APPLICATION OF WELDBONDING TO A-10 PRODUCTION AIRCRAFT

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ABSTRACT

The weldbonding process - a combination of adhesive bonding and resistance welding - has been transitioned from the laboratory to the manufacturing floor. Key cost drivers to make the process cost-competitive with conventional adhesive bonding are identified. The development of the phosphoric acid anodize process and the solid-state resistance welding controls is described. During the manufacturing scale-up phase, major subjects include adhesive application studies, nondestructive testing, durability testing, and production of panels for a prototype aircraft. Actual transfer of technology to the manufacturing environment is covered in the implementation phase.

INTRODUCTION

The aluminum weldbonding process is one which incorporates the technology of both adhesive bonding and resistance welding. The original work was performed in Russia and the early development work in the United States was performed by Lockheed-Georgia Company under the sponsorship of the U. S. Air Force Materials Laboratory. A number of other United States aircraft companies became interested in the process and attempted to solve one of the major problems which was brought out in the early development work - unacceptable environmental durability. These early development programs clearly showed that the weldbonding process was capable of substantial increases in static and fatigue strength as compared to conventional spotwelded or riveted construction.

The environmental stress durability problem was brought about by the incompatibility of the surface preparation necessary for quality spotwelds on the one hand and adhesive bonding on the other. As a result, the Air Force continued sponsorship of programs aimed at the development of a suitable surface preparation which would be environmentally durable and not interfere with the process of making quality spotwelds.

This development activity was conducted at Northrop Corporation with transfer of technology and up-scaling to production status at Fairchild Republic Company for use on the A-10 aircraft. The significant technical achievements were the development of (1) a chemical surface treatment, including a modified aluminum deoxidizer and a low voltage phosphoric acid-sodium dichromate anodize and (2) the use of a microprocessor controlled resistance welder. These developments, modified at Fairchild Republic for production implementation and improved durability, were used in the production program. The adhesive used in the development program and continued into the production program, is a paste adhesive developed by B.F. Goodrich especially for weldbonding.

MANUFACTURING IMPLEMENTATION

Component Selection

The major criteria for selection of the component were (1) suitability for determining the applicability of the weldbond process for aircraft structure and (2) a design which would provide a useful comparison to existing assemblies joined by conventional adhesive bonding. A list of potential assemblies was constructed and a trade-off matrix developed to rate the candidate assemblies for the weldbonding process. Selected areas where weldbonding appeared to offer advantageous use are illustrated in Figure 1.

The assembly which was finally selected for the development program and for subsequent production use was an aerodynamic skin/beaded pan assembly which is used extensively throughout the mid-fuselage section. This assembly was selected primarily because it would be a minimum change on production aircraft and also because the original A-10 design called for the use of the weldbonding process. Weldbonding was not used in the original production version because of the problems mentioned earlier. The manufacturing plan called for five panel assemblies, each approximately 4 square feet (0.4 square meter), per aircraft. Furthermore, this type of construction offered the potential for a large number of similar parts on the A-10.

Preproduction Panel Fabrication

As part of the preproduction program, eight weldbonded beaded fuselage panels were fabricated in the laboratory and installed on a specially configured two-place A-10 aircraft. Assembly of

