large scatter of the failure loads indicates the need for higher energy input to achieve consistent weld strength in these "thick-to-thick" materials.

Of particular interest are the test results for the two types of overlap for material combination k, which showed that a weld edge distance of as little as 0.020 inch had no appreciable effect on weld strength. The weld strength of the coupon with 0.020-inch edge distance was only 5 percent below the average weld strength for the 20 coupons. The average weld strength for the minimum-edge-distance coupons was slightly higher than that for the standard-edge-distance coupons (1615 pounds vs. 1558 pounds).

Table 4 presents a summary of the average coupon test results for the various combinations and also shows the minimum average required strength for resistance spot welds in these combinations in accordance with military specification MIL-W-6858B. With the exception of the thickest material (wherein the equipment used had insufficient power capability), the average ultrasonic weld strength for all combinations of the aluminum alloys was more than 2.5 times the resistance weld strength. The comparison is graphically shown in Figure 15.

The welds in titanium alloy likewise showed higher average strength than required for resistance spot welds, although the margin is not so great. Interestingly, although 0.016-inch material was one member in all titanium alloy welds, the average weld strength increased with increase in thickness of the second sheet, as shown in Figure 16.

Fatigue Tests

For the fatigue tests, each coupon was installed in a constant-amplitude load fatigue machine and tested as required to provide an S-N curve for the welded material. This procedure involved picking a load in a flat part of the curve and running for 3 million cycles to demonstrate "run-out" (no failure). The load was then increased as shown in Table 5 until a failure occurred.

Table 3. Miscellaneous Coupon Tensile-Shear Test Results

Material Combination	Coupon No.	Failure Load (lb)
b. 0.020-inch 2024-T3 Alclad/ 0.025-inch 6061-0 Alclad	1	566
	2	532
	3	545
	4	530
	5	514
	6	557
	7	545
	8	556
	9	557
	10	558
	Average	546
c. 0.016-inch 2024-T3 Alclad/ 0.016-inch 2024-T3 Alclad	1	388
	2	390
	3	344
	4	382
	5 (0.80)	308
	6	400
	7	422
	8	408
	9	385
	10	402
Average (excluding No. 5)		391
d. 0.016-inch 2024-T3 Alclad/ 0.040-inch 2024-T3 Alclad	1	577
	2	544
	3	554
	4	553
	5	518
	6	561
	7	580
	8	582
	9	592
	10	552
	Average	561
e. 0.016-inch 2024-T3 Alclad/ 0.063-inch 2024-T3 Alclad	1	420
	2	404
	3	385
	4	391
	5	429
	6	427
	7	455
	8	390
	9	422
	10	389
	Average	411

(Continued)

Table 3 (Continued)

	Material Combination	Coupon No.	Failure Load (lb)
f.	0.016-inch 2024-T3 Alclad/ 0.100-inch 2024-T3 Alclad	1	550
		2	517
		3	570
		4	553
		5	557
		6	525
		7	538
		8	545
		9	549
		10	587
		Average	549
g	0.016-inch 6Al-4V Titanium/ 0.020-inch 6Al-4V Titanium	1	793
		2	1000
		3	840
		4	908
		5	882
		6	980
		7	613
		8	740
		9	860
		10	1030
		11	647
		12	660
		13	1080
		14	902
		15	970
		16	900
		17	826
		18	890
		19	800
		20	780
		Average	855
h.	0.016-inch 6Al-4V Titanium/ 0.040-inch 6Al-4V Titanium	1	955
		2	1000
		3	1020
		4	953
		5	1153
		6	965
		7	860
		8	750
		9	322
		10	870
		11	850

(Continued)

Table 3.(Continued)

Material Combination	Coupon No.		Failure Load (lb)
h. 0.016-inch 6Al-4V Titanium/ 0.040-inch 6Al-4V Titanium (Concluded)	12		810
	13		1000
	14		830
	15		1018
	16		832
	17		1075
	18		886
	19		1085
	20		900
		Average	932
i. 0.016-inch 6Al-4V Titanium/ 0.063-inch 6Al-4V Titanium	1		820
	2		955
	3		813
	4		1140
	5		755
	6		1545
	7		1370
	8		1025
	9		1065
	10		1180
	11		1125
	12		1020
	13		1087
	14		1175
	15		1010
	16		1020
	17		1035
	18		1070
	19		950
	20		1270
		Average	1072
j. 0.032-inch 2024-T3 Alclad/ 0.032-inch 2024-T3 Alclad	1		1050
	2		1385
	3		1370
	4		1470
	5		1270
	6		1320
	7		1350
	8		1385
	9		1215
	10		1045
	11		1410
	12		1445

(Continued)

Table 3 (Continued)

Material Combination	Coupon No.	Failure Load (lb)
j. 0.032-inch 2024-T3 Alclad/ 0.032-inch 2024-T3 Alclad (Concluded)	13	1265
	14	1380
	15	1510
	16	1380
	17	1370
	18	1400
	19	1365
	20	1165
	Average	1328
k. 0.040-inch 2024-T3 Alclad/ 0.040-inch 2024-T3 Alclad	1	1510
	2	1590
	3	1420
	4	1625
	5	1650
	6	1530
	7	1480
	8	1480
	9	1665
	10	1625
	Average	1558
l. 0.063-inch 2024-T3 Alclad/ 0.063-inch 2024-T3 Alclad	1	2490
	2	2550
	3	3000
	4	3015
	5	3115*
	6	3345*
	7	2620
	8	2880
	9	2535
	10	1625
	11	2675
	12	1420
	13	1475
	14	1260
	15	2625
	16	2915
	17	1490
	18	2940
	19	1605
	20	3255*
	21	2935
	22	3085*
	23	2480
	24	2710
	25	2045
	Average	2483

*Material next to the weld failed, instead of across the weld.

(Continued)

Table 3 (Concluded)

Material Combination	Coupon No.	Edge Distance*	Failure Load (lb)
m. 0.100-inch 2024-T3 Alclad/ 0.100-inch 2024-T3 Alclad	1		969
	2		1980
	3		2475
	4		2350
	5		2615
	6		2730
	7		980
	8		2150
	9		2240
	10		2235
		Average	2072
k. 0.040-inch 2024-T3 Alclad/ 0.040-inch 2024-T3 Alclad with minimum edge distance*	1	(0.20-0.11)	1630
	2	(0.22/0.09)	1680
	3	(0.19/0.13)	1510
	4	(0.22/0.07)	1680
	5	(0.15/0.12)	1470
	6	(0.27/0.02)	1530
	7	(0.20/0.08)	1605
	8	(0.22/0.05)	1540
	9	(0.19/0.09)	1640
	10	(0.21/0.05)	1530
	11	(0.22/0.12)	1690
	12	(0.14/0.12)	1715
	13	(0.22/0.08)	1700
	14	(0.21/0.08)	1715
	15	(0.19/0.08)	1695
	16	(0.18/0.10)	1670
	17	(0.19/0.10)	1500
	18	(0.21/0.08)	1655
	19	(0.18/0.11)	1630
	20	(0.20/0.07)	1520
		Average	1615

*Edge distance in inches on each end of coupon weld is shown in parentheses.

Table 4. Summary of Coupon Test Results

Material Welded	Average Tensile-Shear Strength (lb)	Resistance Weld Strength (lb)* Per MIL-W-6858B
0.020-inch 2024-T3 Alclad to 0.025-inch 6061-T6 Alclad	617	175
0.020-inch 2024-T3 Alclad to 0.025-inch 6061-0 Alclad	546	175
0.016-inch 2024-T3 Alclad to 0.016-inch 2024-T3 Alclad	391	140
0.016-inch 2024-T3 Alclad to 0.040-inch 2024-T3 Alclad	561	140
0.016-inch 2024-T3 Alclad to 0.063-inch 2024-T3 Alclad	411	140
0.016-inch 2024-T3 Alclad to 0.100-inch 2024-T3 Alclad	549	140
0.032-inch 2024-T3 Alclad to 0.032-inch 2024-T3 Alclad	1328	325
0.040-inch 2024-T3 Alclad to 0.040-inch 2024-T3 Alclad	1553	435
0.040-inch 2024-T3 Alclad to 0.040-inch 2024-T3 Alclad	1615	435
0.063-inch 2024-T3 Alclad to 0.063-inch 2024-T3 Alclad	2483	840
0.100-inch 2024-T3 Alclad to 0.100-inch 2024-T3 Alclad	2072	1865
0.016-inch 6Al-4V Titanium to 0.020-inch 6Al-4V Titanium	855	520
0.016-inch 6Al-4V Titanium to 0.040-inch 6Al-4V Titanium	932	520
0.016-inch 6Al-4V Titanium to 0.063-inch 6Al-4V Titanium	1072	520

* Required minimum average strength.

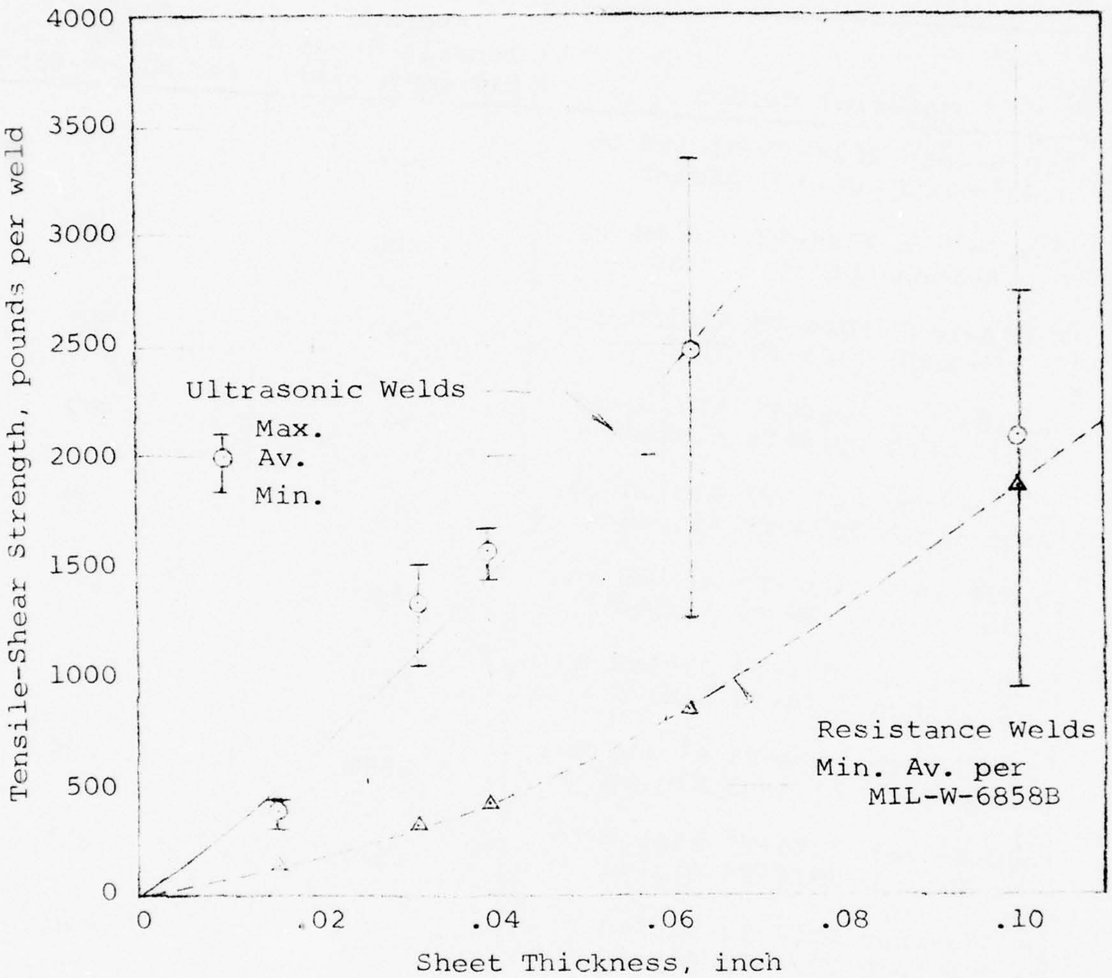


Figure 15. Comparison of Ultrasonic and Resistance Spot Weld Strengths in Various Thicknesses of 2024-T3 Alclad Aluminum Alloy.

