Soldering and Brazing of Advanced Metal-Matrix Structures

Several processing techniques and filler metals have been developed to realize the low weight, high strength capabilities of boron/aluminum composites

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ABSTRACT. There is increased awareness of the potential weight savings resulting from the use of advanced composites in aerospace designs. Boron/aluminum, one of these advanced composites, has been shown to be adaptable to a full range of joining techniques. Soldering of boron/aluminum is applicable over a wide range of temperatures, and has no deleterious effect on the boron filaments. Room temperature lap shear strengths for various solders range from 10 ksi (69 MN/m²) to more than 12 ksi (83 MN/m²); certain solders have lap shear strengths as high as 4.5 ksi (31 MN/m²) at 600 F (589 K). Boron/aluminum is brazed using aluminum-silicon alloys, at temperatures up to 1,140 F (880 K), either by dip brazing in a molten bath or fluxless brazing in a vacuum. Even short exposures at these elevated temperatures can cause serious degradation of the boron filaments. In an effort to reduce brazing temperatures, a development program has been conducted using eutectic diffusion brazing. This fluxless process uses an elemental metal interface. Upon heating, a low melting point eutectic alloy forms and diffuses from the interface, leaving a joint with a remelt temperature 200 to 500 F (366 to 533 K) higher than the brazing temperature.

Introduction

There is increased awareness of the potential weight savings resulting from the use of advanced composites in aerospace designs. These materials exhibit high specific stiffness and high strength-to-weight ratios that result in lower weight and size, and greater range and payload for aerospace vehicles. Only one of these advanced composites, boron/aluminum, has been shown to be adaptable to a full range of joining techniques, including welding, brazing, soldering, riveting, and diffusion bonding.

Boron/aluminum is composed of boron fibers interspersed in an aluminum matrix. The fibers are aligned in rows through the thickness. The basic unit of boron/aluminum is the monolayer, which consists of one row of boron fibers in an aluminum matrix. These monolayers (or plies) are stacked, one atop the other, and bonded together to form a continuous material (Fig. 1). All plies may be oriented with the fibers in the same direction (unidirectional) or at various angles to each other (crossplied). Boron/aluminum has the density of aluminum, but strength comparable to steel. The room temperature tensile strength in the longitudinal direction for 50 volume per cent boron in aluminum is 216 ksi (1,490 MN/m²), with a modulus of 31 msi (213 GN/m²). Even at 600 F (589 K), which is considered to be the maximum use temperature, the strength is greater than 150 ksi (1,040 MN/m²) (Ref. 1). The room temperature shear strength, measured by the double-slotted shear test described in Ref. 2, is approximately 23 ksi (159 MN/m²).

Commercial acceptance of boron/aluminum (and other advanced composites) has been hampered by several factors, including the final cost of structural members, the lack of suitable joining techniques, and processing temperature limitations. Application of soldering and brazing to boron/aluminum structures has helped to minimize these factors.

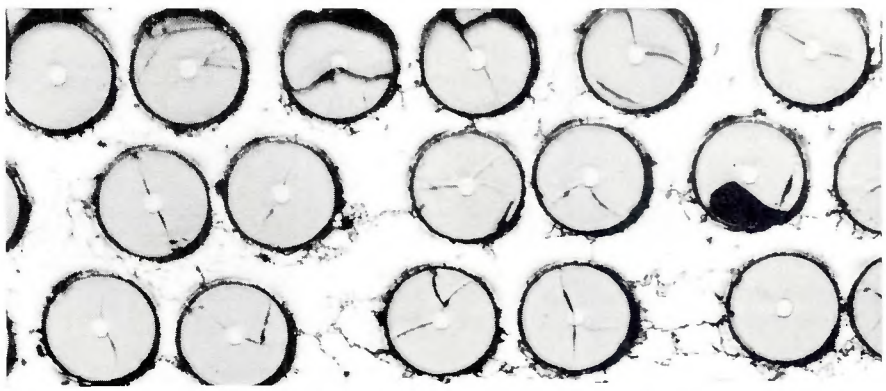

Fig. 1 — Microstructure of Borsic/aluminum braze panel. Borsic fibers interspersed in Al-Si matrix X 100, reduced 40%

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Soldering

Soldering is an excellent method for attaching metal-matrix composites to similar or dissimilar metals, such as titanium, since processing temperatures fall below the point where filament degradation occurs. Soldered structures can be used at operating temperatures up to 600 F (589 K) — generally believed to be the upper operating temperature limit for boron/aluminum or Borsic/aluminum structures.

Alloy Selection

Surface preparation of boron/aluminum for soldering has been found to be critical in attaining highly reliable joints. It has been shown that zincate coatings followed by thin electroless nickel plating of about 0.0002 in. (0.05 mm) is effective in promoting soldering ease, alloy flow, and general strength increase (Ref. 2). This result is attributed to higher wettability of the nickel surface, leading to generally better flow conditions. Electroless nickel plating is used in preference to electrolytic processes because it allows the nickel to be plated on exposed boron filaments, which are electrically nonconductive. Depending upon the joint configuration, electroless nickel plated specimens result in joints with 10% to 30% greater strength than those plated with electrolytic nickel systems. The significant difference is attributed to the dewetting action associated with electrolytic nickel systems resulting from any exposed boron filaments.

An electroless nickel plate about 0.0002 in. (0.05 mm) thick on both boron/aluminum and titanium alloys has proven to be a readily solderable combination. Titanium — normally a difficult material to plate — is nickel plated by excluding surface oxide formation with the use of citrate and tartrate coatings soluble in the ammoniacal solution of the plating bath. Standard methods of electroless nickel plating titanium require vacuum heat treatment at 900 F (755 K) for one hour to produce the adherent bond for soldering. Similarly, electroless nickel plated boron/aluminum is baked for one hour at 350 F (450 K).

