Joining of Boron/Aluminum Composites

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Conventional joining methods have been applied successfully to boron/aluminum composites by modifying the procedures to accommodate the anisotropic properties and structure of the material. Joining methods investigated at Convair include soldering, brazing, eutectic diffusion brazing, fusion and resistance welding, diffusion bonding, adhesive bonding, mechanical fastening, spot bonding, and combinations of these methods. The shear strength of bonded, brazed, or soldered joints is generally limited by the inherent interfacial bond strength between the boron filaments and outer ply of the aluminum matrix (about 15,000 psi). Mechanical fasteners and resistance welds do not suffer from this limitation and can provide high strength joints either alone or by supplementing the other joining methods. The application, properties, strengths, and weaknesses of each process are discussed.

Introduction

ENGINEERS and designers are becoming aware of the potential for weight savings resulting from use of advanced composites. These materials exhibit high specific stiffnesses and densities, which lead to lower weight, smaller physical size, and/or greater range and payload for aircraft. Resin matrix composites reinforced with fiberglass, boron, or graphite are examples. After seven years of development, one metal matrix composite, boron/aluminum, is becoming well known throughout the aircraft industry.

Boron/aluminum (B/Al) is fabricated by alternating rows of 4.0- or 5.6-mil-diam filaments of boron and 1- to 3-mil foils of aluminum, and then diffusion bonded under pressure in vacuum to form a consolidated, dense sheet or plate. Boron filaments are very stiff and brittle with strengths of 500 to 600 ksi and a modulus of 57 msi. By varying the aluminum foil thickness and the spacing of the filaments during layup, the volume fraction of boron can be varied. The properties of the resultant composite approximate the "rule of mixtures."

Progress in the fabrication, manipulation, and use of B/Al has led to tensile strengths consistently over 215 ksi, modulus over 31 msi, and density equal to that of aluminum for unidirectionally reinforced B/Al. The material is strongly anisotropic, and the tensile strength perpendicular to the filament direction is on the order of 25 ksi with a modulus of 20 msi. Properties can be varied greatly to suit any particular application by varying the filament volume fraction, cross-plying the filaments, and heat treating the aluminum matrix.

Designs based on B/Al material properties have shown impressive weight savings of up to 60% compared with conventional materials. In practice, however, it is difficult to efficiently introduce and remove the high loads that composites can support. Consequently, joints between composites and between composites and conventional materials have been complex and heavy. Weight penalties at the joints can eliminate the weight savings gained through the use of composites.

Development of the B/Al material has led to improved properties, and coupled with the recent methods of low-cost forming and machining, this composite is becoming cost effective for aerospace applications. To provide more efficient joints, Convair has been investigating the following joining methods: soldering, brazing, eutectic diffusion brazing, fusion and resistance welding, diffusion bonding, adhesive bonding, mechanical fastening, spot bonding, and combination joints. These processes, their application, and their properties, are discussed in succeeding sections.

Discussion

Soldering

Soldering is a joining method, applicable over a wide range of temperatures, that has no deleterious effect on the boron filaments. Successful soldering requires the use of a diffusion barrier to prevent the required aggressive fluxes from attacking the thin aluminum surface layers of the composite. Electroless nickel plating provides this protection and increases the wettability of the solder, permitting the use of a wide range of solders. The plating has an additional benefit of adhering to the ends of any exposed boron filament, which greatly improves the bond strength. By its dewetting action, bare boron can prevent the soldering of the aluminum between the filaments.

Soldering B/Al to titanium is similar to soldering to aluminum since both mating surfaces are nickel plated. Heat treatment of the plating on both the aluminum and titanium improves the plating adhesion sufficiently to prevent adhesive failures of the nickel. Electroless nickel plating of titanium is made possible by the use of a citrate (or tartrate) solution, which substitutes a citrate (or tartrate) surface layer for the naturally occurring oxide layer prior to plating.

Allstate 157, Eutectic 509, and Allstate 105 with flow temperatures of 425°F, 509°F, and 750°F, respectively have been used extensively at Convair. These solders are useful from −320°F to 500°F and are significantly stronger than adhesives throughout this temperature range. Lap shear strengths in excess of 10,000 psi can be readily obtained up to 200°F as shown in Table 1.

