Resistance Diffusion Bonding Boron/Aluminum Composite to Titanium

New joining process allows low cost incorporation of B/Al into titanium aircraft and missile components for applications at temperatures to 600 F

BY M. S. HERSH

ABSTRACT. Resistance spot-diffusion produces sound joints between boron/aluminum and titanium using standard electrodes and production welding equipment. Mechanical properties of these joints were excellent over the temperature range of 70 to 600 F. Data presented includes static, fatigue, creep, and crippling strength.

Resistance diffusion bonding has been applied primarily to joining B/Al "hat" stiffeners to titanium web panels. Single stiffener/web test components have been tested to failure over the 70 to 600 F temperature range without failure of the spot joints. Large, multiple-stiffener panels have been fabricated and tested. To date, no premature joint failure has occurred in any of the more than 4,000 spots produced. In addition to stiffener/panel joints, stiffener splices have been produced successfully.

This new joining process allows low-cost incorporation of B/Al into titanium aircraft and missile components. The high modulus and light weight of the composite can be used in areas where its high cost is justified, without requiring its usage in less critical areas. The ability to withstand structural loads at 600 F allows application in areas heretofore considered out of the range of B/Al application.

Metric Conversion

1 in.	25.4 mm
1 lb	0.454 kg
1 lb/in.	175 N/m
1 psi	6.895 kN/m^2
1 ksi	6.895 MN/m^2
F (Temp.)	1.8 K — 460
1 mm	0.03937 in.
1 kg	2.204 lb
1 N/m	0.0057 lb/in.
1 kN/m^2	0.145 ksi
1 MN/m^2	0.145 ksi
K (Temp.)	(F + 460)/1.8

Introduction

Resistance spot joining of boron/aluminum (B/Al) composite to titanium was initially developed as a laboratory curiosity. Joints were produced by centering the weld nugget within the titanium and melting the aluminum matrix of the composite onto the hot (not molten) titanium surface. This joining process was developed and applied to a number of research programs (Ref. 1). Though relatively strong, the joints had two drawbacks: relatively wide scatter in strength from spot to spot, and frequent expulsion (spit) at the joint.

To improve joint quality and reliability, an attempt was made to produce joints without melting the aluminum. This was accomplished by resistance diffusion bonding. Using standard electrodes and production resistance welding equipment, sound joints were produced. As before, a molten nugget centered in the titanium conducted heat into the aluminum matrix of the composite. However, the temperature of the aluminum was maintained near, but below, its melting temperature. Diffusion occurred producing a diffusion zone 5 to 10×10^{-6} in. thick. Mechanical properties were consistent and, of course, weld expulsion was practically eliminated. Because of slight variations in the B/Al sheet, the interface temperature occasionally exceeds the aluminum melting point and a slight amount of expulsion can occur.

Advantages of this type of joint over the molten aluminum joint include reduced expulsion, more reliability, joint uniformity, and improved fatigue properties.

Process Development

Development of the resistance diffusion bonding process was metallurgically controlled. The development proceeded until the desired microstructure was obtained, and then the mechanical properties of joints produced by that schedule were tested. The desired microstructure was a very thin diffusion zone, free of intermetallics, with no melting of the aluminum. The largest feasible joint was desired and it was hoped that a 3/8 in. diam joint was possible.

Schedule Development

Starting with the original molten aluminum schedule, three major changes were made. First, an electrode was changed. In the original schedule, heating of the aluminum matrix of the composite was desired, as was concentrating the heat, so that a nugget could be produced. A Class III, radiused-tip electrode was used. In