Solders for both 200 and 600 F (366 and 589 K) applications were selected on the basis of consideration of strength, temperature, and adaptability to use with boron/aluminum composites. Alloys chosen for initial evaluation were 95% cadmium-5% silver; 95% zinc-5% aluminum; 96.5% tin-3.5% silver; and 82.5% cadmium-17.5% zinc. These solders have flow temperatures of 750, 720, 425, and 509 F (672, 656, 492, and 538 K), respectively.

Room temperature and elevated temperature tests were conducted on single overlap shear specimens. The specimens were 0.040 in. (1.02 mm) thick by 0.5 in. (12.7 mm) wide boron/aluminum joined to 0.125 in. (3.2 mm) thick by 0.5 in. (12.7 mm) wide 6061-T6 aluminum with a 0.125 in. (3.2 mm) overlap. Actual joints were made by fluxing both surfaces to be joined with the manufacturers' recommended flux, clamping the overlapping parts in a stainless steel fixture for alignment, and heating with a soft, slightly caburizing oxyacetylene flame. Joint clearance was contact only, and a small piece of solder alloy was preplaced at one end of the joint; upon heating the joints were formed through capillary action.

Table 1 summarizes lap shear test results for three alloys selected for potential applications. Joints made with 82.5% cadmium - 17.5% zinc alloy were found to be extremely brittle and occasionally cracked during cooling, whereas joints made with the other alloys were relatively ductile.

The 95% cadmium-5% silver alloy was chosen for 200 F (366 K) applications. Its shear strength at 200 F of 12.90 ksi (89 MN/m^2) satisfies most design requirements for a boron/aluminum structural joint intended for operation at that temperature. Its strength drops off rapidly above 500 F (533 K), making the alloy unsuitable for 600 F (589 K) applications.

The 95% zinc-5% aluminum alloy with a strength of 4.4 ksi (30 MN/m^2) at 600 F (589 K) was selected for use at that temperature. Although the alloy is as strong as the cadmium-silver alloy at 200 F (366 K), the latter was selected for the lower temperature application on the basis of its better flow characteristics and the better visual appearance of the finished joint.

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 until the failure is wholly in the solder (Fig. 2). Lap shear joints of boron/aluminum to titanium have the equivalent strength of those between boron/aluminum and boron/aluminum since the failure occurs in the soldered joint or in the composite plies.

Lap shear specimens were also prepared with 0.0002 in. (0.05 mm) of cadmium plated over the electroless nickel. This system was evaluated to determine if it would improve wettability and encourage better flow of

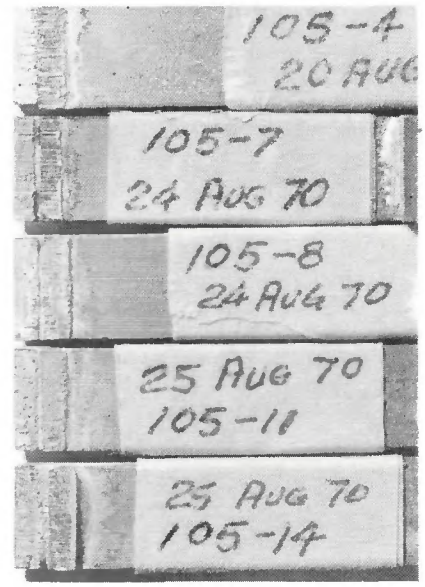

Fig. 2 — Failure surfaces of boron/aluminum with 95% cadmium-5% silver braze alloy

Table 1 — Results of Lap Shear Tests for Soldered Boron/Aluminum Specimens

Solder composition	Test temperature F	Test temperature K	Failure stress ksi	Failure stress MN/m^2	Failure mode [a]
95% cadmium, 5% silver	70	294	11.68	81	1
	200	366	12.90	89	1
	300	422	10.17	69	1
	400	478	6.79	47	2
	500	533	4.22	29	3
	600	588	0.82	5.6	3
95% zinc, 5% aluminum	70	294	11.60	80	1
	200	366	13.60	94	1
	600	588	4.43	30	2
82.5% cadmium, 17.5% zinc	70	294	10.67	74	1
	200	366	13.31	90	1
	300	422	8.52	59	2

(a) Failure mode:
1. Composite interlaminar shear
2. Combination of 1 and 3
3. Braze alloy adhesive and cohesive failure.