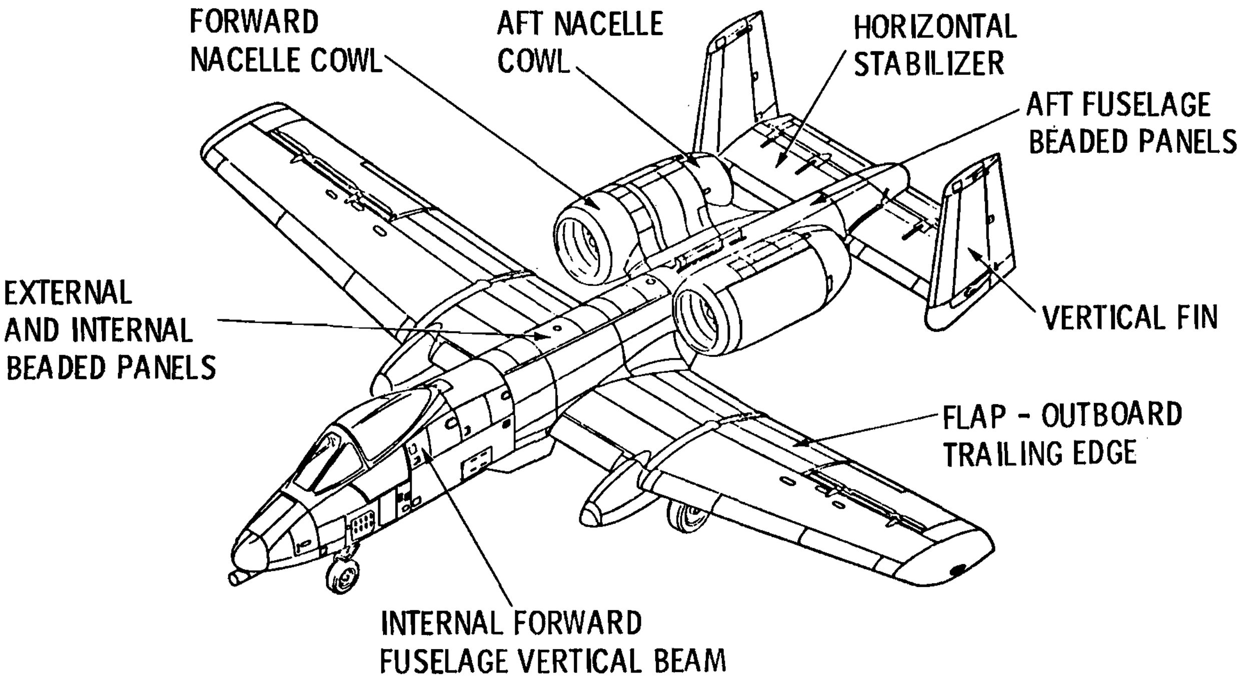

FIGURE 1. A-10 Candidate Assemblies for Weldbonding Fabrication

the panels was accomplished in normal fashion. The first flight of the aircraft took place in May 1979 and 300 flight hours have been logged to date. Inspection has not revealed any problems with the panels.

Technology Transfer to Manufacturing

The personnel training task was exacerbated by the fact that the bonding facility of Fairchild Republic is located in Hagerstown, Maryland, approximately 300 miles (500 km) from the Manufacturing Technology Laboratory in Farmingdale, New York. Extensive travel and careful planning were required. Manufacturing Technology engineers worked closely with personnel at the Hagerstown facility in modifying the chemical processing tanks and in ordering, setting up and qualifying the resistance spotwelder equipped with a microprocessor control. Production personnel were trained in performing the tasks described in the newly issued Fairchild process specification.

Production tooling was also designed and fabricated during this period. Close coordination was especially important since the existing autoclave bonded panels to support production were being processed simultaneously. The technology transfer, equipment procurement and installation, and tool development required about eight months.

Process Improvements

A number of changes were made to the basic process in order to accommodate it to the Fairchild manufacturing facility and to improve the production flow. The fabrication of preproduction panels also pointed out the need for certain manufacturing changes. As an example, it was determined that air entrapped during adhesive application could, under certain circumstances, coalesce in or near cutout areas which were originally designed with no spotwelds. Accordingly, additional spotwelds and vent holes were placed in areas which were subsequently trimmed away after curing.

The chemical processing tanks are located in a non-air conditioned area and seasonal temperature fluctuations caused concern that the oxide thickness could vary significantly with temperature change. Accordingly, an investigation was conducted to determine the effect of temperature, which fortunately showed acceptable oxide thicknesses over a wide range of solution temperatures. The results are shown in Figure 2. It was determined that the anodizing time could be varied, if necessary, to compensate for extreme temperature conditions.