Failure modes vary with the test temperature. At low temperatures the composite fails by interlaminar shear, usually at the outer aluminum foil, exposing the boron filaments. As the useful temperature limit of the solder is reached, the failure surface passes through a mixed mode

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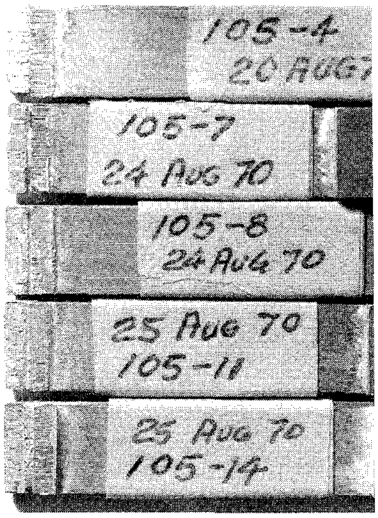


Fig. 1 Failure surfaces of B/Al with Allstate 105 braze alloy. From top down: 1) 70°F composite interlaminar shear failure, 2) 300°F, 3) 400°F mixed failure mode, 4) 500°F braze alloy adhesive and cohesive failure, and 5) 600°F.

until the failure is wholly in the solder (Fig. 1). Lap shear joints of B/Al to titanium have the equivalent strength of those between B/Al and B/Al because the failure occurs in the soldered joint or in the composite plies.

Brazing

B/Al brazing is usually accomplished using an Al/Si braze alloy at temperatures of approximately 1100°F by either dip brazing in a molten salt bath or fluxless brazing in a vacuum. Even short exposure at 1100°F, however, can cause significant reduction in boron filament strength. Borsic (silicon carbide-coated boron) filaments are affected to a lesser degree.

To retain useful strength in the composite, brazing times must, therefore, be kept to a minimum. For parts approximately 0.125 in. thick, 5 min of preheating in air circulation furnace at 900°F followed by 1 min in the salt bath at the brazing temperature is adequate. Longer exposure, in addition to degrading the filaments, allows excessive dissolution of the matrix by the flux and impairs the surface finish. The brazement may be water quenched directly from the salt bath to produce a T4 condition matrix if heat treatment is required. Vacuum-brazed parts require the full heat treatment cycle.

Fluxless brazing requires clean oxide-free surfaces; parts should be brazed within a few hours of cleaning. Finished parts, however, are much cleaner, and large overlaps can be made without danger of flux entrapment. The thermal capacity of the vacuum furnace and the lack of quenching facilities exposes the material to high temperatures for longer times, leading to more fiber degradation. Braze joints that have lap shear strengths in excess of the interlaminar shear strength of composites (approximately 15,000 psi) can be readily produced between B/Al and B/Al or aluminum.

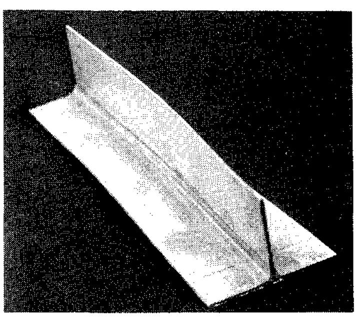


Fig. 2 Failed Con Brazed intercostal crippling specimen.

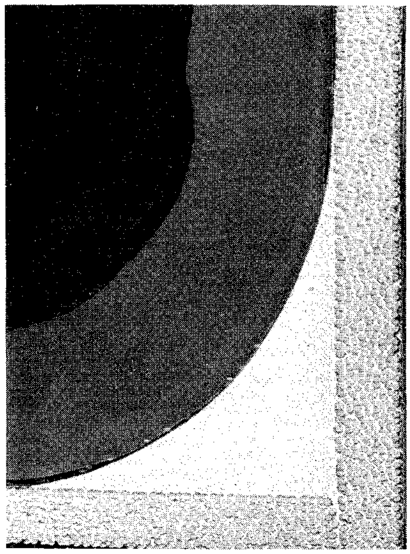


Fig. 3 Con Brazed T-section fillet.

Al/Si braze alloys can be brazed on nickel-plated titanium to develop full-strength joints or to produce joints on bare titanium with lap shear strengths above 7000 psi. An interfacial zone between the bare titanium and the braze alloy is formed, but this does not appear to have a significant effect on joint properties.

Con Braz joining is a Convair-developed process of brazing flat sheets and plates of composite material into a sheet or plate with a predetermined strength and guaranteed quality. The composite is cut into the finished dimensions and assembled on a fixture into the required structural shape. For example, a typical I-section would be built from three flat strips joined into a single structure by brazing. Con Braz fabrication does not detrimentally affect the properties of the composite, and after fabrication no finish machining is required; inspection of the part is limited to nondestructive testing of the brazed joints. Figure 2 shows a failed intercostal crippling specimen fabricated by dip brazing two consolidated B/Al sheets. The strength of Con Braz T-sections exceeds the strength of those made by any conventional tape layup method by over 40%. Figure 3 shows the natural fillet formed during the Con Braz operation; the excellent wetting of the composite by the braze alloy is clearly shown.

Using the Con Braz process, structures such as I- or T-sections with cross-plied B/Al or titanium web having a high shear strength can be made inexpensively without complex tape layups. Figure 4 shows an example of a 2-ft-long B/Al beam with a titanium web.

