AIAA 80-0763R

Properties of Large Multispot Ultrasonically Welded Joints

T. Renshaw* and A. Sarrantonio†
Fairchild Republic Company, Farmingdale, N.Y.

Using ultrasonic spotwelds, two series of overlap joints were prepared with aluminum alloys and tested in tension. In the first series between 4×12×0.063 in.-thick panels, it is shown that on a one-for-one basis ultrasonic welds produce joints superior to those made with ¼-in. steel fasteners. In the second series on 7075-T6 and 2024-T3 alclad sheets 12×30×0.063-in. thick, joints were made with different numbers and arrays of spots. Joints based on row separations of 2 in. and pitches on the order of ¾ in. are shown to be optimum and able to develop sheet stresses in excess of the yield strengths at failure. At pitch distances greater than ¾ in., the higher individual spot loads can lead to shear and nugget failures as well as lower sheet stresses at failure. With a more dense population than at optimum pitch, there is a distinct reduction of sheet stress at failure. This is due, apparently, to restricted yield strain redistributions along the edges of the close packed rows of spots.

Introduction

THE Fairchild Republic Company has been engaged in development work in ultrasonic welding for several years. In a recent paper[1] material was presented on the background, the equipment, the process model, and the typical welding practices involved in ultrasonic welding. That paper highlighted the improvements of individual spot strengths that were produced as a result of proprietary modifications of the basic ultrasonic welder. Figure 1 is a summary of the progressive stages of improvement in weld strengths on aluminum alloys. The two most recent runs meet the scatter requirements set forth in the Military Specification on Resistance Spot and Seam Welding (MIL-W-6858D). This report will cover tests performed on large multispot joints between overlapping sheets. These tests were conducted to research the optimum number and arrangement of ultrasonic spot welds on simple joints. The welds were made on a modified Sonobond M-8000 welder in accordance with the practice described in Ref. 1 and produced as individual spots (approximately 5/8-in. diam) of the quality shown in the last run in Fig. 1. It is to be understood as work in progress.

Testing

First Series

This series of moderately sized joints was prepared for a comparison study with mechanical fasteners. The series was restricted to 0.063-in.-thick alclad 2024-T3 sheet. 4-×12-in. panels with pairs of bonded doublers on the ends were spotwelded or fastened with 6 in. of overlap. The mechanical fasteners employed were the commercial Hi-Lok type which develop a considerable clamping action when installed. (This effect has a decided influence on the fastener's load carrying capacity.) The panels were end loaded with pins in the testing machine.

Second Series

This series consisted of both 7075-T6 and 2024-T3 alclad 0.063-in.-thick panels. The ends were reinforced with bonded pairs of 0.25-in.-thick 7075-T6 plates, and 1.25-in.-diam holes were drilled to establish single point loading in the test machine. Overall, the panels were 12×30 in. with four to six in. of overlap in the joint area, depending on joint design. After the initial tests of some pairs of panels, the joint area containing any yielded material was cut away and the panels were reused for additional tests.

Surface preparation prior to spotwelding involved cleaning in an alkaline detergent solution and deoxidizing in a nitric acid/chromic acid solution, usually withn 36 h before welding.

Results

First Series

This test series is summarized in Table 1. Tests were made of three-, six-, and nine-element joints formed by either ultrasonic welding or Hi-Lok fasteners. Photographs of some of the comparable specimens are provided in Figs. 2-4. These figures show that the ultrasonic welds provided the superior joint in each case.

Second Series

The results of testing this series are listed in Table 2. Those joint tests that consisted of two rows of spots separated by 2 in. are presented in Fig. 5 on a plot of the sheet stress at failure vs the number of spots in the joint. For these same tests, the average load carried by each spot is plotted vs the number of spots in Fig. 6.

Figures 7-9 comprise a photo series depicting the test of panel 5. Figure 7 shows the panel mounted in the test machine; Fig. 8 shows it under a load of approximately 50,000 lb; and Fig. 9 shows the panel after failure at 51,800 lb. The distortions of reflected light in Fig. 8 provide some perception of the local plastic strains and sheet deflections. Photos of noteworthy failure patterns are provided in Figs. 10-12.