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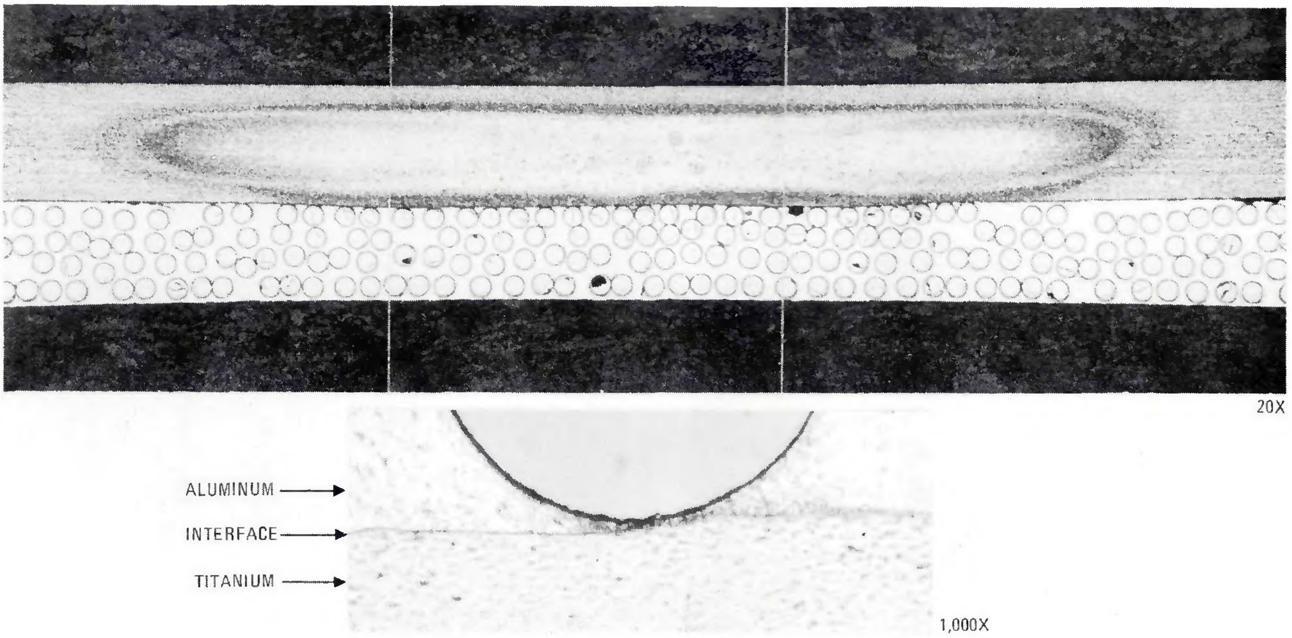
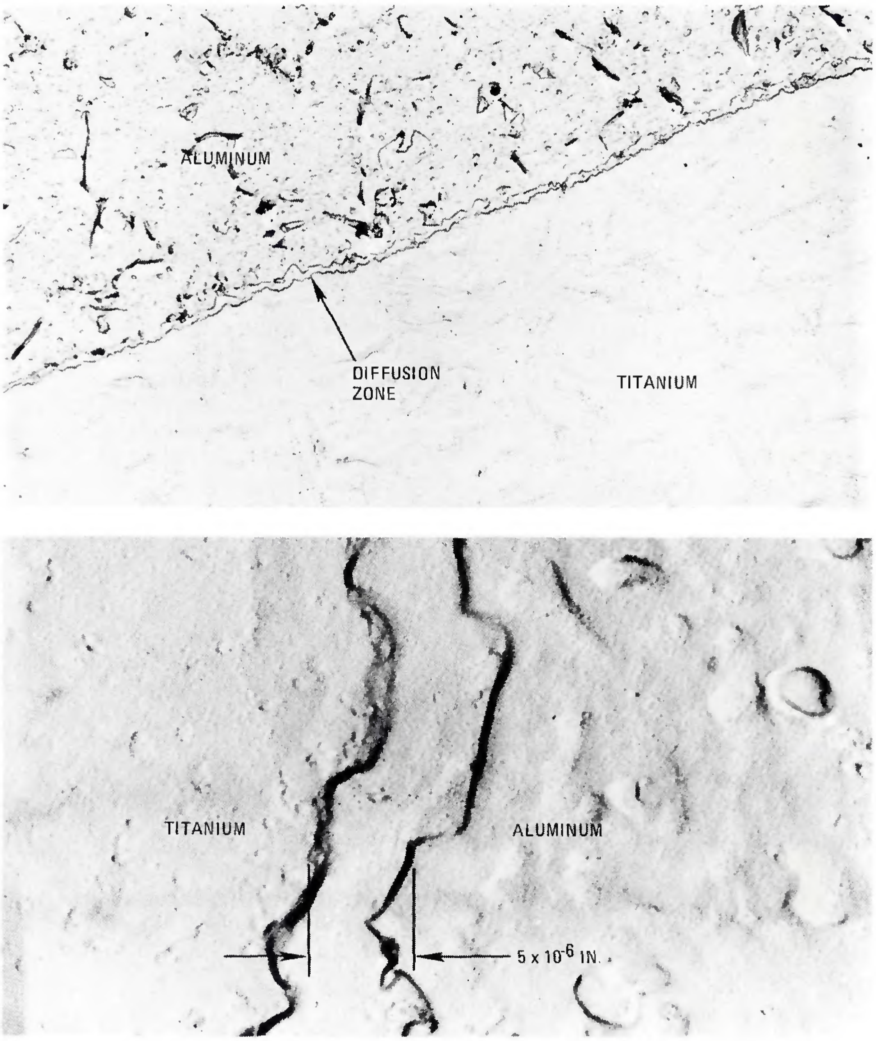


Fig. 1 — Resistance diffusion bond microstructure. Large molten nugget is visible in titanium. No melting of aluminum matrix has occurred and no aluminum-titanium interaction is visible under light microscope examination of prepared specimens. Both photos reduced 36%



ARROW IN UPPER PHOTOMICROGRAPH (3,500X MAGNIFICATION) INDICATES LOCATION OF LOWER PHOTOMICROGRAPH.

Fig. 2 — Diffusion zone in resistance diffusion bond. No melting of composite matrix has occurred