Table 1 Average lap shear test results with Eutectic 509 and Allstate 105 low-temperature braze alloys (0.040-in. UD B/Al to 125-in. 6061-T6 aluminum)

Alloy	Test temperature, °F	Strength, psi	Failure mode[a]
509	70	10,670	a
509	200	13,310	a
509	300	8,520	b
105	70	11,680	a
105	300	10,170	a
105	400	6,790	b
105	500	4,220	c
105	600	825	c

[a]Failure Modes: a) Composite interlaminar shear failure; b) Combination of 1 & 3; c) Braze alloy adhesive & cohesive failure.

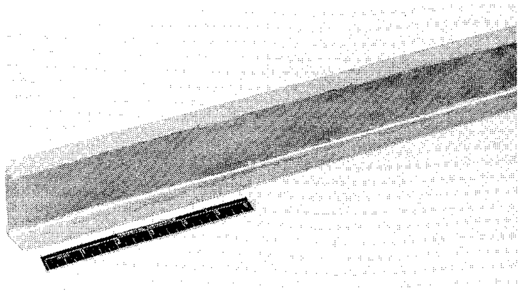


Fig. 4 Con Braz joined B/Al I-section with titanium web.

B/Al can be resistance brazed to B/Al using Al/Si braze foils. While the process is thickness limited, high-temperature-capable joints can be produced without degrading the boron filaments. Resistance brazing is accomplished by placing braze foil between the parts being joined and heating the parts with a resistance welding machine. This process can be used on almost unlimited size components. Relatively low heat inputs are required since only the braze has to be melted. Accurate electrode alignment is critical. Proper setup and electrode alignment time is approximately 3 hr, but once completed the setup is stable for at least 2 weeks, requiring only minor adjustments (less than 15 min).

Brazing of composites is complicated by the paucity of braze alloys with flow temperatures in the 900–1000°F range. Above this range the strength degradation of the boron becomes a serious problem; below this range solution heat treatment of the composite is not feasible, and the elevated temperature strength of the braze is limited.

Eutectic Diffusion Brazing

To reduce the brazing temperature of B/Al and eliminate filament degradation, considerable development has been performed with eutectic diffusion brazing. This fluxless process utilizes an elemental interface metal that diffuses together with the aluminum to form a low-melting eutectic alloy, which brazes the joint and then diffuses into the composite matrix. This removes the low-melting alloy from the brazed zone. Thus, the remelt temperature is as high as the melting point of the aluminum alloy base metal, 200–500°F higher than the brazing temperature. Several elements are suitable to diffusion braze aluminum, including silver, copper, magnesium, germanium, and zinc with eutectic temperature of 1051°F, 1018°F, 820°F, 795°F, and 720°F, respectively. Silver and copper are unsuitable for 2000- and 7000-series alloys because the brazing temperatures are higher than the incipient melting points of the alloys. Zinc and magnesium tend to oxidize in air and inhibit bonding.

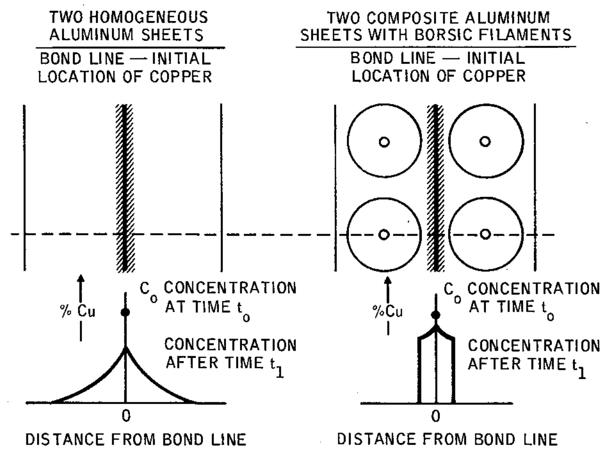


Fig. 5 Effect of filaments on diffusion rate of copper in aluminum.

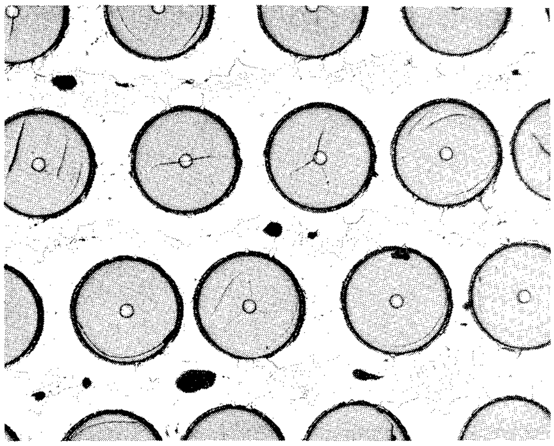


Fig. 6 Microstructure of eutectic-bonded Cu-Borsic/6061 Al after heat treatment showing high concentrations of Cu remaining at bond lines.

