Comparison of Properties of Joints Prepared by Ultrasonic Welding and Other Means

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This is the third in a series of papers on the work being done at the Fairchild Republic Company to develop and evaluate ultrasonic welding as a means for aluminum sheet metal assembly. This paper covers a large-joint testing program that compares the static and fatigue properties of joints prepared by mechanical fastening, adhesive bonding, resistance spotwelding, resistance weldbonding, ultrasonic welding, and ultrasonic weldbonding. Overlap joints 12 in. wide are used for static, monotonic fatigue, and random spectrum fatigue tests. In addition, relative weight and cost factors have been assessed and incorporated into an overall trade study of the various joining methods.

Introduction

A DEVELOPMENT program has been in progress at the Fairchild Republic Company for some time to prepare the ultrasonic welding process for use in aircraft assembly. The impetus has been the potential that the process has for very significant cost and weight reductions. This is the third in a series of papers that report on the progress of the program on aluminum sheet metal. The first paper[1] demonstrated that modern, properly controlled welders could produce high strength spots with acceptable dispersions. The second paper[2] reported on the strength of large, single overlap joints made with various arrangements and numbers of ultrasonic spotwelds. It was shown that such joints could be loaded to sheet stresses above the yield strength with simple double rows of spots placed at either end of the overlap.

The additional large panel data that are reported in this paper are a natural expansion of those reported in Ref. 2. Using the standard joint pattern established in Ref. 2, the tests cover a series of interlayer situations which can exist in the assembly of aircraft. Fatigue data are also reported for these joints.

Other types of joints than ultrasonically welded ones were also prepared and tested in order to develop directly comparable static and fatigue properties. Weight and cost comparisons have been included in order to generate a broad-based trade study.

Materials and Equipment

All of the data reported herein were developed on aluminum alloy 7075-T6, bare and clad. The bulk of the joints tested were fabricated from 0.063-in.-thick sheets with a limited amount on the 0.1-in.-thick sheet.

Where adhesive bonds were made, the system normally consisted of the 0.011-in.-thick film adhesive FM-123 (product of the American Cyanamid Co.) over the brush-applied adhesive primer BR-127 (product of the American Cyanamid Co.) on metal surfaces prepared by deoxidizing in a nitric acid-chromic acid solution. In one case, a resistance-weldbonded joint was made with the 1444B paste adhesive (a product of B.F. Goodrich Co.).

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Weldbond joints made with either resistance or ultrasonic welds are cured without dies in an oven; whereas straight adhesive bonds are subjected to 15 psi pressure loading on the bond area during the cure cycle.

Where sealant was used, it was the polysulfide-type PR 1221-A-12 (a product of the Products Research and Chemical Corp.).

The ultrasonic welding was done on a modified Sonobond M-8000 welder in accordance with the general practices described in Ref. 1. This practice involved developments proprietary to Fairchild Republic, which have continued to evolve since the preparation of Ref. 1. A recent distribution of the strengths of 100 welds made with a particular schedule is shown in Fig. 1 and in Fig. 2 as a probability plot. Spots like these have diameters in the order of ⅝ in. Sheets thicker than 0.063 in. can also be welded, although with losses in spot shear strength. Strengths of 2500 lb can be obtained between sheets that are 0.125 in. thick; and 4000-lb strengths can be obtained when a 0.063-in. sheet is welded to a 0.187-in. sheet.

The resistance welding was accomplished on a 150 KVA Sciaky machine. On this size machine, 0.125 in. is the maximum thickness sheet that can be welded and produce a nominal 1000-lb capability spot.

Table 1 is an assembly of the typical individual spot failing load levels of both resistance and ultrasonic welds with different interlayer situations that were to be used in the large joint tests. These data represent the best values that can be obtained on the equipment; lower-valued spots are achievable when desired.

Mechanically fastened joints were made with steel bolts of the Hi-lok type. Controls on these fasteners call for a "transition" fit which allows a -0.001- to a $+0.002$-in. interference when assembled. The joints tested here, however, all were made with the positive interference in every hole.