Discussion

Ultrasonic spotwelding has high potential to become a low-cost, lightweight sheet metal joining method. The small element data shown in Fig. 1, represented a sufficient quality to justify expanded studies of larger multiweld joints. If mechanical fasteners are to be replaced with these weld spots by structural design engineers, then the justification of their integrity must be broad and thorough.

The data in Fig. 1 cannot be used directly in joint analyses since it was generated[1] with antimoment (antipeel) blocks acting to force failures to occur by either shear of the spot or tearing of the strip at the edge of the spot. Testing of spot strength without moment restraints would have allowed large peel forces to develop whose magnitude would be sensitive in complex ways to spot dimensions, sheet thicknesses, etc. This is pointed out in the Golan and Reissner paper,[2] in which a

Presented as Paper 80-0763 at the AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics and Materials Conference, Seattle, Wash., May 12-14, 1980; submitted June 4, 1980; revision received April 13, 1981. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1980. All rights reserved.

*Senior Engineer, Manufacturing Technology Department.
†Senior Engineer, Instrumentation Department.

Table 1 Tests on 0.063-in.-thick 2024-T3 clad sheet 2×4-in. panels with a 6-in. overlap and bonded end reinforcements

Attachments	Failing load and method, lb	Sheet stress at failure, psi	Average element load, lb
3 ultrasonic spots, in line lengthwise	14,000 shear of welds	56,000	4,760
3 ultrasonic spots, in line lengthwise	11,400 shear of welds	45,600	3,800
3 Hi-Loks, ¼ in. diam, in line lengthwise	9,200 fasteners tear out	36,800	3,070
3 Hi-Loks, ¼ in. diam, in line lengthwise	8,100 fasteners tear out	32,400	2,700
6 ultrasonic spots, 3 rows of 2	16,500 shear through welds	66,000	2,750
6 Hi-Loks, ¼ in. diam, 3 rows of 2	14,000 material failed through fastener holes	56,000	2,330
9 ultrasonic spots, 3 rows of 3	15,600 material failed at the end reinforcement	62,400	1,730
9 ultrasonic spots, 3 rows of 3	14,900 end loading hole failed in bearing	59,600	1,650
9 Hi-Loks, ¼ in. diam, 3 rows of 3	11,900 material failed through fastener holes	47,600	1,320
Full test of 20×4-in. test material	15,900 simple fracture	63,600	–

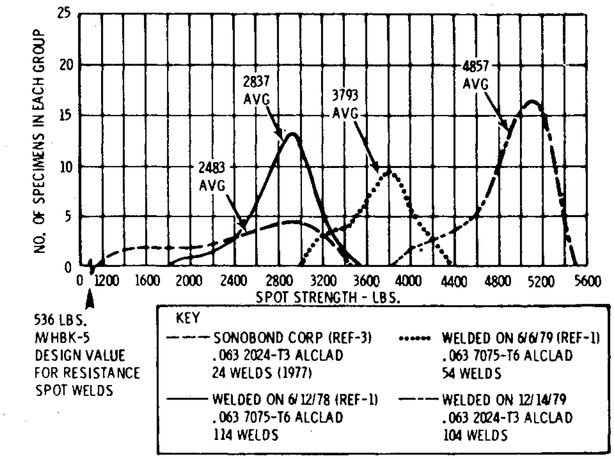


Fig. 1 Strength distributions of elemental specimen test groups prepared at different points in time. Significant improvements are evident in load capability and range of distribution.

solution is presented for a single-lap, cemented joint with an exceedingly thin adhesive layer. This solution appears to have applicability for the case of ultrasonic welds where a metal-to-metal bond exists, with only a small dispersed residue of oxides and other contaminants forming a somewhat weaker plane of material than the sheet materials themselves.

Complex load distributions and interactions can be expected when numbers of spots are applied to test panels. It was the intent of this effort to search out, by testing, those numbers and arrangements of spots that would lead to the most efficient and strongest joints.

The first series listed in Table 1 is a straightforward comparison with fasteners on a one-for-one basis. The data speaks for itself in demonstrating the superior strengths of the ultrasonic joints and in revealing that holes are more serious conditions in a joint than are the geometry conditions of spot weld. It is to be noted that the failure mode (i.e., spot shearing) seen in Figs. 2 and 3 is an undesirable mode since this type of failure could go undetected if only part of a joint opened up.