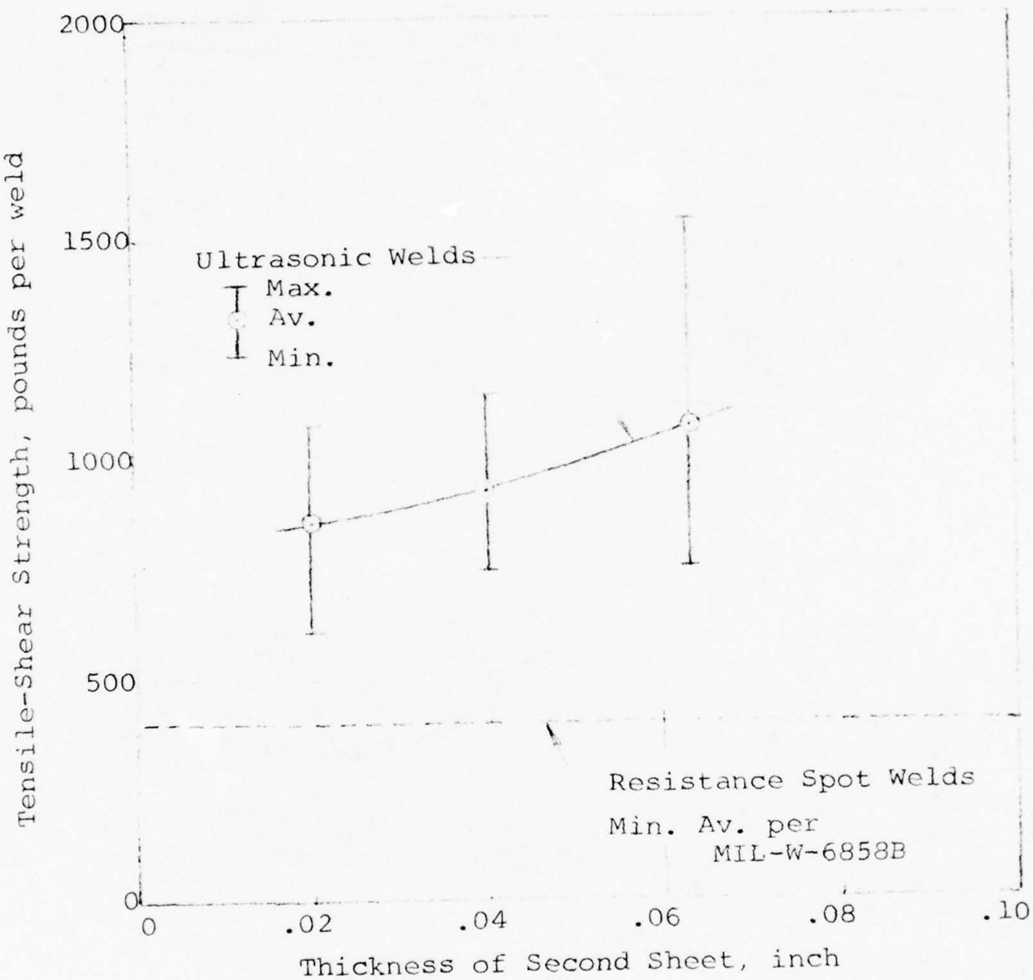


Figure 16. Ultrasonic Weld Strength of Coupons of 0.016-Inch Ti-6Al-4V to Dissimilar Thicknesses of the Same Material.

Table 5. Fatigue Test Loads

Load Number	Tension - Tension (lb) Maximum	Minimum
Test Load No. 1	100.0	10.0
Test Load No. 2	125.0	13.0
Test Load No. 3	156.0	16.0
Test Load No. 4	195.0	20.0
Test Load No. 5	244.0	25.0
Test Load No. 6	305.0	31.0
Test Load No. 7	381.0	39.0

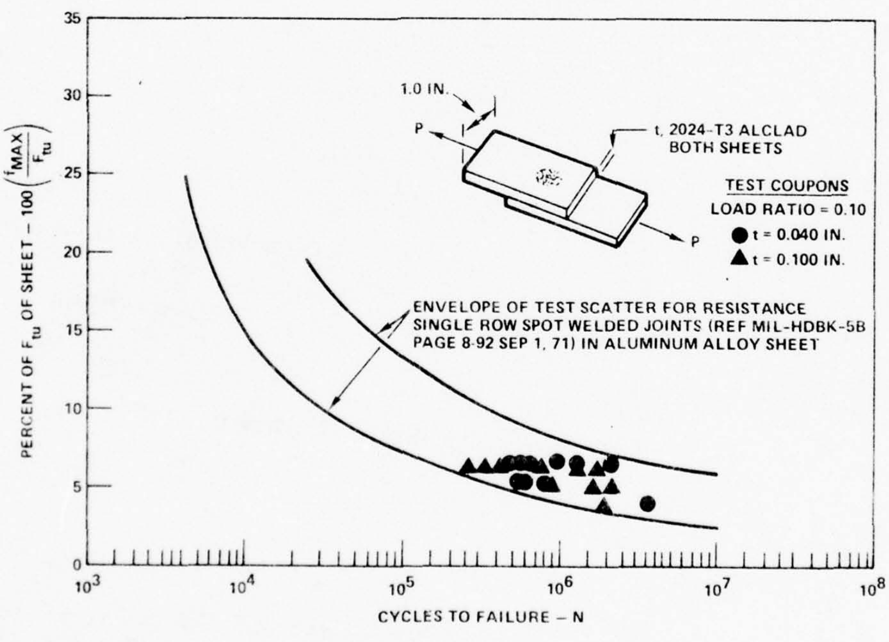


Figure 17. Fatigue Strength of Ultrasonically Welded Coupons.

As previously noted, only material combinations k and m (0.040-inch and 0.100-inch 2024-T3 Alclad) were subjected to fatigue tests, and the number of coupons thus tested was minimal because fatigue test data were not required to prepare the ultrasonic welding process specification. The tests that were performed verified that ultrasonic welds have fatigue characteristics comparable to those of resistance spot welds. Fatigue test results for the low-load, high-cyclic-rate conditions are shown in Figure 17.

Although an S-N curve is not required for the welding process specification, it will become a standard to be used for quality control sampling during the anticipated production of components welded by the ultrasonic process.

Metallographic Evaluation

Representative welded coupons were sectioned and prepared for metallographic examination. Photomicrographs of the sections are presented in Appendix A.

The mechanism of ultrasonic welding imposes dynamic shear stresses in the area of contact between the faying surfaces. The shearing forces cause local plastic flow at the weld interface such that oxide and other barrier films are ruptured and dispersed. The plastic flow and dispersion create nascent metal contact and solid-phase bonding of the newly formed surfaces.

When welding clad aluminum, the effects of the interfacial plastic deformation would be expected to be seen in the softer clad surfaces. The photomicrographs show that the deformation in the weld area is essentially restricted to the cladding layer with negligible structural alteration of the core material. Occasional fragments of incompletely fragmented and dispersed surface films were observed along the original bond interface, and these fragments are highlighted in the sections of the weld areas photographed. Residual fragments of the original surface films are usually observed in ultrasonic bonds in aluminum.

Photographs were also taken of five of the failed 0.100/0.100-inch 2024-T3 Alclad coupons because of the large scatter of the failure load data. These observations revealed that bonding occurred over only 25 to 50 percent of the contact area, and consequently the tensile-shear test loads were low and erratic. The incipient bonding characteristics of these samples indicate that insufficient ultrasonic power input was available to weld this material thickness combination.

Salt Spray Test

Four weld coupons of combination a (0.020-inch 2024-T3 Alclad to 0.025-inch 6061-T6 Alclad) were subjected to a 300-hour salt immersion test. Two of the coupons were primed and painted in accordance with the standard practice used at Hughes Helicopters for external surfaces on the YAH-64 aircraft. The other two coupons were tested in the unpainted condition. The test, performed in accordance with Federal Standard Test Method No. 151, consisted of immersing the coupons in a salt solution for 10 minutes and then air-drying them in a cabinet for 50 minutes until 300 one-hour cycles had been performed.

Following the test, the weld area of each of the coupons was sectioned and subjected to microscopic inspection. Photomicrographs of the coupons revealed that no intergranular corrosion had taken place.

COMPONENT FABRICATION AND TESTING

FABRICATION OF FIRST DOOR ASSEMBLY

It was originally intended that the port electronic access door (shown in Figure 5), selected for implementation of the ultrasonic welding process, be fabricated from an outer skin of 0.020-inch 2024-T3 Alclad and an inner waffle skin of 0.025-inch 6061-T6 Alclad aluminum alloys. However, the 6061 clad material was not readily available, and bare 6061 alloy was substituted.

The inner waffle skin was formed from 6061-0 material by the Clearwater Die Company, using a hydropress and Kirksite die. The formed skin was then heat-treated to the T-6 condition. The solid outer skin was purchased as a single flat sheet and trimmed to size. These components were prepared by Hughes Helicopters and delivered to Sonobond Corporation for welding.

For welding the assembly, the inner and outer skins were clamped in the Hughes-fabricated fixture of Figures 11 and 12. Consecutive welds were made around the periphery of the door and around each of the six inner waffles. The welding was performed with the inner 6061-T6 material adjacent to the welding tip, and the welds were spaced on approximately 1.25-inch centers. Welding machine settings (which were re-evaluated when 6061-T6 bare material was used for the inner skin instead of the clad material) were: 2100 watts input power, 850 pounds clamping force, and 0.5 second weld time. The time required for welding the entire door was approximately 60 minutes.

Extra tabs were provided on two edges of the door, and two welds were made on each of these tabs to provide four coupons for independent testing. These tabs were sheared off before the doors were tested.

DOOR ASSEMBLY TESTING

Initially it was planned to fly a prototype YAH-64 aircraft with the welded door assembly installed on the aircraft in order to check the ability of the assembly to withstand actual air loads. However, the two YAH-64 prototype flight aircraft were delivered to the Army before a prototype welded door assembly could be made available for flight testing. As a substitute for actual flight testing, simulated flight tests of the doors were performed in the Hughes Helicopters Structures Laboratory.

Investigation of door assembly design criteria established that the most severe structural design condition (ultimate) is with the door in the closed position and subjected to a 150-knot wind applied uniformly across the door face. This loading results in a force of approximately 461 pounds (ultimate) across the 5.16-square-foot door area, or 89.3 pounds per square foot.

In order to test the door assembly in a very conservative manner, Hughes initially planned to support the assembly at only four points (the two hinges and two latches) and apply a 461-pound minimum load across the door assembly outer face using an air bag. The static load was to be applied gradually and held for a minimum of 3 seconds. Since the door assembly would not be supported around its periphery by its edge gasket, this test would readily serve to qualify the welded door assembly. However, it was later decided to test the assembly in a more realistic manner by supporting it around the periphery.

The door assembly was checked for form, fit, and function. The assembly was then installed in the test setup shown in Figure 18, and a vacuum load was applied to the concave side of the door assembly. When the vacuum reached 11.3 inches of mercury (5.55 psi), the loading was discontinued due to air leakage. The test setup was resealed, and subsequent loading was accomplished to an indicated 13.3 inches of mercury (6.53 psi); at this point door yielding occurred and the test was stopped.

A photograph of the yielded door is presented in Figure 19. It is noted that the door was painted on the inside to permit each weld to be identified (numbered). Strain and deflection readings were obtained at each load increment of of the first loading but not during the final loading. The data are graphically presented in Figure 20. Figure 20b reflects the data from strain gage No. 2. Strain gages No. 1 and No. 3 gave faulty readings due to their location, and those readings are not included. Analysis of Figure 20 indicates that the door did not see any additional load once a deflection of 1.1 inch occurred.

These data establish that the door assembly successfully withstood an indicated load of 4858 pounds without failure of any of the welds; this is approximately ten times the aerodynamic design load of 461 pounds.

The welded tabs sheared from the edges of the door before the air load test were cut into coupons for tensile-shear test. Each coupon had one weld, centered, and the edge distance was approximately 3/8 inch. The tensile-shear tests were conducted in the manner described for the weld coupon investigation.