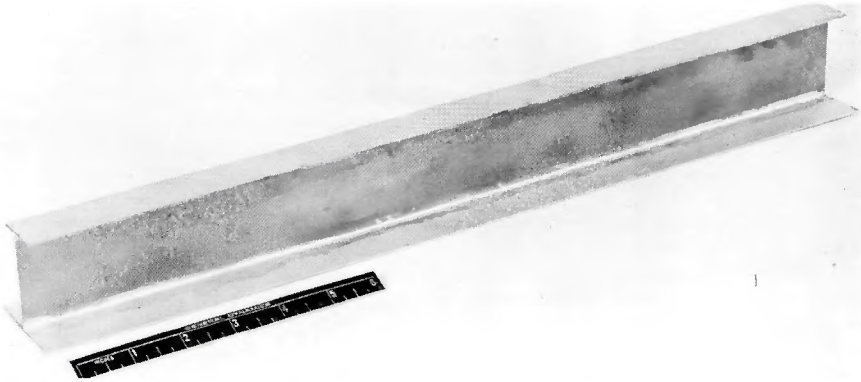

Fig. 3 — Con Braz joined boron/aluminum I section with titanium web

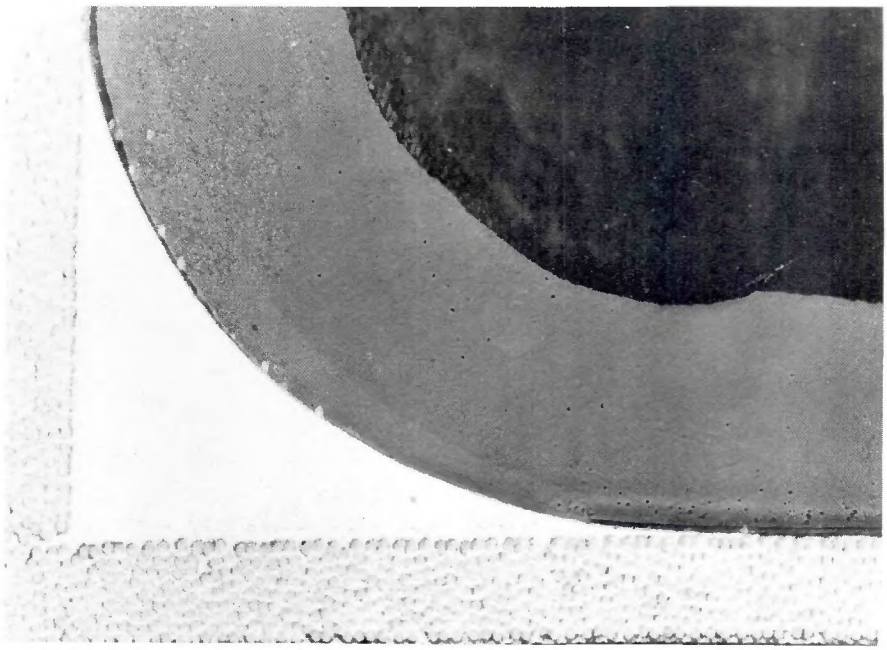

Fig. 4 — Con Braz Tee section fillet, X10, reduced 50%

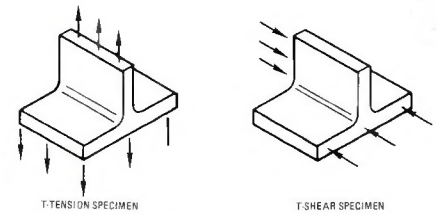

Fig. 5 — Loading direction for Con Braz joined Tee sections.

the solder to yield increased joint strength. The lap shear tests resulted in an average shear strength of 10.3 ksi (71 MN/m^2). It was concluded that using cadmium over nickel offered no improvement in brazing ease or joint strength. Further, on the basis of ultrasonic C-scan of the joints, it was found that the system could possibly be detrimental.

Con Braz Joining

One primary application of soldering boron/aluminum is the Con Braz joining process. In this technique, flat sheets and plates of composite (previously consolidated) are cut to size, assembled in a fixture, and soldered into the desired configuration.

Con Braz joining is suitable for making structural sections such as Tee sections, angles, I sections, and hats. Typical I sections can be assembled with unidirectional boron/aluminum caps and a titanium or crossplied boron/aluminum web to give increased shear strength in the web area. In other fabrication processes, this approach is either impossible or requires a complex tape layup procedure. Figure 3 shows a Con Braz joined I beam with boron/aluminum caps and a titanium web.

Con Braz joining results in the formation of a natural radius between the composite and the solder, with complete composite surface wetting. Figure 4 illustrates the natural fillet formed at the joint area. Close examination reveals interdiffusion of the solder and aluminum matrix alloys to approximately the third ply in from the surface.

Before proceeding with development of this process, it was necessary to determine the tension and shear strengths of Tee joints made with the Con Braz process. Tee sections were assembled from 0.15 in. (3.8 mm) thick diffusion bonded boron/aluminum sheet. The specimens were 1 in. (0.02 m) long with a 2 in. (0.05 m) base and 1.5 in. (0.04 m) leg. Joint surfaces were electroless nickel plated before soldering. The joints were soldered with the 95% cadmium-5% silver alloy and tested at both room temperature and 200 F (366 K). Figure 5 shows the direction of loading. Test results, summarized in Table 2, indicate that the strength of the solder can be fully realized in structures of this kind at both ambient and 200 F (366 K) temperatures. Con Braz joined Tee sections with undirectional boron/aluminum and titanium details have been subjected to thermal cycling between −320 and 200 F (77 and 366 K) with no evidence of cracking or other damage.

If necessary, joint strengths can be increased by using external fillets machined from boron/aluminum or aluminum to increase the joint area. To ensure complete flow of the solder throughout the joint area, solder in the form of 0.005 in. (0.13 mm) thick foil is preplaced between the supplementary fillet and other part details.

To demonstrate the feasibility of using soldering to fabricate long sections suitable for aircraft structure, a combination heating and tooling module was designed and fabricated for Con Braz joining. The module is stationary and the parts to be joined are hand fed through the module by an operator who watches the soldering operation from above. The length of the finished component is limited only by the length of available material and floor space.

