Resistance Spot Welding of Metal Matrix Composite

Continuing effort in nondestructive testing, procedure development, and joint evaluation significantly broadens the scope of resistance spot welding aluminum-boron composites

BY MICHAEL S. HERSH

ABSTRACT. This paper is a continuation of "Resistance Welding of Metal Matrix Composites" as published in the Welding Research Supplement during September 1968. The quality and strength of spotwelds is greatly affected by the quality of the composite sheets prior to joining. Panels are radiographed and ultrasonically C-scanned to determine material quality. The effectiveness of nondestructive testing and the correlation of these data to resultant spot weld quality is discussed, as well as radiography, ultrasonic inspection, and localized micro-resistance measurements. These three inspection methods can be combined to characterize the internal composite structure. Broken filaments, disbonds, variations in local filament density, and combinations of these can be discerned.

The bulk of the data presented is for one or more layers of 0.020 in. thick, 50 v/o boron unidirectionally reinforced 6061 aluminum matrix (Al-B), spot welded 0.020 in. thick, 2024-T3 aluminum alloy. For simple two-layer welds (Al-B to Al), a new schedule was required as the solidus temperature of 2024 is approximately 150° F lower than that of 6061 aluminum. Therefore, when welding 2024 to 6061 matrix composite the nugget fusion will occur at a temperature at which the 2024 is more fluid than the 6061. This requires a significant reduction of the weld and forge pressures to prevent expulsion. Concomitantly, weld heat must also be reduced to prevent gross melting of the 2024 alloy. This results in a smaller weld nugget (than would be typical for the 6061 alloy welded to 6061 matrix composite) and reduced cross-tension strength.

When the 2024 aluminum was sandwiched between two sheets of composite, the effect of differences in melting points could be adequately compensated for by lowering the heat and pressure and increasing the forge delay. Spot welding of another sheet of Al-B composite to a Al-B/Al/Al-B buildup resulted in a much larger spot diameter (0.350 in. vs. 0.220 in.), an increase in lap shear strength, and increased indentation.

Results of lap shear tests of silicon carbide-coated boron-reinforced aluminum are included. The effect of welding parameters on weld nugget strength and size are illustrated with 0.024 in. 45 v/o, ± 45 deg to load axis, cross-ply reinforced Al-B composite.

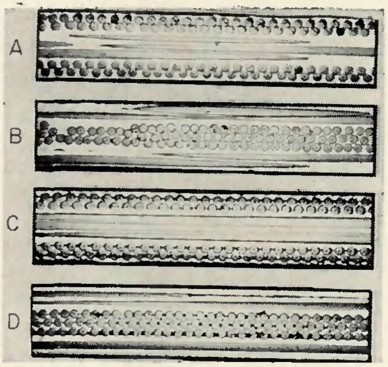
Introduction

In the year since this author's first paper on resistance welding of composites[1] considerable effort has been expended on development of boron filament-reinforced aluminum matrix composites (Al-B), application of this material, and joining of composites. At least 50 papers have been published dealing with metal matrix composites in the last year, but almost nothing has been published about resistance spot welding of composites.

Table 1—Effectiveness of Nondestructive Testing (NDT) on Aluminum-Boron Panel Defect Determination

Composite material condition	Defect (abnormal response) indication from the following nondestructive test: Radiography	Ultrasonic C-scan	Micro-resistance	Typical structure[a]
Sound				A
Broken[b] filaments	X			Not shown
Missing[c] filaments	X	X		B
Disbond		X	X	C
Disbond and missing filaments	X	X	X	D

[a] Typical structures corresponding to letter designations are shown below:



[b] Or displaced.

[c] Or extra filaments which cause local variation in volume fraction.

This indicates either that proper use of this excellent joining process for metal matrix composites is not being fully utilized or that others are not publishing their data. Resistance welding was successfully employed on the Air Force Program[2] described in the above referenced paper to fabricate a 5 ft diameter adapter, and considerable effort in this area is continuing. This paper discusses the value of nondestructive testing in evaluation of material to be welded and its effect on welding; development of welding schedules for the material combinations evaluated during the past year; state-of-the-art capability of resistance welding Al-B composites; and anticipated future direction of resistance welding composites.

Use of NDT for Resistance Spot Welding

The weldability of diffusion-bonded Al-B sheets is significantly affected by the quality of the interfoil bonding.[1] Nondestructive testing, therefore, is most beneficial in determining the quality of the sheets. Three techniques used at Convair are radiography, ultrasonic inspection, and—most recently—micro-resistance measurements.