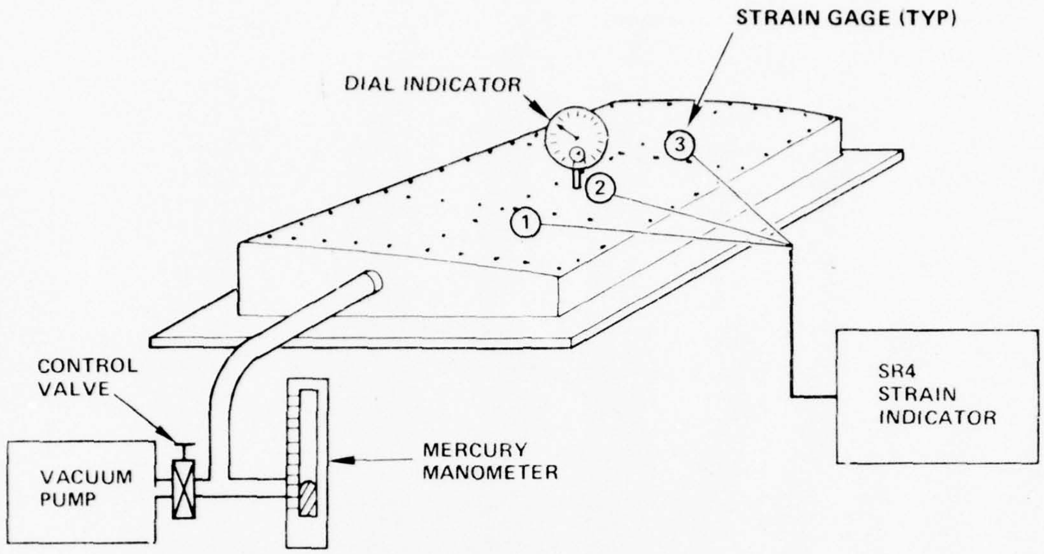


Figure 18. Test Setup for Ultrasonically Welded Door Assembly.

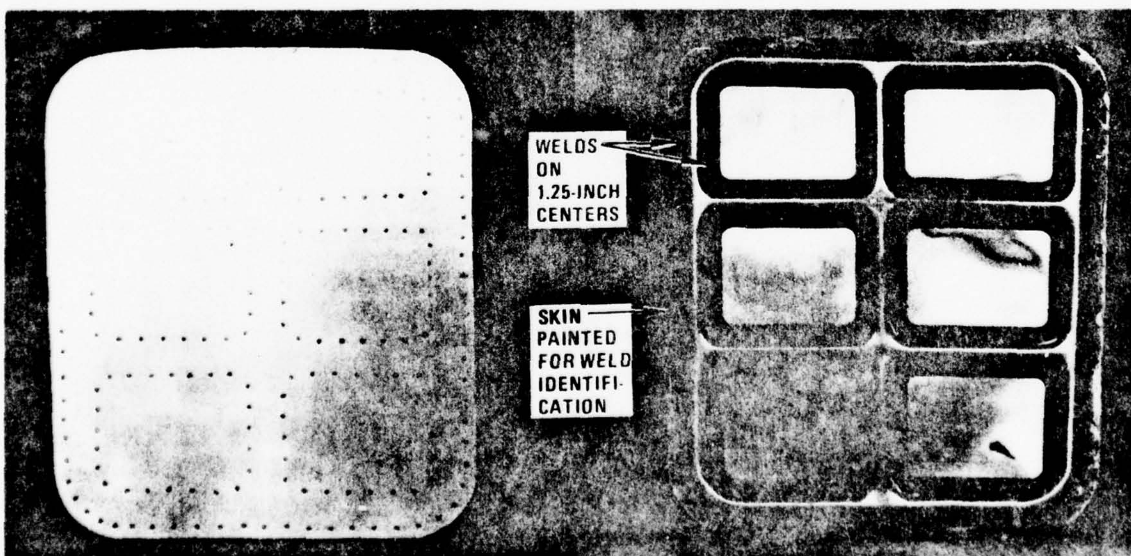
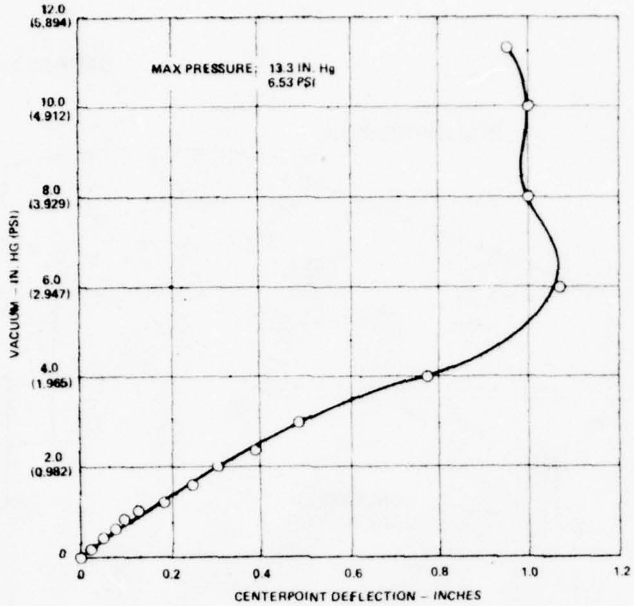
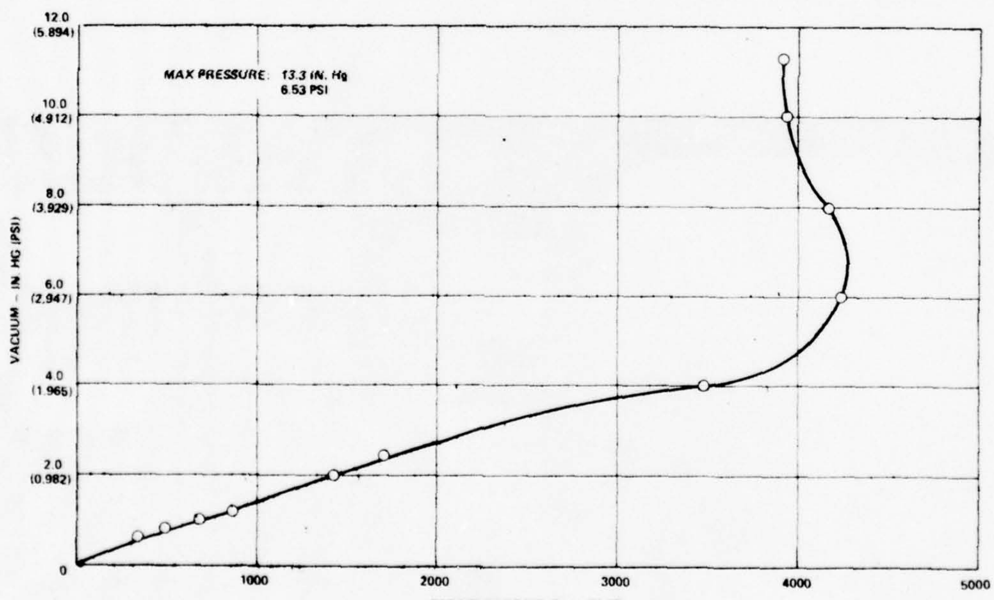


Figure 19. Door Assembly No. 1 After Air Load Test.



a. Deflection Versus Pressure.



b. Strain Gage Versus Pressure.

Figure 20. Results of Simulated Flight Test.

The results were as follows:

Coupon No.	Failure Load (lb)
1	398
2	583
3	384
4	482
Average	462

Indentation measurements on welds made on the first door showed a distribution similar to that obtained on the coupon specimens of Figure 7 and a maximum value of about 0.0025 inch.

FABRICATION OF ADDITIONAL DOOR ASSEMBLIES

Upon verification that the first door was welded satisfactorily, three additional door assemblies were welded, using the same welding machine settings as for the first assembly. These doors likewise each had four additional welds on tab extensions of the edges, to be used for tensile-shear testing.

The first door assembly had been assembled with all welds spaced on 1.25-inch centers. Since the door assembly strength was so much greater than required, it was decided to gradually increase the weld spacing on the three subsequent doors, as shown in Figure 21, and thus reduce the time required for welding the complete door. The modified weld spacings were as follows:

1. The first of these three doors had periphery welds spaced on 1.5-inch centers (Door No. 2). The six inner waffles were each secured by five vertical welds and four horizontal welds (corners counted twice) for a total of 14 welds per waffle. Welding time for the complete assembly was 45 minutes.

2. The second door assembly had periphery welds spaced on 2.0-inch centers (Door No. 3) with the inner waffles each secured by 10 welds (four vertical and three horizontal). Welding time was reduced to 20 minutes.

3. The third door assembly had periphery welds spaced on 3.0-inch centers (Door No. 4) with the inner waffles each secured by six welds (the four corners and two in the middle vertically). Welding time was further reduced to 10 minutes.

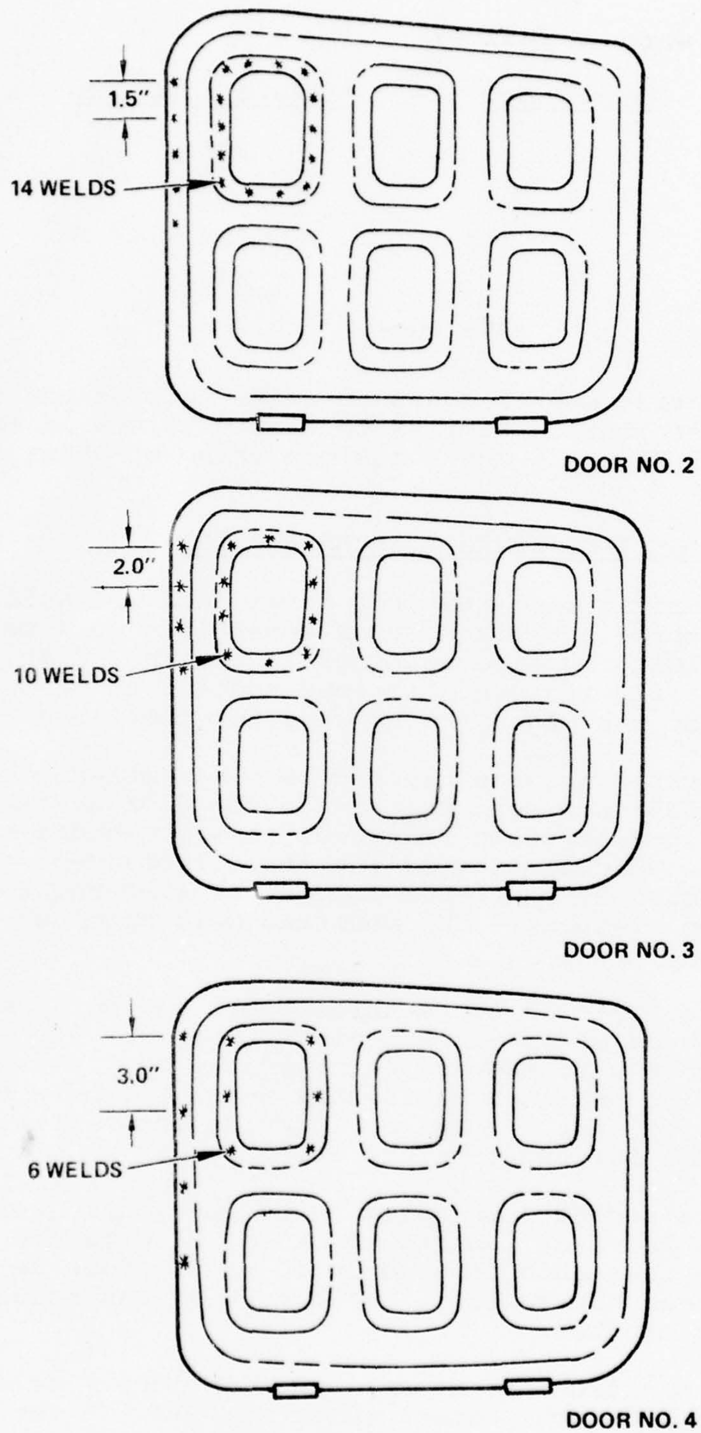


Figure 21. Modified Weld Spacing on Door Assemblies.

During welding of Door No. 1 at Sonobond, it was found that the welding support fixture was not really necessary. Doors No. 2 and No. 3 were welded with "C" clamps on the door tabs to maintain alignment. The "C" clamps were dispensed with for Door No. 4, and alignment was maintained manually by the operator.

TESTS ON ADDITIONAL DOOR ASSEMBLIES

The three additional door assemblies were airload tested in a manner similar to that used for the first assembly. The test setup was the same as shown in Figure 18, except that strain gages were not used.