The second series listed in Table 2 was much more varied in the numbers and patterns tested. The test panel numbers represent the sequence in time of panel preparation and testing. The test variants that were applied sequentially, therefore, were applied as a result of day-to-day re-evaluations of preceding tests.

Panel 1 was pulled simply to obtain a reference base for a single row of spots.

Panel 2 was tested as a double row. When prepared, the technique of locating spots was not good and the rows are

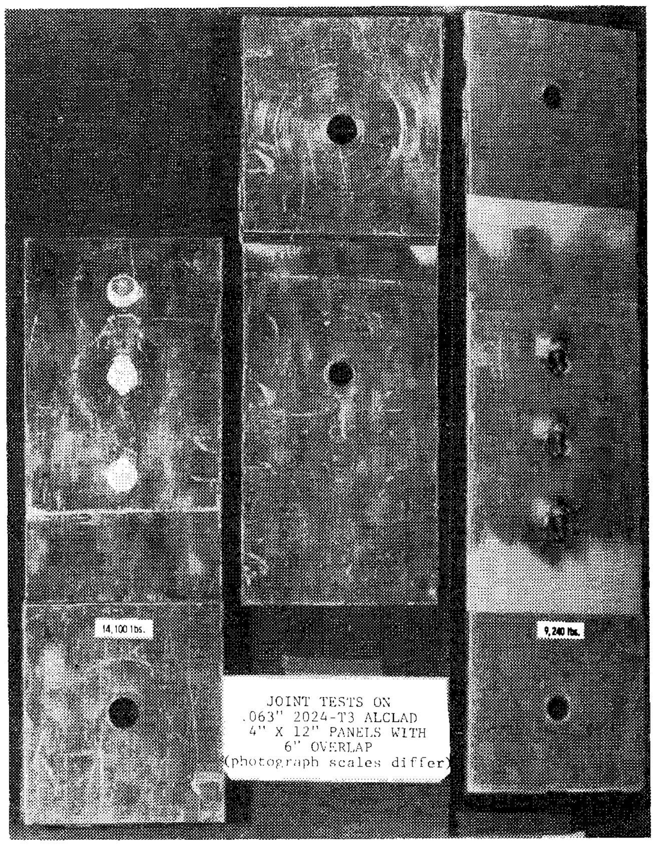


Fig. 2 A test of three-element joints shows ultrasonic spot welds carry 14,100 lb and ¼-in. Hi-Loks, 9240 lb, at failure.

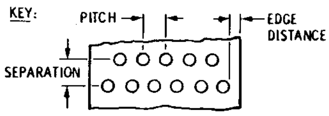
somewhat ragged and nonuniform. Nevertheless, this panel had the highest test value in the entire series.

Panel 3 was tested to evaluate the effect of row separation. The result indicated that increasing row separation beyond 2 in. was not beneficial.

Panel 4 was a test of a staggered array which was introduced to make the spots more effective (see Fig. 11). It was reasoned that where two spots are in line, only the outer half of each spot carried load effectively because the adjacent halves were in a joint area where sheet stress is shared by two sheets. Most joints thereafter were prepared in staggered arrays as a matter of principle. A review of the full series does, however, make it uncertain that staggering is generally advantageous.

Panels 5 and 6 tested the effects of introducing third rows of spots on the concept that they would reduce the peak stresses at the outer edges where failures normally occurred.

Table 2 Joint arrangements, test results, and failing modes of large panel joint test of 30 × 12 × 0.063-in. sheets



