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Material and Fabrication Development and Application Studies of Aluminum-Boron-Stainless Steel Composites

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The recent development of a new composite material with superior properties for structural applications is described. The development consisted of selection of matrix and filament materials, the fabrication of a number of composite panels qualification testing, evaluation of secondary fabrication methods and design application studies. It was demonstrated that the new composite material, aluminum-boron-stainless steel (A1-B-SS), could be made in various forms, shapes and sizes, that it possessed very desirable mechanical and physical properties, and that it could be satisfactorily cut, machined, formed and joined by a variety of methods. The potential weight savings (typically 30-45 percent)` and other attractive properties make the A1-B-SS composite particularly promising for a number of structural applications.

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J. L. CHRISTIAN

During the past four years, aluminum-boron (Al-B) composite material was developed (1,2)[1] and has been applied in various aerospace structures. Al-B possesses a number of very desirable properties (e.g. high shear strengths, good environmental properties, and ability to be formed and joined into useful hardware). However, Al-B is not competitive with other high strength, high modulus composite materials on a specific (density compensated) basis because of its low transverse tensile strength (15 ksi). This can be readily observed in the specific interaction curves shown in Fig.1. There are a number of possible ways in which the low transverse tensile strengths of Al-B can be improved. These include mechanical treatments, thermal treatments, cross-plying with boron or other high strength filaments (e.g. stainless steel), and combinations of the preceding. Each of these approaches were evaluated (3), and it was found that an aluminum-boron-stainless steel (Al-B-SS) composite material gave the most promising results. The following sections describe the development of the Al-B-SS composite material, and of primary and secondary fabrication processes and the results of design studies for the application of the Al-B-SS to various aerospace structures.

[1] Numbers in parentheses designate References at end of paper.

COMPOSITE MATERIALS DEVELOPMENT

Materials development consisted of: 1) the selection of matrix and filament materials, composite lay-ups and processing parameters; 2) the primary fabrication of a number of composite sheets and complex shapes, and 3) qualification and evaluation testing.

After considerable study, the selection of matrix and filament raw materials was made. Final selection consisted of 6061 aluminum for the matrix, boron (or, in some cases, silicon carbide coated boron) for the primary filament, and type AM-355 stainless-steel wire for the secondary filament. Type 6061 aluminum alloy was chosen for the matrix material because it is readily available in foil or plasma sprayed forms, its diffusion bonding parameters have been developed, and because it possesses attractive mechanical and physical properties. Boron was chosen for the primary filament for its high strength and modulus properties. AM-355 stainless steel wire was selected as a secondary (cross-plying) filament because of its high strength (475 ksi), availability in small diameter (0.002 in.), low cost and compatibility with the 6061 Al matrix and processing parameters.

Various lay-ups were evaluated. One of the most promising lay-ups consisted of 45 volume percent (v/o) of boron in the longitudinal (0 deg)

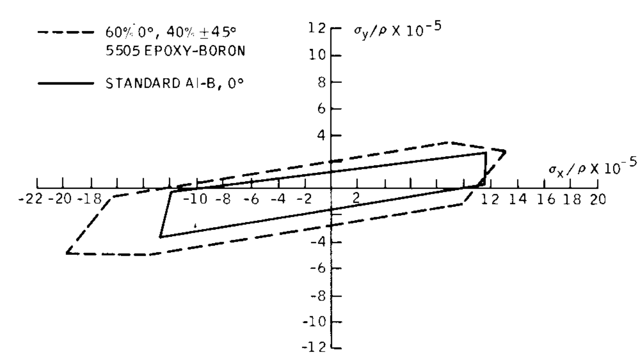

Fig.1 Specific interaction curves for epoxy-boron and standard Al-B composite materials

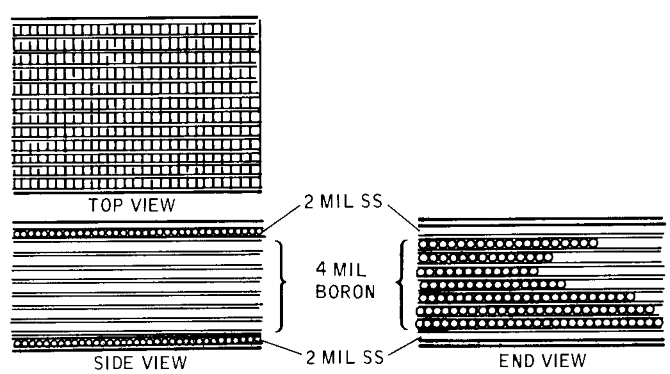

Fig.2 Schematic of lay-up of aluminum-45 v/o boron-5 v/o stainless-steel composite material

direction, and 5 v/o of stainless-steel wire in the transverse (90 deg) direction. It was found that placement of the stainless-steel wire on the surface (i.e., 2$^1/_2$ v/o on each face) resulted in considerable improvements in the handleability and secondary fabrication, particularly forming and joining, of the composite material. Although this particular lay-up, as shown schematically in Fig.2, is particularly attractive for a number of applications, it should be remembered that the Al-B-SS composite material can be "tailor made" to fit various structural requirements.