The X-ray absorption difference between tungsten (atomic number 74) and aluminum (13) makes radiography feasible for detecting variation in boron-reinforced aluminum matrix composites. The individual half-mil diameter tungsten cores upon which the boron is deposited are distinguishable on the radiographs even in multi-layer material. Alignment, spacing, and integrity of the tungsten cores conveys information about the boron which may or may not be visible on the

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radiograph.[3]

One of the more useful techniques of testing thin materials for defects aligned parallel to the principal surfaces is the through-transmission method of ultrasonic inspection. A variation of this method is a single-transducer, reflector-plate technique, where the ultrasonic energy transmitted through the specimen is returned to the transduced from a smooth reflector. If disbonds are present, reflection of sound at the interfaces results in less transmitted energy. The resultant is readily detected as a decrease in the strength (amplitude) of the reflected signal. A C-scan recorder is mechanically linked to the system to produce a series of line scans synchronized with the movement of the test transducer (or test specimen) and provides a full-scale plan view of the test object showing defects in either black or white or variable shades of grey.[3]

By applying a low current through an Al-B sheet clamped between the electrodes of a resistance welding machine (a convenient way of getting good mechanical contacts) the through resistance of a local area can be qualitatively measured. With only a small amount of calibration, disbonds in the composite can be readily determined. These three NDT methods used together can discriminate between the five material conditions, found in A1-B sheet, which are of interest—Table 1. It should be noted that some qualitative evaluation of the severity of disbond is also available with the ultrasonic and resistance measurements.

Table 2—Correlation Between Composite Quality (As Determined by Ultrasonic C-Scan) and Spot Weld Expulsion

Relative quality of panel at spot weld location	Spot weld quality — Good spot	Slight splitting	Severe splitting
Sound material	11	1	0
Slight disbond	2	3	0
Poorly bonded	2	0	3

Anderson and DeLacy[3] state that: "Of the various NDT applied to composites, radiographic and ultrasonic tests have proven most beneficial so far. However, the sensitivity of tests must be relatively high, approaching current state-of-art thresholds. At these very high sensitivities, the complicated substructures of composite material stand out as noise. Methods of noise suppression and image enhancement are highly desirable, perhaps essential.

"Whatever the methods of NDT which prove most effective, data analysis and data display techniques need immediate attention. Computer and other mechanical/electronic devices should be integrated with NDT test and inspection equipment."

A small continuing effort is in progress to correlate effect of material condition on spot welding. To date, results have been obtained (see Table 2 and Fig. 1) which correlate C-scan quality indication and spot weld expulsion.

Nondestructive testing has only limited usefulness in evaluating spot weld quality. Radiography is the primary postweld inspection method used, and it clearly indicates expulsion and broken filaments.[1] Expulsion, by far the most common defect, is evident to the welder during spot welding, and broken filaments almost never occur unless the expulsion is very severe or the electrode indentation is excessive.

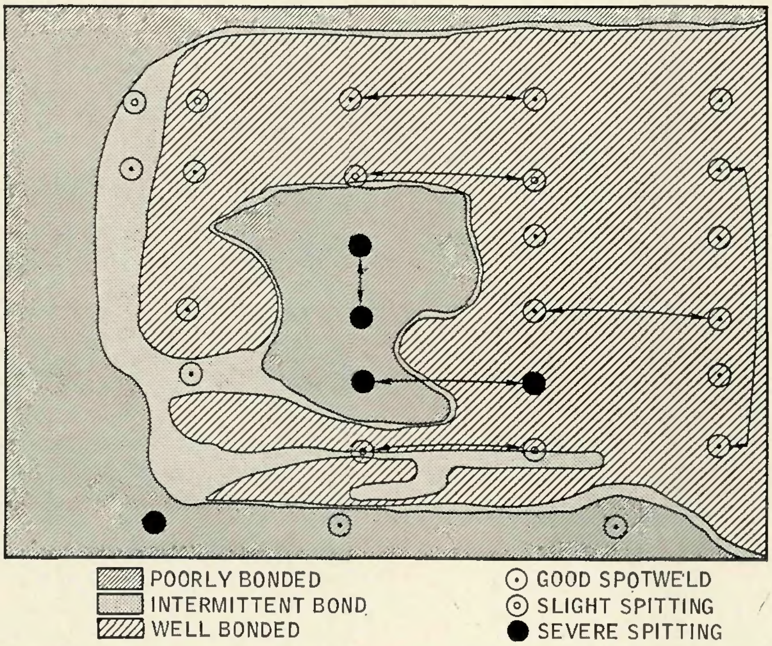


Fig. 1—Relative composite quality (per ultrasonic C-scan) and spot weld quality

Metallography is a most important tool in evaluating resistance spot welds. A particular problem of metal matrix composites is that quickly prepared macro specimens on the welding shop floor are not possible. To prepare a specimen, composites require mounting, careful polishing, and etching. This cost and delay (4 to 6 manhours) hampers spot welding development.[4]