Test Panel	Alloy	Rows	Edge Distance (in.)	Pitch (in.)	Separation (in.)	No. of Spots	Spot Arrangement	Thickness (in.)	Area (in.²)	Failing Load (lbs.)	Stress in the sheet at Failure (psi)	Average Spot Load (lbs.)	Failing Mode
1	7075	1	7/8	3/4	-	15		.062	.744	30,000	40,320	2000	Peeled
2	7075	2	7/8	13/16	2	26		.061	.732	52,600	71,860	2020	Tore along row of 13
3	7075	2	1 1/8	13/16	4	26		.062	.744	51,800	69,620	1990	Tore along row of 13
4	7075	2	1 1/8	1 1/16	2	19		.062	.744	50,800	68,300	2670	Tore along row of 10
5	7075	3	1 1/8	1 3/8	1	23		.062	.744	51,800	69,620	2250	Tore along row of 7
6	7075	3	1 1/8	1 7/8 / 15/16	1 / 2	23		.062	.744	49,000	65,860	2130	Tore along row of 6
7	7075	2	1 1/8	7/8	2	23		.0625	.75	49,200	65,330	2140	Tore along row of 11
8	7075	2	1 1/8	7/8	1	23		.062	.744	44,300	59,540	1930	Tore along row of 11
9	2024	2	1 1/8	7/8	2	23		.0615	.738	39,600	53,660	1720	Tore along row of 11
10	2024	NOT USED											
11	7075	2	1 1/8	1 3/16	2	17		.0625	.75	48,800	65,070	2870	Tore along row of 8
12	7075	2	1 1/8	1 3/8	2	15		.062	.744	46,000	61,830	3070	Tore along row of 7
13	7075	2	1 1/8	1 3/4	2	14		.062	.744	47,800	64,250	3310	Tore along row of 6
14	2024	2	1 1/8	1 1/2	2	14		.062	.744	37,400	50,270	2670	Peeled
15	2024	2	1 1/8	5/8	2	32		.061	.732	41,500	56,690	1300	Tore along row of 16
16	7075	2	1 1/8	2 1/4	2	10		.062	.744	41,800	56,200	4180	Tore along row of 5
17	2024	2	1 1/8	2 1/4	2	10		.0615	.738	35,900	48,640	3590	Nuggeted and Peeled
18	7075	2	7/8	5/8	2	34		.062	.744	46,100	61,960	1360	Tore along row of 17
19	2024	2	1 1/8	3 7/8	2	6		.0615	.738	23,900	32,380	3980	Nuggeted
20	7075	2	1 1/4	3 7/8	2	6		.062	.744	26,200	35,220	4370	Nuggeted
21	7075	4	7/8	1 3/16	2 / 5/8	36		.062	.744	50,200	67,470	1390	Tore along outer row
22	7075	2	7/8	3/4	2	28		.062	.744	45,150	60,690	1610	Tore along row of 14
23	7075	2	7/8	15/16	2	24		.062	.744	49,100	66,990	2050	Tore along row of 12

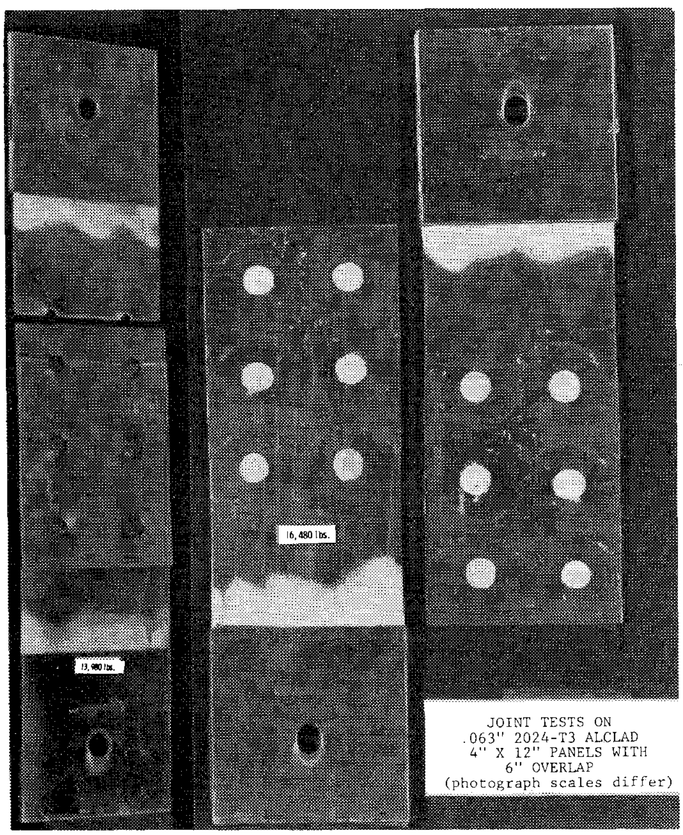


Fig. 3 A test of six-element joints shows ultrasonic spot welds carry 16,480 lb and ¼-in. Hi-Loks, 13,980 lb, at failure.