The primary fabrication of Al-B-SS composite material is accomplished by the diffusion bonding process consisting of pressing the composite lay-ups in an evacuated chamber under high temperatures and pressures (8000 psi and 900 F for 1 hr are typical processing parameters). The lay-ups may consist of alternating layers of aluminum foil and filaments (this type lay-up is normally used for the processing of flat sheet material), or it may consist of a lay-up of Al-B and Al-SS monolayer tapes. The latter type lay-up is typically used for the processing of complex shapes such as tubing, angles, tees, fittings, and complex contoured parts. Some typical examples are shown in Fig.3. The monolayer composite tapes are initially made by either a plasma spraying or diffusion bonding process.

A number of Al-B-SS composite sheets, as well as various other shapes, were fabricated. Nine of the composite sheets (ranging in size from 4 x 8 to 12 x 12 in.) were subjected to qualification and evaluation testing. This testing consisted of NDT, thickness measurements, v/o determinations, metallographic examinations and mechanical property testing. Nondestructive testing included both X-ray and ultrasonic C-scan evaluations [test methods are described in reference (4)]. The NDT results indicated generally well-bonded panels with good quality lay-up of the boron filaments and stainless-steel wire. Thickness measurements indicated excellent control of the primary processing with maximum deviations of ±0.0015 in. in nominal 0.040-in. thick panels. Volume percent determinations showed actual volume percentages of 40.9 to 45.4 boron and 5.0 to 6.2 stainless steel for the nominal Al-45 v/o boron-5 v/o stainless-steel composites. Metallographic examinations showed the Al-B-SS material to be well diffusion bonded with fairly good control of filament lay-up and spacing. A typical microstructure is shown in Fig.7.

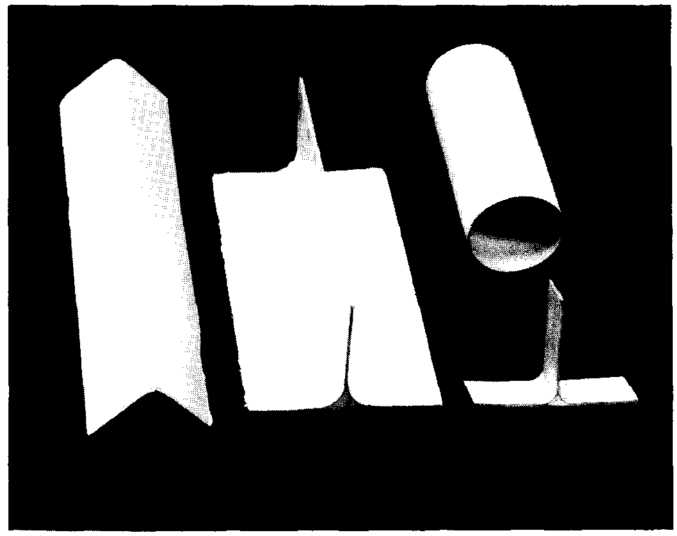

Fig.3 Examples of various complex shapes processed from composite tapes

Table 1 Mechanical Properties of Aluminum-Boron-Stainless Steel Composites (0.040 Inch Thick Sheet; Seven Layers of Boron at 0° and Two Layers of AM-355 Stainless Steel at 90°)

Composite Material				Long. Tensile		Trans. Tensile			Effective Shear
Matrix	Filament	v/o	Condition*	F_{tu}(KSI)	E(MSI)	F_{tu}(KSI)	F_{ty}(KSI)	E(MSI)	F_{su}(KSI)
6061 Al	Boron AM-355 Steel	35 5	F	124	22.4	41.9	19.1	11.5	24.2
			ST&A	123	23.3	41.2	29.3	13.9	22.6
6061 Al	Boron AM-355 Steel	45 5	F	167	29.7	35.8	18.3	17.9	19.3
			ST&A	159	31.3	32.7	24.0	19.4	22.4

* F = as fabricated
ST&A = solution treated (980°F, 30 min. W.Q.) and aged (350°F, 8 hrs.)