Resistance Spot Welding Schedules

A 6 by 18 by 1 in. typical wing span segment (spar beam) was fabricated using A1-B composite.[4] Resistance spot welding was the primary joining method for this structure shown in Fig. 2. All of the composite material used in the spar beam was four-ply, 0.020 in. unidirectionally-reinforced (UD) $50\ ^{v}/_{o}$ Al-B (some of the weld development was performed in 5-ply, 0.025 in. UD, $50\ ^{v}/_{o}$ Al-B). The web was 0.020 in. 2024-T3 aluminum. There are three basic weld joints in the beam; they are:

1. Composite to aluminum.

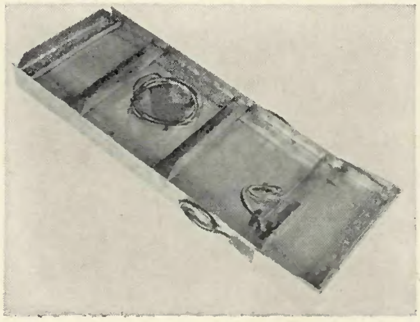


Fig. 2—Spar beam, strain gage locations and general configuration of the 6 by 18 by 1 in. beam

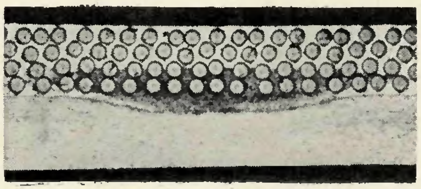


Fig. 3—Spot weld cross section 20 mil Al-B to 20 mil 2024-T3 Al. The nugget is off center due to the differences in conductivity between Al-B and Al, even though an extreme difference in electrode composition and tip radius was used. X37 (reduced 13% on reproduction)

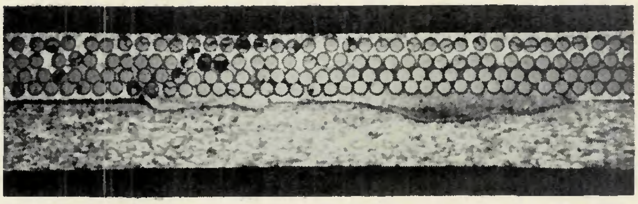


Fig. 4—Spot weld cross section 20 mil Al-B to 20 mil 2024-T3. This spot weld was made at the same schedule as the weld in Fig. 3. The change in micro structure is due to differences in resistivity in the composite. X37 (reduced 23% on reproduction)

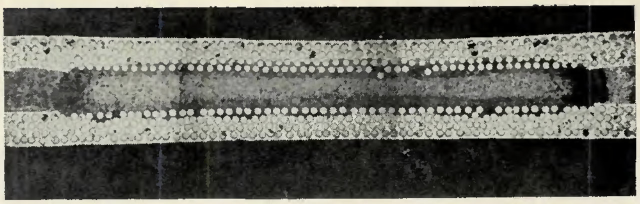


Fig. 5—Spot weld cross section 20 mil Al-B to 20 mil 2024-T3 Al to 20 mil Al-B. High weld and forge pressure resulted in 10% indentation, some distortion at the edge of the nugget and only about 30% penetration. X18 (reduced 23% on reproduction)

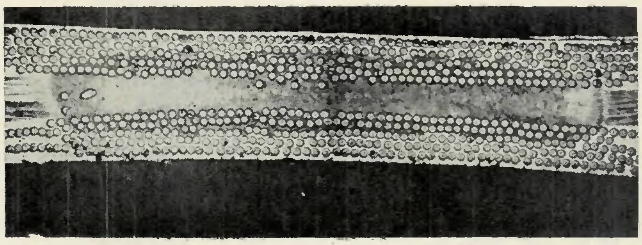


Fig. 6—Spot weld cross section 25 mil Al-B to 20 mil 2024-T3 Al to 25 mil Al-B. Moderate weld and forge pressure resulted in less than 5% indentation, no distortion and about 50% penetration. X21 (reduced 22% on reproduction)