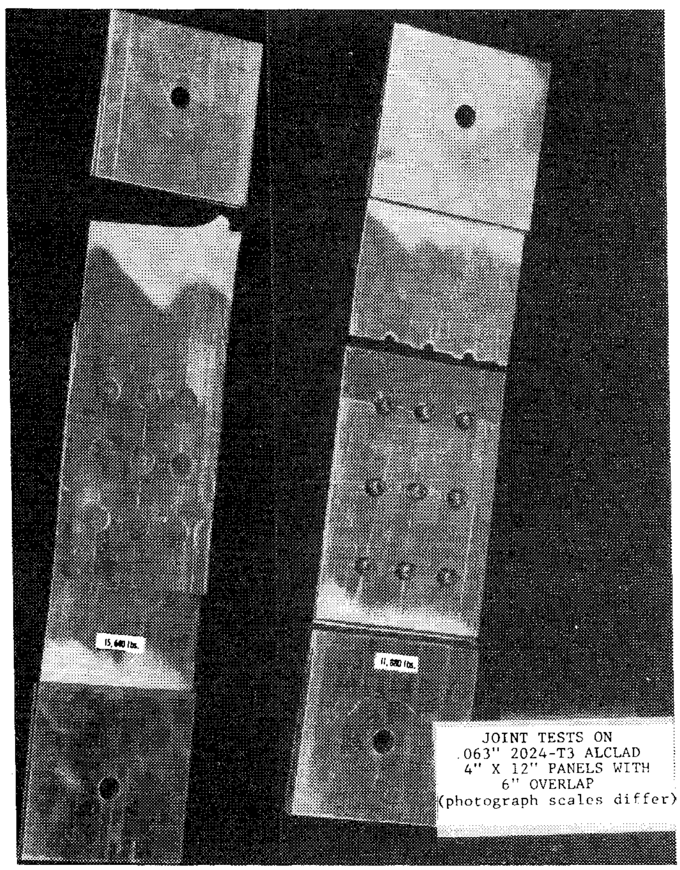


Fig. 4 A test of nine-element joints shows that ultrasonic welds carry 15,640 lb without failure, while the Hi-Lok joint failed through the minimum section at 11,880 lb.

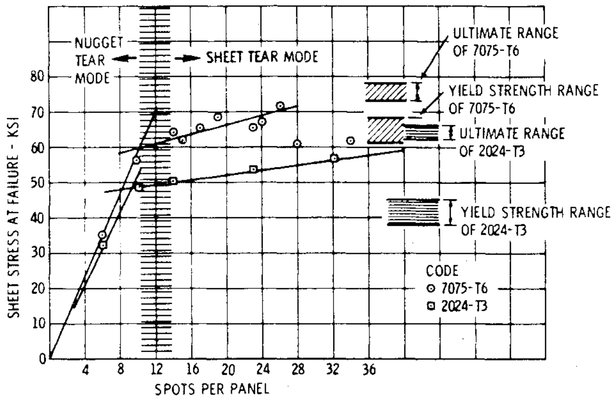


Fig. 5 Sheet stress obtained on single overlap joints containing two rows of spaced ultrasonic spot welds separated by 2 in. vs spot density of the joint.

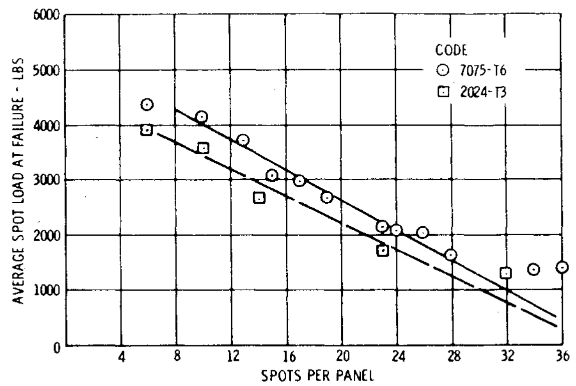


Fig. 6 The variation of average spot weld loading at failure for joints based on two rows separated by 2 in. as a function of spot density in the joint.