This technique has been used successfully with conventional metals, for instance in sealing the caps on nuclear fuel cells, but the presence of filaments in the composites complicates the process because the rate of diffusion of the coating metal into the aluminum is greatly retarded. With only the base metal, the coating can diffuse freely down a steep concentration gradient (Fig. 5, left). In a composite, the coating is impeded and even reflected back by the filaments embedded about 0.5 mil below the surface (Fig. 5, right), and the homogenization rate of the coating and matrix is drastically reduced. This limitation has proved to be serious in eutectic bonding, especially when copper is used, because the brittle eutectic film is unable to disperse and the mechanical properties are degraded. This inability of the copper to disperse even after heat treatment is shown in Fig. 6. Considerable research and development is still required before this, the most "theoretically" perfect process for joining B/Al, becomes feasible for structural components. Additionally, the expense of plating the surfaces (especially when vapor deposition is required) and the requirement of an inert of vacuum environment for bonding put this technique at a severe economic disadvantage.

Fusion and Resistance Welding

All of the fusion welding processes are unsuitable for joining B/Al because the filaments are completely destroyed in the molten zone and the weld nugget is severely embrittled. Resistance welding, however, is a feasible and very successful method for joining B/Al to B/Al or to aluminum alloys. Resistance welding melts the aluminum matrix without damaging the boron filaments (Fig. 7). (The absence of damage has been verified by microradiography. Filament splitting depicted in Fig. 7 is a result of specimen preparation.) The weld nugget essentially casts around the filaments, and a high joint efficiency is attainable. The process is economical and can produce leak-tight joints. On the debit side, access from two sides

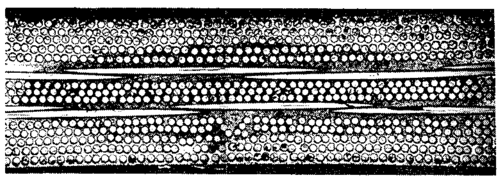


Fig. 7 Cross section of typical resistance spotweld (25×).

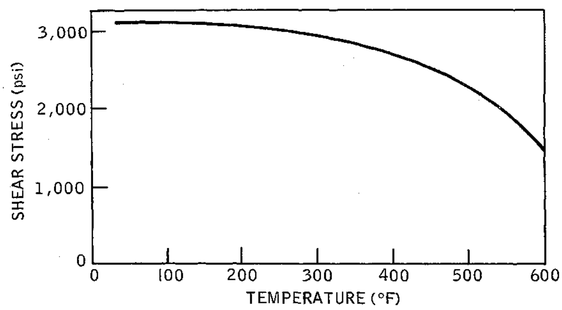


Fig. 8 Lap shear strength of B/Al-to-titanium joints bonded with Hexcel 951 polyimide adhesive.

is required, the process is sensitive to material quality, and joints have relatively low cross-tension strength. The cross-tension strength, however, is sufficiently high to resist the lateral stresses introduced in a compression-loaded composite column. Material quality is critical since the internal resistance of the material is dependent on the interfacial bonds within the material. Defects such as surface damage and expulsion, in addition to variations in bond area, can occur because of changes in local resistance that are frequently not detectable by simple nondestructive inspection.

Resistance-welded joints can be heat treated after welding, significantly increasing the joint strength in directions not parallel to the boron filaments. In unidirectionally reinforced comoosites, spotweld joint strengths of 150 ksi (based on the width of the spotweld) can be produced. Many different buildups of two, three, and four thicknesses have been successfully resistance welded, including all combinations of UD and CP B/Al, 6061 and 2024 Al, and B/Al reinforced with stainless steel wires in the transverse direction. Table 2 shows typical lap-shear and cross-tension properties of some of these joints.

Table 2 Typical mechanical properties of resistance spot welds in B/Al composites (single-spot specimens approximately 0.22 to 0.26 in. diam)

SHEET GAGE (IN.) & MATERIAL	STRENGTH (LB.) LAP SHEAR	CROSS TENSION	LAP SHEAR EFF. (%)[a]
0.020 UD B/Al to 0.020 UD B/Al	630	68	98
0.024 CP B/Al to 0.020 UD B/Al	453	78	100
0.025 UD B/Al to 0.035 CP B/Al	770	104	92
0.030 UD B/Al[b] to 0.030 UD B/Al	753	–	81
0.035 CP B/Al to 0.035 CP B/Al	803	–	93
As above with postweld heat treatment	980	–	100[c]
0.020 UD B/Al to 0.020 2024 Al	523	42	82
0.024 CP B/Al to 0.040 6061 Al	422	75	93
0.020 UD B/Al to 0.024 CP B/Al + 0.020 UD B/Al	436	91	68
0.020 UD B/Al to 0.020 2024 Al + 0.020 UD B/Al	618	–	96
0.020 UD B/Al to 0.024 CP B/Al + 0.040 6061 Al	557	87	88
0.020 2024 Al between 2-0.020 UD B/Al	857	–	95[d]
0.040 6061 Al to 0.025 CP B/Al + 0.020 UD B/Al	333	74	–
0.025 UD B/Al to 0.035 CP B/Al + 0.025 UD B/Al	478	98	60
0.035 CP B/Al to 0.035 CP B/Al + 0.035 CP B/Al	850	–	95
0.025 UD B/Al to 0.035 CP B/Al + 0.040 6061 Al	430	119	54
0.040 B/Al-SS to 0.040 B/Al-SS parallel to boron	1,370	–	85
As above, perpendicular to boron	720	–	100