Door No. 2 was loaded incrementally and deflection readings recorded. At 7.2 inches of mercury, the vacuum seal was broken. During reloading, a weld failure occurred at 5.5 inches of mercury. Loading was increased to 7.7 inches of mercury, where permanent deformation occurred at the door edge, and the test was discontinued. Figure 22 shows the failure area and the broken weld location.

Doors No. 3 and No. 4 were sealed with a Mylar cover and then incrementally loaded. No weld failures occurred for either door. Permanent deformation took place at approximately the same locations as for Door No. 2.

Figure 23 provides a comparison of deflection data for all the door assemblies.

Prior to air testing the door assemblies, the welded tabs were sheared from the edges of each door and cut into tensile-shear test specimens. The four welds on the tabs from Door No. 3 all failed during removal from the door. Tensile-shear tests on coupons from Doors No. 2 and No. 4 gave the following results:

Door No.	Coupon No.	Failure Load (lb)
2	1	245
	2	127
	3	Failed during removal from door
	4	126
	Average	125

Figure 22. View of Door No. 2 Edge Failure and Weld Failure Locations.

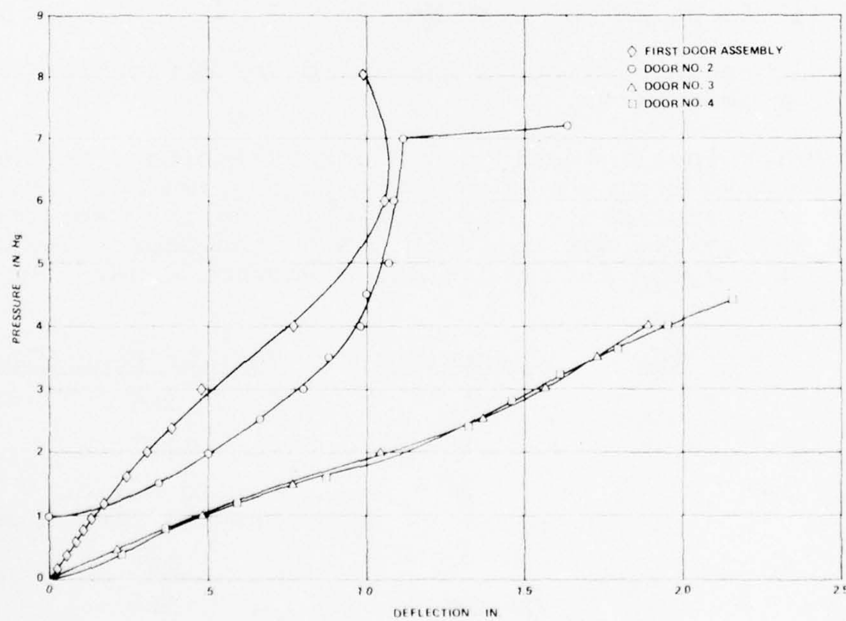


Figure 23. Comparison of Deflection Data for All Ultrasonically Welded Access Door Assemblies.

Door No.	Coupon No.	Failure Load (lb)
4	1	575
	2	343
	3	293
	4	510
	Average	430

The low values obtained for Door No. 2 and the weld failures for Door No. 3 during removal from the assembly were attributed to the "C" clamps which were attached to the door assemblies in the tab areas during welding. These clamps apparently damped the vibratory energy so that insufficient energy was transmitted into the bond zone. The substantially higher values obtained for Door No. 4, which was welded without the clamps, seem to support this view.

For verification, Doors No. 2 and No. 3 (after air load test) were sectioned, and two tensile-shear specimens were cut from the center of each door. Test results on these specimens were as follows:

Door No.	Specimen No.	Failure Load (lb)
2	A	538
	B	490
3	A	587
	B	551

Since these failure loads were well above the failure loads for the Door No. 1 coupons, the effect of clamping in the vicinity of the test tabs was substantiated.

CONCLUSIONS FROM DOOR ASSEMBLY TESTING

The conclusions drawn from the tests on the door assemblies are as follows:

1. The weld spacing on Door No. 2 (with 1.5-inch centers) appears to be the optimum spacing from a strength/cost effectiveness tradeoff.

2. When ultrasonically welding a door assembly, the door tabs (if used for quality control) must not be clamped or otherwise restricted during welding of the tabs.

3. Door assemblies ultrasonically welded under the conditions noted in <u>1.</u> and <u>2.</u> above have from 5 to 10 times the necessary shear strength for an access door of this type.

PROJECTED COST EFFECTIVENESS OF ULTRASONIC WELDING

Consideration was given to the cost effectiveness of ultrasonic welding in comparison with adhesive bonding, the conventional method for assembling personnel access doors for aircraft at Hughes Helicopters. Hughes has compiled direct manufacturing cost data for adhesive bonding which could be extrapolated to full-scale production, but no such data were available for ultrasonic welding because of the lack of production experience in door assembly. Thus no definitive cost comparison could be made. The data provided below represent projected cost savings based on a few judicious estimates and assumptions.

ASSEMBLY SEQUENCE

Examination of the projected assembly sequences for the two processes highlights the simplification of door assembly by ultrasonic welding:

Bonding	Ultrasonic Welding
1. Surfaces are carefully cleaned using gloves.	1. Surfaces are cleaned without any special provisions.
2. Surfaces are then primed.	2. Surfaces need not be primed.
3. Bonding must occur within 1 hour after priming. Part is handled with cotton gloves for cleanliness.	3. No special handling is required, nor is there any critical assembly time.
4. Complex bonding fixture requires steam and cold water lines to expedite curing.	4. A holding fixture is used to index and clamp parts together during initial tacking.
5. Temperature during bonding can cause burns and bodily harm.	5. No hazardous elevated temperatures are involved.
6. Adhesive film, stored in deep freezer, must be installed and clamped between the faying surfaces.	6. No extra parts are required that need to be stored or installed during part assembly.

DIRECT LABOR COSTS

For the cost of ultrasonic welding, one weld per 1.5 linear inches was assumed. With hand-held assemblies, it was estimated that 75 percent of each weld cycle would be used in moving from one weld location to another. Since the weld itself requires approximately 0.5 second, the assemblies could be ultrasonically welded at the rate of about 30 welds per minute. In limited manual production, the actual welding would probably be performed at about 25 percent of this rate, or eight welds per minute.

Hughes estimated that the originally designed YAH-64 access door assembly would require about 2.7 man-hours for cleaning, bonding, and assembling. The redesigned YAH-64 door assembly was conservatively estimated to require 40 minutes for ultrasonic weld assembly. At a labor rate of $25.00 per hour, the adhesive bonded door would thus cost $68.00 and the ultrasonically welded door $17.00 per door, a saving of 75 percent. Since the aircraft has six access doors that could be ultrasonically assembled, and a production run of 535 aircraft is anticipated, the total program savings in labor alone would be $218,280 (for adhesive bonding) less $54,570 (for ultrasonic welding), or in excess of $163,000.

ENERGY COSTS

Energy savings are likewise impressive. The bonded door requires a 4-hour curing cycle in an oven utilizing 660,000 BTU per hour, and two doors can be processed at one time. Fabrication of one door therefore requires 1,320,000 BTU or 387 kilowatt-hours. Ultrasonic welding requires about 2500 watt-seconds per weld or about 0.14 kilowatt-hours per door. Assuming a cost of $0.05 per kilowatt-hour, the energy costs would be $19.35 for the bonded door and $0.008 for the ultrasonically welded door. With six doors for 535 aircraft, the relative costs would be $62,114 versus $22.50, representing an additional saving of more than $62,000.

EQUIPMENT COSTS

The cost of an ultrasonic welder with appropriate tooling for fabricating the door was estimated at less than $30,000. The cost of adhesive bonding equipment at Hughes could not be readily isolated because of the age of the equipment and internal usage factors, and such costs would vary with different manufacturers. However, in view of the substantial savings in labor and energy costs, the capital investment for ultrasonic welding equipment certainly appears justified.

ULTRASONIC WELDING PROCESS SPECIFICATION

On the basis of the data obtained during this program, Hughes Helicopters in cooperation with Sonobond Corporation prepared a process specification for ultrasonic welding of nonstructural and secondary structure components. This has been identified as Hughes Process Specification HP 11-9 and has been tentatively approved for use by Hughes Helicopters pending approval by the Army. This proposed specification is included herein as Appendix B.

The specification was prepared following the general format of Hughes Process Specification HP 11-3D, which is applicable to resistance spot, seam, and projection welding.

It is noted that this specification now has shear strength requirements only for the material combination of 0.020-inch 2024-T3 Alclad welded to 0.025-inch 6061-T6 Alclad aluminum alloys. This is the only material combination that was extensively tested (75 to 100 coupons) during the program. As other combinations are selected for use, they will likewise be extensively tested and added to the process specification.

CONCLUSIONS AND APPLICATIONS

1. Ultrasonic welding, as exemplified in the welding of the YAH-64 electronic access door assembly, produces bonds of superior strength for aircraft secondary structures.

    a. Single-spot coupons of aluminum alloys demonstrated tensile-shear strengths of more than 2.5 times the strengths of resistance spot welds.

    b. Simulated flight tests of the ultrasonically welded access doors showed strengths exceeding the ultimate design loading of the assemblies by a factor of from 5 to 10.

    c. Weld strength was shown to be insignificantly affected by edge distance.

2. Ultrasonic welding offers the potential for significant weight savings. Redesign of the access door for this process resulted in weight reduction from 5.5 pounds to 3.3 pounds, a reduction of 40 percent.

3. In comparison with adhesive bonding, ultrasonic welding was indicated to be a very cost-effective method of assembling secondary structures.

    a. Savings in manufacturing labor were estimated to be about 75 percent.

    b. In excess of 99 percent savings in energy utilized for assembling the door were projected.

4. Based on the results obtained on this program, Hughes Helicopters has tentatively approved ultrasonic welding as a means for joining secondary structures on the AAH program, pending formal approval by the Army.

5. The ultrasonic welding process specification included as Appendix B can be implemented to include a range of material and material thickness combinations with moderate additional effort.

6. The process can be adapted to the assembly of many other helicopter secondary structures that are now bonded, resistance spot welded, or riveted, such as floors, fire-walls, keel beams, panels, sheet/stringer combinations, shelving, and access hole reinforcement. A suggested list of possible applications prepared by Hughes Helicopters is provided in Table 6.

7. Other possible applications involve the use of portable ultrasonic welding equipment to repair damaged aircraft at the intermediate and depot maintenance levels. New doublers, stiffeners, brackets, etc. could be welded to repaired or replaced secondary structures in the field, thereby reducing maintenance costs and turnaround time. A conceptual design for a portable welder is shown in Figure 24.