Testing Practice

The large panel joints were statically tested in a 100,000-lb machine. The joints were made between 12-in.-wide by 20-30-in.-long sheets that had the ends reinforced with bonded pairs of 0.25-in.-thick 7075-T6 plates. Loads were introduced at the ends through 1.25-in.-diam pins to assure uniform loading. Except for two mechanical tests described elsewhere, all joints were made with double rows of elements separated by 2 in., and centrally arranged in the overlap. A uniform pitch was established to accommodate the number of joint elements in each row.

Fatigue test joints were prepared and mounted in similar ways; however, test loads were introduced from a 25,000-lb hydraulic cylinder. Computers were used to introduce and

Table 1 Typical resistance and ultrasonic spotweld strengths (pounds/spot) with and without different interlayers on a 0.063-in.-thick 7075-T6 sheet

	Typical strengths on a 0.063-in.-thick 7075-T6-sheet, lb			
	Resistance welds nonclad	Resistance welds alclad	Ultrasonic welds nonclad	Ultrasonic welds alclad
No interlayer	1200	1200	22-2500	4-5500
Sealant interlayer	1100	1100	17-2500	3700
Weldbond				
FM-123 adhesive film (not cured)	Not weldable	Not weldable	17-2300	2500-3660
Goodyear A1444B paste adhesive (not cured)	1100	1100	...	17-2800

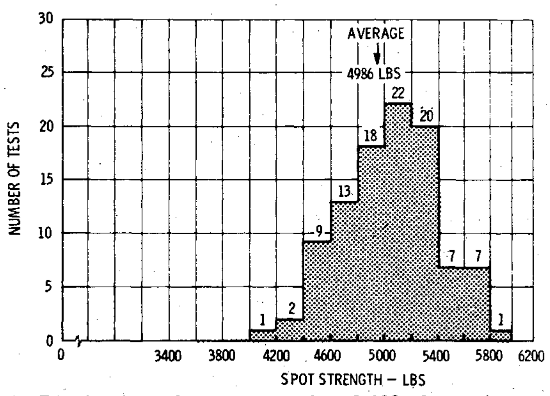

Fig. 1 Distribution of shear strengths of 100 ultrasonic spotwelds made consecutively on 0.063-in.-thick 7075-T6 alclad sheets.

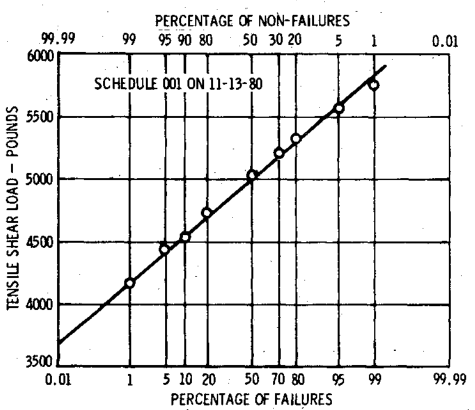

Fig. 2 Probability plot for 100 test specimens covered in Fig. 1.