A number of different methods of adhesive application were investigated

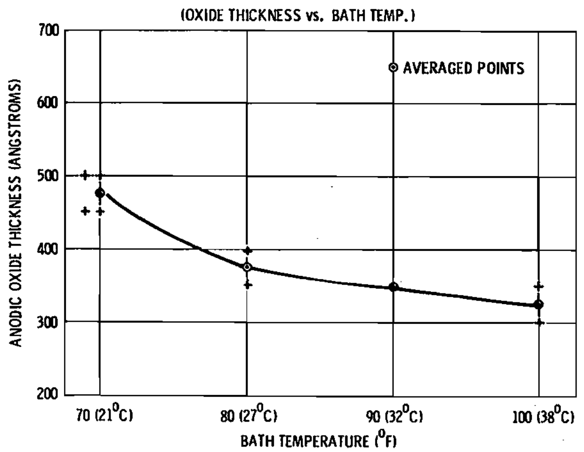

FIGURE 2. Effect of Bath Temperature on Anodic Oxide Thickness

including spraying, extrusion (with a sealant gun), and various configurations of rollers. It was determined that a locked plastic roller produced the most uniform results while minimizing air entrapment. Comparison of adhesive applied to both surfaces to be joined versus one surface revealed that either method was satisfactory but significant time savings could be achieved by applying to one surface only. This method was adopted for production use.

The use of an anti-stick solution prior to welding relieved the electrode sticking problem and resulted in a more rapid spotwelding rate.

Description of Production Equipment

Chemical Process Equipment

The tanks comprising the weldbond process line are all 14 ft. (4.3 m) long, 3 ft. (0.9 m) wide and 6 ft. (1.8 m) deep. Solution volume in the alkaline-cleaner, deoxidizer, and anodizing tank is approximately 1,675 gallons (6,350 liters) allowing for a solution level 8 inches (20 cm) from the top of the tank. Stainless steel type 316 is suitable for the vapor-degreaser, and the anodizing tanks. Koroseal lined steel is needed for the deoxidizer tank because of its fluoride content. The other tanks are fabricated from cold rolled steel.

In the rinse tanks, two levels of spray nozzles provide deionized water for effective removal of chemicals from the surface of the aluminum. A three-phase DC rectifier rated for 100 amps at 6 volts is used for anodizing and has proven more than adequate for the throughput. Several loads of 160 square feet of surface (15 square meters) representing 10 sets of parts drew 28 to 30 amps at 1.6 volts.

Resistance Welder/Microprocessor Controller

Conventional resistance welders are used for spotwelding. The machines should have a minimum rated capacity of 100KVA and a cycle pulse time of at least 10 cycles at peak secondary current. Ten cycle machines and up are required to avoid transformer saturation. Welding current/current decay total cycle times of 15-25 cycles are typical for welding aluminum sheet thicknesses of 0.025 to 0.090 inch (0.6-2.3 mm). This particular weldbonding process requires up slope and down slope heat cycle programming to avoid weld nugget expulsion and/or cracking. Weld current programming and weld forge cycling is accomplished through the use of a microprocessor (Pertron PWC-300). A certified welding schedule is established for each aluminum alloy/temper/thickness combination. Control codes are used for each specific welding operation, such as check contact gauge, apply weld force, hold, apply welding current, initiate forge force, etc. The control code weld schedule, once established, is converted to a teletype tape which is used to introduce the weld schedule into the microprocessor, where it is held in memory.

Production Process

The current manufacturing process flow is illustrated in the flow diagram in Figure 3.

Deoxidation and Anodization

Prior to anodizing, the detail parts are degreased in trichloroethane and then alkaline cleaned. The next step is immersion in a deoxidizer solution (nitric acid; Amchem 7/17) for 6-8 minutes, spray rinse, and reimmersion in the deoxidizer. Anodization is carried out at 1.2 volts for alclad material or 1.6 volts for bare aluminum alloys for a period of 25 minutes. A phosphoric acid-sodium dichromate solution at ambient temperature (see Figure 2) is used to yield an oxide (boehmite) thickness of 400-800 angstroms. Anodization is followed by spray rinsing in deoxidized water and oven drying for 30 minutes at 150 to 160°F (65 to 71 C).