The module uses three 1,200 watt T3 quartz radiant heat lamps in three Research Inc. Model 5305A strip heaters to heat the part to the soldering temperature. These units have a 6 in. (0.15 m) long polished aluminum reflector that concentrates the radiant heat over a 1.5 in. (0.04 m) wide by six in. (0.15 m) long target area. The lamp units are watercooled to avoid overheating the reflector and lamp ends. Overheating oxidizes the reflector, thus increasing the emissivity of the reflector surface and reducing the effi-

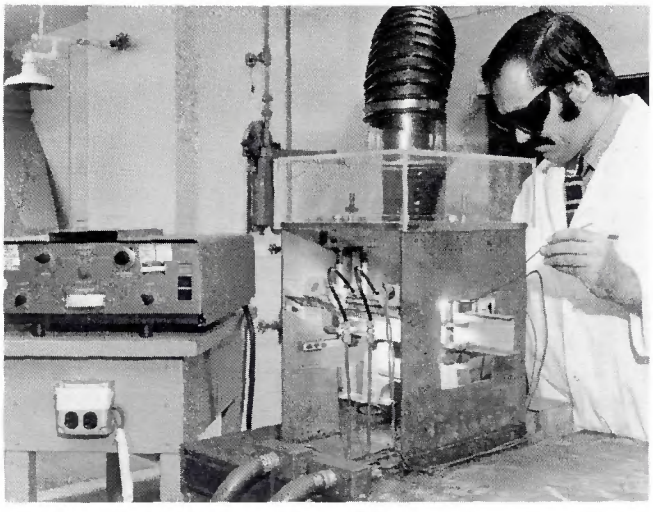

Fig. 6 — Con Braz joining of boron/aluminum I section stiffener

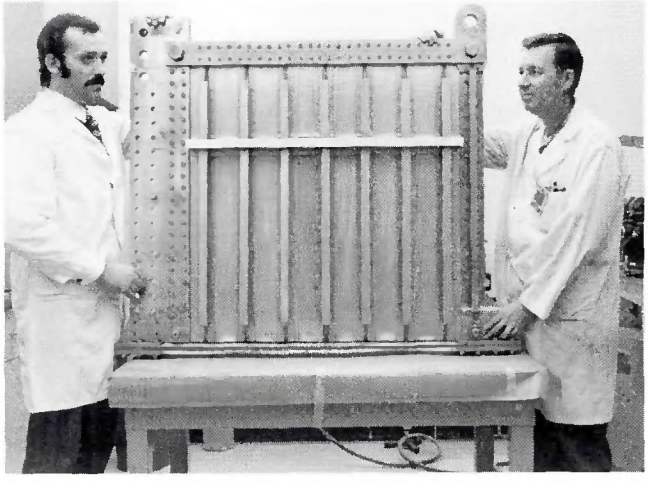

Fig. 7 — Completed boron/aluminum shear beam component showing 15 Con Braz joined I sections

Table 2 — Average Tension and Shear Strengths of Soldered Boron/Aluminum Tee Sections

Test Mode	Test temperature F	K	Failure stress ksi	MN/m²
Tension	70	294	5.70	39
Shear	70	294	10.60	73
Tension	200	366	5.50	38
Shear	200	366	10.70	75

ciency of the heating unit. Quartz lamp end seal temperatures must be maintained below 600 F (589 K) to ensure a satisfactory lamp life. If the seal temperature exceeds this limit, oxidation of the element at the junction with the quartz envelope is accelerated and the lamp life is considerably reduced.

To try out the module, tooling was initially fabricated to make a 0.5 in. (12.7 mm) thick Tee section, Tooling consisted of two identical stages with spring loaded stainless steel rolls that guided the part through the module and maintained an even pressure on the individual part details to ensure intimate contact at the joint area during soldering. To improve efficiency and reduce stray glare from the lamps, polished aluminum reflectors were added between the lamps forming a chamber with open ends. The top was left partly open to permit visual examination of the joint during soldering.

An extractor system was installed over the unit to remove any fumes generated during the soldering operation. It was constructed from clear acrylic sheet to allow unrestricted visibility of the joint by the operator. Figure 6 shows the Con Braz joining module being used to fabricate an I section stiffener.

Heating and joining tests were conducted using 0.5 in. (12.7 mm) thick 6061 aluminum Tee sections. Static heating tests were conducted to verify the ability of the strip heaters to bring the part to 800 F (700 K), which would satisfy the requirement for the solder alloy(s) to be used. A 0.5 in. (12.7 mm) thick section can be continuously joined at a rate of about 3 in. (0.08 m) per minute. Should production quantities of Con Braz joined sections be required, the maximum speed could be increased by installing a preheating zone to increase the heating rate of the part.

Maximum heating rate and maximum speed could then be attained by installing a closed loop control system, consisting of a radiation pyrometer sighted on the part with a feedback to a temperature controller that transmits, to the power controller, a signal proportional to the temperature deviation from setpoint. The power controller would then regulate input to a drive motor, which would drive the part through the module at a rate sufficient to maintain the area being soldered at the set point temperature.

A 40 by 38 in. (1.02 by 0.96 m) boron/aluminum shear beam component of a Space Shuttle thrust structure shear web beam was designed and fabricated to demonstrate the ability of these boron/aluminum joining methods to withstand both thermal and load cycling (Ref. 1). Twenty-two boron/aluminum sheet metal I section stiffeners were fabricated for this shear beam component. Composite thickness varied from 0.068 to 0.109 in. (0.17 to 0.28 mm) and stiffener length ran from 11 to 40 in. (0.28 to 1.02 m). All stiffeners were joined in the Con Braz joining module, using a 95% cadmium-5% silver alloy. The sections were joined in two passes: the first to make a Tee section, the next to join the second cap to the assembly to form an I section.