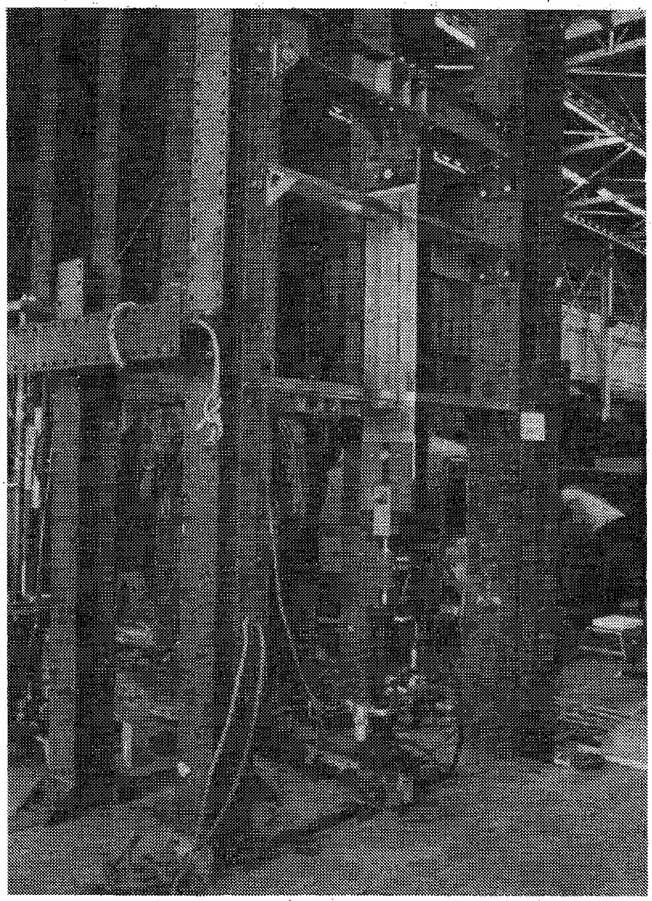

Fig. 3 Fatigue test setup for random spectrum testing.

control the loads. The spectrum fatigue testing consisted of a randomized mixture of load levels representative of those that the upper aft fuselage of the A-10 aircraft would experience in 6000 h of service life. One life consists of some 261,500 individual cycles that are expected to occur in the useful life of that aircraft. Load levels were adjusted to the peak stress in the spectrum in the same way that a change in material section area would produce a change in stress. Compression loads were removed from the spectrum. A test panel in the test rig is shown in Fig. 3.

Results and Discussion

Joint Tests with Sealant

A series of static test joints were prepared with a sealant interlayer, since it is a normal candidate material to fill spaces between faying surfaces on aircraft to preclude entry of moisture or fuel.

The results of these tests are presented in Fig. 4, with the number of spots in the joint plotted against the sheet stress at failure. The plot titled "no sealant" is data taken from Ref. 2 for comparison purposes. It will be noted that the data plots on two slopes, with the first being the sum strength of the number of spots present in the joint. The second slope exists above the yield strength of the sheet; here joint strength is raised by reducing the unit load carried by each spot, and hence lowering the inclination to reach ultimate failure locally around the spot. In the additive slope, failure occurs by nugget tear-out (i.e., the cracks circle around the spots) or by shear when contaminated. In the second slope above the yield stress, failure occurs by tearing across the sheets, with cracks starting at each spot and running together. The plot with sealant covers the somewhat weaker results obtained owing to an evident effect of contamination in the spots. With 20 spots in the joint, the plot reverts to the no-sealant case, since failures are then by sheet tear and the individual spot shear strengths are not a factor.

The third plot of data is from joints with sealant between sheets that have had "alodine" chemical films produced on their surfaces for additional corrosion resistance. It is evident that the contamination effect is worsened, for the spot strengths fall off considerably and the joints cannot be loaded to the yield strength of the sheet.

Other difficulties developed in working with the polysulfide sealant. It tended to start to precure if the temperature of the workpiece rose. Curing action progressively reduced the strength of a series of spots. Close-packed joints could only be prepared by applying external cooling with a cold stream of CO_2 gas.

Joint Tests with Resistance Welds and Fasteners

Even though abundant data exist on the properties of joints prepared with fasteners and spotwelds, it is not in a form that allows direct comparison with the joint type used in the ultrasonic test program. A limited number of such joints were made and tested in order to generate comparisons. These data are presented in Fig. 5, again along with the plot of the ultrasonic weld joints. The ¼-in.-fastener plot is nonlinear because of the loss of section area in making holes.

A more complex joint, designed to minimize the section loss in the end rows of fasteners, was also tested. It was made with a row of 6-5/16-in. Hi-loks in the center of the 6-in. overlap, with two adjacent rows of 5¼-in. Hi-loks and with two outer rows of 6-3/16-in. Hi-loks. The rows were 1 in. apart, and in adjacent rows the fasteners were staggered and uniformly spaced. The joint failed at 54,100 lb. The resistance welds at maximum permissible packing were not able to load the sheet above the yield strength.

Joint Tests with Adhesives (Weldbonds)

Weldbonded joints (i.e., those combining a spotweld and adhesives) were prepared and tested to determine their strength. These data points for a 0.063-in.-thick sheet are displayed in Fig. 6, again with reference to the plot of simple ultrasonically welded joints. These joints permit the sheets to be loaded to their ultimate strength, well above the other joints.