Process control samples are taken to determine the adequacy of surface preparation (wedge-crack test) on each process batch and thickness of oxide (scanning electron microscope) on a less frequent basis. Frequency of testing is being adjusted based upon consistency of results, which to date has been good.

VAPOR DEGREASE

ALKALINE CLEAN

RINSE

INSPECT FOR CONTAMINATION BY WATER-BREAK TEST

WATER BREAKS OR CONTAMINATION

DEOXIDIZE

SPRAY RINSE

DEOXIDIZE

SPRAY RINSE

ANODIZE

SPRAY RINSE (TWICE)

OVEN DRY

APPLY PRIMER AND ADHESIVE

ASSEMBLE PANEL

APPLY ELECTRODE ANTI-STICK SOLUTION

WELD

CURE ADHESIVE

VISUALLY INSPECT

INSPECT FOR VOIDS

RADIOGRAPHICALLY INSPECT (WHEN REQUIRED)

FIGURE 3. Manufacturing Process Flow

Application of Weldbond Adhesive

Corrosion inhibiting adhesive primer (BR-127) is applied by brush at the peripheral trim lines in the area on the skin where the beads join the skin, and in the area where fastener holes will be drilled. This process change was instituted as a result of tests showing substantially improved environmental durability.

The weldbond adhesive (A-1444B from B.F. Goodrich) is applied to the faying surface of the beaded pan only, using a pneumatically operated sealant gun loaded with a plastic cartridge filled with adhesive and fitted with a plastic nozzle. The adhesive is uniformly spread over the faying surface using a locked plastic roller to achieve a final uncured glue line thickness of 0.008 to 0.012 inch (0.2-0.3 mm). A wet film gauge is used to monitor the uncured adhesive thickness. The adherend faying surfaces are carefully mated using the indexing holes in each adherend within one hour after completion of adhesive application, and are subsequently spotwelded. Spotwelding can follow the adhesive application by up to five days at 80°F (27 C) without adverse effects.

Resistance Welding

Following the application of the paste adhesive, the panels are coated with an electrode anti-stick solution to prevent excessive electrode sticking to the assembly being welded. The panel is next introduced into a weld fixture which establishes the desired contour prior to welding. The weld fixture is also used to locate each spotweld. The panels are then welded using a certified weld schedule. A typical weld schedule consists of approximately seven cycles of heat-up and about fifteen cycles of current decay. Approximate time to accomplish a single spotweld and to move to the next location is eight seconds. Spotweld spacing depends on detail thickness, contour and amount of faying surface to be bonded. The spotwelds are primarily for fixture purposes; however, they also serve to help prevent panel edge peeling. After all spotwelds have been made, the panels are removed from the weld fixture, the anti-stick film is removed by solvent wiping and the panels are transported to the curing ovens.

Curing

The panels are introduced into curing fixtures which are made of aluminum for expansion compatibility. The clamping fixtures consist of a bottom lightweight contour cradle and a top edge picture frame. The part is placed in the oven and brought to the curing temperature of 250°F (121°C) and maintained for three hours. Following the cure, the panels are removed from the curing fixture and the adhesive "run-off" controlling tapes are detached. Initial studies have indicated that the welding operation establishes and maintains contour and in all likelihood the curing fixtures are not needed. These studies are continuing as part of a productivity improvement program.

Inspection

Emphasis is placed on process control during the chemical processing (oxide thickness measurement and surface preparation) and during resistance welding (lap-shear test and macro-examination of nugget). One panel assembly from each production lot is currently radiographically inspected after final trim and fastener hole drilling.

Test Results

An extensive series of structural and environmental tests were performed to compare the performance of weldbonded and autoclave bonded panels. The panels were fabricated of the same materials and thicknesses as used in the A-10 fuselage center section panels. A summary of some of the more significant tests is described below.