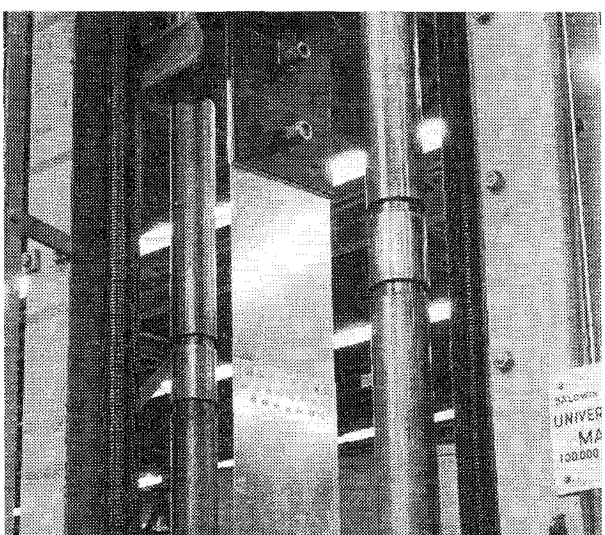


Fig. 7 An ultrasonically spot welded single overlap joint between 12 × 30 × 0.063-in.-thick panels of 7075-T6.

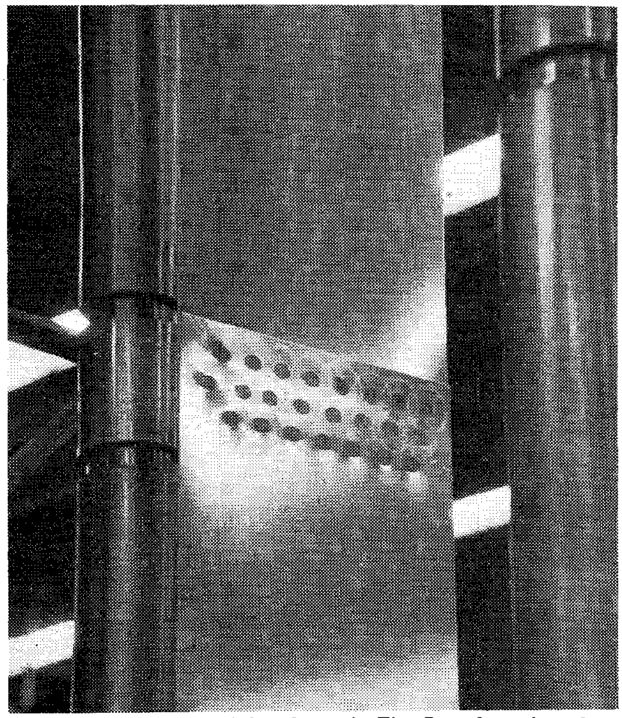


Fig. 8 Close-up of the joint shown in Fig. 7 at the point when a 50,000-lb load had been reached.

Panel 7 repeats the same numbers in the simple staggered array. The differences of test results are not sufficient to establish any value for the three-row arrays. Since failures persisted along the outer rows, it is evident that they were not unloaded by the center rows.

Panel 8 showed a distinct drop in load-carrying capacity as the separation of rows was dropped to 0.875 in. from the norm of 2 in. It is doubtless a result of a greater bending moment contribution to the peak stresses.

Panel 9 was the first data point on 2024-T3 sheets.

Panel 10 was not used in test.

Panels 11-13, 16, and 20 produced data on joints with progressively lower numbers of spots in order to fill out the data for Figs. 5 and 6.

Panels 14, 15, 17, and 19 were additional data points for the 2024-T3 plots in Figs. 5 and 6 using the standard joint concepts of staggered spots separated by 2 in.

Panel 18 tested the concept of dense rows of adjacent, slightly overlapped spots (see Fig. 12). The result indicates that a negative effect probably was produced due to a restriction on normal load redistributions around spots and the restriction of yield strain to a narrow zone along the rows.

