AIAA 82-4216

Fatigue Behavior of Weldbonded Joints

Gregory V. Scarich* and Govind R. Chanani†
Northrop Corporation, Hawthorne, Calif.

The effects of material and process variables on fatigue behavior were determined for a newly developed, low-cost weldbonding process for the assembly of durable aircraft structures. The weldbonding process involves spot-welding components through a previously applied adhesive, and then oven-curing the assembly to achieve a bonded structure. Both low-load and high-load transfer specimen geometries with each of two alloy combinations (7075-T6/7075-T6 and 2024-T3 alclad/7075-T6) were evaluated. Fatigue behavior of weldbonded specimens with different nugget sizes and different manufacturing defects was compared with that of riveted and adhesive-bonded specimens. In low-load transfer fatigue, weldbonding was better than riveting, but not as good as adhesive bonding, while in high-load transfer fatigue, weldbonding was equal to or better than riveting and adhesive bonding.

I. Introduction

WELDBONDING was developed to reduce the cost of joining aluminum components such as airframe skins to doublers. The process involves spot-welding components together through a previously applied adhesive, and then oven-curing the assembly to achieve a bonded structure. The spot welds replace expensive fixturing which would otherwise be needed for adhesive bonding during the cure cycle, and an economical oven can be used in place of an autoclave. The process also eliminates expensive hole preparation and fastener installation costs associated with mechanical fastening. The weldbond system used for this work was developed under Northrop Independent Research and Development and Air Force Materials Laboratory contracts.[1-3] A summary of the process follows: the parts to be joined are alkaline cleaned, deoxidized, phosphoric acid/sodium dichromate anodized at 1.0-1.5 V, coated with a modified epoxy paste adhesive (B.F. Goodrich A1444B) at the faying surface, spot-welded together, and oven-cured at 121°C (250°F) for 1 h.

Since the weldbond joint strength comes primarily from the adhesive bond and the purpose of the spot weld is to hold the parts together during the adhesive cure cycle, it may not be necessary for the spot weld to meet normal airframe strength and quality requirements (MIL-W-6858 Class A).[4] However, the effects of the spot weld on the structural integrity of a weldbonded structure must be considered. Hence the effects of spot-weld nugget size and spot-weld spacing on the fatigue behavior of weldbonded joints were evaluated. In addition, the effects of certain weld defects, intentionally produced by poor process control, on the fatigue behavior were also evaluated. Two material combinations were evaluated: 1) 7075-T6 bare skin with 7075-T6 bare doubler, and 2) 2024-T3 alclad skin with 7075-T6 bare doubler. However, most of the evaluation was performed on the 7075-T6/7075-T6 combination.

Table 1 summarizes the various test parameters evaluated. All of the failed specimens were fractographically examined to determine fatigue-crack initiation sites.

II. Experimental Procedure

The low-load transfer specimen, shown in Fig. 1, was designed to simulate a typical aircraft skin stiffened with doublers. The design is basically no-load transfer with some load transfer occurring at the doubler radius. The tests were conducted in tension-tension fatigue at a frequency of 10 Hz with a load ratio, R (minimum load/maximum load), of 0.1 in a temperature and humidity [24 ± 3°C (75 ± 5°F) and 50 ± 5% rh] controlled laboratory environment. A majority of the tests was performed at a maximum stress of 220 MPa (32 ksi) to produce fatigue failure in reasonable times for the various conditions being evaluated. Several specimens were strain gaged and tested to verify alignment. The maximum bending was found to be less than 2%.

The high-load transfer specimen, shown in Fig. 2, was designed to simulate a lap joint and to force failure to occur in the joint rather than in the base material. This was done by bonding doublers to the specimen as shown. The same adhesive as in the lap joint was used to bond the doublers. The assembled specimens (joint and doublers) were cured in the same cycle. Preliminary testing had shown that without the doublers the specimen failed near the edge of the lap, which prevented a comparison between weldbonding and adhesive bonding. The riveted high-load transfer specimen (Fig. 3) was based on MIL-STD-1312-21A for shear-joint fatigue testing of fasteners.[5] The results of tests with this specimen geometry can be compared only indirectly to the results of weldbonded and adhesive-bonded specimens because of differences in specimen geometries. The fatigue load levels were selected to produce failures in the 10^4-10^6 cycle range. The high-load transfer tests were conducted with the same load ratio and environmental conditions as the low-load transfer tests.

To evaluate the effects of weld nugget size, the welding current was varied to produce nuggets in the desired size range. Three nugget sizes for the 7075-T6/7075-T6 weldbonded specimens were selected based on past experience[1,2]: small, with a 4.6-5.7-mm (0.18-0.22-in.) diameter; medium, with a 5.8-7.0-mm (0.23-0.27-in.) diameter; and large, with a 7.1-8.4-mm (0.28-0.33-in.) diameter. For comparison, MIL-W-6858[4] specifies a minimum nugget size of 5.1-mm (0.20-in.) diameter for 1.60-mm (0.063-in.) thick sheet and the rule-of-thumb diameter is five times the sheet thickness, 7.6 mm (0.30 in.). Any significant variations from the intended range are noted in the tabulated results. For the 2024-T3 alclad/7075-T6 weldbonded specimens, all nuggets were medium size. All specimens were radiographically inspected to determine nugget quality and nugget sizes.

Spot-weld spacing was varied on low-load transfer specimens to evaluate its effect on fatigue. The weldbond process places limits on the range of spacing because the spacing must be large enough to avoid shunting and small enough to control the bondline thickness. Working within

Received Feb. 24, 1981; revision received Oct. 23, 1981. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1981. All rights reserved.

*Engineering Specialist, Aircraft Division.

†Senior Technical Specialist, Aircraft Division.