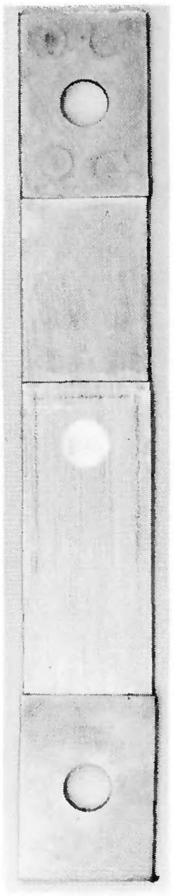
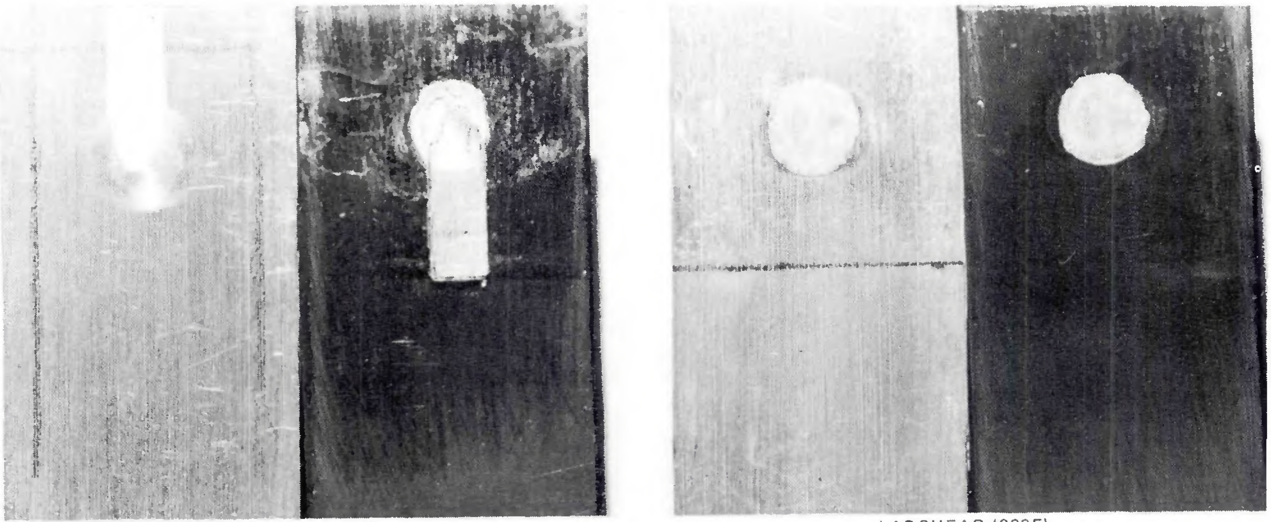


Fig. 3 — Boron/aluminum-titanium diffusion-bonded fatigue or creep specimen


NET TENSION (70F)

LAP SHEAR (600F)

Fig. 4 — Failed diffusion-bonded specimens

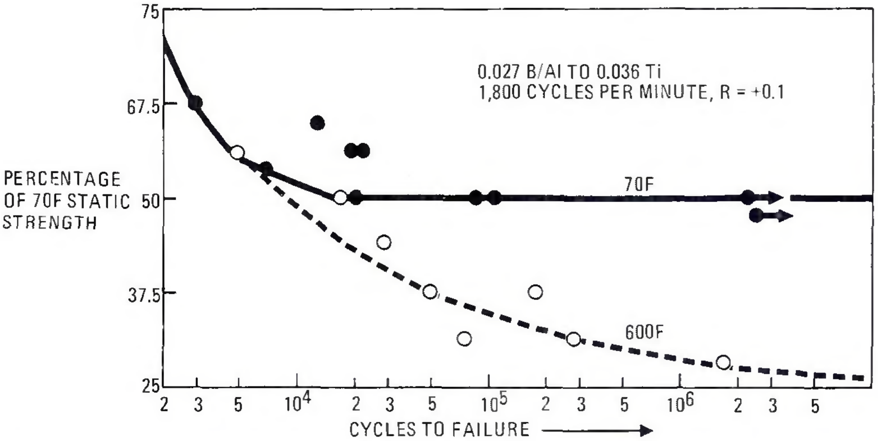


Fig. 5 — Fatigue strength of B/Al resistance diffusion-bonded to titanium

the diffusion bond schedule, a Class I, flat-tip electrode was used, reducing the direct heating of the B/Al, but also significantly reducing contact pressure. This change was the first step in the attempt to heat the B/Al, as much as possible, by conduction from the titanium. Conduction heating is more controllable and has a much lower probability of melting the aluminum.

Second, the pressure was increased. In the original schedule the forge pressure (about 2,000 pounds) did not initiate until the end of the weld. It was primarily a means of stopping nugget growth and of eliminating interface voids. In the diffusion bond schedule, the weld pressure (about 1,100 pounds) was used only for the first impulse — to get some interface temperature rise. The forge pressure was used throughout the rest of the bonding cycle to insure intimate contact over a large area. Another result of these two changes was to greatly reduce the weld heat input, a function of the interface resistances.

The third change followed directly from the first two changes. The weld heat input was raised by increasing both phase shift (weld current) and number of impulses. The geometric constraints resulted in a large proportion of the welding energy being used to heat the titanium. Heat input parameters were optimized for the largest joint area, without any occurrence of melting.

Metallurgical Examination

It is always exciting to see a new process being developed; resistance diffusion bonding of B/Al to titanium was no exception. As the analysis predicted, a macro examination of the joint indicates a molten nugget within the titanium, but no apparent effect upon the aluminum matrix of the composite (Fig. 1, top). Even at high optical magnification, no aluminum-titanium interaction is visible (Fig. 1, bottom). The nugget diameter was 0.320 in. — not as high as hoped for, but sufficient to carry a large load. Finally, with the help of the electron microscope, the diffusion zone became evident (Fig. 2). At very high magnification, an inclusion-free diffusion zone of 5×10^{-6} in. is clearly visible.

Mechanical Properties

Static, fatigue, and creep tests were performed to determine if resistance diffusion bonding was capable of structural application from 70 to 600 F. Figure 3 shows the configuration of the creep and fatigue specimens. The static specimens had no doublers and were tested with vise grips. All specimens tested at 70 and 250 F failed at the spot in net tension (Fig. 4, left). The specimens tested at 600 F failed in shear (Fig. 4, right).