The two radiant lamp units at the top of the module were directed at the bottom of the web of the part. The radiant lamp under the base of the section was located close to the part to promote maximum heating from the bottom. This method reduced the possibility of melting the joint at the top of the part when the second cap was being joined to the Tee to make the I section.

Static heating tests were conducted to determine the power input required to produce an equilibrium temperature of 800 F (700 K) at the joint area. At the optimized heating intensity, overheating of the part and its subsequent detrimental effects did not occur. With a manually fed mode of operation, this rate provides improved control and permits incremental feeding of the part through the unit.

The composite areas adjacent to the joint are protected by brushing on a thin coat of a brazing stopoff agent, which prevented both staining of the surface by excess flux and excessive wetting of the part by unrestricted flow of the solder. The joint area was prefluxed, followed by preplacement of the solder at the joint area. Details were fed through the module and observations made to determine when the alloy melted and flowed through the joint. Any inadequately joined areas were supplemented by hand feeding a prefluxed rod into the required area. The part was fed through the module at a speed consistent with producing a good joint of uniform quality. Ultrasonic C-scan inspection of both joint surfaces indicated excellent joints.

Con Braz joining with the heating/tooling module allowed close temperature control at the joint

area. With other brazing techniques this control is difficult when thin gage material is being joined. The equilibrium temperature control system for the Con Braz joining module allows the joint area of the part to be held at the soldering temperature for an indefinite time without risk of overheating. This promotes good flow of the solder and allows careful examination of the joint during soldering.

Two of the stiffeners, with bases 2.25 in. (0.06 m) wider than the others, were soldered using an oxygen-gas torch since the small length of joint involved could not justify making new tooling for the Con Braz module to accommodate these larger details.

Torch soldering is considerably slower than using the Con Braz joining module, since assembling and aligning the part details must be accomplished manually before joining, whereas the spring loaded rolls of the Con Braz joining module align the details automatically. With torch soldering, heating is effected over a much smaller area and controlling the joint temperature is more difficult, requiring considerably more skill and care by the operator than is necessary when using the Con Braz joining module. Also, joining is interrupted for fixture relocation (to provide access to all areas of the joint).

Approximately 80 ft (24.4 m) of joint were made by this process, with about 6% being rejected due to poor quality materials.

No failures of the radiant quartz lamps in the heating units occured. When using the equilibrium temperature control system and feeding the part manually through the Con Braz joining module, the soldering speed was approximately 1.5 to 2 in. (0.04 to 0.05 m) per minute. Modification of the module to include automatic control and permit full use of the maximum heating capability can increase the feed rate to about two to three feet per minute.

One side of the completed shear beam component is shown in Fig. 7; fifteen of the soldered I beams are evident.

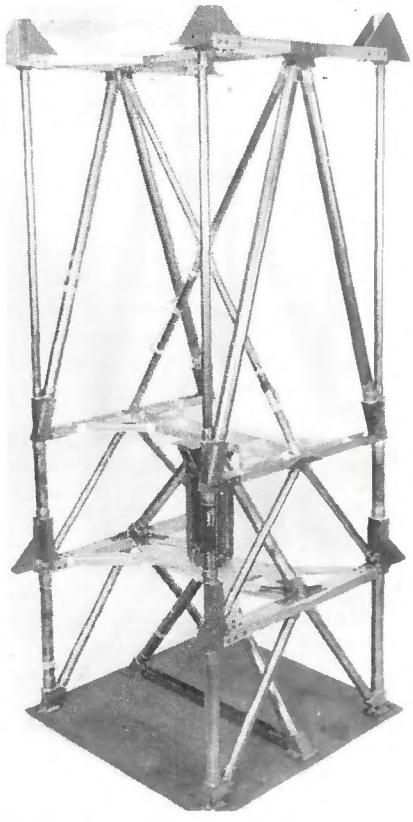

Fig. 8 — Boron/aluminum truss

Tube Fittings

OV1 satellites, when launched in the dual configuration by an Atlas launch vehicle, are supported by an aluminum truss structure some 80 in. (2.04 m) high and 30 in. (0.76 m) wide and deep. This support structure was built of boron/aluminum tubes to provide increased design efficiency and a 51% weight reduction (Ref. 3). Boron/aluminum tubing was soldered to aluminum fittings with a 96.5% tin-3.5% silver alloy that had a flow temperature of 425 F (492 K). Tests were run to develop the soldering process and to verify critical tension and compression joints. The structural joints were stronger than adhesively bonded joints and required less overlap. Figure 8 shows the completed truss assembly with the 32 boron/aluminum tubes soldered into the fittings. Three Con Braz joined boron/aluminum channels are also used in the assembly.

Brazing

Boron/aluminum may be brazed with such aluminum-silicon alloys as 713 Al, 718 Al, and 719 Al at brazing temperatures between 1,070 and 1,140 F (850 and 889 K). Short exposure times at temperatures above about 1,025 F (824 K) result in a reaction between the aluminum matrix and the boron filaments with a subsequent loss in filament strength. For that reason, a boron filament coated with 0.0005 in. (0.01 mm) of silicon carbide (trade-named Borsic) is used. The silicon carbide acts as a diffusion barrier between the boron and the aluminum matrix, delaying the onset of any interaction until about 1,100 to 1,125 F (866 to 881 K). This feature allows use of several aluminum-silicon alloys for brazing.

Vacuum Brazing

Two forms of braze alloy Borsic or boron/aluminum monolayer tape are commercially available for vacuum brazing.