Panel 21 was a final variation on the idea of increasing spot density per row without restricting the yielding redistribution of loads around the spots. The result is a respectable load value but not one superior to the simpler and more efficient double row of staggered spots such as test panels 4, 7, or 23.

Panels 22 and 23 are final data points exploring the optimum pattern for a 12-in.-wide sheet of 7075-T6.

Those data obtained with double rows of staggered spots are plotted in Fig. 5 using coordinates of the sheet stress obtained just at failure and the numbers of spots in each panel. It is to be noted that, with welds numbering below about 12 spots in these 12-in.-wide panels, the failures are by nugget pull out. Such failure mode is associated with an intense stress field about the spot and a relatively low general sheet stress; while the sheet cracks start at the spot edge, they follow the most intense resolved stresses around the spot rather than across the sheet.

Above about 12 spots, the increasing sheet stress, the lowering of the load carried by each spot (see Fig. 6), and the smaller distance between spots cause the failures around each

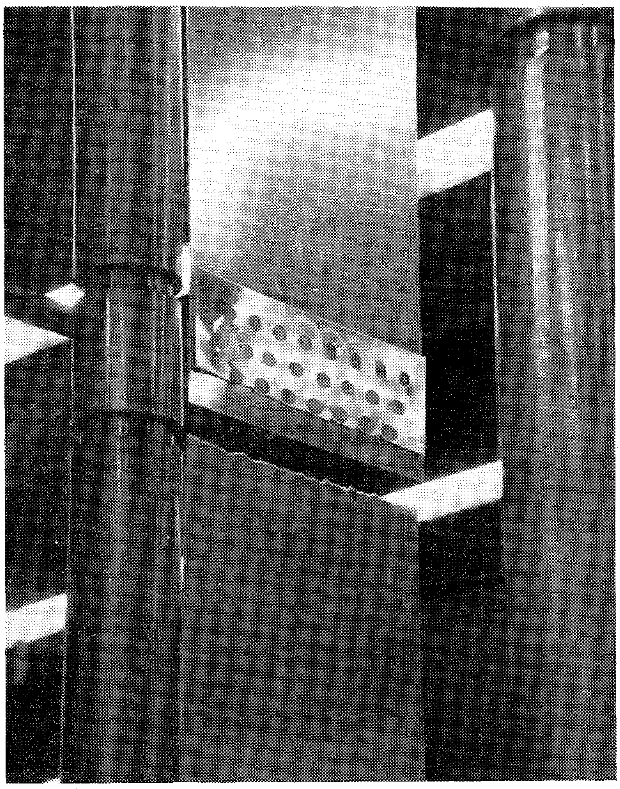


Fig. 9 The joint shown in Figs. 7 and 8 after failure at a load of 51,800 lb.

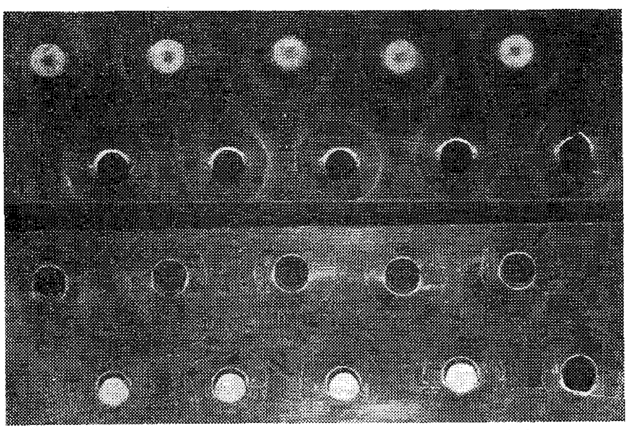


Fig. 10 This is a close-up of the failure of the 10-spot joint on panel 16. The section on the top has separated from being directly over the bottom section by motion to the top. This reveals that every spot failed by nuggeting (or the cracks running around the welds). Several of the holes show that cracks also started to move transversely across the sheet.