Exposure Testing

An environmental chamber was used to simulate ground ambient and altitude conditions at 35,000 feet (10,700 m). Fifty cycles of the following procedure were used on autoclave and weldbonded panels.

1) 3.5 psia (24×10^3 N/sq.m) at a temperature of -45°F (-43 C)
2) Stabilize and maintain for 2 hours
3) Increase chamber pressure to ambient at temperature of 120°F (49 C) at 95 to 100% relative humidity
4) Stabilize and maintain for 2 hours

After completion of fifty cycles, the panels were inspected by x-ray and Fokker bond tester to determine any bondline deterioration. Subsequently, the panels were dissected and visually examined for evidence of moisture intrusion, surface corrosion or pitting. No deterioration was noted.

Following nondestructive examination, thirty fatigue specimens were cut from the skin and bead of the weldbonded control and environmentally exposed panels. Test conditions were selected to produce failure at 10^4 cycles and 10^6 cycles. Test results showed no significant difference between specimens from the control panel and the exposed panel.

In addition, one autoclave bonded and one weldbonded panel were subjected to 95 to 100 percent relative humidity at 95°F (35 C) for 120 days. These panels were prepared by applying an epoxy polyamide primer to all exposed surfaces, then removing it from all edges to expose the bond line. Visual examinations revealed no evidence of corrosion or moisture intrusion in the interior of the beads of either the autoclave bonded or weldbonded panel.

Lap-Shear Specimen Testing

Typical shear strengths comparing weldbonding with spotwelding and adhesive bonding for one-inch (2.54 cm) overlap joints are shown in Table 1. It can be seen that the lap shear strengths of the weldbond joints were significantly improved over spotwelds and were roughly comparable to autoclave bonded joints (using the commonly used FM-123 adhesive system for comparison).

Static and Spectrum Fatigue Panel Testing

The results of the shear panel static tests on .025/.032" (0.6/0.8 mm) are summarized in Table 2. The panels were reinforced around the edges and loading corners, mounted in a hydraulic

Joining Method	7075-T6 Bare to 7075-T6 Bare (lb.)	2024-T3 Bare to 2024-T3 Bare (lb.)	2024-T3 Bare to 7075-T6 Bare (lb.)	2024-T3 Alclad to 7075-T6 Bare (lb.)
Weldbond	5200(2360kg)	3800(1720kg)	3900(1720kg)	4000(1820kg)
PABST	5200(2360kg)	3800(1720kg)	4000(1820kg)	4000(1820kg)
FM-123/FPL	5100(2310kg)	3800(1720kg)	3700(1680kg)	3700(1680kg)
Spotwelds	900(410kg)	820(370kg)	820(370kg)	950(430kg)
Specimens were 0.063(1.6mm) x 1 inch (2.54 cm) with 1 inch (2.54 cm) overlap. Results average of 4 tests.				

TABLE 1. LAP SHEAR TEST RESULTS

Skin Thickness 2024-T3 Clad (in)	Beaded Pan Thickness 7075-T6 Bare (in)	Autoclave Bonded Panel Failing Load (lb)	Weldbonded Panel Failing Load (lb)
0.071 (1.8mm)	0.050 (1.3mm)	91,500 (41,600kg)	82,500 (37,500kg)
0.040 (1.0mm)	0.050 (1.3mm)	65,000 (29,500kg)	67,000 (30,400kg)
0.025 (0.6mm)	0.032 (0.8mm)	33,000 (15,000kg)	35,600 (16,200kg)

TABLE 2. SUMMARY OF STATIC SHEAR PANEL TEST RESULTS

test frame and loaded across the diagonal of the panel.

Spectrum fatigue tests were conducted on 0.025/0.032 inch (0.60/0.8 mm) panels mounted in the same configuration fixture as the static shear panels. The fatigue test spectrum used for evaluation was the same as the 6,000 flight hour test spectrum used in testing the A-10 fatigue airframe. Test results on 0.040/0.050 in. (1.0/1.3 mm) panels also showed comparable behavior between weldbonded and autoclave bonded panels. It was concluded that there were not significant differences in static strength or fatigue life that could be attributed to the weldbond process (see Table 3).