Table 1 Summary of variables investigated for fatigue evaluation of weldbonded joints

	Low-load transfer	High-load transfer
	Nugget size and spacing, manufacturing defects	Nugget size, manufacturing defects
7075-T6/7075-T6 Manufacturing variables	Surface cracked nugget Subsurface cracked nugget High indentation nugget Expulsion Material defects	Expulsion Subsurface cracked nugget
7075-T6/7075-T6 Comparison tests	Adhesive bond Adhesive bond with antipeel rivets Riveted	Adhesive bond Adhesive bond with a disbond Riveted
2024-T3 Alclad/ 7075-T6	One nugget size and spacing	One nugget size

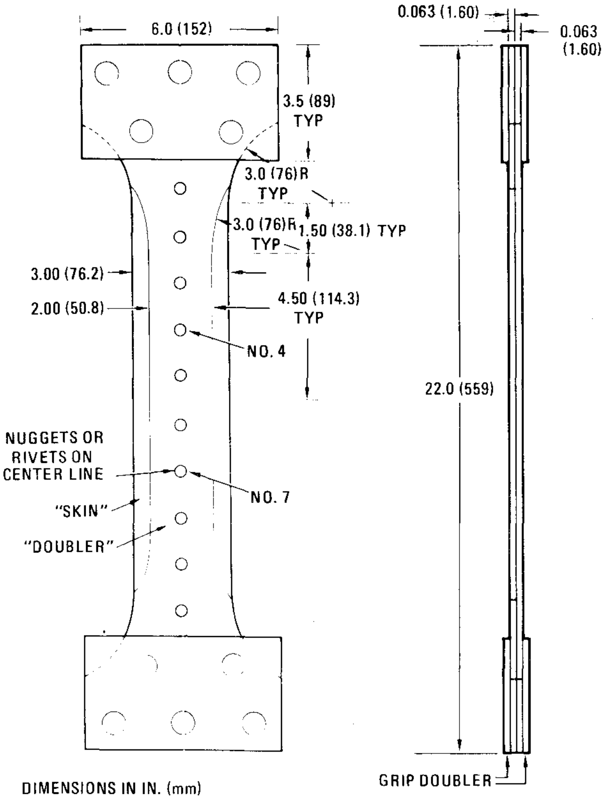


Fig. 1 Low-load transfer fatigue specimen.

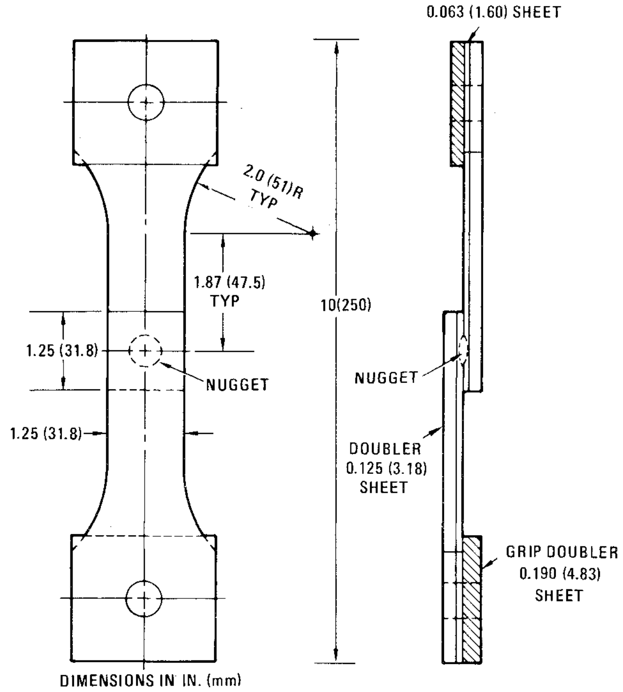


Fig. 2 Weldbonded and adhesive-bonded high-load transfer fatigue specimen.

these limits, spacings of 25, 38, 51, and 76 mm (1.0, 1.5, 2.0, and 3.0 in.) were selected.

Various weld nugget defects were intentionally produced by deviating from the normal weldbonding weld schedule and/or surface preparation procedures. For the low-load transfer specimens, two of the nuggets (nos. 4 and 7, Fig. 1) were intentionally flawed. Since different deviations in the weldbond procedures were required for the various types of defects, the nugget sizes were not the same for each type of defect. The deviations in the weldbond procedures to obtain the defective nuggets are described below:

1) Cracked weld nuggets were produced by polishing the sheet at the nugget location to remove the surface oxide produced by anodizing and by using a lower electrode force. Cracked nuggets of two types were made, those with visible surface cracks (surface cracked nuggets) and those without visible surface cracking (subsurface cracked nuggets). Two cracked nuggets were produced on each of the six low-load transfer specimens. Three specimens contained one nugget with a surface crack. The other nuggets had subsurface cracks of varying crack sizes. The cracks were approximately elliptical in shape, centered within the weld nugget, and ranged in size (length by depth) from 4.3×1.5 mm to 8.1×2.8 mm (0.17×0.06 in. to 0.32×0.11 in.). The crack sizes were not determined for the two high-load transfer specimens with cracked nuggets. Both the surface and subsurface cracked nuggets were easily detected by radiography. The size of the cracked nuggets was large.

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

3) High indentation nuggets were produced by using higher current and higher electrode force. The size of high indentation nuggets was very large—about 9.4-mm (0.37-in.) diameter.

The FPL etch/BR-127 primer/FM 123-2 adhesive system[6] with a 121°C (250°F)/90-min. bagged cure at 280-Pa (40-psi) positive pressure was selected for adhesive-bonding comparison tests, since this system is well known and widely used to fabricate aircraft structures. Adhesive-bonded low-load transfer specimens were also fabricated with antipeel rivets. These specimens used two round-head 3.2-mm (⅛-in.) diameter rivets (MS 20470-AD) with a 114-mm (4.5-in.) spacing. The rivets were installed wet per MIL-S-81733[7] with Products Research and Chemical Corporation PR 1431G Type IV corrosion-inhibitive sealant.

To evaluate the effect of a flaw that could occur in a high-load transfer adhesive-bonded structure, high-load transfer specimens were fabricated with a 18-mm (0.7-in.) diameter disbond (approximately 25% of the joint area). This defect was formed by cutting a hole in the film adhesive and placing a 76-μm (0.003-in.) thick Teflon disk in the hole. The disbond was centered in the lap.

Low- and high-load transfer riveted specimens, as shown in Figs. 1 and 3, were used to establish a baseline. These specimens were riveted with flush-head 4.0-mm (5/32-in.) diameter rivets (MS 20426-AD) on 16-mm (5/8-in.) centers. Riveted low-load transfer specimens were also fabricated with electric-discharge-machined (EDM) flaws per MIL-A-83444, "Aircraft Damage Tolerance Requirements." Two combinations of the locations of three types of flaws were used, as shown in Fig. 4.