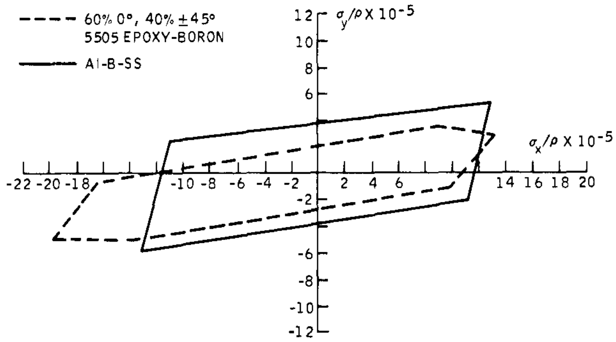

Fig.4 Specific interaction curves for epoxy-boron and Al-B-SS composite materials

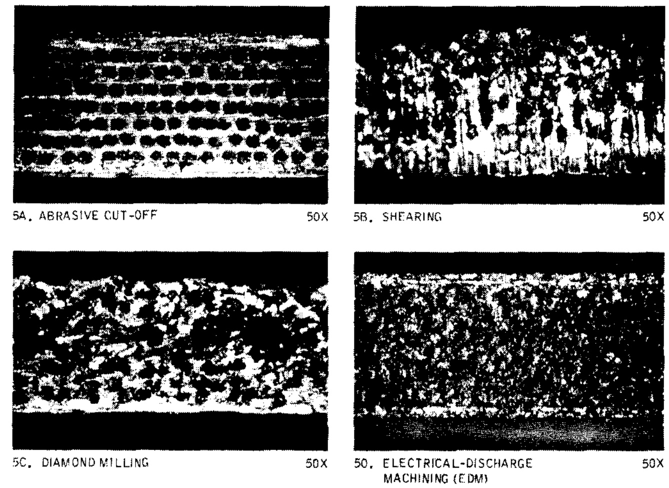

Fig.5 Typical edge finishes for various cutting and machining processes

Mechanical property testing consisted of the determination of ultimate tensile strength and modulus in the longitudinal direction (i.e. parallel with the boron filaments), tensile yield and ultimate strengths and modulus in the transverse direction, and an effective shear strength in the longitudinal direction. Tests were performed in the as-received (F) and solution treated and aged (ST&A) conditions, at room temperature. The test results (reported in Table 1) are averages of at least four and generally six to ten individual test points. A significant improvement of the transverse tensile strength as a result of adding the stainless-steel wire is evident. The mechanical properties of the as-received Al-45 v/o B-5 v/o SS composite material were used to compute the interaction curves shown in Fig.4. These curves show the distinct advantage of the Al-B-SS material as compared to epoxy-boron or standard Al-B composites. The test results given in Table 1 were used as typical values for the design application studies.

FABRICATION DEVELOPMENT

The development and evaluation of secondary fabrication processes (cutting, machining, forming, and joining) was performed on Al-B-SS composite sheet material. The procedure used was to evaluate those processing methods and techniques which were found to be most successful for fabricating standard Al-B composite material (1, 2, 5, 6). A number of successful methods were found for the cutting, machining, forming, and joining of the Al-B-SS composite material. In addition, it was also found that the addition of the stainless-steel wires improved the handleability (i.e. less material damage during shipping and shop fabrication), the formability, and joint properties as compared to the standard Al-B composite material.

Methods evaluated for cutting and machining of the Al-B-SS composite material included shearing, abrasive cut-off, electro-discharge machining, punching and milling, drilling and routing, using both high-speed steel tools and diamond coated tools. The same procedures and techniques that were used for the cutting and machining of Al-B, detailed in reference (2), were evaluated here. It was found that each of the preceding methods were successful, but resulted in varying degrees of edge smoothness and filament damage as can be seen from the photographs of typically prepared edges given in Fig.5. It was found that the SiC abrasive cut-off method produced the best edge (i.e. most smooth and least filament damage) followed by EDM, diamond drilling, milling and routing, and finally, by shearing and punching. For quite thin section sizes (0.020-in. thickness), the sheared or punched edge is relatively smooth; however, for thicker sections, a rougher edge results which may require a dressing or reaming operation.