In one form, on one side of the filaments is a surface made up of a 0.002 in. (0.005 mm) 6061 aluminum foil; the other side is a 0.0014 in. (0.04 mm) 6061 aluminum foil and a 0.001 in. (0.03 mm) aluminum-silicon braze foil. This combination avoids placing the brazing filler metal in direct contact with the filaments, thereby reducing the chance of severe filament degradation by the molten braze.

The other commercial tape is a single layer of boron or Borsic filaments sandwiched between a sheet of aluminum-silicon braze foil and plasma-sprayed 6061 aluminum.

Monolayer sheets can be stacked and vacuum brazed in an autoclave or press to produce a flat panel or structural shape. Monolayer Borsic or boron/aluminum tape can also be obtained with a single layer of filaments diffusion bonded between two layers of 6061 or 1100 aluminum. Such sheets can be vacuum brazed by stacking them with alternate layers of an aluminum-silicon braze foil.

Flat panels of the required thickness are made by cleaning and stacking the monolayer Borsic/aluminum tape with or without alternating braze foil, depending upon the type of monolayer used. The assembled stack is placed between two ground flat metal plates, then sealed in a vacuum tight steel envelope. Application of almost any commercial brazing stopoff agent to the platen surfaces before assembly prevents the Borsic/aluminum from bonding to the steel platens during the brazing cycle. The envelope is then evacuated and processed to consolidate the composite panel. Successful parts have been made by either evacuating and sealing the pack before consolidation or by pumping a vacuum throughout the consolidation cycle.

Consclidation is achieved in either an autoclave or a press that heats the part to the brazing temperature [between 1,070 and 1,140 F (850 and 889 K)] while maintaining a bonding pressure between 15 and 200 psi (103 and 1,380 N/m^2). Temperature and pressure are interrelated and dependent upon part configuration, tool design, and vacuum envelope design.

Strengths of Borsic/aluminum flat panels containing a nominal 45 volume per cent of filaments have been reported to be between 142 and 187 ksi (978 and 1,290 MN/m^2) (Refs. 4 and 5), depending upon the specific consolidation parameters used. These specimens were tested with all filaments running parallel to the direction of the applied test load. The strengths considerably exceed those of the strongest aluminum alloys of the same density as Borsic/aluminum, and compare favorably with steels of about three times that density.

Autoclave fabrication is more suitable for structural sections because the isostatic gas pressure allows use of simpler tooling to ensure uniform application of the bonding pressure to all part surfaces than would be possible with a single axis loading press.

Pressure application is not as serious a problem in flat panel fabrication. High temperature presses offer the advantage of step pressing techniques that do not limit part length. Step pressing has been used extensively in producing large flat panels. Both open face and matched die tooling concepts can be used, depending upon the configuration of the part. Figure 9 shows open face tooling used for brazing an angle section and matched die tooling used for fabricating a Tee section. Note that in the Tee section a natural space occurs at the center of the cap and leg intersection. To prevent this void, a filler wire of 1100 or 6061 aluminum is added. During consolidation, the aluminum wire consolidates with the aluminum in the tape to form a sound structure. The wire size can be calculated by equating the cross sectional area of the void to that of the wire. The filler wire is first annealed and then formed in a roll die to the shape of the void.

Borsic/aluminum plasma-sprayed braze tape has also been used to fabricate seamless tubes in an autoclave. Bonding pressures used in this process are 1 to 10 ksi (6.9 to 69 MN/m²) — considerably higher than those used for flat panels or other structural sections.

Figure 10 shows a 4.5 in. (0.11 m) diam brazed Borsic/aluminum tube with a 0.17 in. (4.3 mm) thick wall that was tested in compression at room temperature. The failure load of 456,000 lb (207,000 kg) is equivalent to a stress of 266 ksi (1,830 MN/m²).

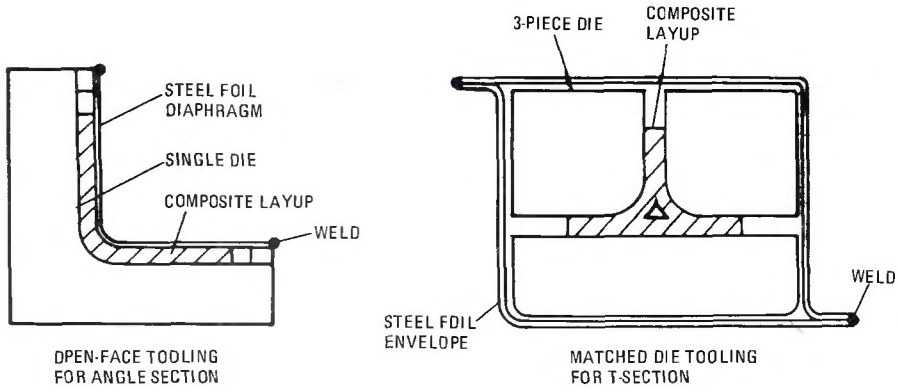

Fig. 9 — Autoclave tooling for boron/aluminum section fabrication

Table 3 — Results of Crippling Tests on Metal-Matrix Tee Sections.