Doublers were used in grip areas on both low- and high-load transfer specimens to avoid premature failure. For riveted specimens the grip doublers were adhesive bonded after riveting. For weldbonded specimens the grip doublers were weldbonded. For adhesive-bonded specimens the grip doublers were adhesively bonded. The specimen and doubler assemblies were cured in one cycle.

III. Results and Discussion

The majority of the experimental work on this program was performed on 7075-T6 joined to 7075-T6. After completion of these tests, selected tests were performed on 2024-T3 alclad joined to 7075-T6. The results obtained with 7075-T6/7075-T6 will be discussed first, followed by a discussion of the 2024-T3 alclad/7075-T6 results.

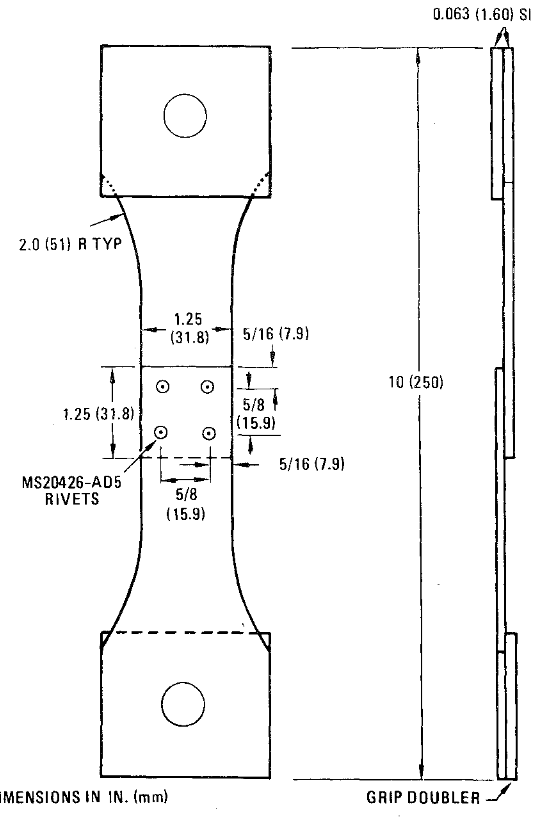


Fig. 3 Riveted high-load transfer fatigue specimen.

Low-Load Transfer Joints of 7075-T6/7075-T6

Effects of Nugget Size and Spacing on Fatigue Life

Test results on the effects of nugget size and spacing on fatigue life are listed in Table 2. Figure 5 summarizes the effects of nugget size and spacing on the fatigue life. These results show that weldbonded specimens with smaller nuggets tend to have better fatigue life. The improved fatigue life of specimens with smaller nuggets may have been due to the smaller volume of the relatively weak fusion zone and heat-affected zone. Also, residual stresses may be lower in the smaller nuggets since less heat is required for producing the smaller nuggets. An analysis of the fatigue results vs nugget spacing showed that nugget spacing did not affect fatigue life significantly.

The microstructure of several representative weldbonded nuggets is shown in Figs. 6-8. Figure 6 is typical of most of the

Table 2 Effect of nugget size and spacing on weldbonded low-load transfer fatigue. Material: 7075-T6 Al, 1.60 mm (0.063 in.) thick; test conditions: 220 MPa (32 ksi) maximum stress, $R(\sigma_{min}/\sigma_{max}) = 0.1$

Target nugget size[a]	Spot spacing mm	Spot spacing (in.)	Cycles to failure
Small	25	(1.0)	695,000
Small	25	(1.0)	755,040
Small	38	(1.5)	204,450[b]
Small	38	(1.5)	459,590
Small	38	(1.5)	514,760
Small[c]	38	(1.5)	544,360
Small[c]	38	(1.5)	611,420
Small	51	(2.0)	340,350
Small	51	(2.0)	395,420
Small[d]	76	(3.0)	529,600
Medium	25	(1.0)	90,750
Medium	25	(1.0)	313,550
Medium	25	(1.0)	321,010
Medium	38	(1.5)	177,700[e]
Medium	38	(1.5)	206,700
Medium	38	(1.5)	215,990
Medium	38	(1.5)	465,130
Medium	38	(1.5)	547,380
Medium	51	(2.0)	391,900
Medium	51	(2.0)	403,360
Medium	51	(2.0)	449,940
Medium	76	(3.0)	182,120
Medium[c]	76	(3.0)	240,850
Large	38	(1.5)	70,920
Large	38	(1.5)	72,420
Large	38	(1.5)	85,260
Large	38	(1.5)	207,200
Large[g]	38	(1.5)	463,690
Large	51	(2.0)	161,380
Large	51	(2.0)	254,430
Large	76	(3.0)	83,450
Large	76	(3.0)	139,400
Large	76	(3.0)	209,530
Large	76	(3.0)	232,480

[a] Peak current was varied to produce various nugget sizes—small: 4.6-5.7-mm (0.18-0.22-in.) diameter; medium: 5.8-7.0-mm (0.23-0.27-in.) diameter; large: 7.1-8.4-mm (0.28-0.33-in.) diameter. [b] Initiation site was a small depression within nugget indentation. [c] Nugget diameter—3.3 mm (0.13 in.). [d] Nugget diameter—6.4 mm (0.25 in.). [e] Initiation site was a small pit on sheet surface. [f] Nugget diameter—7.6 mm (0.30 in.). [g] Nugget diameter—8.9 mm (0.35 in.).