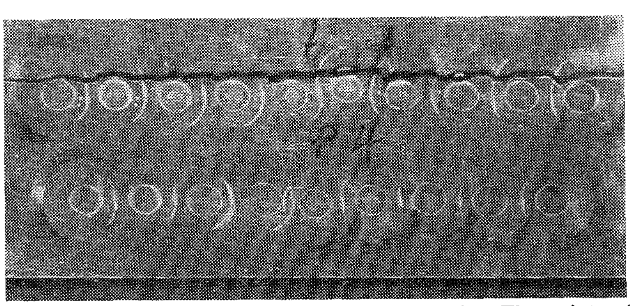


Fig. 11 A sheet tear failure typical of this series. The points of contact of the two pieces at the outer edges show that these were the points of last separation and that cracks developed in the central areas and moved to the edges. Each spot developed an independent crack origin so that they ran to and toward each other and joined up with jog steps.

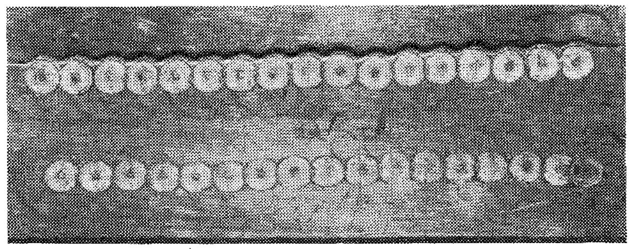


Fig. 12 The failure pattern typical of rows of contacting spots. Again it is noted that the cracks move from the central areas out to the edges. Note that the central gap between the contacting pieces is smaller than that to be seen in Fig. 11. This implies a lower yield strain in the sheet at the point of failure in this case.

spot to run toward each other and sever the sheet transversely. The modes are illustrated in the photos of Figs. 10-12. For both materials, the data, despite its scatter, indicates that sheet stress at failure can be elevated slowly toward its ultimate strength up to a maximum value. At this point, it appears that there should be 24-26 spots applied to a 12-in.-wide panel with 2-in. separation of rows in order to obtain maximum failure stress in the sheet and hence the maximum safety margin over the working stress.

While lesser numbers of spots similarly arrayed are utilized more efficiently while attaining nearly the same failure stress, it is nevertheless advisable to keep well above that density ($\cong 12$) where shear failures could occur and to stay well in the range of the sheet-tear failure mode. This is equivalent to loading individual spots to average shear loads of 2000 lb or less at joint failures. The 24-26 spot range translates to pitch ranges of 13/16-15/16 in.

It is to be expected that these relationships which have been developed for 0.063-in.-thick sheets will vary for other sheet thicknesses. For instance, the spot loading at which nuggeting will occur will probably drop for thinner sheets and rise for thicker sheets.

Summary and Conclusions

This report presents initial data on the properties of large, overlap, tension joints prepared by ultrasonic spot welding of aluminum alloys. A first series of tests, where ultrasonic welds were compared to mechanical fasteners, demonstrated on a one-for-one basis that the former developed superior joints in tension loading.

A second series of tests on 12-in.-wide panels provided broad information on the attainable sheet stresses, the spot loads, and the failure modes as a function of spot concentration and pattern. Joints in 7075-T6 were strong enough to load the sheets to the yield stress of that material. Joints in 2024-T3 were able to load the sheets to levels well above the yield strength.

It is shown that an optimum spot concentration apparently exists for ultrasonic tension joints in that lower concentrations lead to undesirable shear or nugget failures and higher concentrations lead to a marked reduction in the maximum attainable sheet stress at failure.

Acknowledgment

The authors wish to acknowledge the exceptional contributions of H.G. Ellis who skillfully and diligently performed the welding and testing tasks for this effort.

References

[1] Renshaw, T., Curatola, J., and Sarrantonio, A., "Developments in Ultrasonic Welding for Aircraft," *Proceedings of 1979 National Technical Conference,* Vol. 11, Society for Advancement of Material and Process Engineering, Azusa, Calif., 1979.

[2] Goland, M. and Reissner, E., "The Stresses in Cemented Joints," *Journal of Applied Mechanics,* Series E, *Transactions of the ASME,* Vol. 66, 1944, pp. 17-27.

[3] Devine, J. and Dingle, G., "Ultrasonic Welding of Helicopter Secondary Structure Components," U.S. Army Aviation Research and Development Command Rept. 77-8, St. Louis, Mo., Oct. 1977.