The static lap shear strength at 70 and 250 F exceeds 50% of the base metal strength, with more than 80% of the 70 F strength remaining at 600 F (Table 1). At 600 F, as shown in Table 2, considerable creep does occur, but 200 lb per spot can be sustained for more than 300 hr. The fatigue test results (Fig. 5) were the most exceptional. At 70 F, a load equivalent to 50% of the static strength can be sustained indefinitely. At 600 F, creep reduces the long life load-carrying capability. The B/Al-Ti diffusion bond is structurally usable (50% of 70 F strength) for more than 10^6 cycles.

Subelement Specimens

Crippling Specimens. Six 600 F crippling specimens were tested. The three with 0.027 in. thick B/Al hats failed at an average load of more than 5,000 lb. The three with 0.034 in. thick

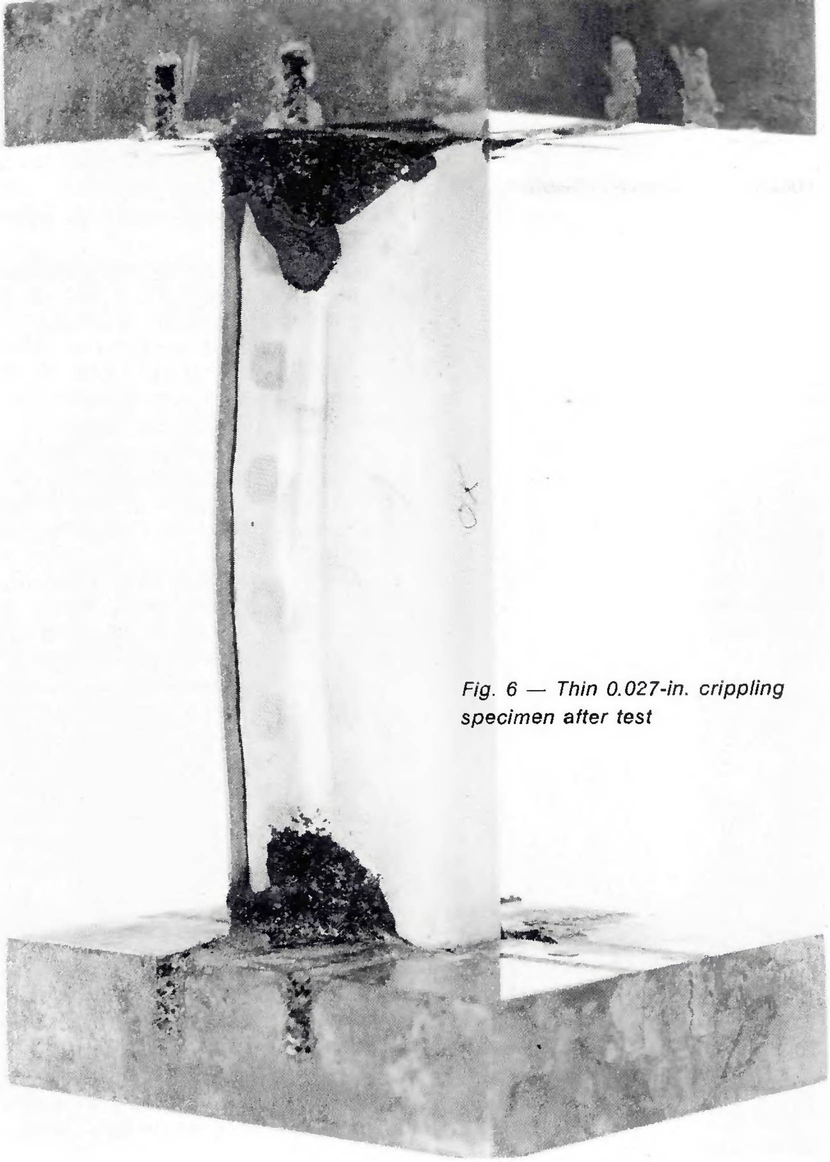


Fig. 6 — *Thin 0.027-in. crippling specimen after test*

Fig. 7 — *Compression stringer-splice specimen before testing*

Table 1 — Average Shear Strength of Resistance Diffusion-Bonded B/Al to Titanium (0.030 UD B/Al, 0.036 Ti)[a]

Test temp, F	Failure stress, ksi
70	105
250	120
600	85

(a) B/Al F_{tu} = 200 ksi; area based upon nugget diameter (0.32 in.) × thickness

Table 2 — Average 600 F Creep Strength of Resistance Diffusion-Bonded B/Al to Titanium (0.027 UD B/Al, 0.036 Ti)

Test load, lb	Hours to failure
400	1
300	19
250	78
200	320

B/Al hats failed at an average load of almost 8,000 lb. Figure 6 shows a typical specimen after testing.

Splice Specimens. The most complex subelement specimens fabricated were two stringer-splice tension and two stringer-splice compression specimens.

The splice specimens were welded without any tools or fixtures, in the following sequence:

1. Titanium hat splice to the top of the B/Al hat
2. Angle doublers to the outside of the B/Al hat; side spots first, flange spots second
3. B/Al hats to titanium skin

Weld schedules used for the splice specimens were very similar, except for the electrodes and holders used against the B/Al hat. The schedules used 14 to 16 weld impulses of 8 cycles each (no preheat was used). Weld heat was 31 to 33% phase shift on a 100 kVA, a-c machine. Weld pressure of 1,125 lb was used for the first impulse, with a forge pressure of 2,100 lb for the rest of the weld time. The electrode used on the titanium side of all joints was Class I, full face, ⅝ in. diam with a 10 in. spherical tip radius.