It appears that the number of welds in a weldbonded joint are not significant, except insofar as they assure proper contact of the surfaces of the metal sheets to the adhesive film. Tests of a resistance-weldbonded joint made with the 1444B paste adhesive, as well as of a straight adhesive bond, are included in Fig. 6. It was noteworthy that the weldbond failures occurred in the sheet at other locations than the joint, whereas the straight adhesive bond failed at a lower test value in the joint by peel that initiated at the corners.

Figure 7 provides additional weldbond and adhesive bond data for a 0.1-in.-thick alclad sheet, as well as the two-slope plot for joints fabricated without adhesive. The weldbonded joint, having only four spots, had them at the corners of the lap, where peel normally initiates on adhesive joints. This placement raised the failing stress 5000 psi above that of a straight adhesive bond test joint (plotted on the 0 spot line), and changes the failure mode from peel to sheet overload. This is a synergistic interaction.

Fatigue Testing

Ultrasonically spotwelded joints, ultrasonically weldbonded joints, and mechanically fastened joints were fatigue tested. Constant amplitude cycling ($R = 0.1$) of the joints produced the data in Fig. 8. It is seen that simply spotwelded joints produce a regular S/N curve reflecting a consistent response to the characteristic stress concentration at the spots. The tests at a sheet stress of 15 ksi and below had failures start by crack growth at the outermost circumference of each spot. Above 15 ksi on these plain joints, failure occurred by progressive shearing of the spots between the sheets. The single data point for a weldbonded joint demonstrated a life improvement over plain joints in excess of an order of magnitude. That joint, even so, was not fully tested, since failure occurred in the sheet 1 in. away from the joint.

Random spectrum testing results are displayed in Fig. 9. Again, a regular relationship is demonstrated between stress

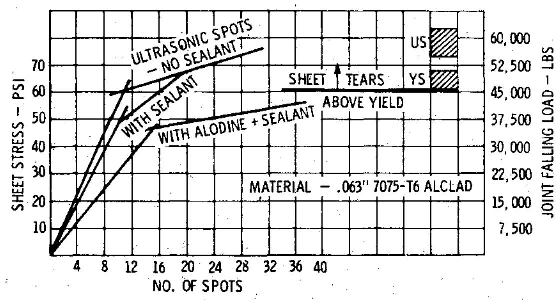

Fig. 4 Plot of large panel joint tests with sealant interlayers (joints are formed by two equal rows of spots 2-in. apart).

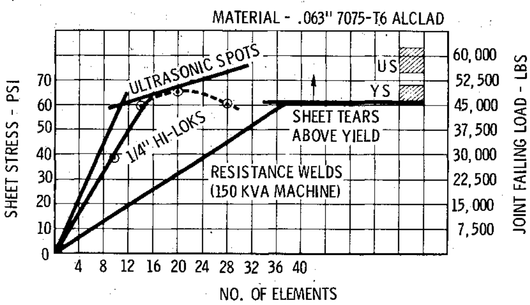

Fig. 5 Plot of large panel joint tests with resistance welds and ¼-in.-thick steel fasteners.

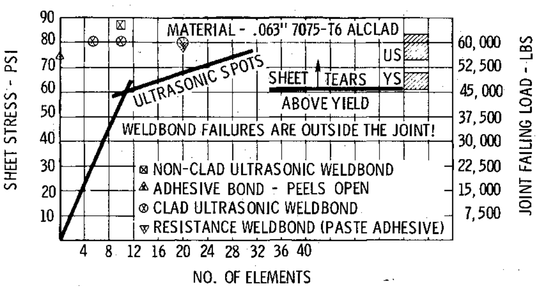

Fig. 6 Plot of large panel joint tests with adhesive interlayers on a 0.063-in.-thick 7075-T6 alclad sheet.