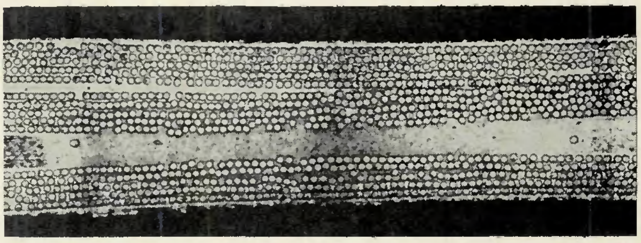
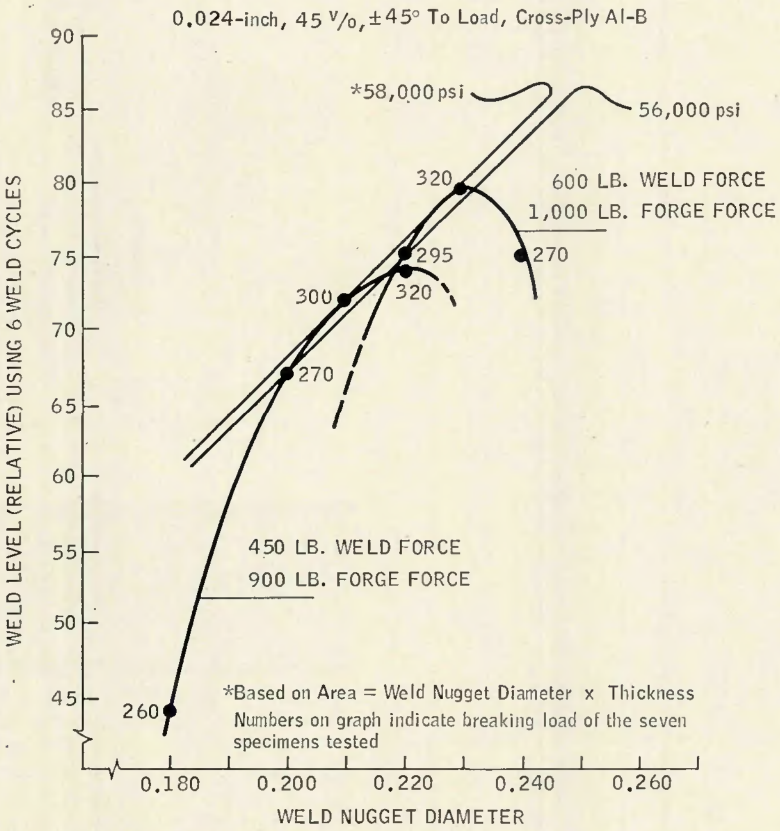


Fig. 7—Spot weld cross section 25 mil Al-B to 20 mil 2024-T3 Al to 25 mil Al-B to 25 mil Al-B. The joint shown was made as two separate spots; the first spot was Al-B to Al to Al-B with the last sheet of Al-B welded on, using the same schedule. X15 (reduced 22% on reproduction)

2. Composite to aluminum to composite.

3. Composite to previously spot welded joint 2 (above).

The spar beam was fabricated on an a-c, three-phase, 440 v, 150 kva machine with forge delay capability. The welding procedure developed for the composite to 2024 aluminum was significantly different from the schedule used to weld composite to 6061 aluminum.[5] The solidus temperature of 2024 is approximately 150° F lower than that of 6061 aluminum. Therefore, when welding 2024 to 6061 matrix composite, the nugget fusion will occur at a temperature at which the 2024 is more fluid than the 6061. This requires a significant reduction of the weld and forge pressures to prevent expulsion. Concomitantly, weld heat must also be reduced to prevent gross melting of the 2024 alloy. This results in a smaller weld nugget than would be typical for the 6061 alloy weld to 6061 matrix composite and reduced cross-tension strength.[4] The combination of Class I flat electrode on the composite side and Class III, 4 in. radius electrode on the aluminum side previously developed[1] was retained for this joint. Figures 3 and 4 show cross sections of these welds.