Table 3 Effects of weldbond manufacturing defects on low-load transfer fatigue.
Material: 7076-T6 Al, 1.60 mm (0.063-in.) thick; nugget spacing: 38 mm (1.5 in.); test conditions: $R(\sigma_{min}/\sigma_{max})=0.1$

Specimen no.	Defect	Initial flaw size (length × depth) mm	(in.)	Maximum stress MPa	psi	Cycles to failure
C1	Surface cracked nugget	6.4×2.3	(0.25×0.09)	110	15,900	22,000
C3	Surface cracked nugget	7.1×2.8	(0.28×0.11)	66	9,500	87,980
S4	Subsurface cracked nugget[a]	[b]	[b]	220	32,000	11,140
S1	Subsurface cracked nugget	4.6×2.0	(0.18×0.08)	130	19,000	197,140
S2	Subsurface cracked nugget	5.3×2.3	(0.21×0.09)	110	15,900	308,530
S3	Subsurface cracked nugget	4.3×1.5	(0.17×0.06)	110	15,900	2,619,400
C2	Subsurface cracked nugget	8.1×2.8	(0.32×0.11)	88	12,700	61,000[c]
H2	High indentation nugget	...	...	220	32,000	33,000
H3	High indentation nugget	...	...	220	32,000	51,480
H1	High indentation nugget	...	...	220	32,000	54,970
E1	Expulsion	...	...	220	32,000	28,530
E3	Expulsion	...	...	220	32,000	39,690[d]
E2	Expulsion	...	...	220	32,000	77,700[e]

[a] Nugget spacing—25 mm (1.0 in.). [b] Not available. [c] Specimen also contained a surface cracked nugget that was estimated to be within approximately 1000 cycles of failing. [d] Failure initiated at a pit on sheet surface within a nugget with expulsion. [e] Failure initiated at a pit on sheet surface within the indentation of a good nugget.

nuggets. The arrow in Fig. 6 shows a dark-etching area which at first appears to be a crack. However, energy dispersive analysis showed these dark areas to be copper-rich zones rather than cracks. The nugget shown in Fig. 7 is somewhat less typical. It has a row of dark-etched zones across the nugget (Fig. 7a). These zones were also found to be copper-rich, but microcracking or incomplete fusion occurred within this zone, as shown in Figs. 7b and 7c. Fatigue failure in the weldbonded specimens initiated either in the fusion zone near the edge of the nugget, as seen in Fig. 8, or from porosity caused by alloy segregation, incomplete fusion, or trapped adhesive.

Effects of Manufacturing Defects on Fatigue Life

For this evaluation, flawed spot-weld nuggets were intentionally made in low-load transfer specimens. The intentionally induced flaws were surface and subsurface cracked nuggets, spot welds with high surface-indentation, and expulsion around nuggets.

The fatigue results for intentionally flawed low-load transfer specimens are listed in Table 3. To allow comparisons to the other low-load transfer fatigue results, these results were extrapolated to 220 MPa (32 ksi) along constant K_t curves for 7075-T6 sheet material (Fig. 9). It can be seen that surface and subsurface cracked nuggets significantly reduced the fatigue life of low-load transfer weldbonded specimens. This reduction is due to eliminating or shortening the crack-initiation phase of the fatigue failure.

High surface-indentation spot welds had lower fatigue properties than weldbonded specimens with flawless nuggets of normal indentation. This is probably due to the rather large [approximately 9.4-mm (0.37-in.)] diameter nugget associated with the creation of a deep indentation as well as the increase in stress concentration due to indentation itself.

Specimens with expulsions had lower fatigue lives than that for flawless weld nuggets (Table 3). However, only one specimen had a fatigue crack initiation site that could be directly related to expulsion. Cracks in the other two specimens initiated from other sources, as listed in Table 3, and had fatigue lives lower than for flawless weld nuggets.

Besides these intentionally induced defects, each fatigue failure was examined to determine the fatigue-crack initiation site. These examinations revealed some defects and inadvertent handling damage. The results were separated into those defects common to any aluminum fabricating process,

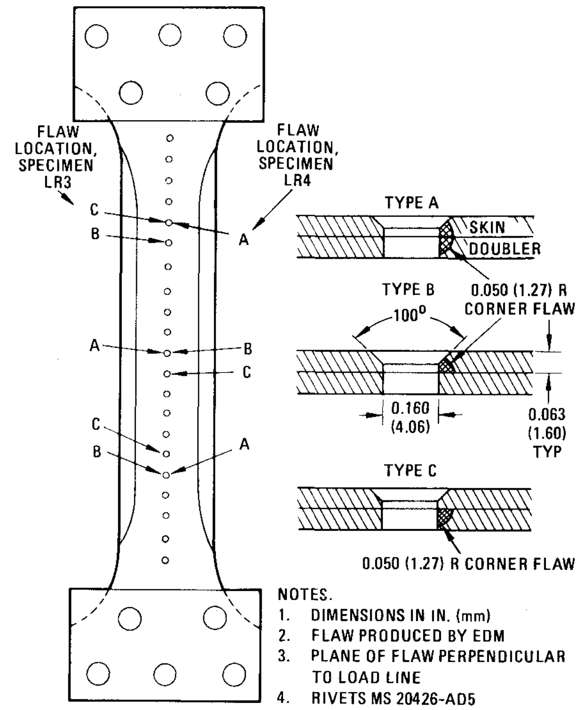


Fig. 4 Low-load transfer fatigue specimen with preflawed rivet hole.

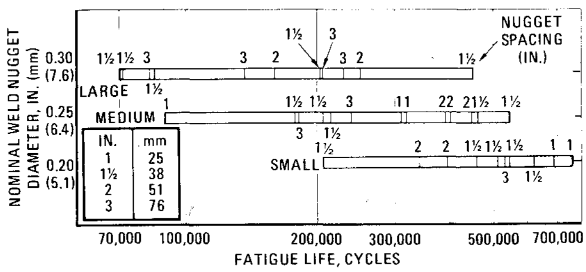


Fig. 5 Effect of nugget size and spacing on the fatigue life of 7075-T6/7075-T6 low-load transfer weldbonded specimens at 32 ksi and $R=0.1$. Each vertical bar (I) represents a data point.