Various electrodes were used on the B/Al side of the joints. The electrode used inside the hat for the top splice welds was Class I, ⅝ in. diam, ⅜ in. face, flat tip. The electrode used for the flange welds and for welding

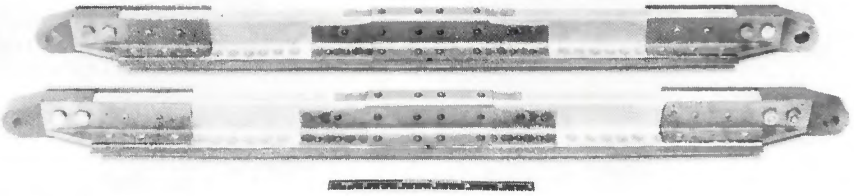


Fig. 8 — Tension stringer-splice specimen before testing

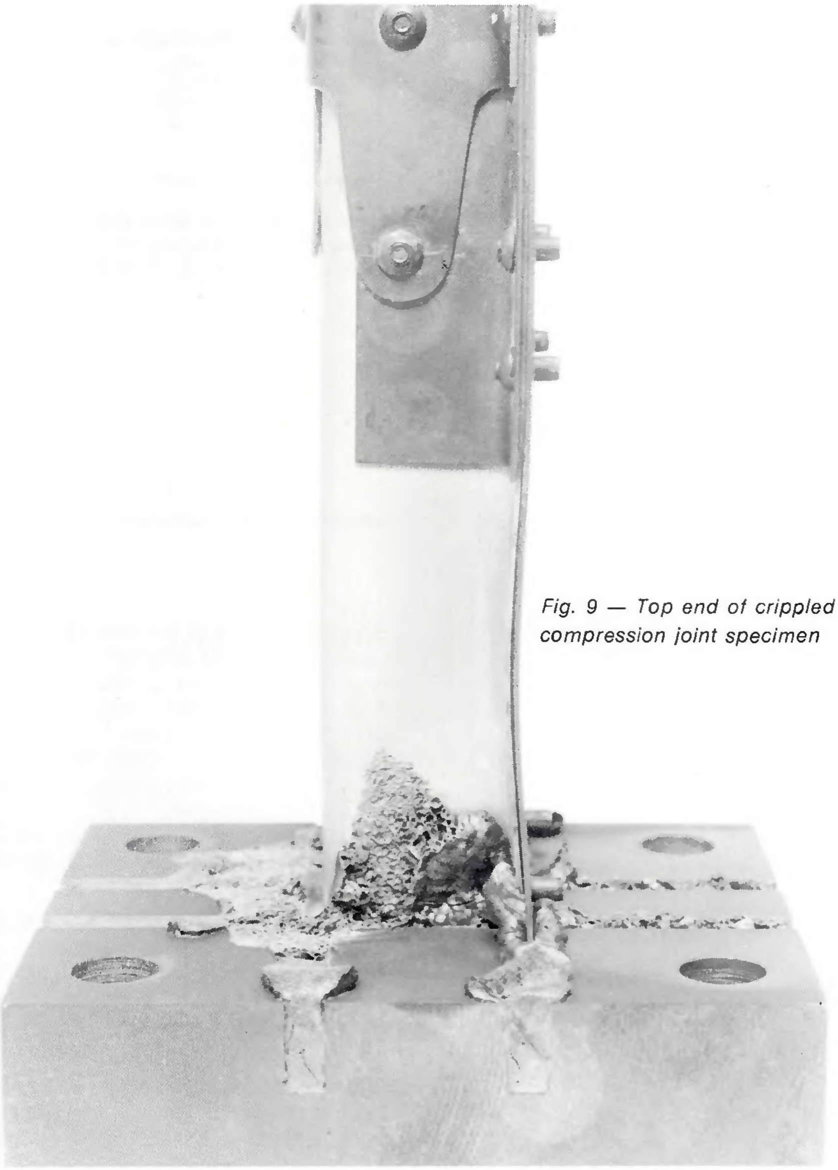


Fig. 9 — Top end of crippled compression joint specimen

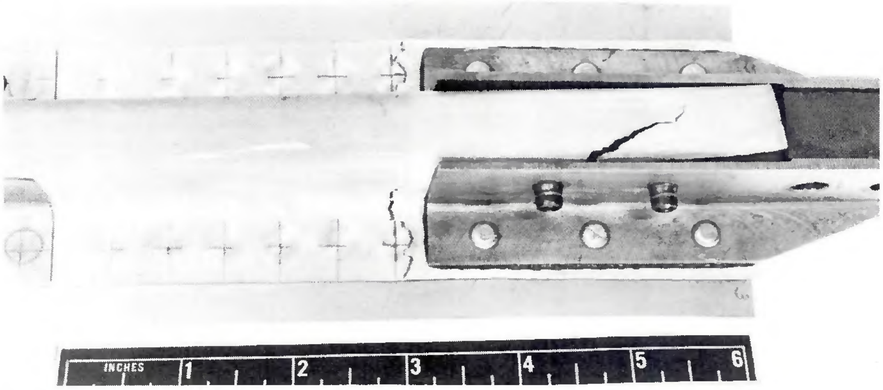


Fig. 10 — Closeup of failure area on first tension splice specimen

the hats to the titanium skin was similar, except that the former had a ½ in. face and the latter a ⅝ in. face. For the welds on the side of the hats, a ½ in. diam, flat, Class I button tip was used in a specially modified offset holder.