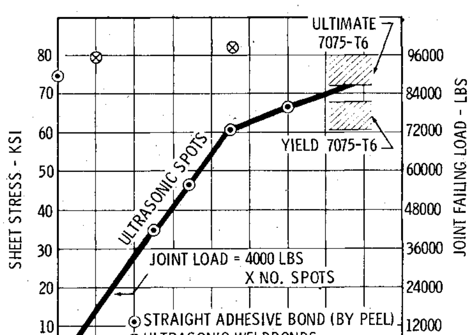

Fig. 7 Plot of large panel joint tests with adhesive interlayer on a 0.1-in.-thick 7075-T6 alclad sheet.

level and fatigue life. While most of these data are based upon clad sheet, there is one data point for a joint made with a bare (i.e., nonclad) sheet. Its shorter life by comparison with the 24 spot alclad case is consistent with the characteristically smaller and weaker spots (see Table 1). One test point is shown for a mechanically fastened joint with 28 fasteners (described more fully in an earlier section on static tests). This joint endured 1.6 lives of cycling; however, since every

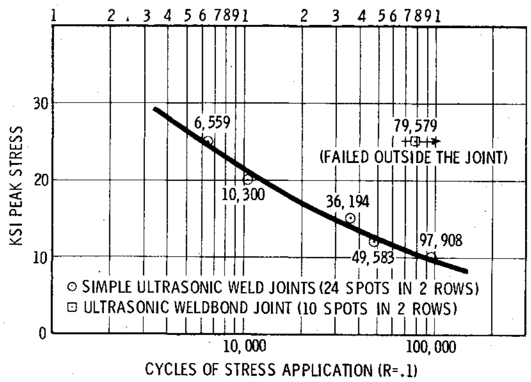

Fig. 8 Fatigue tests of large, single overlap joints; constant amplitude stressing of a 0.063-in.-thick 7075-T6 alclad sheet.

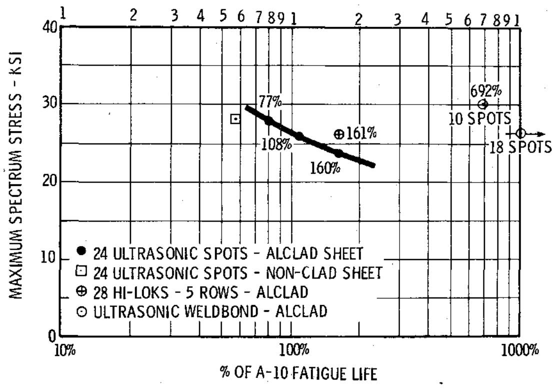

Fig. 9 Variable amplitude randomized spectrum fatigue tests on large, single overlap joints of 0.063-in.-thick sheets.

Table 2 Trade study comparison of joining methods with test data from a 0.063-in.-thick alclad 7075-T6 sheet and 12-in.-wide single overlap joints

TYPE	JOINT DESIGN	OVERLAP	STATIC STRENGTH (LBS)	% EFFICIENCY	FATIGUE A-10 SPECT. #3 LIVES	WEIGHT FACTOR	COST FACTORS	UTILITY FACTORS
MECHANICAL	28 HI-LOKS 5 ROWS 3 SIZES	6"	54,100	90	1.6 (26 KSI MAX. CYCLE STRESS)	HEAVIEST – EXTRA 1/3 LB OF HARDWARE	HIGHEST – MIN. OF 2 MAN HOURS ADD $28 + FOR HARDWARE	– IS COMMON A/C PRACTICE – HIGH SKILL LEVEL REQUIRED – VERY VERSATILE
MECHANICAL	2 ROWS OF 10 EACH 2" SEPARATION	6"	49,000	82	NO DATA	–	–	–
ULTRASONIC WELDS	2 ROWS OF 12 EACH 2" SEPARATION	4"	52,500	87	1.1 (26 KSI MAX. CYCLE STRESS)	NIL LOWEST	LOWEST 5 MINUTES TO WELD	– FLAT TO SHALLOW CONTOURS – LOW SKILL – WIDE THICKNESS CAPABILITY – REQUIRES SOME (?) INTERLAYER
ADHESIVE BOND	FM-123 FILM ADHESIVE 15 PSI PRESSURE	3" 6"	56,200 59,900	93 100	NO DATA (EXPECTED TO BE GOOD)	NIL	HIGH – AMORTIZE $8,500 BONDING TOOL COST – COSTLY FACILITIES – ENERGY INTENSIVE	– EFFECTIVE ONLY ON LONG PRODUCTION RUNS – LIMITED COMPLEXITY OF ASSY.
ULTRASONIC WELDBOND WITH FM-123	2 ROWS OF 5 EACH 2" SEPARATION	5"	60,000	100	6.9 (30 KSI MAX. CYCLE STRESS)	NIL	2ND LOWEST – SIMPLE SURFACE PREP. – EASY CORROSION CONTROL – SIMPLE FILM ADHESIVE LAYUP – OVEN CURE	– FLAT TO SHALLOW CONTOURS – LOW SKILL – WIDE THICKNESS CAPABILITY
RESISTANCE WELDBOND	2 ROWS – GOODRICH 1444B PASTE ADHESIVE	4"	60,800	100	NO DATA (EXPECTED TO BE GOOD)	NIL	– RECURRING COSTS EXCEED ADHESIVE BONDING – EXP. SURFACE PREP. – EXP. CORROSION PROTEC. AND PASTE ADHESIVE LAYUP – OVEN CURE	– JUST AS ABOVE EXCEPT LIMITED THICKNESS CAPABILITY
RESISTANCE WELDS	2 ROWS OF 19 EACH	4"	45,400	76	NO DATA	NIL (LOWEST)	LOW	– JUST AS ABOVE – REQUIRES SEALANT INTERLAYER