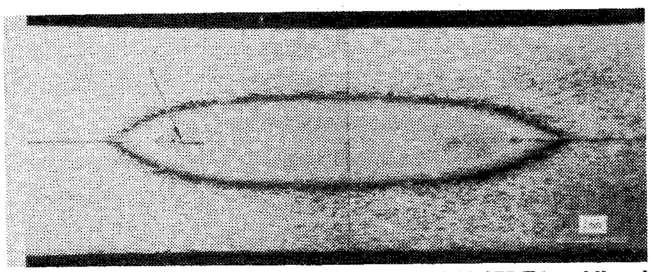
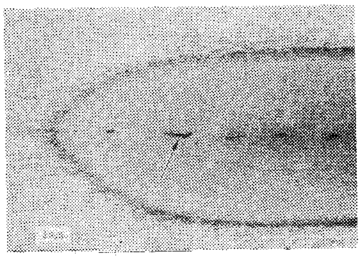
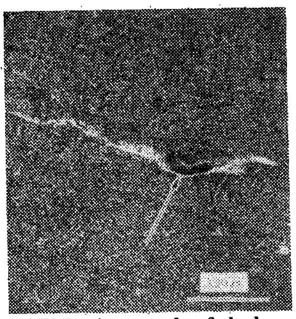


Fig. 6 Section through small nugget 7075-T6/7075-T6 weldbond (optical micrograph).



a) Section through fatigue failure (optical micrograph).



b) SEM micrograph of dark area indicated in a), microcracking or incomplete fusion shown by arrow.

c) Fracture surface, microcracking or incomplete fusion shown by arrow.

Fig. 7 Microstructural features of a 7075-T6/7075-T6 weldbond—medium nugget.

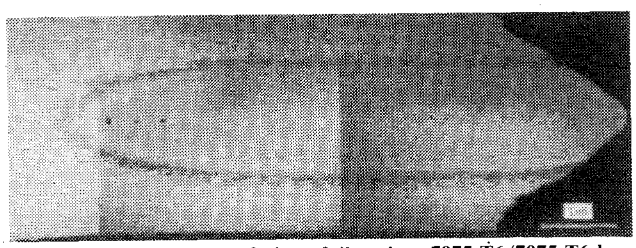


Fig. 8 Section through a fatigue failure in a 7075-T6/7075-T6 low-load transfer weldbonded specimen—medium nugget.

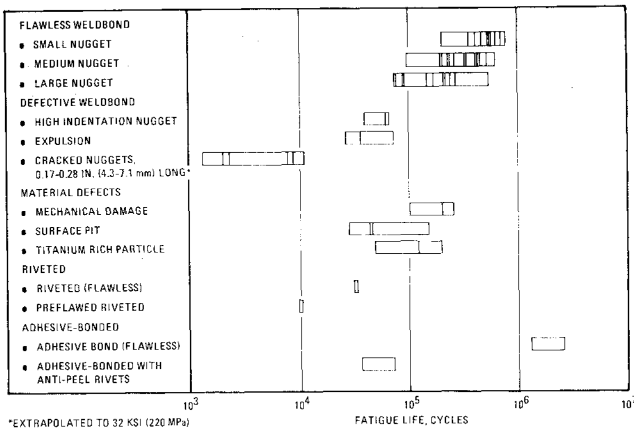


Fig. 9 Comparison of 7075-T6/7075-T6 low-load transfer fatigue results at 32 ksi and $R = 0.1$. Each vertical bar (|) represents a data point.

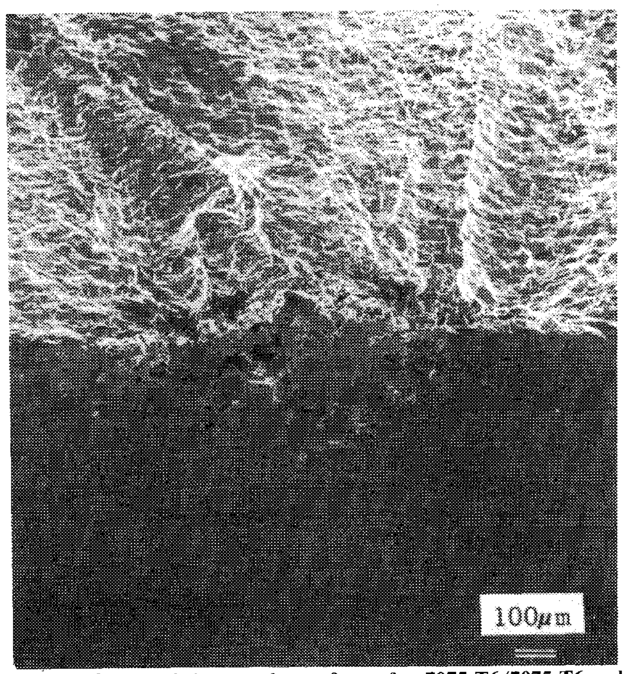


Fig. 10 Severe pitting on the surface of a 7075-T6/7075-T6 weldbonded specimen.

such as nicks and minor scratches, and those related to weldbonding. One type of defect which could have been due to weldbonding or normal aluminum fabrication and handling procedures was pitting. One heat of material used for making weldbonded specimens was found to be extensively and deeply pitted [200-250 μm (0.008-0.010 in.) deep], as shown in Fig. 10. One possible explanation for the pitting is that the material got wet in storage. Because of this possibility, these results were considered to be material-related failures. However, for three other specimens with fatigue cracks initiating at small pits [10-25 μm (0.0004-0.0010 in.) deep] it was difficult to determine whether the pits were related to the weldbonding process or were present in the as-received material. Nevertheless, the results of these latter tests are listed and plotted as if the failures were related to the weldbond process.

Other manufacturing defects that initiated fatigue failures included mechanical damage, such as scratches and nicks, and inclusions. These results and the results of adhesively bonded specimens that also failed owing to similar manufacturing defects are summarized in Table 4 and also in Fig. 9. Large inclusions were found to be the initiation sites in two specimens made from different lots of material. The inclusions in both specimens were near the specimen surfaces and were found by energy dispersive analysis to be rich in titanium, which is added for grain refinement. Thus these results indicate that the weldbond process per se is less deleterious than normal handling and material defects on the fatigue properties of low-load transfer joints.