The splice specimens were welded without event (see Figs. 7 and 8). A few joints had slight aluminum expulsion. Spot location on the hat splice was difficult to control. The setup screws were left in and, therefore, no alignment problems were encountered. The flange width on one specimen was shallow, resulting in a scalloped appearance of the flange edge after welding, but no splitting of the B/Al.

Splice Specimen Testing. The compression specimens were tested at 600 F. After premature failure of the first specimen, due to overheating the second specimen crippled at a load of 7,835 lb. The failure was due to crippling of the stringer and skin adjacent to the splice area (Fig. 9). There was no evidence of failure in the joint area. The load of 7,835 lb achieved on the second test indicates that the joint design is adequate for the purpose intended.

Tension splice specimens were tested at ambient temperature (70 F). The end fittings of the specimens were attached to clevises on pull rods attached to the table and head of a tensile machine.

Ultimate loads achieved for the two specimens were 18,230 and 21,490 lb, which compares favorably with a design ultimate load of 11,100 lb — corresponding to a tension load intensity of 3,660 lb per in.

The first specimen failed in the load introduction area with no apparent failure in the splice area. Figure 10 shows the tension failure across the spot welds adjacent to the load introduction fitting. The second specimen was tested in a similar manner and failed in a similar manner (Fig. 11). Failure in this specimen initiated at the end fitting at a load of 20,800 lb. The failure of the hat section at the edge of the splice doubler, through the spot welds, occurred at a load of 21,490 lb. The average stress in the boron/aluminum at this load was approximately 110,000 psi without considering peaking due to stress concentrations at the welds or due to bending induced by the end failure.

Compression Panel Fabrication

Compression panels were welded using a wooden box fixture. The welding was performed in the following sequence:

1. Working from the center stringers outboard, join the center seven spots in each row.

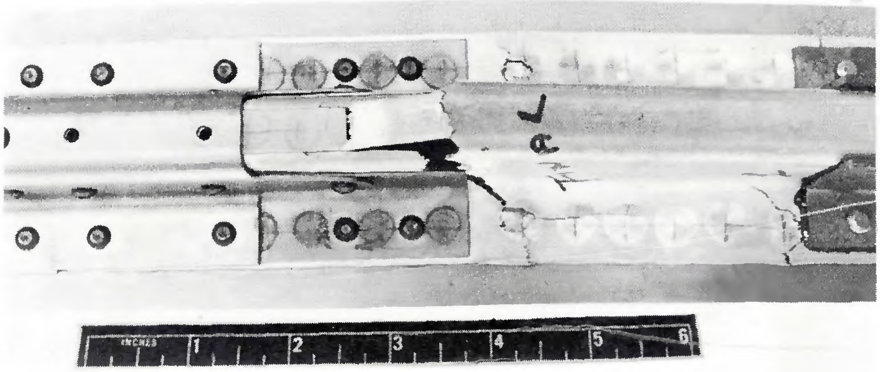


Fig. 11 — Closeup of failure area of second tension splice specimen

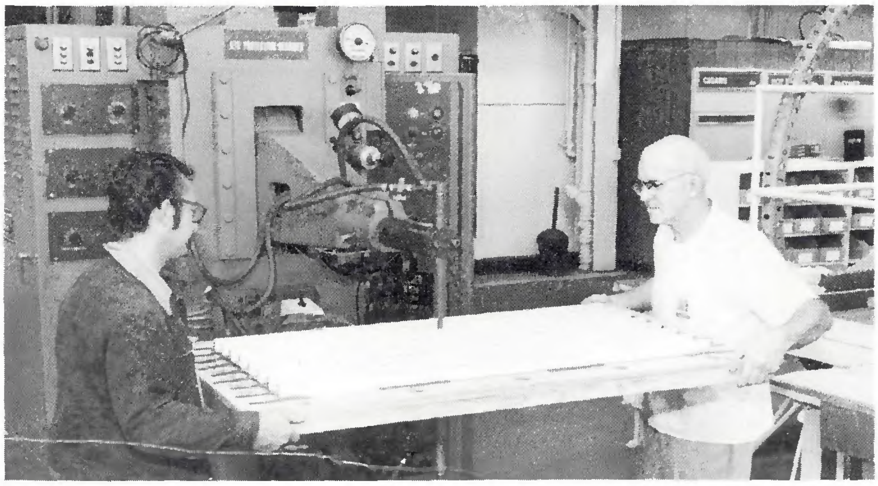


Fig. 13 — B/Al compression panel weld setup. The panel is allowed to rest on the lower electrode to illustrate panel curvature in the relaxed position. During welding, the fixture is raised to remove weight from the lower welding electrode