Table 6. Possible Applications of Ultrasonic Welding for Aircraft Secondary Structures

Secondary Structure	Applicable Aircraft	Method Now Used
1. Floor hat sections and stiffeners to skin	OH-6A, TH-55, AAH, and most production aircraft	Resistance spot welding
2. Instrument panel doublers, stiffeners, and inner waffle skins to outer skins	OH-6A, TH-55, AAH, and most production aircraft	Resistance spot welding and bonding
3. Firewall stainless steel stiffeners to titanium webs	OH-6A and AAH	Resistance spot welding and automatic riveting.
4. Main rotor blade trailing edges	OH-6A, TH-55, and AAH	Riveting and bonding
5. Engine and equipment access door inner skin waffle to outer skin	OH-6A and AAH	Bonding and bonded honeycomb (proposed for AAH)
6. Belly structure doublers to skin	OH-6A, TH-55, and AAH	Resistance spot welding
7. Ammo compartment doors	AAH	Bonding
8. Fuel tanks	TH-55	Resistance spot welding
9. Map cases	All aircraft	Riveting and resistance spot welding
10. Personnel and cargo access door inner waffle skin to outer skin	All aircraft not using honeycomb	Bonding or riveting
11. Pilot's seat back	TH-55	Resistance spot welding
12. Forward bulkhead stiffeners to web	OH-6A	Resistance spot welding
13. Stabilizer stiffeners to skin	TH-55	Resistance spot welding

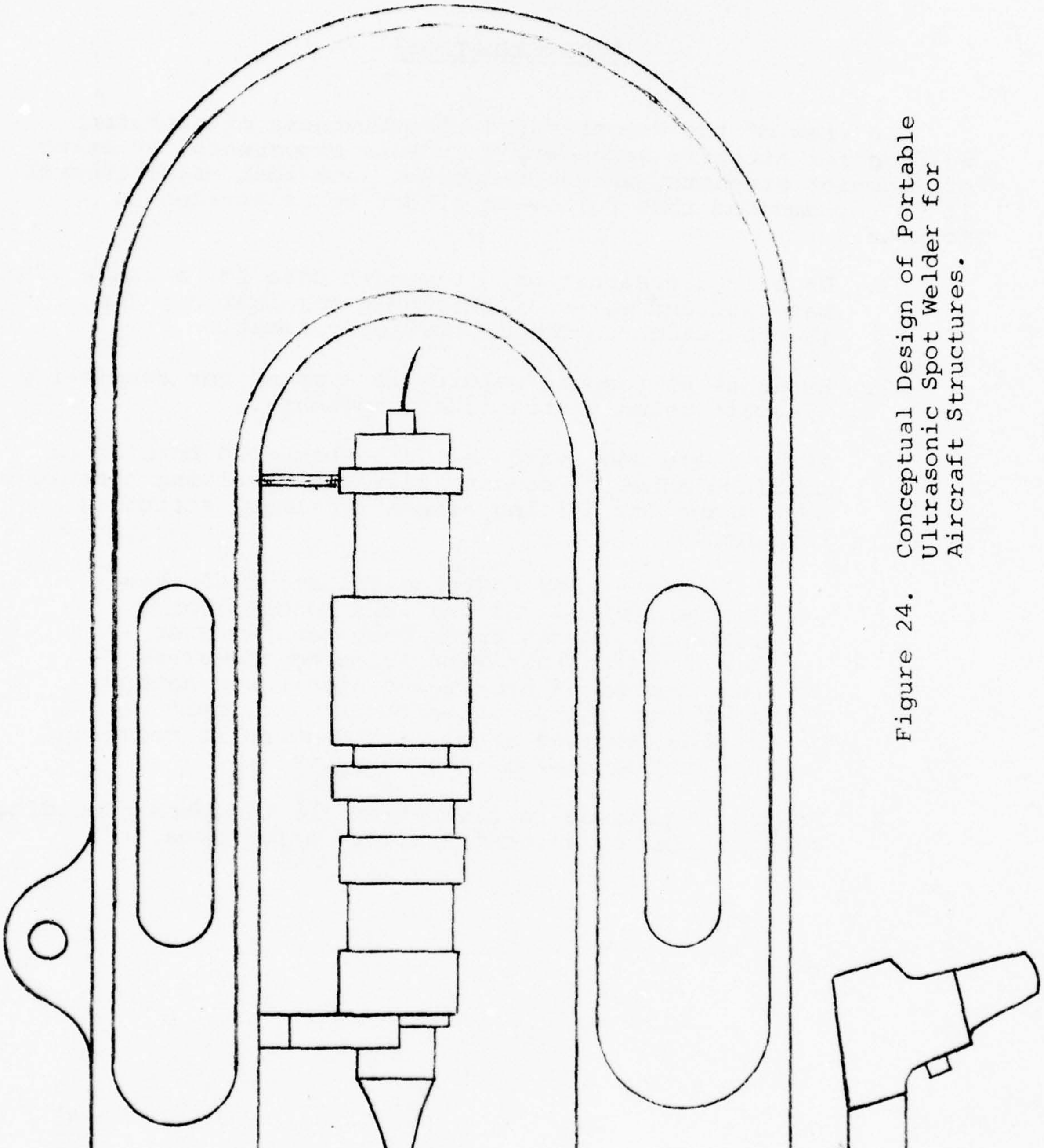


Figure 24. Conceptual Design of Portable Ultrasonic Spot Welder for Aircraft Structures.

RECOMMENDATIONS

In view of the demonstrated effectiveness of ultrasonic welding for aircraft secondary structure components, in terms of superior strength, weight reduction, and cost effectiveness, it is recommended that follow-on effort be undertaken as follows:

1. Develop ultrasonic weld strength data for a range of material and material thickness combinations for incorporation in the process specification.

2. Evaluate ultrasonic welding as a means for assembling aircraft primary structure components.

3. Investigate and evaluate ultrasonic weld bonding (a combined adhesive bonding/ultrasonic welding technique) as a means for joining aircraft primary structure components.

   A limited study (outside the scope of this program) of ultrasonic weld bonding for a nationally known truck body manufacturer demonstrated that with selected adhesives this technique provides a higher strength bond than either adhesive or ultrasonic welding applied singly and appears to reduce the curing time of the adhesive.

4. Prepare a process specification for ultrasonic welding/weld bonding of aircraft primary structures.

APPENDIX A

PHOTOMICROGRAPHS OF CROSS SECTIONS OF TYPICAL ULTRASONIC WELDS IN MATERIAL COMBINATIONS *a* THROUGH *g*

a. Figure A-1. 0.020 Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.

b. Figure A-2. 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-O Alclad.

c. Figure A-3. Two Sheets of 0.016-Inch 2024-T3 Alclad.

d. Figure A-4. 0.016-Inch to 0.040-Inch 2024-T3 Alclad.

e. Figure A-5. 0.016-Inch to 0.063-Inch 2024-T3 Alclad.

f. Figure A-6 0.016-Inch to 0.100-Inch 2024-T3 Alclad.

g. Figure A-7. 0.016-Inch to 0.020-Inch 6Al-4V Titanium.

a. Magnification: 100X

2024-T3 Alclad above
6061-T6 Alclad below

Note cladding on
surface of 2024-T3
Alclad sheet.

b. Weld Interface at
500X Magnification

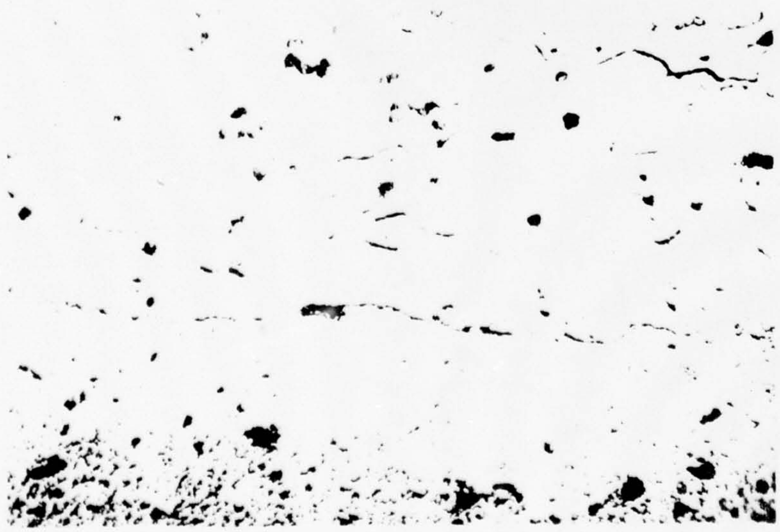
Interface shows
residual undispersed
oxide film fragments

Figure A-1. 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6
Alclad.

a. Magnification: 100X

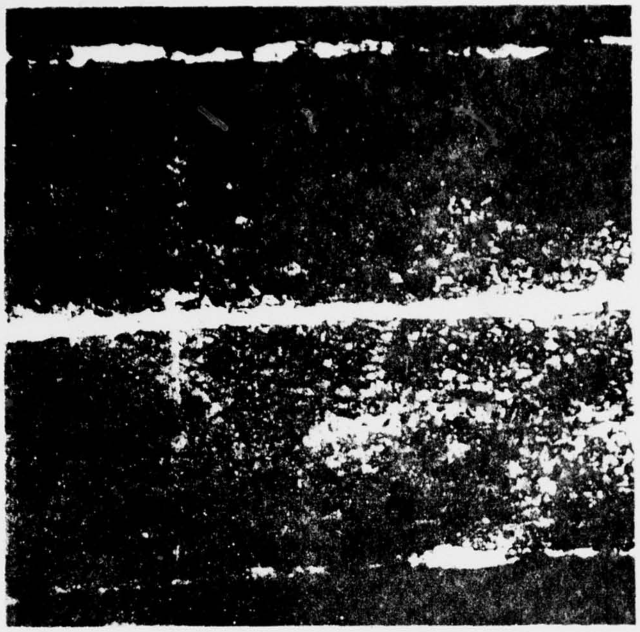
2024-T3 Alclad above
6061-0 Alclad below

The interface shows
areas of residual
undispersed oxide
film.



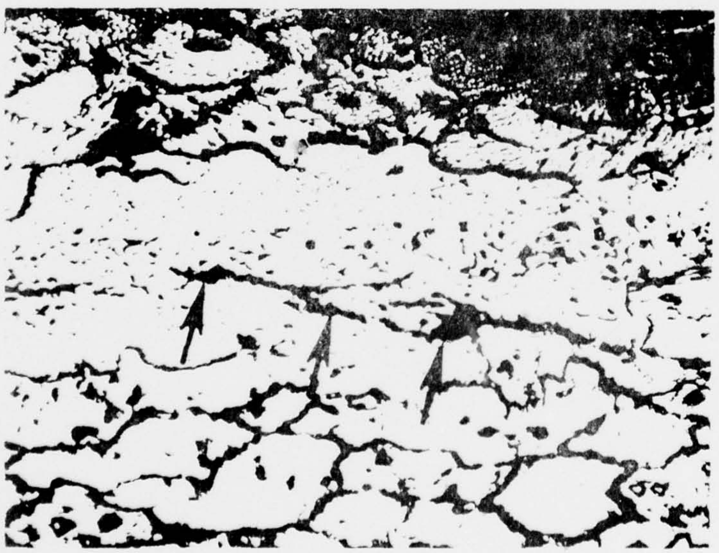
b. Weld Interface
at 500X
Magnification

Figure A-2. 0.020-Inch 2024-T3 Alclad to 0.025-Inch 6061-T6 Alclad.



a. Magnification: 100X

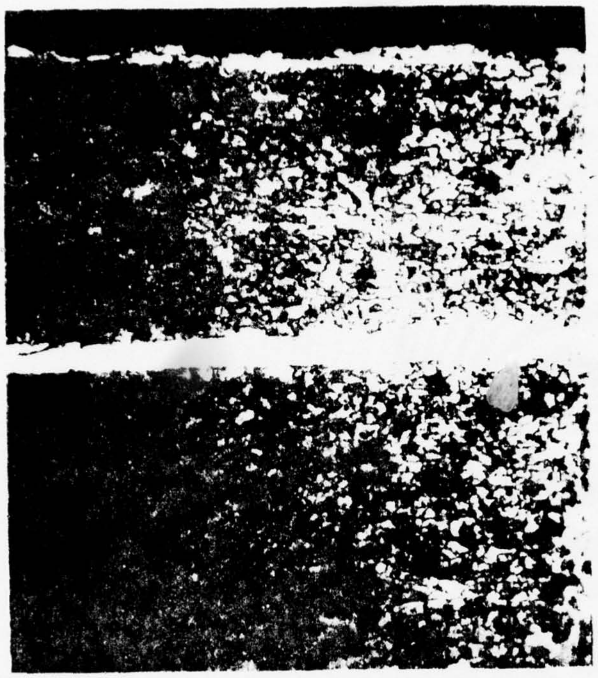
Note cladding on surfaces of both sheets and at the weld interface.



b. Weld Interface at 500X Magnification

Arrows indicate undispersed oxide film fragments.

Figure A-3. Two Sheets of 0.016-Inch 2024-T3 Alclad.



a. Magnification: 100X

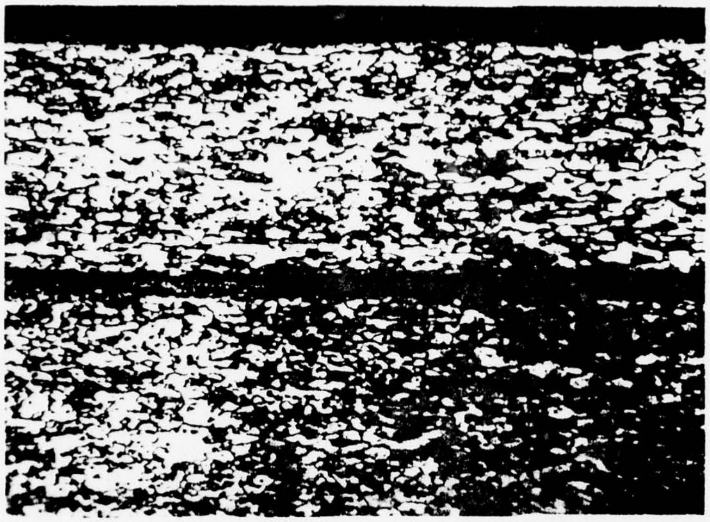
0.016-Inch Material above

Note cladding on surface and at interface.

b. Weld Interface at 500X Magnification

Arrow indicates void resulting from etching.