Comparison Tests

The low-load transfer fatigue results for riveted, adhesive-bonded, and adhesive-bonded with antipeel rivets specimens are listed in Table 5. A comparison of these results at a maximum stress of 220 MPa (32 ksi) is shown in Fig. 9. Both riveted specimens failed at about 33,000 cycles under the same loading conditions and both specimens had cracks growing

Table 4 Effects of manufacturing and material defects not relatable to weldbonding on low-load transfer fatigue. Material: 7075-T6 Al, 1.60 mm (0.063 in.) thick; test conditions: maximum stress = 220 MPa (32 ksi), $R(\sigma_{min}/\sigma_{max}) = 0.1$

Joining system	Cycles to failure	Failure initiation site
Adhesive bond[a]	64,700	250-μm (0.010 in.) deep nick in skin
Adhesive bond[a]	153,200	Surface pit, 25 μm (0.001 in.) deep
Weldbonded, small nugget, 76 mm (3.0 in.) spacing	198,980	Titanium-rich inclusion at surface, 25 μm (0.001 in.) deep
Weldbonded, large nugget, 38 mm (1.5 in.) spacing	48,400	Titanium-rich inclusion at surface, 51 μm (0.002 in.) deep
Weldbonded, medium nugget, 51 mm (2.0 in.) spacing	124,960	Titanium-rich inclusion at surface, 51 μm (0.002 in.) deep
Weldbonded, medium nugget, 25 mm (1.0 in.) spacing	11,140	X-ray detected weld cracks (incorrect weld settings)
Weldbonded, small nugget, 25 mm (1.0 in.) spacing	46,610	Surface pit, 250 μm (0.010 in.) deep
Weldbonded, small nugget, 38 mm (1.5 in.) spacing	48,970	Surface pit, 200 μm (0.008 in.) deep
Weldbonded, small nugget, 76 mm (3.0 in.) spacing	29,240	Surface pit
Weldbonded, medium nugget, 25 mm (1.0 in.) spacing	247,610	Scratches, 100AA surface roughness
Weldbonded, large nugget, 38 mm (1.5 in.) spacing	98,750	Scratches, 100AA surface roughness
Weldbonded, with expulsion, 38 mm (1.5 in.) spacing	192,960	Burr on specimen edge

[a]FPL/BR-127/FM 123-2.

Table 5 Adhesive-bonded and riveted low-load transfer fatigue results. Material: 7075-T6 Al, 1.60 mm (0.063 in.) thick; test conditions: $R(\sigma_{min}/\sigma_{max}) = 0.1$

Joining system	Maximum stress, MPa	psi	Cycles to failure
Adhesive bond[a]	220	32,000	2,532,840[b]
Adhesive bond[a]	220	32,000	1,229,990
Adhesive bond[a] with antipeel rivet[c]	220	32,000	37,300
Adhesive bond[a] with antipeel rivet[c]	220	32,000	75,170
Riveted[d]	220	32,000	33,160
Riveted[d]	220	32,000	32,930
Preflawed riveted[c,e]	220	32,000	9,237[f]
Preflawed riveted[c,e]	130	19,000	63,510[g]

[a]FPL/BR-127/FM 123-2. [b]Failed in grip. [c]MS20470-AD4 rivets on 110-mm (4.5-in.) centers. [d]MS20426-AD5 rivets on 15.7-mm (0.62-in.) centers. [e]Rivet holes contained 1.27-mm (0.050-in.) radius EDM flaw (see Fig. 4). [f]Specimen LR4, failed from flaw type A (Fig. 4). [g]Specimen LR3, failed from flaw type B (Fig. 4), test stopped when skin completely cracked but with no crack visible in the doubler.

from at least five other rivet holes. These results indicate good reproducibility of the fatigue data on riveted specimens since cracks had initiated in 12 of the 42 rivet holes. One adhesively bonded specimen failed at 1.2 Mc in the radius; the other specimen failed in the grip area after 2.5 Mc. The two adhesively bonded specimens with antipeel rivets failed at 37,000 and 75,000 cycles with the cracks initiating in the rivet holes. As demonstrated in Fig. 9, the low-load transfer fatigue behavior of weldbonded specimens is better than that for both riveted specimens and for adhesive-bonded specimens with anti-peel rivets. However, the adhesive-bonded low-load transfer specimens have better fatigue properties than the weldbonded specimens.

Results for the preflawed, riveted low-load transfer specimens at 220 MPa (32 ksi) maximum stress are summarized in Fig. 9 and listed in Table 5. The low-load transfer fatigue behavior of the preflawed, riveted specimens is on the upper band of weldbonded specimens with cracked nuggets.

High-Load Transfer Joints of 7075-T6/7075-T6

Effects of Nugget Size on Fatigue Life

Test results are listed in Table 6. Figure 11 shows the effects of nugget size on the fatigue life of the high-load transfer weldbonded specimens. The weldbonded specimens with large weld nuggets generally had a better fatigue life; opposite results were obtained for the low-load transfer weldbonded specimens. The fatigue life of the high-load transfer specimens depends primarily upon the nature of the adhesive bond. Because the weld nugget is located in the center of the lap joint rather than near the edges of the joint, the weld nugget has only a secondary effect on fatigue life. Larger nuggets in these specimens result in a thicker adhesive bondline, suggesting that the increased thickness of the adhesive caused better fatigue behavior in the specimens with large nuggets.

Table 6 Effect of nugget size on the fatigue life of weldbonded high-load transfer fatigue specimens. Material: 7075-T6 Al, 1.60 mm (0.063 in.) thick; test conditions: $R(\sigma_{min}/\sigma_{max}) = 0.1$

Nugget size[a]	Maximum load kN	(lb)	Cycles to failure
Small[b]	15.7	(3,500)	3,010
Small	15.7	(3,500)	4,860
Small[b]	10.1	(2,250)	98,560
Small	10.1	(2,250)	99,020
Small[b]	9.0	(2,000)	1,083,090
Large	15.7	(3,500)	5,380
Large	15.7	(3,500)	8,450
Large	15.7	(3,500)	12,020
Large	10.1	(2,250)	130,970
Large	10.1	(2,250)	133,670
Large	10.1	(2,250)	187,780
Large	10.1	(2,250)	235,230
Large	10.1	(2,250)	296,120
Large[c]	9.0	(2,000)	934,870
Large[d]	9.0	(2,000)	1,229,810

[a]Small: 4.6-5.7-mm (0.18-0.22-in.) diameter; medium: 5.8-7.0-mm (0.23-0.27-in.) diameter; large: 7.1-8.4-mm (0.28-0.33-in.) diameter. [b]Diameter—3.8 mm (0.15 in.). [c]Diameter—6.6 mm (0.26 in.). [d]Diameter—9.1 mm (0.36 in.).