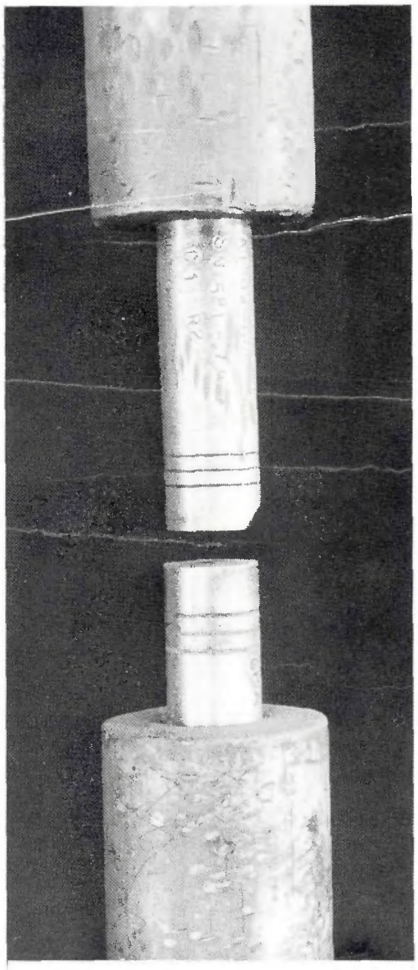


Fig. 12 — Electrodes used to spot join the B/Al-Ti compression panel. (Note that top electrode is beveled to clear B/Al hat radii)

2. Working from the center stringers outboard, join 20 spots from the middle outward, alternating welding direction.
3. Working from the center stringers outboard, join the remaining spots in each row.

Welding Schedule. The welding sequence was selected to minimize distortion. The sequence was varied from the sequence described above only to minimize distortion. The weld schedule used 18 impulses, each consisting of four cycles of preheat and eight cycles of weld heat (21% phase shift on a 150 kVA, a-c machine). Weld pressure of 1,150 lb was used for only the first impulse, with a forge pressure of 2,150 lb used for the rest of the weld time. Full face, ⅝ in. diam, Class I electrodes were used. The electrode used against the titanium was machined to a 10 in. spherical radius. The electrode used against the B/Al hat was machined flat and modified, as shown in Fig. 12.

The weld schedule development criterion was a failure of the composite in tension at the edge of a single spot joint. The average failure load was approximately 1,000 lb for more than 40 specimens tested during development, setup, and in-process checks. The lowest value recorded was 820 lb.

Panel Welding. The first panel welded had expulsion of more than 80% of the spots. This was attributed to failure to clean the titanium sheet adequately. The titanium sheet was properly cleaned for the second panel and the frequency of expulsion was significantly reduced. The first panel was joined using the wooden box fixture to support the panel, but without any clamps. The fixture was pushed against the panel for each weld to keep the panel weight off the bottom electrode. This aids in reducing distortion. Figure 13 illustrates the panel weld setup.

The first panel was welded without incident, but had a slight bow in both directions; the center of the panel, when lying hat side up, raised approximately 0.25 in. Figures 14 and 15 show the first panel, as welded. The 1,176 spot impressions were bright and shiny on the B/Al side, and ringed with oxide on the titanium side. Spot uniformity was excellent.

The first set of spots on the second panel, seven per stringer, was completed without incident (Fig. 16). During joining of the next set of spots, distortion and twisting began to occur. Welding was stopped and the panel clamped to the fixture at 16 locations. The welding then proceeded in a "work-out-the-bulges" sequence, placing spots at locations that minimized or reduced the apparent distortion. The resultant panel had a slight twist and bow, but few or no ripples or waves in the titanium skin.

Warpage and Straightening. Slight warpage of the titanium sheet was apparent on both panels after welding. This was attributed to the shrinking effect of the multitude of welds used to join the stringers to the sheet. The warpage was primarily a curvature in the transverse direction; however, a small longitudinal bowing was also evident. The second panel also displayed a small amount of torsional warpage.

The panels were creep-straightened during bonding of the test fixture end fittings. There was no apparent transverse bow or twist in either panel after the bonding operation, and only a slight longitudinal bow (0.040 in. measured at the center when supported on a flat plate).