NOTES: UD B/Al – Unidirectionally reinforced, one ply per 0.005 in. thickness

CP B/Al – Crossplied, 0°-90°, reinforced composites
0.024 inch is 0°-90°-90°-0° ply orientation
0.035 inch is 0°-0°-90°-90°-90°-0°-0° ply orientation

B/Al-SS – Seven ply unidirectionally reinforced B/Al with one ply of 0.002 in. dia. AM355 stainless steel fibers on each surface

a. Based on width of spot weld & following basic composite strengths:
UD B/Al 160,000 psi F_{tu}
CP B/Al (0.024 in.) 80,000 psi F_{tu}
CP B/Al (0.035 in.) 100,000 psi F_{tu} in 0° direction & 75,000 psi F_{tu} in the 90° direction
B/Al-St 150,000 psi F_{tu} parallel to boron, 35,000 psi F_{tu} perpendicular to boron filaments
2024 Al 60,000 psi F_{tu}

b. Borsic/Al (silicon carbide coated boron filaments) fabricated from plasma sprayed tapes with 140,000 psi F_{tu}

c. Heat treatment increases the composite F_{tu} approximately 12%. This value is based on 180,000 psi F_{tu}

d. Based on the 0.750 inch width of 2024-T3 aluminum which failed

Diffusion Bonding

Diffusion bonding is the most commonly used fabrication process for the basic composite foil or sheet. Diffusion occurs at lower temperatures than brazing, thus reducing the amount of boron degradation, although higher pressures are required to compensate for the lower temperature. The high-pressure requirement limits the size of all diffusion bonded parts except simple flat shapes, which can be step pressed.

Solid-state diffusion bonding causes little or no deformation of the parts; they are just held in very close surface contact. Close control of tolerances result. Part cleanliness is critical because an oxide layer will inhibit joining. The oxide layer must be completely removed.

Deformation diffusion bonding breaks-up the oxide layer as massive plastic strain takes place at the joint. This reduces the cleaning requirements, but the embedded oxide particles may cause subsequent cracking. Deformation diffusion bonding is not practical because of the danger of breaking the boron filaments. Solid-state diffusion bonding of aluminum is extremely difficult because of the tenacity of the aluminum oxide film. For these reasons, diffusion bonding is impractical as a joining process.

Adhesive Bonding

B/Al can be adhesive bonded using all procedures and adhesives applicable to aluminum. The only major difference is the allowable cleaning procedure. The aggressive cleaners used for aluminum remove an excessive amount of material from the B/Al surface. Therefore, less aggressive and less effective cleaners are used for B/Al, and the resultant bond strength is somewhat lower. If adhesive bond strength is critical, great care with the cleaning process is essential. Even with very careful cleaning, joint strengths and temperature stability limits of most adhesives are generally lower than brazes. High-shear-strength adhesives usually have low peel and tensile strength.

Polyimide resins have been successfully utilized in commercially available adhesives for use at temperatures up

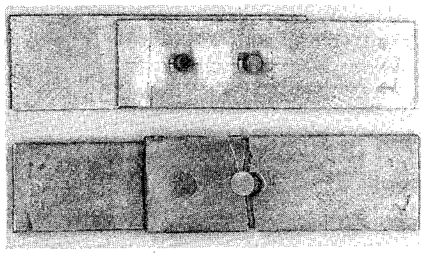


Fig. 9 Failure modes of riveted B/Al specimens. The unheat-treated specimen (above) failed in bearing; the heat-treated specimen (below) failed in net tension.

to 600°F. Excellent lap shear strengths of over 3000 psi at 70°F and 1500 psi at 600°F have been generated on titanium-to-advanced-composite joints (Fig. 8). Standard manufacturer's recommended processing and cure cycles may be followed as long as care is taken not to damage filaments in the composites. B/Al adherends can be treated with procedures now used for aluminum. However, only narrow strips (1 in. wide) can be bonded with such adhesives, since large amounts of volatiles are evolved during cure. In addition, such adhesives cure to a rather brittle material, and care should be taken to avoid peel loads in the bond line.

Mechanical Fastening

The use of mechanical fasteners necessitates drilling holes in the composite through the boron filaments. In addition to losing the strengthening effect of the cut boron filaments, loads have to be transferred by shear through the surrounding matrix into the adjacent uncut filaments, which are then subjected to high stress concentrations.