Effects of Manufacturing Defects on Fatigue Life

The effects of two types of defects that can occur with poor weldbond process control were evaluated. Results for these two types of defects (subsurface cracked nuggets and expulsion around nuggets) are summarized in Table 7 and plotted in Fig. 11. The cracked nugget had no effect on the fatigue life of these high-load transfer specimens because this type of specimen tests primarily the adhesive bond. Expulsion

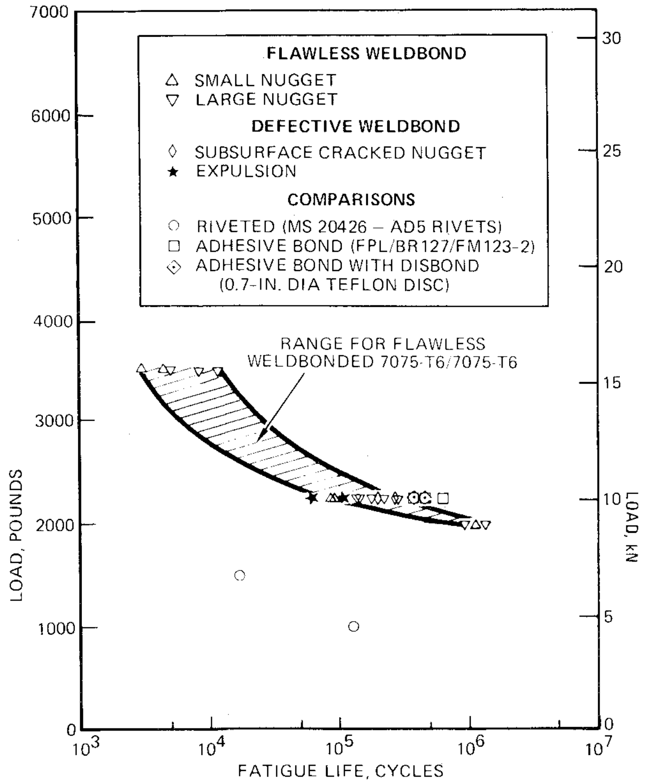


Fig. 11 Fatigue behavior of 7075-T6/7075-T6 high-load transfer specimens.

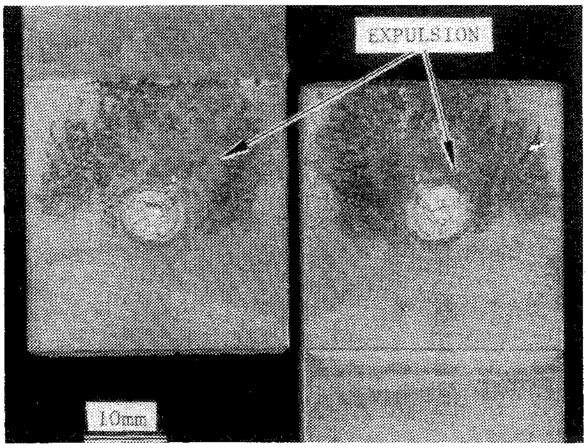


Fig. 12 Expulsion in 7075-T6/7075-T6 high-load transfer weldbonded fatigue specimen at $R = 0.1$.

Table 7 Effect of weldbond manufacturing defects on high-load transfer fatigue. Material: 7075-T6 Al, 1.60 mm (0.063 in.) thick; test conditions: maximum load = 10.1 kN (2250 lb), $R(\sigma_{min}/\sigma_{max}) = 0.1$

Defect	Nugget size[a]	Cycles to failure
Subsurface cracked nugget	Large	207,620
Subsurface cracked nugget	[b]	283,090
Expulsion	Medium	68,930
Expulsion	Medium	106,640

[a]Medium: 5.8-6.9-mm (0.23-0.27-in.) diameter; large: 7.0-8.4-mm (0.28-0.33-in.) diameter. [b]Nugget diameter—9.0 mm (0.35 in.).

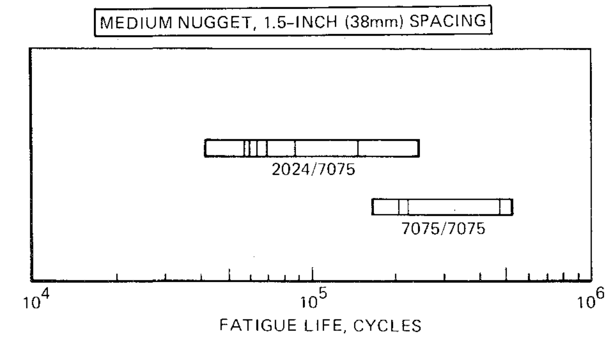


Fig. 13 Fatigue behavior of weldbonded 2024-T3 alclad/7075-T6 low-load transfer specimens at 32 ksi and $R = 0.1$. Each vertical bar (|) represents a data point.

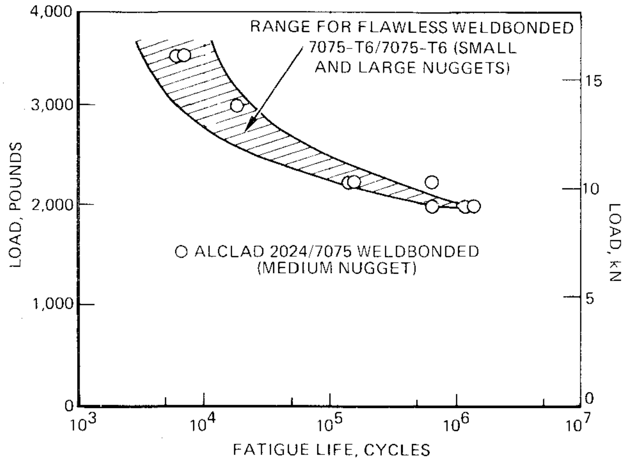


Fig. 14 Fatigue behavior of weldbonded 2024-T3 alclad/7075-T6 high-load transfer specimens at $R = 0.1$.

reduced the fatigue properties of these specimens over specimens without defects. This reduction is probably the result of two factors: 1) the severity of expulsion reduced the bond area and 2) more importantly, the expulsion destroyed the bond at the more highly stressed edge of the joint (Fig. 12). Debonding at the edge of the joint is the most damaging in fatigue for this type of specimen.