Figure A-4. 0.016-Inch to 0.040-Inch 2024-T3 Alclad.



a. Magnification: 100X

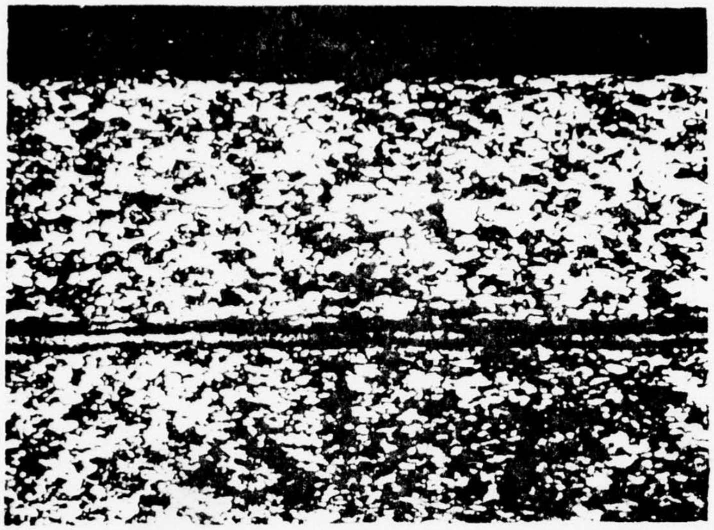
0.016-Inch Material above

Note aluminum cladding at interface.

b. Weld Interface at 500X Magnification

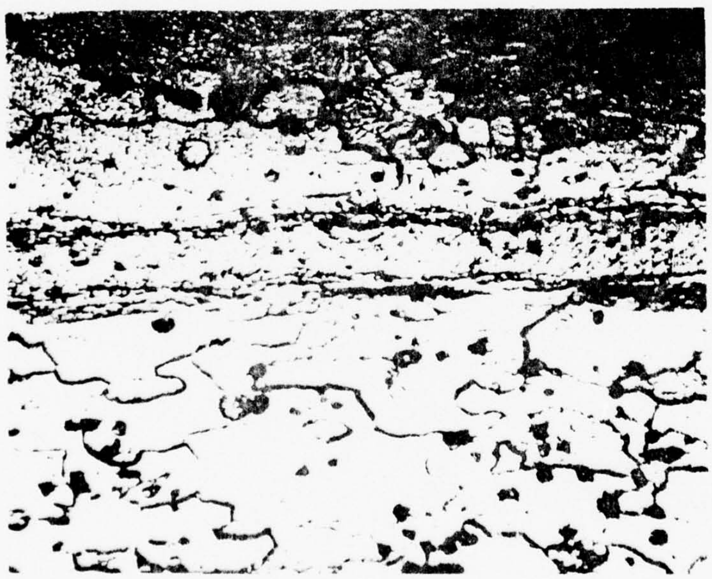
Residual undispersed oxide film fragments are evident throughout the interface.

Figure A-5. 0.016-Inch to 0.063-Inch 2024-T3 Alclad.



a. Magnification: 100X

0.016-Inch Material above



b. Weld Interface at 500X Magnification

Residual oxide film fragments throughout the interface.

Figure A-6. 0.016-Inch to 0.100-Inch 2024-T3 Alclad.

a. Magnification: 100X

b. Weld Interface at 500X Magnification

Residual oxide film fragments are dispersed throughout the interface.

Figure A-7. 0.016-Inch to 0.020-Inch 6Al-4V Titanium Alloy.

APPENDIX B

HUGHES PROCESS SPECIFICATION HP 11-9

ULTRASONIC WELDING

Hughes Helicopters
division of summa corporation

ENGINEERING ORDER

E.O. NO. 131362

MODEL	EFFECTIVE ON	E.O. TYPE	AUTHORITY
77	Record	New Process	MJO 0136
		PARTS MADE: MAY BE REWORKED / OK TO USE; RECORD X / NOTED	CCN/MOD

REL. DATE	BY:
9-28-77	S.W.pa

AFF. GROUP	SPECIFICATION AFFECTED NO.	YES	NO	ATP FTP AFFECTED NO.	YES	NO	INTERCHANGEABILITY AFFECTED YES	NO	E.O. BY
		☐	☒		☐	☒	☐	☒	G. Dingle

DRAWING TO BE CHANGED: YES ☐ NO ☒

DOCUMENT	REV.	SIGNIFICANT CHANGE YES ☐ NO ☒	GROUP	DATE
HP 11-9	New	ULTRASONIC WELDING	11-40	9/27/77

NEXT ASSY.

APPROVED BY	DATE
PE 77 [illegible]	9-27-77
PA [illegible]	9/27/77
STRESS [illegible]	8-8-77
MFG [illegible]	9-26-77
TECH DEPT. [illegible]	8-30-77
MAT'L & PROCESS [illegible]	8-3-77
CHANGE CONT.	
CONF. CONT. [illegible]	9-27-77
SPRT. SERVICES	
SYSTEMS [illegible]	9-27-77
GOV'T APP	

COPIES TO

SAXLUND (7)

REFERENCED E.O.'S

REASONS & REMARKS

Provides new process

E.O. NO. 131362

FORM 9022 REV. 2/74

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
New	Released on EO 131362	09/27/77	

SCOPE

This specification establishes the requirements and procedures for joining assemblies by the ultrasonic welding process for the following materials:

Group A	Aluminum and Aluminum Alloys
Group B	Steels, Austenitic, Ferritic and Precipitation Hardening Steels, Nickel and Cobalt Base Alloys
Group C	Titanium and Titanium Alloys

PREP	[illegible] 8-2-77	Hughes Helicopters Division of Summa Corporation		Centinela and Teale Streets Culver City, California 90230	
APPD	J. C. French RHH 8-3-77	TITLE: ULTRASONIC WELDING			
	[illegible] 8/8/77				
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9-27-77	[illegible]	SIZE A	CODE IDENT NO. 02731	NO. HP 11-9	REV.
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FORM 1642

1. SCOPE

1.1 This specification establishes the requirements and procedures for joining assemblies by the ultrasonic welding process for the following materials:

Group A	Aluminum and Aluminum Alloys
Group B	Steels, Austenitic, Ferritic and Precipitation Hardening Steels, Nickel and Cobalt Base Alloys
Group C	Titanium and Titanium Alloys

2. APPLICABLE DOCUMENTS

2.1 Government documents. The following documents of the issue in effect, on date of the invitation for bids or request for proposal, form a part of this specification to the extent specified herein. In case of conflict between these documents and this specification, the requirements of this specification shall prevail.

STANDARDS

Military

MIL-STD-453	Radiographic Inspection

2.2 Non-Government documents.

SPECIFICATIONS

Industry

Hughes Helicopters

HP 9-5	Specific Metal Cleaning Methods
HP 9-10	Paint Stripping of Metal Surfaces
HP 9-12	Aluminum Alloy Spot Weld Etch
HP 9-25	Vapor Degreasing of Materials

2.2.1 Copies of specification, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

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OTHER PUBLICATIONS

American Welding Society

AWS A2.0-68 Welding Symbols

2.2.2 Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.

3. REQUIREMENTS

3.1 Equipment.

3.1.1 Welding. Welding equipment shall consist of a suitable power source and necessary support instrumentation and controls to reliably indicate and control all equipment variables.

3.1.2 Standardization. Welding tips, designated sonotrodes and anvils by one equipment manufacturer, shall meet the requirements established by the equipment manufacturer.

3.1.3 Jigs and fixtures.

3.1.3.1 All tooling required to locate welds or hold detail parts during the weld cycle shall be so constructed that they do not interfere with the functioning of the welding equipment.

3.1.4 Equipment maintenance.

3.1.4.1 Each item of equipment shall be inspected at the frequency level established by the equipment manufacturer.

3.1.4.2 Welding tips shall be maintained to the manufacturer's requirements so that consistent welds are produced.

3.1.4.2.1 Welding tip contours shall be maintained to the manufacturer's requirements or to the contour established by suitable testing by the using contractor. The contour surface of the weld tip shall be maintained between 200 and 300 microinches rms using the EDM (electric discharge machining) process to produce the welding tip.

3.1.4.2.2 Welding tips may be dressed to remove material pickup; however, the contour and surfaces finish shall not be changed by the tip dressing operation.

3.1.5 Shear testing machines. The contractor shall provide a shear testing machine accurate to within ±2 percent of the indicated reading. Portable shear testing machines shall be checked for accuracy at intervals not to exceed 2 months.

3.2 Weld classification.

3.2.1 Classes. Welding shall be accomplished on secondary structural and nonstructural assemblies only. Weld classification for secondary structural shall be Class B and shall be Class C for nonstructural.

3.3 Shear strength requirements.

3.3.1 Requirements. Shear strength requirements shall be established by the procedure outlined in 3.7 when new alloy combinations are to be joined.

3.4 Materials and methods of preparation.

3.4.1 Joining. Any alloy or combination of alloys may be joined by this process provided the procedure outlined in 3.7 has been performed.

3.4.2 Characteristics. Materials welded by this process will have their ductility characteristics only slightly affected (3 percent or less). Thus, a special heating sequence for the purpose of tempering the weld is not required.

3.4.3 Cleaning.

3.4.3.1 The maximum time allowed between the cleaning of parts and the welding operation shall be 72 hours for Group A and B materials, and 12 hours for Group C materials. In the interval, the parts shall be suitably stored in a closed area to preclude any contamination.

3.4.3.2 Parts to be welded shall be clean and free from oxides, scale, ink, grease, and other foreign materials.

3.4.3.3 Cleaning shall be accomplished in accordance with HP 9-5, HP 9-10, HP 9-12, or HP 9-25 as applicable. In general, Group A materials may be cleaned by vapor degreasing per HP 9-25. Group C materials may be cleaned using chemical etch per HP 9-5.

3.5 Mating parts.

3.5.1 Contacting. Mating parts assembled for welding shall fit so that before the first and each successive weld is made, the surfaces to be joined by the weld are in contact or can be made to contact each other with minimum pressure (i.e., less than 5 pounds force).

3.6 Qualification of welding machines.

3.6.1 Qualification tests. Welding machine qualification tests shall be performed to determine the consistency of machine operation at or near the desired operating range. To have equipment qualified and approved for production welding, test specimens shall be prepared as specified herein. The machine qualification data shall be recorded on a form like or similar to Figure 1. The qualification record shall be valid when stamped by an authorized inspector.

3.6.2 Test materials.

3.6.2.1 Test material shall be selected within the alloy group from which parts are to be fabricated.

3.6.3 Machine qualification.

3.6.3.1 Machines shall be qualified to meet the weld requirements for the highest classification for which they are intended for use in production.

(To Be Accompanied by Welding Schedule)

Company______ Address______ Date______

Mfr. of Machine______ Serial No.______ Mfr. of Control Panel______

Qualification Group: (Note material covered by group (a) or (b) or both see section______

Control Mfr.'s Type Number______

Thickness Range: (Note minimum and maximum thickness actually qualified)

Surface Preparation______

SHEET COMBINATION	Upper	Material
		Thickness (inches)
		Condition
	Lower	Material
		Thickness (inches)
		Condition
	Defects, Sections or Radiographic	

WELDED SPECIMENS	SHEAR STRENGTH, POUNDS PER WELD				
		1	26	51	76
		2	27	52	77
		3	28	53	78
		4	29	54	79
		5	30	55	80
		6	31	56	81
		7	32	57	82
		8	33	58	83
		9	34	59	84
		10	35	60	85
		11	36	61	86
		12	37	62	87
		13	38	63	88
		14	39	64	89
		15	40	65	90
		16	41	66	91
		17	42	67	92
		18	43	68	93
		19	44	69	94
		20	45	70	95
		21	46	71	96
		22	47	72	97
		23	48	73	98
		24	49	74	99
		25	50	75	100

Total of Shear Strengths______

Average of Shear Strengths______

Min. Value obtained on Test______

Variation in Shear Strength______

Average Weld Diameter______ Minimum Weld Diameter______

Minimum Shear Strength on Table______

______ (Laboratory Director's [illegible]) ______ ([illegible])

Figure 1. Machine Qualification Data (Part 1)

Company__________ Address__________ Date__________
Mfr. of Machine__________ Serial No.__________ Mfr. of Control Panel__________
Qualification Group: (Note material covered by group (a) or (b) or both see section__________
Control Mfr.'s Type Number__________
Thickness Range: (Note minimum and maximum thickness actually qualified)

Surface Preparation		
	Upper	Material
		Thickness (inches)
		Condition
	Lower	Material
		Thickness (inches)
		Condition

Machine Control Settings

1.