Mechanical fasteners produce reliable joints with high, local cross-tension strength that resist peeling stresses. Fasteners can be applied with minimum risk, but at a weight penalty. Typical test data is given in Tables 3 and 4. The lap shear strength and fatigue resistance of a riveted joint is inferior to resistance spot-welded or bonded joints. High-compression-loaded fasteners with aluminum washers, however, are superior to all other joining methods in fatigue resistance. Squeezed rivets are not satisfactory for unidirectionally reinforced B/Al because of the tendency to split the composite. Controlled-expansion fasteners, such as blind rivets and Huckbolts, are satisfactory for all composite types. Test results show that the manufactured head of the fastener should be placed against the B/Al composite in B/Al-to-aluminum or titanium joints.

Bearing failures at 84–120 ksi stress levels are typical for riveted joints in as-fabricated composite. The exact values depend on rivet type, manufactured head location, and composite type. Heat treating the composite prior to riveting increases the bearing strength up to over 140 ksi, changes the failure mode to net tension at the rivet hole, and increases the shear strength to over 20 ksi (Fig. 9).

Spot Bonding

Two different B/Al-to-titanium spot bonding processes have been developed at Convair. Both are resistance processes and are referred to as spot joining and spot brazing. With a ⅜-in.-diam spot size, each process develops a lap shear strength over 1000 lb.

Table 3 Typical B/Al single, universal head, rivet joint data

Composite type	Flmt. orient., deg.	Thick, in.	Width, in.	Fail. load, lb.	Max. stress, psi	Fail. mode[a]
Unidirectional	0	0.035	0.65	1395	61,500	a
	0	0.035	0.65	1408	62,000	b
	90	0.035	0.65	350	15,400	c
	90	0.035	0.65	449	19,800	c
Crossply	0–90	0.024	0.90	1060	49,100	c
	0–90	0.024	0.90	705	32,600	c
	0–90	0.024	0.90	708	32,800	c
	0–90	0.020	0.90	998	46,100	c

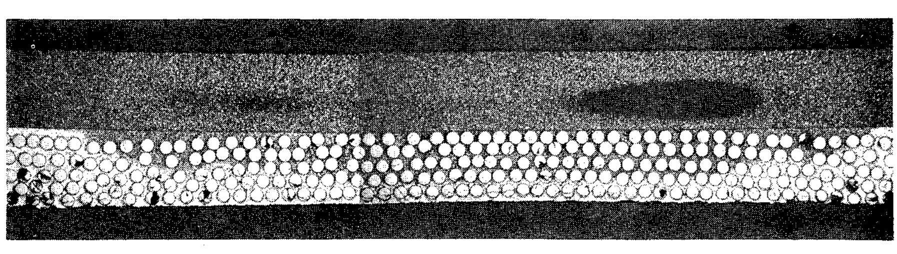
[a]Failures modes: a) Tension in composite at fastener hole; b) Composite shearout; c) Tension in composite away from fastener hole.

Spot joining melts the aluminum at the interface, where it solidifies onto the titanium. The joint is heated under pressure for a few seconds in a resistance welding machine. Heat concentrated in the titanium flows into the aluminum by conduction and forms a molten nugget in the composite matrix at the interface. The nugget attaches to the titanium upon solidification under pressure. No apparent diffusion of aluminum into titanium or titanium into aluminum occurs (Fig. 10). Failure of the joint usually occurs within the composite. No plating or special preparation of the titanium is required, and standard electrodes and equipment are used. Adding a second spot nearby increases the strength of the joint. On unidirectionally reinforced B/Al, the strength is effectively doubled (from 1113 to 2193 lb), equivalent to a joint strength of 13,000 psi. However, the low cross-tension strength of 100 lb per spot is a drawback for some potential applications. Properties consistent within ±10% of the average load have been obtained. Results are very sensitive to material quality.

Spot brazing was recently developed to overcome gauge limitations and inconsistencies encountered in the spot joining of B/Al to titanium. The process is capable of larger nugget diameters, overlapping to join large areas, and high-quality, reproducible joints. The titanium is plated first with electroless nickel and then with a thin layer of copper; the B/Al is copper-plated directly. The copper interface is diffusion bonded with some interface melting but without the formation of massive copper/aluminum brittle intermetallic compounds. A high-strength, ductile joint results (Fig. 11).

The plating procedure developed for B/Al incorporates a nonaggressive cleaning procedure, a standard zincate treatment, and cyanide copper plating. For this study, 0.001 or 0.002 in. of copper was deposited on the composite. The plating procedure for titanium is more complex than for the B/Al because of the difficulty in getting an adherent plating on titanium. Electroless nickel plating of approximately 0.0002 in. was first put on the titanium. This process includes velvetizing the titanium surface followed by a tartrate pretreatment. The standard Convair procedure for cyanide-copper plating was then used: acid

Fig. 10 Cross section of resistance spot joint (25×).