Nondestructive Evaluation. Nonde-

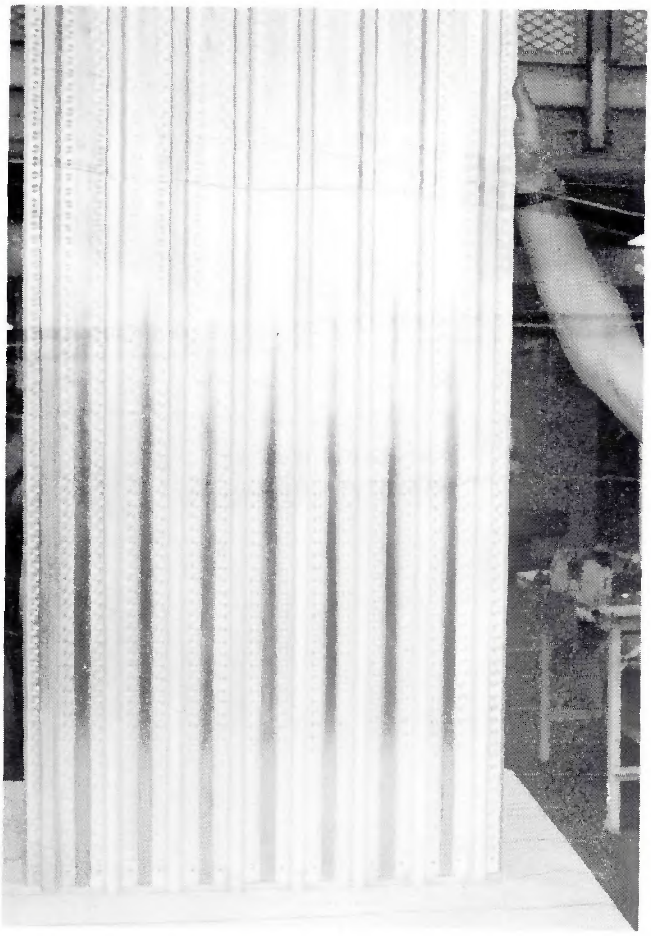


Fig. 14 — Front side of B/Al-Ti compression panel

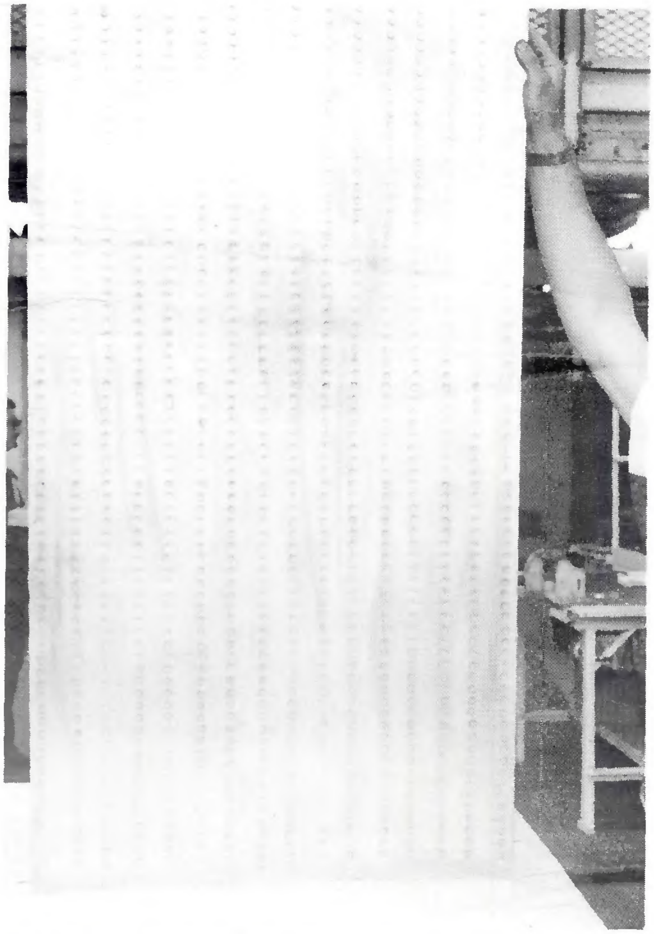


Fig. 15 — Rear side of B/Al-Ti compression panel

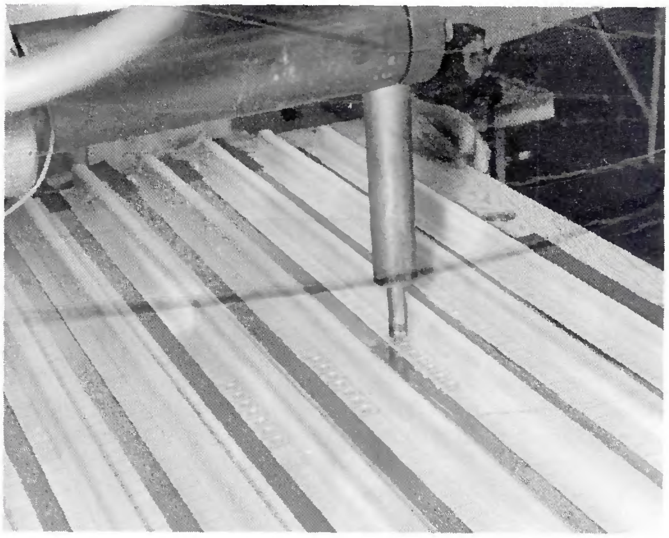


Fig. 16 — Resistance spot joining B/Al compression panel

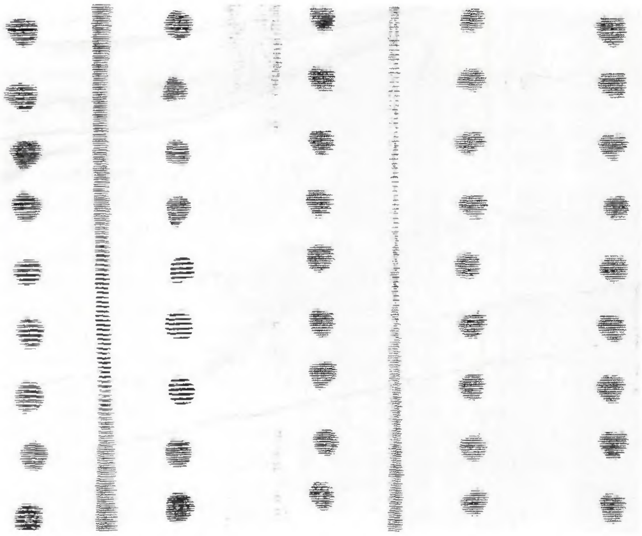


Fig. 17 — Typical B/Al compression panel C-scan

structive evaluation of the second test panel was accomplished using ultrasonic C-scan. The methods used were established earlier in the program during inspection of the crippling specimens. Figure 17 is a section of the C-scan record for the panel tested. It shows a portion of three stringers near the midpoint between the panel ends. The welds shown in this section of the scan are typical of those throughout the entire panel.

Acknowledgment

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Reference

1. Hersh, M.S., "Versatility of Resistance Welding Machines for Joining Boron/Aluminum Composites," *Welding Journal* 51 (9), 1972, pp. 626 to 632.