2.

3.

4.

5.

6.

etc

Figure 1. Welding Schedule (Part 2)

3.6.3.2 One machine of each distinctive type shall satisfactorily pass the complete qualification test before any part or assembly welded on that machine type is considered acceptable as an item on a contract.

3.6.3.2.1 Distinctive types of equipment are those differing in any of the following respects:

a. Manufacturer of the machine or control panel, type of machine, or model number.

b. Electrical rating, capacity, or transducer frequency.

c. Detail clamping method.

NOTE

Additional machines of the same distinctive type as the approved machine may be qualified by the establishment of satisfactory production settings for each such machine.

3.6.4 Requalification.

3.6.4.1 When the equipment has once been qualified, it need not be requalified for future contracts or production provided no change in basic material or range of machine settings are involved. A change of equipment location within a facility, not involving a change in power source, does not require requalification. Requalification of equipment shall be required if the machine is rebuilt or if significant operational changes are made therein.

3.6.5 Test specimen.

3.6.5.1 To qualify a welding machine 106 welds shall be made using 0.063 inch bare 2024-T3 material. No maintenance or control adjustments shall be permitted during the welding of a set of specimens. The process details used in specimen preparation for qualification (such as material cleaning method, machine settings, and electrode configuration) shall be those which would be used in production.

3.6.6 Test requirements.

3.6.6.1 Of the 106 welds produced, 100 welds shall be shear tested and six welds shall be sectioned for metallurgical examination.

3.6.6.2 The average tensile shear value shall be 1850 pounds minimum and the difference between the highest and the lowest values shall be 245 pounds maximum. The failure of one weld to meet these requirements shall be cause for failure of the entire test set and the welding equipment shall be adjusted, modified, or repaired before repeating the qualification test.

3.6.6.3 The six metallurgical specimens shall be cross sectioned, polished, and etched (at or as close to the center of the weld zone as possible). Weld quality shall meet the requirements of 3.10, unless otherwise specified in this section, when examined at 100X to 200X magnification.

3.6.6.4 The shear and metallurgical specimens shall be fabricated to the multiple weld configuration of Figure 2, except as noted, and shall be subsequently cut into single weld specimens prior to testing. Dimensions of each shear test specimen shall be as given in Table I.

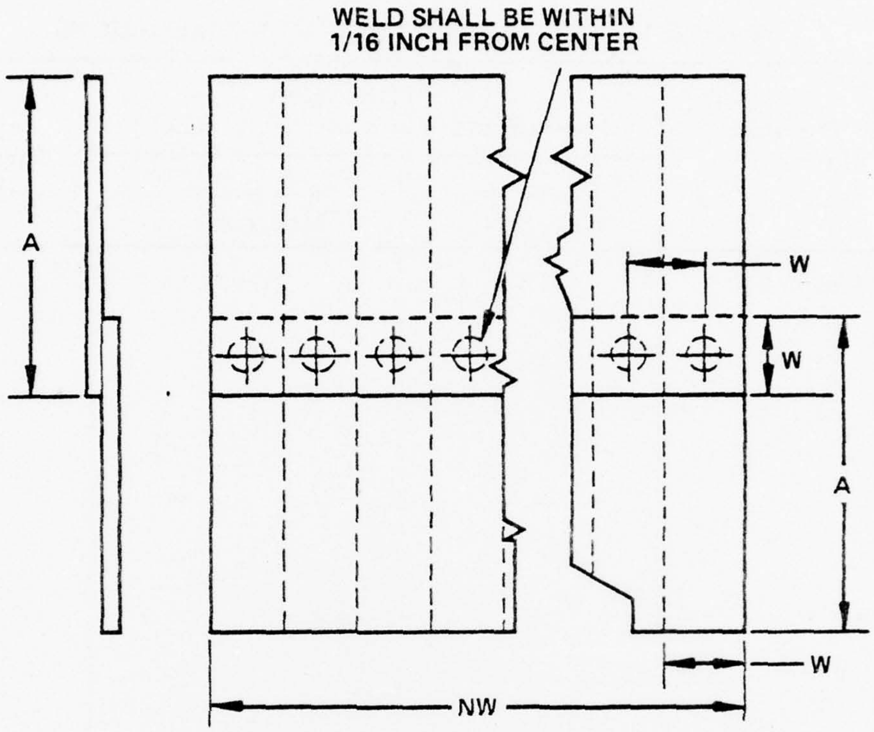
3.6.6.5 All test welds shall be radiographically examined in accordance with MIL-STD-453 prior to shear testing to assure that the welds are sound and crack free.

3.6.7 Machine and process data.

3.6.7.1 Four copies of a form similar to Figure 1 shall be completed for each machine and submitted for approval to the authorized Product Assurance representative. After receiving approval, a copy of the form shall be posted on the machine. The other copies of the form shall be forwarded to Manufacturing, Product Assurance Engineering, and Material, Processes, and Standards Departments.

3.7 Certification of welding process or schedule.

3.7.1 Welding schedules. Suitable welding schedules shall be established for each material or permissible combination of different materials and each thickness combination to be welded in production on the machine under consideration. Thickness combination, of the metals listed, falling within both the following limits shall not require separate welding schedules, provided acceptable welds can be produced within the control adjustment limit of Section 4.



(Values for W and A are shown in Table I.)

1. N = Number of spot welds as specified in the applicable paragraphs of the specification. The number of spot welds per set shall be not less than 20.

2. Multiple-spot shear specimen for other than foil thicknesses (to be cut after welding).

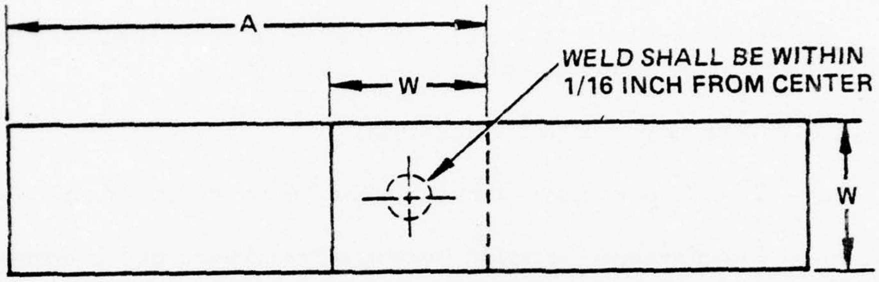
3. Group B and C material shear specimens shall be as shown in Figure 3.

4. See Figure 4 for metallurgical test specimen configuration.

Figure 2. Multiple Weld Test Panel Configuration

TABLE I. SHEAR TEST SPECIMEN DIMENSIONS

Sheet Thickness (Inch)	W - Dimension Overlap and Width Minimum (inch)		Length A-Dimension (Inch)
	Group A Materials	Group B and C Materials	
0.016 to 0.050	1	1	4
0.051 to 0.100	1	1	4



(Values for W and A are shown in Table 1.)

Figure 3. Single-Spot Shear Specimen

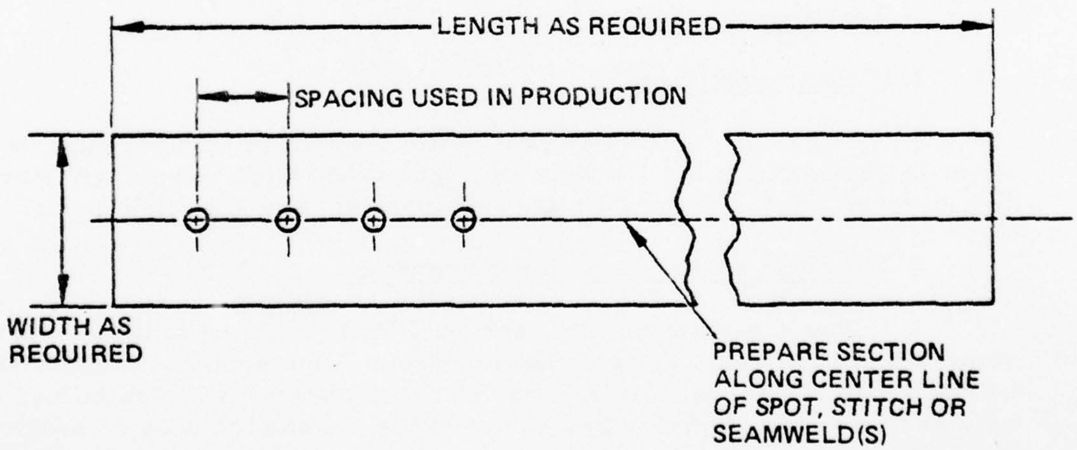


Figure 4. Metallurgical Test Specimen Configuration

3.7.1.1 For Group A materials:

a. 0.004 inch or 10 percent variation in thickness of either outer sheet, whichever is greater.

b. 0.004 inch or 10 percent variation in overall thickness of the combination to be welded, whichever is greater.

3.7.1.2 For Group B and C materials:

a. Twenty percent variation in thickness of either outer sheet.

b. Ten percent variation in overall thickness of the combination to be welded.

3.7.2 Requirements.

3.7.2.1 The welding schedule shall be established prior to the welding of production parts and shall include the cleaning process used, all details of the machine setup, and the control settings for each machine to be used in production welding. The suitability of the welding schedule shall be established by making and testing not less than the number of welds listed in Table II. The welding schedules and test results shall be approved by Product Assurance Division inspection personnel.

3.7.3 Test requirements.

3.7.3.1 Shear specimen.

3.7.3.1.1 The (two thickness combination) shear specimens shall be prepared as shown in Figure 3 and Table I, and then tested using a machine described in 3.1.5. Shear strength requirements are specified below.

3.7.4 Minimum shear strength requirements.

3.7.4.1 The shear strength of each weld shall be in accordance with the minimum requirements of Table III (for Group A materials), Table IV (for Group B materials), and Table V (for Group C materials). The failure of one weld shall be cause for rejection of the entire set and the welding equipment shall be adjusted, modified, or repaired prior to repeating the test for the particular combination involved.

TABLE II. NUMBER OF WELDS REQUIRED FOR SCHEDULE ESTABLISHMENT

Weld Method	Material			
	Group A		Group B and C	
	Ultimate Stress Specimens	Metallurgical Specimens	Ultimate Stress Specimens	Metallurgical Specimens
Single Weld	*Shear	*Micro-Section	*Shear	*Micro-Section

*This quantity intentionally left blank. To generate shear data for Tables III, IV, and V, the procedure of 3.6.6.1, 3.6.6.3, 3.6.6.4, and 3.6.6.5 shall be used. All shear data shall be recorded.

TABLE III. MINIMUM REQUIRED SHEAR STRENGTH AND MINIMUM AVERAGE SHEAR STRENGTH FOR GROUP A MATERIAL*

Material Combination	Shear Strength (Failure Load Pounds)	
	Minimum	Minimum Average
0.020 2024-T3 Alclad to 0.025 6061-T6 Alclad	543	617

*Except as noted, this table intentionally left blank for lack of shear test data.

TABLE IV. MINIMUM REQUIRED SHEAR STRENGTH AND MINIMUM AVERAGE SHEAR STRENGTH FOR GROUP B MATERIAL*

Material Combination	Shear Strength (Failure Load Pounds)	
	Minimum	Minimum Average

*This table intentionally left blank for lack of shear test data.

TABLE V. MINIMUM REQUIRED SHEAR STRENGTH AND MINIMUM AVERAGE SHEAR STRENGTH FOR GROUP C MATERIAL*

Material Combination	Shear Strength (Failure Load Pounds)	
	Minimum	Minimum Average

*This table intentionally left blank for lack of shear test data.

3.7.5 Average shear strength requirements.

3.7.5.1 The average shear strength of each set of welds shall be equal to or greater than the minimum average strength shown in Tables III, IV, or V (as applicable).