Material	Ultimate stress ksi	MN/m²
Borsic/6061 plasma-sprayed material — diffusion bonded	36.2	250
	37.9	261
	44.1	304
	28.3	195
Boron/6061 diffusion bonded material — Con Braz joined	45.0	310
	66.6	459
	54.8	378
Borsic/713 braze/6061 plasma sprayed — vacuum brazed	40.9	282
	34.8	240
	34.1	235

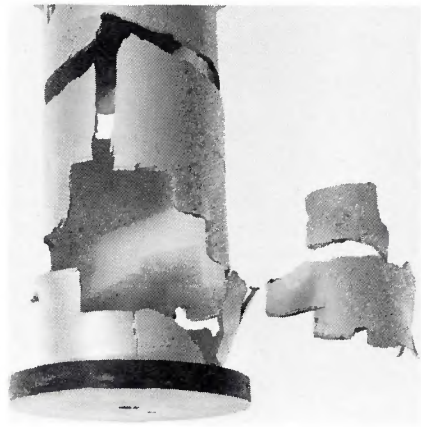

Fig. 10 — Brazed Borsic/aluminum tube, 4.5 in. (0.11 m) diam, after compression testing

Dip Brazing

Dip brazing has been used to fabricate structural shapes from previously consolidated composite sheet material. Standard aluminum dip brazing techniques are used with aluminum-silicon brazing filler metals.

A typical cycle used to form a Tee section from 0.040 in. (1 mm) thick diffusion bonded sheet material involves preheating the part for 4 min at 1,000 F (810 K), then dip brazing for 45 sec at 1,100 F (866 K) in a salt bath. The structure is quenched in hot water to remove the salt and flux. Time in the braze bath is held to a minimum to avoid solution of the filler metal to a depth sufficient to allow migration of the filaments. One Tee section made using this process failed in crippling at 141% of design ultimate. Table 3 compares results of this test, along with those for two other 6 in. (0.15 m) long Tee sections dip brazed using different fabrication parameters, with tests of parts fabricated with other processes (Ref. 2). The other processes are (1) layup of boron/6061 aluminum plasma sprayed tape on a tool and diffusion bonding in a high pressure autoclave; and (2) layup of Borsic/aluminum braze plasma sprayed tape on a tool and brazing in a low pressure autoclave.

Dip brazed specimens exhibited a higher crippling strength than all other specimens. The generous fillet radius present in the Con Braz joined section effectively reduces the critical dimension of the individual elements of the section and increases the allowable stress.

Brazed metal-matrix structures have also been used successfully to stiffen aluminum ring structures. In one example, 100 layers of composite tape were dip brazed into a ring structure, then attached to an aluminum structure by low temperature soldering.

Eutectic Diffusion Brazing

To reduce the brazing temperature of boron/aluminum and to avoid filament degradation, considerable attention has been devoted to developing eutectic diffusion brazing. This process is a fluxless technique in which an applied surface coating and the matrix metal diffuse to form a low melting-point eutectic alloy that brazes the joint.

The eutectic phase diffuses away from the bond line into the matrix during prolonged soaking at elevated temperature. This feature raises the remelt temperature to a temperature near the melting point of the base metal, 200 to 500 F (366 to 533 K) higher than the brazing temperature.

Elements potentially suitable for eutectic diffusion brazing aluminum-matrix composites are silver, copper, magnesium, germanium, and zinc; their eutectic temperatures with aluminum are 1,051, 1,018, 820, 795, and 720 F (839, 820, 711, 697, and 655 K), respectively. Silver and copper are unsuitable for 2000 and 7000 series alloys because their

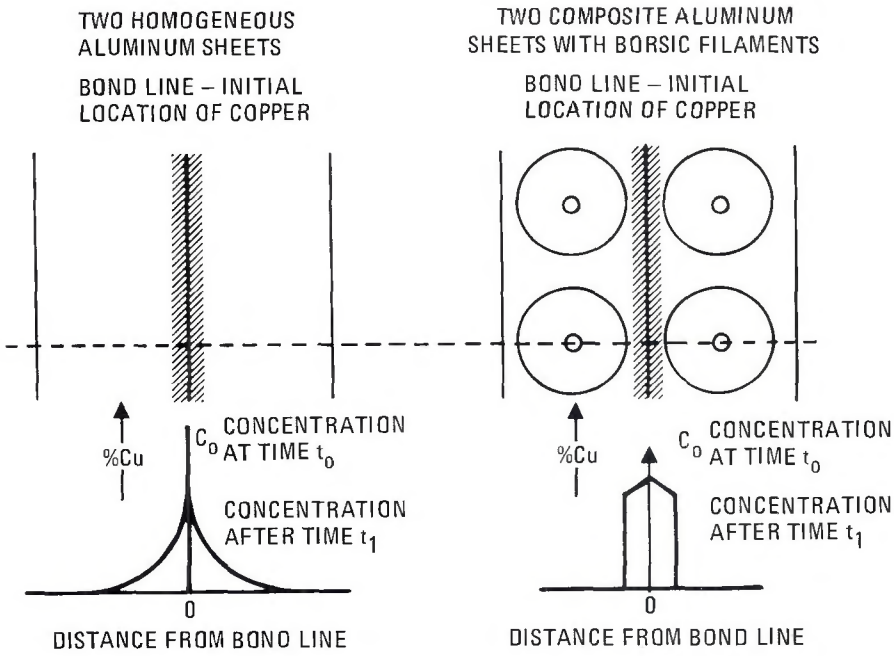

Fig. 11 — Effect of filaments on diffusion rate of copper in aluminum

brazing temperatures are higher than the incipient melting points of the alloys. Zinc and magnesium oxidize rapidly in air (during layup on the bonding tool), which tends to inhibit bonding.

Eutectic diffusion brazing has been used successfully with non composite materials (e.g., in sealing the caps on nuclear fuel cells), but the presence of filaments in the composites complicates the process. With only the matrix material and no filaments, the coating can diffuse freely down a steep concentration gradient (Fig. 11). In a composite, the filaments impede this diffusion and the homogenization rate of the coating and matrix is drastically reduced.