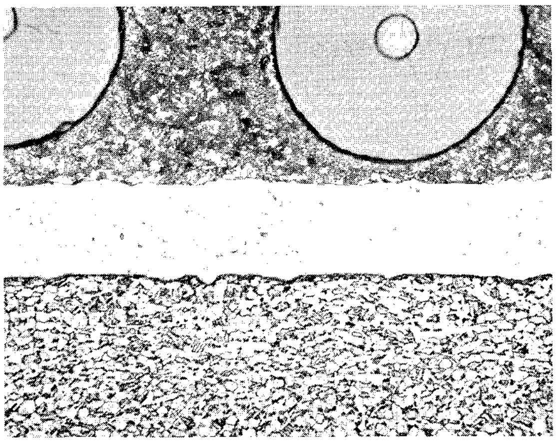


Fig. 11 Resistance spot braze joint interface (500×).

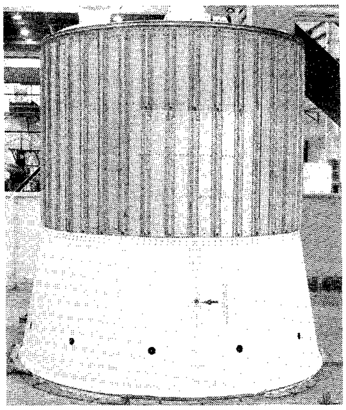


Fig. 12 Payload adapter for Atlas booster.

etch, nickel strike, copper strike, and copper plate. The same 0.001 or 0.002 in. of copper that was plated on the B/Al was also plated on the titanium coupons.

The initial schedule developed for the spot brazing process was for titanium-to-titanium, and after this schedule was developed, it was modified for B/Al-to-titanium. In this process, the specimens are resistance heated under pressure using a standard resistance spot-welder. The pressure accelerated the Cu-Cu diffusion. Attempts to join B/Al to B/Al were unsuccessful because the composite matrix melted at the Al-to-B interface prior to the formation of the Cu-Cu joint.

This portion of the program was a feasibility study and proved to be successful. Joint shear strengths of 10,000 psi were obtained with failure in the composite matrix. As shown in Fig. 11, the joint is sufficiently strong to sustain over 1100 lb with a 0.36-in.-diam bond. No aluminum matrix degradation is visible in the photo-micrograph and none was found during detailed examination of the specimen.

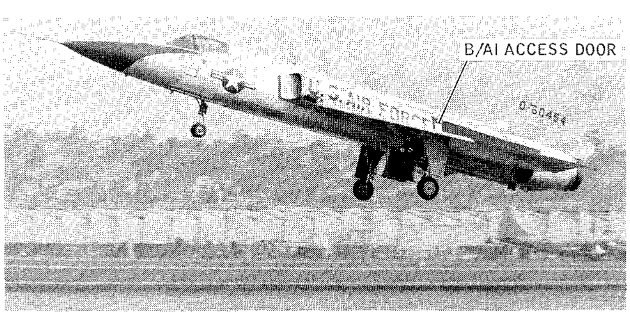


Fig. 13 F-106 flight test of B/Al access door.

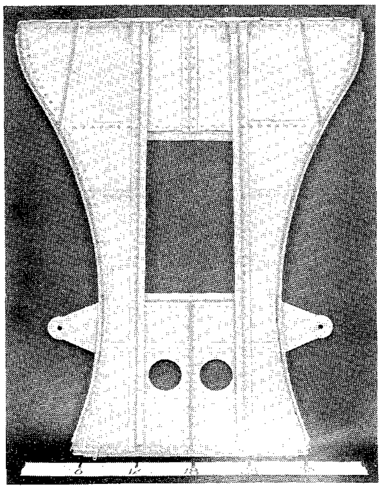


Fig. 14 F-111 fuselage bulkhead.

Combination Joints

Combinations of the various joining methods just discussed may produce more efficient joints. Soldering, brazing, or bonding in conjunction with welding or fastening are candidates for structural application. Adhesive bonded joints reinforced with mechanical fasteners resulted in a 300% lap shear strength increase over joints made by either adhesives or fasteners alone. Research and development work is continuing in order to explore the potential advantages of combining available joining methods.

Two different adhesives have been evaluated: CREST 7343, a low-strength, ductile, room-temperature-curing polyurethane adhesive and HT 424, a high-temperature, brittle, 340°F curing epoxy-phenolic adhesive with moderately high-temperature strength. The CREST 7343 raised the effective shear strength slightly, but was not effective in improving the joint tensile strength. The HT 424 was very effective in raising the joint strength. Brittleness of the adhesive apparently did not result in premature adhesive failure.

The UD B/Al joints using HT 424 failed in shear with an effective shear strength of 52 ksi, which is sufficient to preclude any splitting of stringers riveted to skin structures. The CP B/Al jointed with this adhesive increased the joint tension strength from 47 to 58 ksi, an increase of over 23%. The possibility of a shear failure in a structural joint was completely eliminated by raising the effective shear strength above 65 ksi.