fastener had been installed with positive interference, it is likely that this result is on the high side of the normal scatter. Experience has shown that the endurance of such joints is quite sensitive to fit and also to the clamp-up effect of the bolt, both of which may vary in production.

The really striking data points on Fig. 9 are those developed on ultrasonically weldbonded joints. The point shown as having in excess of ten lives at a maximum cycle stress of 26 ksi was actually a complex test run at a series of increasing load levels. Three lives were applied at 26 ksi maximum cycle stress, then one life at 28 ksi maximum cycle stress, then one life at 30 ksi maximum cycle stress, and finally 54,000 cycles were applied at a constant amplitude of 28 ksi. The part failed in the end pin hole, when one of the doubler plates separated away. There was no evident fatigue damage in the joint area. This weldbonded joint was made with 18 spots.

A second attempt to obtain a valid, complete fatigue life data point on the weldbonded joints is registered on the 30 ksi maximum cycle stress line. This weldbonded joint contained ten spots in total. Failure occurred by crack growth at a single spot, which spread to the critical size for the sheet. It appears, however, that the adhesive zone between the spot and the end of the overlap had been debonded at some point during the load cycling. Presumably, this was a progressive loss of bond contact due to shear loads. Once the debond zone reached the spot, the local loads became concentrated on it and eventually caused it to develop the failing crack. In a sense, one can interpret the weld spot as having delayed the progressive adhesive shear failure by picking up the local loads before its own failure resulted.

Trade Study/Summary

It is only necessary to introduce relative factors such as weight, cost, and utility to the static and fatigue properties in order to generate an overall comparison or trade study that would indicate the relative status of ultrasonic welding for aircraft assembly. Such a study is presented in Table 2. It is evident that the weldbond approach provides superior properties in static and fatigue tests. Ultrasonic weldbonding will be cheaper than resistance weldbonding because of simpler surface preparation procedures and because of the simple-to-handle film adhesive. It is also a more versatile process, since it handles a wider range of sheet thicknesses and because it welds through a corrosion-inhibiting adhesive primer, something that resistance welders cannot do.

While mechanical assembly practices introduce extra weight and are relatively expensive, they have the important characteristics of being very adaptable (i.e., applicable in complex geometric situations) and generally stress-free (i.e., produce a stable spacial configuration). Spotwelding must be done on large machines which require clear access from both sides of the workpiece, hence such processes are limited to flat or moderately curved assemblies. Spotwelding often will introduce residual stresses that can affect the spacial shape of the workpiece. That sometimes limits the utility of resistance welding. The distortion situation with ultrasonic spotwelding has not yet been fully evaluated.

It may be summarized that there are important advantages that will result from the introduction of ultrasonic welding as an industrial process for the assembly of aircraft. While it is unlikely to significantly replace mechanical assembly methods, because of their applicability to the more awkward assembly situations, it will contribute to cost and weight reductions to the degree that fasteners can be eliminated.

Acknowledgments

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References

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[2] Renshaw, T. and Sarrantonio, A., "Properties of Large Multispot Ultrasonically Welded Joints," *Journal of Aircraft*, Vol. 18, Sept. 1981, pp. 761-765.