High Load Transfer Fatigue Tests

Lap shear specimens were used to evaluate the fatigue behavior of the basic adhesive and the weldbond systems. Control specimens were fabricated and tested for performance comparison using FM123-2 adhesive and autoclave bonding. Prior to the test, all specimens were examined by x-ray and Fokker bond tester. The loads chosen were 3400 pounds (1540 kg) and 2,000 pounds (907 kg) with cyclic frequency of 30 hz, R = 0.1 to produce failure at 10^4 and 10^6 cycles, respectively.

The results of this test are shown in Table 4. The data show that:

(1) There is good reproducibility data for the A1444 adhesive bonded samples and the FM123-2 metalbonded samples. Reproducibility is attributed to a constant bondline thickness.

	Spectrum	Initial Crack % Life	Growth to 90° Arc % Life	Residual Strength* (lb.)
Autoclave Bonded	1.11	38.5	82.0	33,500 (15200kg)
	1.00	69.0	113.6	33,200 (15100kg)
	0.90	72.0	140.0	31,600 (14400kg)
Weldbonded	1.11	60.0	120.0	34,000 (15500kg)
	1.00	78.0	138.0	36,100 (16400kg)
	0.90	72.0	188.0	32,400 (14700kg)

*Static Panel Strength - 34,300 lb. (15600kg) Average

TABLE 3. SPECTRUM FATIGUE RESULTS FOR THE 0.025/0.032-INCH (0.6/0.8 MM) PANEL

(2) The weldbond data have a large scatter factor. Measurement of the bondline thickness with a film thickness gage after specimen failure revealed the probable cause.

Bondline Thickness versus Fatigue Strength

Data scatter in fatigue testing prompted a further investigation of the effect of bondline thickness on fatigue for weldbonded specimens. Tests were conducted on lap shear specimens with various bondline thicknesses. The test results, shown in Figure 4, indicate a clear relationship to thickness of bondline. The data show the need for control of bondline thickness in fatigue and fracture critical structures.

Low Load Transfer Fatigue Tests

Low load transfer fatigue tests with fastener holes intersecting spotwelds on weldbonded specimens were used to study the fastener hole-spotweld effect. The results of these tests are shown in Table 5. The low load transfer fatigue test results show that:

(1) The metalbonded specimens are more resistant to fatigue than the weldbonded specimens. It should be noted that the simulated fastener holes were drilled into one-half of each of the welds on the weldbonded

P Max. (lbs.)	Weldbond Specimens Nf (cycles to failure)	Weldbond Specimens Bondline Thickness (mils)	A1444 Adhesive Bond Nf (cycles to failure)	FM123 Adhesive (Metalbond) Nf (cycles to failure)
2000 (907 kg.)	402,000 1,372,000 1,164,000 176,000*	1.45 (0.037 mm) 2.21 (0.056 mm) 2.03 (0.052 mm) 1.16 (0.029 mm)	2,174,000 1,293,000 2,487,000 2,010,000 9,995,000	5,035,000 10,351,000 9,408,000 15,500,000 13,201,000
3400 (1540 kg.)	29,000 50,000 53,000 21,000	1.91 (0.049 mm) 2.36 (0.060 mm) 2.34 (0.059 mm) 1.65 (0.042 mm)	100,000 157,000 115,000 62,000	35,000 52,000 44,000 39,000

*0.005 in. (0.13 mm) shim, which aligns the specimen with the load line, was installed on the wrong side of the specimen.

TABLE 4 . HIGH LOAD TRANSFER FATIGUE TESTS

specimens; the metalbonded specimens had no welds.

(2) The low fatigue life of the weldbonded specimens is attributed to the fact that the cast structure of the weld flaws the wrought aluminum structure, acting as micro-crack initiators and propagators.

As a result of these tests, caution is exercised in design and manufacturing to insure that fastener holes do not intersect spotwelds on production assemblies.