In view of the limited strength of the surface plies of the composite, it appears that joints which rely on loading through these plies can be improved with mechanical fasteners. These introduce the loads to all the plies through

Table 4 Typical lockbolt joint data

Description	Fail load	Fail. mode	Max. stress, ksi F_b	F_t	F_s	Comments[a]
CP/Ti	817	Net tension	128	50		
CP/Ti	833	Net tension	130	50		
CP/Ti	763	Net tension & bearing	118	48		H-T
CP/Ti	759	Net tension & bearing	118	47		H-T
UD/Ti	896	Net tension	90	118	11	
UD/Ti	1,009	Net tension	101	133	12	
UD/Ti	1,058	Net tension	88	139	22	H-T
UD/Ti	828	Net tension	67	109	17	H-T

[a] CP Crossply B/Al, 0.040 in. thick; UD Undirectional B/Al, 0.040 in. thick; H-T Heat treated to -T6 condition.

the thickness of the composite and hence reduce the shear stress at the bonded interface.

Applications

Several large aircraft and missile components have been fabricated at Convair Aerospace using metal-matrix composites as one of the key structural materials. These include a large payload adapter, an F-106 access door, and a portion of an F-111 fuselage bulkhead. The success of these programs depended to a large degree on the composite joints developed.

The payload adapter (Fig. 12) built in 1968 was the first major metal-matrix structure and is the largest such structure built to date: 4 ft in diameter and 7 ft high. The resistance welded, riveted construction of unidirectional stringers and crossply reinforced skins offered a 45% weight saving over the existing 2024 aluminum design. The stringers failed at approximately 200% of design limit load during testing.

The access door (Fig. 13) built in 1969 was the first B/Al structure to be flight tested. The door, 11⅜ in. high and 11 in. wide, contoured to a 43 in. radius, is approximately 20% lighter than the original design in aluminum. A duplicate test of the adhesively bonded door panel (attached by Camloc fasteners) failed at 160% of the design limit load. The flight article is still in service and about to undergo a new series of flight tests.

The bulkhead (Fig. 14), measuring 48 in. high by 30 in. wide, consists of Borsic/6061-T6 Al with a titanium frame. The crossplied skin is stiffened with unidirectionally reinforced zees, angles, and straight and joggled tees. Joints were made by spot welding, adhesive bonding, and lockbolts. The bulkhead represented a 26% weight saving, and during structural testing failure occurred at 130% design limit load.

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Pilot Control of Shuttle Orbiter during Approach and Landing

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Using a fixed base, six degree-of-freedom piloted simulation of a Shuttle Delta Body Orbiter, a simplified unpowered orbiter energy management technique has been developed and demonstrated from 100,000 ft altitude to touchdown. The results indicate that satisfactory unpowered orbiter landings from random initial conditions and with unknown winds can be accomplished by the pilot, utilizing conventional TACAN distance and heading information for energy management. The effective use of man's skill in this important area can reduce system complexity, enhance system reliability, and reduce over-all program costs.

I. Introduction

THE development of an economical, reusable Space Shuttle that can transport personnel and cargo to and from low Earth orbit is an essential first step in NASA's future space exploration program. A key element in achieving this objective is the development of both manual and automatic modes of recovery from orbit, including standard approach procedures for accomplishing unpowered landings on a routine basis.

As long as the requirement for piloted re-entry and landing exists, it is essential that the piloting techniques and procedures be developed prior to the development of the guidance software. By first developing a simple, reliable technique for a piloted, manual mode of re-entry and landing and then implementing this technique in the guidance equations for the automatic mode, several significant advantages are realized: 1) Complete compatibility between automatic and manual modes. This is required for ease of transition from one mode to the other and to ensure that an automatic mode failure would not present the crew with an insoluable piloting problem. 2) Definition of realistic automatic mode design requirements. 3) Definition of minimum cockpit display and navaid requirements for the manual mode of recovery. 4) Minimum cost to develop an effective (simple, reliable) re-entry GC&N system.

This paper presents the results of a piloted simulation study conducted by Lockheed for NASA/MSC during the first half of 1971.[4] For the purpose of the study a high crossrange delta lifting body configuration was programmed and flight controls loops were designed to yield acceptable handling qualities throughout the aerodynamic operating range.

The energy management technique uses lift to drag (L/D) ratio modulation for flight-path angle control and maximizes the conservation of potential energy until the runway is "made". At this time, the flight-path angle is increased so that final approach may be flown with sufficient kinetic energy to allow a precise flare and landing. Using this technique, touchdown dispersion of 1250 ± 550 ft of runway length and 180 ± 8 knots airspeed were realized.

II. Simulation Systems Description

A. Simulated Vehicle Characteristics

The Space Shuttle Orbiter used in this simulation is a lifting body concept with a delta planform shape (see Fig. 1). With the c.g. at 75% of vehicle reference length, longi-

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