*Based on Area = Weld Nugget Diameter x Thickness
Numbers on graph indicate breaking load of the seven specimens tested

Fig. 8—Effect of heat input and weld pressure on weld nugget diameter and spot strength (0.024 in., 45 v/o, ± 45 deg to load, cross ply Al-B)

When the 2024 aluminum is sandwiched between two sheets of A1-B composite, there is no difficulty centering the weld nugget, but the high weld pressures normally used with 6061 aluminum result in excessive expulsion. When the heat input is sufficiently low (using high weld and forge pressures to eliminate expulsion), the indentation is excessive and only about 30% penetration results—Fig. 5. Reducing the weld and forge pressures to 900 and 1,850 lb, respectively, and adjusting the heat input results in 5% indentation and 50% penetration—Fig. 6.

The above described welding schedule is also used to spot weld a sheet of A1-B to the A1-B/A1/A1-B buildup. The resulting weld, shown in Fig. 7, was larger than the initial weld and resulted in higher spot strength.

A spot welding schedule was also developed for 0.030 in., 6-ply, 50 v/o unidirectionally-reinforced (UD), Al-Borsic (silicon-carbide coated boron filaments), made from plasma-sprayed tapes. It was the same schedule on the same machine used for 0.020 in. A1-B. The higher bulk resistance of the Al-Borsic, due to higher oxide content, results in the sufficiently higher heat input (I^2R heating) needed to weld the thicker material.

Table 3 lists spot welding mechanical properties, developed with the above described schedules; photographs of failed test specimens are also included.

A study of the effect of pressure and weld heat was performed on a three-phase, 100-kva, 60-amp, d-c spot welding machine with preheat and forge delay capability. The material was 0.024 in., 4-ply, ± 45 deg to test axis, cross-plied, 45 $^{v}/_{o}$ Al-B.

The welding and forge pressures, preheat, and welding cycles were varied as shown in Table 4 with the results listed. Forge delay was 0.8 cycles less than weld time and initiated at the beginning of the weld cycle. Weld heat levels are a percentage of the heat setting of 4 volts-secondary. (4.68 v machine capacity). Six-inch radius, Class I electrodes were used. Figure 8 illustrates these results and indicates how a welding schedule for A1-B can be optimized.

State-of-the-Art Capability

The state-of-the-art of joining composites, and particularly resistance spot welding Al-B composites, is steadily advancing. Most of this work has been to increase the scope of the process and the quality of the joints. Little has been done to study joint design, weld failure mechanisms, or dynamic properties of spotwelded structural joints.

During the fabrication of the spar beam, spot welding was used to repair fabrication damage. The sound portions of two damaged uprights (angle stiffeners) were spliced together to produce a structurally sound upright—Fig. 9. Up to four sheets and up to a total buildup of 0.160 in. has been successfully spot welded. A1-B composite has been successfully spotwelded to a number of aluminum alloys and aluminum matrix composite with all standard filament reinforcements. Joint strengths have been high and the joint efficiency has approached 75% where the filaments are cross-plied or at an angle to the test direction.

Research work is in progress to study the effects of:

1. Heat treating the composite matrix.
2. Transverse reinforcements with ductile filaments.
3. Spot joining composites to titanium alloys.
4. Varying the weld settings in relation to NDT quality indications.
5. Multiple spot weld patterns.
6. Spot welding through brazed joints.
7. Spot braze/welding on thick layups.

All of the above-listed studies have shown potential for future applications and are being considered for near-term application. No data are reportable to date on these studies because of incomplete data and/or proprietary/patent decisions.

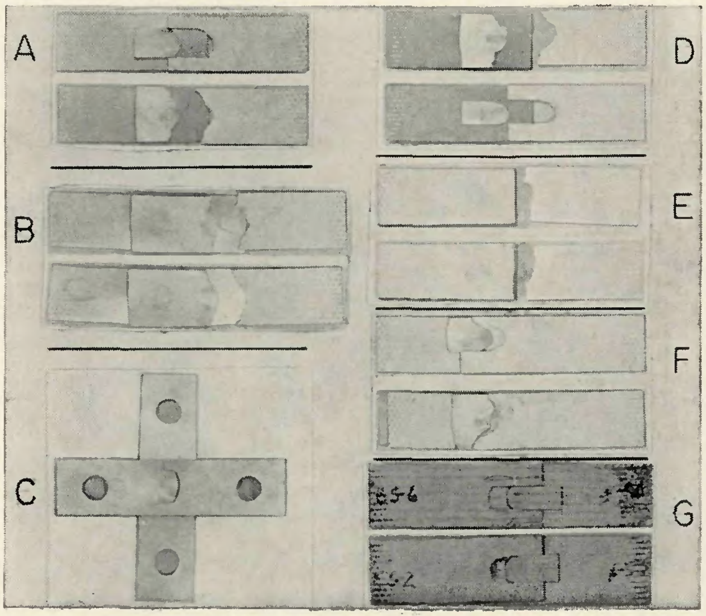
Future Direction of Spot Welding Composites