Damage Tolerance Tests (Fatigue Crack Growth)

Constant amplitude fatigue crack growth tests were conducted on weldbonded and metalbonded specimens to investigate the effect of spotwelds on the crack growth behavior in the bonded sheet metal. Tests were made on control specimens and on specimens with through cracks between spotwelds. In general, the weldbonded specimens failed sooner than the metalbonded specimens, as a result of multiple cracks initiating at the spotweld, finally joining with the through crack. The effect becomes more pronounced at higher stress levels and with close spotweld spacing. Additional tests are planned.

Cost Implications of Weldbond Process Introduction

The weldbond process has been introduced roughly midway into a production program. As a result, the process must compete against an on-going autoclave bonding process with its attendant learning curve benefits. Full-scale

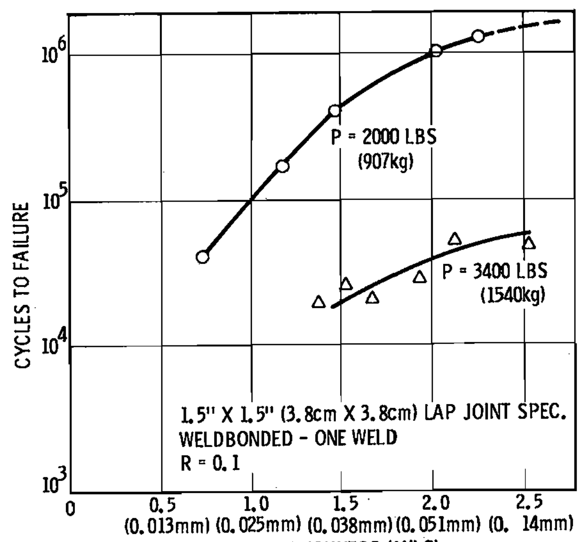

FIGURE 4. B.F. Goodrich Weldbond Adhesive A-1444B Fatigue Life vs. Bondline Thickness

production of weldbonding is just beginning at this time, and comprehensive cost data are not yet available. Nevertheless, certain trends based upon limited experience are emerging which will bear on future acceptance of the weldbond process and its economic viability.

1, The substitution of oven curing for autoclave curing is the major factor in reducing the final manufactured product cost. Significant considerations are capital expenditures (weldbond equipment less than 1/3 of autoclave bonding) and operational expenses, including energy needs (weldbond less than 1/4 of autoclave bonding). Degree of available productive capacity, depreciation write-off factors, equipment maintenance needs, and local energy rates will determine actual savings. Rapid expansion of production capacity is an additional advantage of weldbonding.

2. Direct labor hours are currently higher for weldbonded assemblies. Insufficient data are available at this early point in the production cycle to confidently predict the actual crossover point on the learning curve.

3. Acceptance rate of assemblies which meet specification requirements appear promising.

4. Tooling fixtures for weldbonding are simple and inexpensive; cost savings are clearly possible in this area.

P Max. Load	Weldbond Specimens	Autoclave Bonded Specimens
	N_F	N_F
3500 lb. (1590 kg)	19,000	33,000
	23,000	38,000
	28,000	36,000
	21,000	40,000
	24,000	45,000
1700 lb. (770 kg)	311,000	1,353,000
	316,000	822,000
	296,000	11,365,000
	302,000	709,000
	330,000	1,099,000

TABLE 5. LOW LOAD TRANSFER FATIGUE TESTS (FASTENER HOLE EFFECT)

FUTURE WORK

Plans have been formulated and some experimental work has commenced in order to expand weldbond technology, improve productivity and increase the areas of structural application. Among the tasks identified are the following:

- Use of other than paste adhesives for more rapid application and for use at higher service temperatures.
- Rapid process control and nondestructive testing.
- New tooling concepts resulting in elimination/simplification of tooling.
- Use of ultrasonic welding as a replacement for resistance welding.
- Establishment of the process limits and design allowables of weldbonding for structural applications requiring thicker sections.

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