Mechanical properties of eutectic bonded composite material, particularly when copper is used, are degraded by the inability of the brittle layer to disperse through the matrix. Heat treatment has been used in an attempt to homogenize the structure; but, while successful with 1100 aluminum, it did not prove completely successful with boron/aluminum or Borsic/aluminum. Should continuing investigation lead to resolution of this problem, eutectic diffusion brazing would probably contend technically with other processes for fabricating boron/aluminum composite structures; however, the expense of cleaning and plating the surfaces — especially when vapor deposition is required — places the process at an economic disadvantage compared to braze tape and diffusion bonding techniques.

Discussion

Considerable work has been performed to assess the potential use of soldering and brazing boron/aluminum structures. It has been found that for all types of solder investigated, a protective layer of 0.0002 in. (0.05 mm) of electroless nickel coated on the faying surfaces increases wettability, prevents attack by the flux on the boron fiber/matrix interface, and yields higher allowable joint strengths. For soldered joints seeing service below 200 F (366 K), a 95% cadmium-5% silver alloy, yielding a room temperature lap shear strength of 12 ksi (83 MN/m²) is recommended; for 600 F (589 K) applications, a 95% zinc-5% aluminum alloy, having the same room temperature strength as the cadmium-silver alloy and a strength of 4.5 ksi (31 MN/m²) at 600 F (589 K) is recommended. The cadmium-silver alloy is easier to handle than the zinc-aluminum alloy, and is therefore recommended for applications below 200 F (366 K). Thermal cycling of soldered joints between –320 and 200 F (77 and 366 K) caused no damage to soldered components, indicating that the soldered joint can be used over a wide range of temperatures.

While the zinc-aluminum solder is useful up to 600 F (589 K), there is a vital need for a solder than can be applied in the 950 to 1,000 F (783 to 810 K) temperature range that would have higher properties than the zinc-aluminum system. The shear strength of the composite at 600 F (589 K) is 8 ksi (55 MN/m²); therefore, maximum joint strengths are not achieved with the present system. A secondary benefit of a higher temperature solder would be the possibility of soldering the composite at the solution treatment temperature for 6061 aluminum: 980 F (799 K). This would mean that a soldered joint could be effectively used in a heat treated structure.

One significant application of boron/aluminum soldering is Con Braz joining of structural elements. The use of Con Braz joining to make Tee sections, I sections, and angle joints has proven to be both economical and efficient. Cross tension tensile strengths of Tee joints made with the cadmium-silver alloy were measured at almost 5.5 ksi (38 MN/m²) at 200 F (366 K). In addition, crippling allowables averaged almost 50% higher for Con Braz Tee sections than similar autoclave bonded sections. An analysis was performed to evaluate the cost of a Con Braz joined Tee section and an autoclave bonded Tee section. The Tees were 12 in. (0.3 m) long and 0.040 in. (1.01 mm) thick. The Con Braz Tee section cost only 44% of the autoclave bonded Tee section. Con Braz parts can be fabricated at less cost, at higher production rates, and will yield stronger structures than similar autoclave bonded parts.

An example of the efficient use of Con Braz joining is the fabrication of a boron/aluminum shear beam. Twenty-two I section stiffeners were made by Con Braz joining, using a specially built module. Approximately 80 lineal feet (24.4 m) of joint were made in this manner, with a rejection rate of only 6% (all attributable to poor quality material).

Brazing boron/aluminum, using aluminum-silicon alloys, is more critical than soldering because of the high temperatures involved. Temperatures typically range from 1,070 to 1,140 F (850 to 889 K). At these temperatures, it is necessary to protect the boron filaments by coating them with a silicon carbide layer that prevents an aluminum/boron filament interaction and subsequent strength degradation. The coating increases the cost of the boron/aluminum by about 20% to 30%, and, therefore, is used only when absolutely necessary.

Dip brazing of boron/aluminum has recently been performed. One dip brazed component was a circumferentially reinforced gimbal housing. A disadvantage of dip brazed components is the increased susceptibility to corrosion that is greater than for non-dip brazed components because of the interaction between the salt and the composite. All salt must be removed from the part immediately after brazing if severe corrosion is to be avoided.

Vacuum brazing of boron/aluminum has been investigated as a potential low cost fabrication method for producing composite structures.

Composite tape material using brazing filler metal matrix can be autoclave bonded at pressures as low as 15 psi (103 N/m^2). At these pressures, existing production autoclaves can be used rather than the high cost, high pressure autoclaves or presses currently required for diffusion bonded boron/aluminum.

An alternative low pressure brazing approach is eutectic diffusion brazing in which a plated or vapor deposited alloy forms a bond between aluminun/aluminum interfaces. While this process is promising, strict control is required to minimize fiber degradation and interlaminar embrittlement.

Further development of these low pressure materials is required to increase their strength — which is currently between 20% and 30% below those reported for diffusion bonded boron/aluminum (Refs. 1 and 4) and to decrease the material costs before they can become competitive with current diffusion bonded components. The lower cost capital equipment cannot offset the higher material cost of between $50 and $100 per pound that is due to the requirement for the use of a coated filament. Finally, all major metal-matrix components successfully tested to date have been fabricated using high-pressure diffusion bonded material.

It has been shown that boron/aluminum can be successfully joined by soldering and brazing techniques. Soldering has been shown to not only produce high performance joints in boron/aluminum, but to reduce component fabrication costs. Considerable improvements can be made if a new soldering alloy, compatible with boron/aluminum, can be found for the temperature range of 950 to 1,000 F (783 to 810 K).

References

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