This author is surprised that resistance welding development has not kept pace with the development of metal matrix composites as a whole. Perhaps this is attributable to difficulties in the past associated with the sensitivity of spot welding to com-

Table 3—Spot Weld Mechanical Properties

Test	Test specimen materials	Failed test specimen[a]	Test results load, lb	Failure mode
Single spot lap shear	0.020 in. 50 v/o UD Al-B to 0.020 in. 2024-T3 Al	A	492 532 285[b] 560 520 510 Avg.=523	Net tension at edge of spot in Al-B composite
Double spot lap shear	0.020 in. 50 v/o UD Al-B to 0.020 in. 2024-T3 Al	B	770 735 900 830 Avg.=809	Net tension at edge of spot in Al-B nearest grips
Single spot cross tension	0.020 in. 50 v/o UD Al-B to 0.020 in. 2024-T3 Al	C	40 40 35 48 48 43 Avg.=42	Bending at edge of spot in Al-B composite
Single spot lap shear	0.020 in. 50 v/o UD Al-B to 0.020 in. 2024-T3 Al and 0.020 in. UD Al-B	D	635 640 593 606 Avg.=618	Net tension at edge of spot in top Al-B sheet
Single spot lap shear	0.020 in. 2024-T3 Al (in center) to 2 sheets of 0.020 in. 50 v/o UD Al-B	E	816 898 Avg.=857	Net tension at edge of spot in 2024-T3 Aluminum
Single spot lap shear	0.020 in. 50 v/o UD Al-B to 0.020 in. 50 v/o UD Al-B and 0.020 in. 2024-T3 Al and 0.020 in. UD Al-B	F	650 782 662 Avg.=698	Net tension at edge of spot in top Al-B sheet
Single spot lap shear	0.030 in. 50 v/o UD Al-Borsic to 0.030 in. 50 v/o UD Al-Borsic	G	560 884 660 800 818 676[c] 875 Avg.=753	Net tension at edge of spot in Al-Borsic

[a] Failed test specimens corresponding to letter designations are shown below:



[b] Sheared the weld nugget, not included in average.
[c] Sheared the weld nugget, included in average.

Table 4—Effect of Weld Parameters on Spot Weld Property. (0.024 in., 4-ply, ± 45 deg., CP, Al-B Composite)

Machine setting	Various schedules							
Weld pressure, lb	400	450	450	450	450	600	600	600
Forge pressure, lb	800	900	900	900	900	1,000	1,000	1,000
Preheat cycles	2	2	2	2	2	2	2	2
Preheat level, %	45	45	45	45	45	50	50	55
Weld cycles	6	4	6	6	6	6	6	6
Weld level, %	70	67	67	72	74	75	80	75
Results								
Expulsion	Slight	None	None	None	Moderate	None	None	Moderate
Spot diameter, in.	0.210	0.180	0.200	0.210	0.220	0.220	0.230	0.240
Lap shear load, lb	230	260	270	300	320	295	320	270

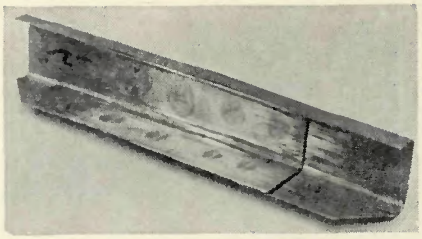


Fig. 9—Upright made from three segments of Al-B spot welded together; upright length is 5½ in.

posite material quality. If that is so, then the improvement in general composite quality which has occured in the last year should renew interest in this joining method. Certainly the results to date, taken as a whole, would indicate that resistance spot welding is an economical and efficient joining process.

Predictions of the future direction of resistance spot welding are affected by the optimism or pessimism of the predictor. This author chooses to be optimistic. Advances in understanding the process better and applying it in multi-row joints is foreseen. Fatigue property development should soon begin and corrosion testing of joints as well. Improvements in joint quality and strength will continue as well as studies of the effect of spot spacing on joint properties. Designers are slowly becoming aware of the capabilities of spot welding, and more test hardware will be fabricated using resistance welding.

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