3.7.6 Shear strength consistency requirements.

3.7.6.1 Group A material. A variation in shear strength of welds in Group A materials of ±12-1/2 percent of the average value will be permitted in 90 percent of the specimens specified in Table II, and a variation of ±25 percent in the remaining specimens. The variation in shear strength for each of three sample welds shall not exceed 30 percent (see 4.8).

3.7.6.2 Group B and C materials. A variation in shear strength of welds, in nonhardening steels (by the welding process) and other alloys in these alloy groups, of ±10 percent of the average value will be permitted in 86 percent of the specimens specified in Table II, and a variation of 20 percent in the remaining specimens. The variation in shear strength for each of three sample welds shall not exceed 30 percent (see 4.8).

3.8 Certification records.

3.8.1 Records posting. Records showing the welding machine settings for all variable controls, and minimum and average weld shear strengths for all alloys and thickness combinations welded on that machine shall be posted on the machine.

3.9 Recertification.

3.9.1 Requirement. Recertification of a welding schedule may be required at anytime, if the authorized inspector for any reason doubts the ability of a machine or machines to make satisfactory welds.

3.9.2 Schedule. When the amount of material in the throat of the machine, the curvature of the part, and other conditions in production welding require control adjustments outside the limits specified in Section 4, specific welding schedules shall be established for each joint requiring such adjustment. The schedule shall also specify the tests and examinations which will be used to determine the conformance of the welds to the requirements specified herein. The test welds shall be made so that they represent welds in the production parts.

3.10 Quality standards.

3.10.1 Appearance.

3.10.1.1 The outer surface of all test specimen welds shall be smooth and free of cracks, tip pick-up, pits, and other defects which indicate that the welds were made with dirty or improperly prepared welding tip surfaces. The maximum acceptable number of defects for production parts shall not be greater than that shown in Table VI.

3.10.2 External defects.

3.10.2.1 Test specimen welds shall be free of external defects. For production parts, except as noted in Section 4, the following defects are not acceptable: pits, surface flash, tip pick-up, expulsion of metal from between the sheets, external cracks, edge-bulge cracks, and blown spots.

3.10.3 Sheet separation.

3.10.3.1 Sheet separation, measured at a distance from the edge of the weld equal to approximately one-half the welding tip indentation, is not acceptable if in excess of 15 percent of the average thickness of the members being joined or 0.006 inch, whichever is greater (for all metals).

3.10.4 Surface indentation.

3.10.4.1 Where aerodynamic considerations are a requisite, the welding tip indentation shall not exceed 0.004 inch. In all other cases welding tip indentations are not acceptable if the depth exceeds 20 percent or 0.005 inch, whichever is greater, of the thickness of the sheet in which the indentation occurs.

3.10.5 Internal defects.

3.10.5.1 Weld defects such as porosity/voids, cracks or microsegregation are acceptable if the maximum extent of the defect does not exceed one of the following limits as indicated by metallographic examination:

a. Twenty-five percent of the weld diameter.

b. Fifty percent of the respective sheet thickness extension into an outer sheet.

c. Extension within 15 percent (of the weld diameter) of the boundaries of the weld zone.

TABLE VI. MAXIMUM ACCEPTABLE NUMBER OF DEFECTS

Nature of Weld Defect		All Groups: Acceptable Without Repair % (1)	All Groups: Additional Repairable % (1)
External Defects	Cracks open to surface	0	0
	Edge bulge cracks	0	0
	Sheet separation exceeding established limits	5	0
	Pits less than 1/16 inch diameter	5	5
	Metal expulsion	5	5
	Tip pick-up	3	0
	Excessive indentation	10	0
Internal Defects (2)	Cracks	6	10

(1) Total of all defects shall not exceed 15 percent.

(2) In excess of limitations established in 3.10.

NOTE: Percentage fractions shall be interpreted as the next highest number of welds for the purpose of determining the additional repair permissible.

3.10.6 Lack of bonding between sections (clad aluminum).

3.10.6.1 The outline of the weld area at the interface shall be generally smooth and regular. There shall be no "unbonded" cladding material within or adjacent to the weld zone.

3.10.7 Unequal thickness combinations.

3.10.7.1 In a joint between members of unequal thickness or of alloys of different strength levels, the minimum shear strength required shall be based on the thickness of the thinner member or the strength of the lower strength material.

3.10.8 Tack welds.

3.10.8.1 Tack welds may be used if specifically allowed by the engineering drawing.

3.10.8.2 Tack welds require no test specimens. However, they shall be of sufficient strength to fulfill their temporary function and shall not exceed the defect levels established for production parts.

3.11 Restrictions and limitations.

3.11.1 Rewelding of faulty welds.

3.11.1.1 Rewelding of a faulty weld is allowed, provided the requirements of 3.10 are not violated.

3.11.2 Single welds.

3.11.2.1 Single welds shall not be used to hold parts together except when specifically allowed by the engineering drawing. A minimum of two welds should always be used.

3.11.3 Sequence of operations.

3.11.3.1 Aluminum assemblies shall be welded prior to the installation of mechanically fastened details when the two processes are to be used on the same part or assembly.

AD-A064 850 SONOBOND CORP WEST CHESTER PA F/G 1/3
ULTRASONIC WELDING OF HELICOPTER SECONDARY STRUCTURE COMPONENTS--ETC(U)
OCT 77 J DEVINE, G K DINGLE DAAJ01-76-C-0913
UNCLASSIFIED RR-77-9 USAAVRADCOM-77-8 NL

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4. QUALITY ASSURANCE PROVISIONS

4.1 Production welding shall be accomplished to obtain welds of uniform strength with acceptable metallographic structure. All test specimens shall be representative of the manufacturing practice. Specimens shall be tested by assigned Product Assurance Division inspection personnel. Prior to production welding, all parts shall be checked for conformance to the requirements of 3.4.

4.2 Schedules.

4.2.1 Qualified personnel shall be responsible for the control of machine settings and all welding schedules. Records of all current schedules shall be available for examination by an authorized inspector at any time.

4.3 Welding symbols.

4.3.1 Welds shall be in accordance with the engineering drawing requirements and shall be symbolized per ASW A2.0-68, see Figure 5.

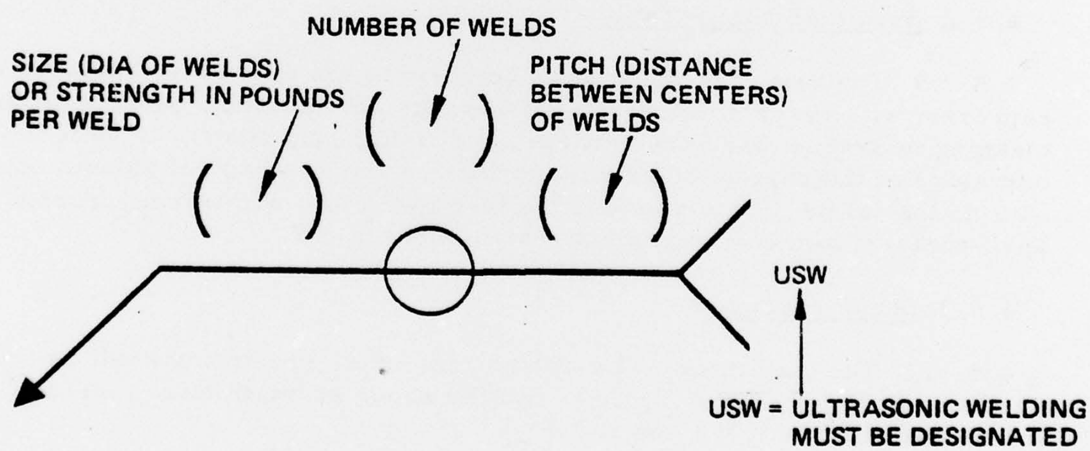

Figure 5. Typical Weld Symbol

4.4 Weld location.

4.4.1 Welds shall be located as specified on the engineering drawing. The edge distance of each weld shall be such that no deformation or bulging occurs at the sheet edge. In any event, the edge distance shall not be less than 0.020 inch.

4.5 Routine check specimen.

4.5.1 Test specimen.

4.5.1.1 A lap joint with three welds, three single weld shear specimens, or a simulated section of the production joint being welded containing three welds, shall be tested or examined, as applicable, for routine check purposes for each of the following conditions:

a. At intervals not to exceed two hours of production welding and at the end of a production run, if more than one hour of welding has elapsed since the last check.

b. At the start of each welding schedule.

c. After replacement of welding tips.

4.5.2 Specimen configuration.

4.5.2.1 The test specimens shall conform to the production parts they represent with respect to material, thickness combination, surface condition, cleaning technique, machine settings, and welding tip contours. When the curvature of the part or other part conditions require control adjustment outside the limits of this section, the test specimens and testing procedures shall conform to the requirements established in 3.7.

4.5.3 Shear specimen.

4.5.3.1 The (two thickness combination) shear specimens shall be prepared as shown in Figure 3 and Table I, and the shear strength must meet the requirements specified in 3.7.4 and 3.7.5.

4.5.4 Metallurgical specimen.

4.5.4.1 Three or more welds from a production weld joint or a simulated section thereof shall be sectioned for examination of the bonding zone at the start of each welding schedule.

4.6 Control adjustment.

4.6.1 When routine specimen check tests indicate that control adjustments are desirable, the settings may be varied by ±5 percent from the established values of by ±10 percent when only one control setting is adjusted. If satisfactory welding cannot be maintained within these limits of adjustment, welding shall be stopped and the machine shall be checked for faulty operation. If it can be shown that conditions other than the certified welding schedule were the cause of the faulty welding and with the correction of the equipment fault the original certified schedule is capable of producing acceptable welds, then establishment of a new welding schedule will not be required.

4.7 Routine shear check test requirements.

4.7.1 The minimum shear strength of the three welded specimens shall not be lower than the minimum shown in Tables III, IV, and V. After shear testing, each of the fractured welds shall be visually examined for evidence of obvious defects.

4.8 Shear strength variation.

4.8.1 The variation in shear strength for each of the three sample welds shall not exceed 30 percent as specified in 3.7.6. If the variation in shear strength is exceeded or when shear strengths are below the permitted value, the previous production representative of that sample for that machine and any subsequent production on that machine under those conditions shall be rejected and subject to Hughes Helicopters Material Review Board action. If investigation reveals that the weld quality has deteriorated due to obvious causes, other than certified welding schedule requirements, such as, faulty machine operations or improper cleaning and with the correction of these conditions the original certified welding schedule is capable of producing acceptable welds, the establishment of a new weld schedule is not required.

4.9 Weld defects.

4.9.1 Production parts shall be visually examined for the presence of external defects specified in 3.10. The accceptable number of external defects on welds in production parts shall not exceed the limits of Table VI.

4.9.2 When a metallographic examination is used, the number of welds having defects exceeding the limits of 3.10, shall not exceed the number indicated in Table VI.

4.9.3 When a radiographic examination is used, the internal defects shall not exceed the allowables of Table VI.

4.9.4 Distribution of defects.

4.9.4.1 The maximum percentage and nature of defects which are acceptable without repair and which are acceptable with repair are indicated in Table VI. Restriction on defects other than those described in Table VI as being acceptable with or without repair shall be randomly distributed unless it is demonstrated that a particular clustering of defects within the limits of Table VI is unavoidable in high quantity production and not detrimental to the service intended. This action must first be approved by HH MRB action.

4.10 Records. All records shall be retained by the vendor for 3 years after completion of the contract.

5. PREPARATION FOR DELIVERY

5.1 Handling. Adequate protection shall be provided to prevent damage during transport and storage unless otherwise specified.

6. NOTES

6.1 Intended use. This ultrasonic welding process is intended for use in the manufacture of Hughes Helicopters aircraft and their ordnance.

6.2 Definitions.

6.2.1 Ultrasonic welding. Ultrasonic welding is a welding process wherein the weld is effected by the introduction of acoustic energy into details held together by a clamping force.

6.2.2 Macrosection. A metallurgical specimen through the weld prepared for examination in the range of from one to 30X magnifications.

6.2.3 Microsection. A metallurgical specimen through the weld prepared for examination in the range above 30X magnifications.

6.2.4 Variation. Percent variation equals the difference between the highest and lowest shear strength value divided by the average of the individual shear strength values, multiplied by 100.

7. APPROVED VENDORS

7.1 Only vendors listed in AVL 11-9 shall perform this process.

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