Comparison Tests

The results of the tests on adhesive-bonded and riveted high-load transfer specimens are presented in Fig. 11, which demonstrates that the adhesive-bonded specimens have only slightly better fatigue behavior than the weldbonded specimens. The riveted specimen results cannot be directly compared to the results of adhesive bonding and weldbonding because of differences in specimen configuration. The significance of these results, however, is that the adhesive system for weldbonding gives excellent fatigue performance relative to a standard riveted joint and also to a well-developed adhesive system in a high-load transfer fatigue mode.

The results for adhesive-bonded specimens made with a disbond, centered in and constituting about 25% of the area of the lap, are also shown in Fig. 11. These results are essentially the same as those without a disbond. The disbond did not extend to the edges of the lap, the critical area in fatigue, and the remaining area of bond was large enough so that no reduction in fatigue life was seen.

Low-Load Transfer Joints of 2024-T3 Alclad/7075-T6

Selected fatigue tests were performed on low-load transfer weldbonded 2024-T3 alclad/7075-T6 specimens; the results are plotted in Fig. 13 with 7075-T6/7075-T6 results as a reference. As seen in this figure, the fatigue properties of the 2024-T3 alclad/7075-T6 are slightly below those for the 7075-T6/7075-T6 combination. This difference may be due either to the different metallurgical structure of the nugget, the lower strength 2024-T3 alclad portion of the specimen, or both.

High-Load Transfer Joints of 2024-T3 Alclad/7075-T6

The high-load transfer fatigue results are plotted in Fig. 14 with the scatter band for the 7075-T6/7075-T6 results as a reference. As shown, the fatigue properties of 7075-T6/7075-T6 and 2024-T3 alclad/7075-T6 high-load transfer specimens are essentially the same. This similarity shows that in the high-load transfer geometry, where the adhesive bond is being tested, the adhesive-bonded qualities are similar in fatigue for these two combinations.

IV. Summary and Conclusions

The effects of material and process variables on the fatigue behavior of weldbonded joints were determined. For this purpose, low- and high-load transfer specimens with two alloy combinations (7075-T6/7075-T6 and 2024-T3 alclad/7075-T6) were evaluated. The fatigue behavior of the weldbonded specimens with different nugget sizes, nugget spacings, and different process defects was compared with that of riveted and adhesive-bonded specimens. Most of this work was performed on the 7075-T6/7075-T6 combination. The effects of poor process control were evaluated by modifying the weld schedules and surface-preparation procedures to produce subsurface and surface cracked nuggets, nuggets with excessive indentation, and nuggets with expulsion. Fractographic and metallographic investigations were performed to explain the fatigue test results and to determine the fatigue-crack initiation sites.

The conclusions obtained from this work are summarized below.

For Weldbonded 7075-T6/7075-T6:

1) Weldbonded low- and high-load transfer specimens have significantly better fatigue properties than riveted specimens.

2) Adhesive-bonded (FPL/BR-127/FM 123-2) specimens have better fatigue properties than the weldbonded specimens, although the difference for high-load transfer specimens is minimal.

3) Weldbonded low-load transfer specimens have better fatigue properties than adhesively bonded specimens with anti-peel rivets.

4) Weldbonded low-load transfer specimens with small nuggets generally have better fatigue properties than specimens with medium and large nuggets. The opposite is true for high-load transfer specimens.

5) Weldbonded low-load transfer specimens with flawless nuggets have as good or better fatigue resistance than specimens with material defects (small pits and titanium-rich inclusions) and with minor handling damage of the type (scratches and nicks) likely to occur in production.

6) Cracked weld nuggets significantly decrease the fatigue life of weldbonded low-load transfer specimens, but do not degrade the fatigue properties of weldbonded high-load transfer specimens.

7) Nuggets with expulsion decrease the fatigue properties of weldbonded low- and high-load transfer specimens.

8) The lives of preflawed, riveted specimens were within the fatigue-life scatter band of weldbonded specimens with cracked nuggets.

For Weldbonded 2024-T3 Alclad/7075-T6 (Medium Nuggets):

1) The low-load transfer specimen fatigue properties are slightly below those obtained for 7075-T6/7075-T6.

2) The high-load transfer specimen fatigue behavior is essentially the same as that for 7075-T6/7075-T6.

V. Acknowledgments

Thanks are due to K.C. Wu and H.E. Langman for preparation of specimens; to B.J. Mays, J.H. Fitzgerald, and D.F. Dittmer for mechanical testing; to J. Schifando, T.P. Remmel, and R.E. Herfert for microstructural analysis, and to R.R. Wells and A.H. Freedman for support and review of this work. This work was supported by the Air Force Materials Laboratory, Air Force Systems Command, U.S. Air Force, Wright-Patterson Air Force Base, Ohio, under Contract F33615-76-C-5412, with T.R. Croucher as the Northrop program manager and with N.E. Klarquist and S.G. Lee as the AFML project engineers.

References

[1] Bowen, B.B., Herfert, R.E., and Wu, K.C., "Development of Corrosion Resistant Surface Treatments for Aluminum Alloys for Spot-Weld Bonding," AFML-TR-75-69, March 1975.

[2] Wu, K.C. and Bowen, B.B., "Advanced Aluminum Weldbond Manufacturing Methods," AFML-TR-76-131, Sept. 1976.

[3] Croucher, T.R., "Advanced Weldbonding Process Establishment for Aluminum," AFML-TR-79-4006, April 1979.

[4] "Welding, Resistance, Aluminum, Magnesium, Nonhardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys: Spot and Seam," MIL-W-6858, March 1978.

[5] "Fasteners, Test Methods, Shear Joint Fatigue—Constant Amplitude," MIL-STD-1312-21A, June 1976.

[6] Marceau, J.A. and McMillan, J.C., "Exploratory Development on Durability of Adhesive Bonded Joints," AFML-TR-76-173, 1976.

[7] "Sealing and Coating Compound, Corrosion Inhibitive," MIL-S-81733, June 1976.