Forming characteristics of the Al-B-SS sheet material were evaluated by roll forming and by brake bending, both performed at room temperature. The results indicated that the addition of the stainless-steel wires improves the ductility and formability of the Al-B composite material. Al-B-SS sheet (0.040-in. thickness) was successfully roll formed to a 12-in. radius parallel with the boron filaments, and a 1.5-in. radius (37.5 t) perpendicular to the boron filaments with no indication of broken filaments or surface cracking. Brake bending of 0.040-in. thick Al-B-SS sheet produced successful bends as low as 0.45-in. radius (11 t) transverse to the boron filaments. These bends were accomplished without the use of attached

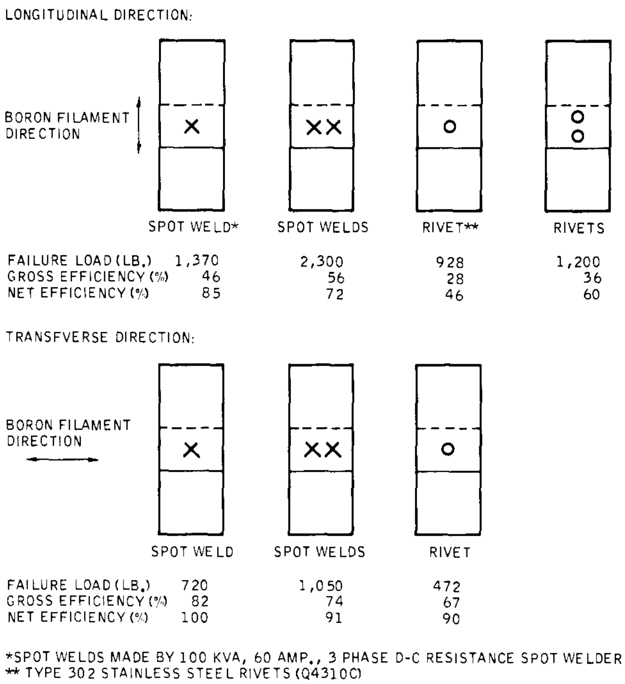

Fig.6 Typical strength properties of Al-B-SS composite joints (Al-45 v/o B-5 v/o SS, 0.040-in. thick)

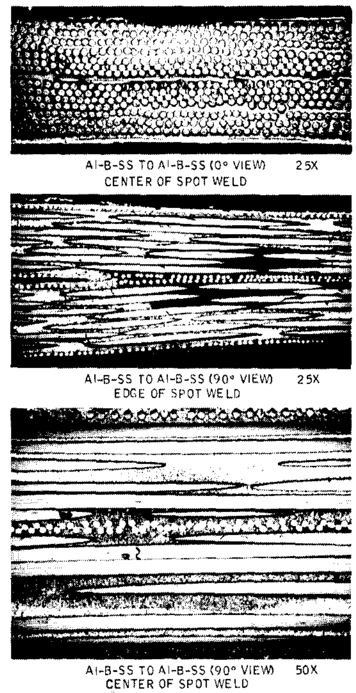

Fig.7 Photomicrographs of resistance spot welds

doublers or elevated temperatures. It was concluded that Al-B-SS can be successfully formed to meet most design and fabrication requirements, and that the use of selectively placed filament material for small radius bends and the build-up of Al-B and Al-SS tape materials for complex contoured parts should enable the widespread application of Al-B-SS composite material.

Joining evaluations consisted of resistance spot welding, riveting, brazing, adhesive bonding, and diffusion bonding. Each of these methods were successful in producing good quality, high strength joints. One of the most successful was resistance spot welding, which resulted in nearly 100 percent joint efficiencies for both the longitudinal and transverse directions of Al-B-SS sheet material (0.040-in. thickness) joined to itself. As can be seen from the test data reported in Fig.6, typical average values for the tensile shear strength of individual resistance spot welds are 1370 lb force for the longitudinal direction and 720 lb force for the transverse direction. This compares with about 1350 (long) and 200 (trans) pounds force/spot for standard Al-B composite material, and about 400 (long or trans) pounds force/spot for aluminum alloy sheet material of the same thickness. The spot welds were made by a 100 kva, 60 amp., three-phase dc resistance spot welder. Metallographic examinations were made on a number of spot welded samples. Typical microstructures are shown in the photomicrographs of Fig.7.

Several riveted joint configurations made from 1/8- and 3/16-in-dia, type 302 stainless-steel headed rivets were evaluated. Some of the typical results are presented in Fig.6. The tensile shear strength values compare favorably with values obtained on standard Al-B and Al-B with doublers (2, 5). The major drawback to rivets and other mechanical joints is the necessity of drilling a hole in the Al-B-SS which causes a discontinuity in the filaments and accordingly reduces the strength of the material. Other joining methods evaluated include brazing, adhesive bonding, and diffusion bonding. Al-B-SS sheet was successfully brazed to itself and to aluminum alloy sheet by aluminum dip brazing (at 1015 F for 3 min). Adhesive bonding of Al-B-SS to itself and to aluminum, titanium, and stainless steel was accomplished with HT-424 adhesive, cured for one hour at 350 F, and 25 psi gage pressure. Diffusion bonding of Al-B and Al-SS tape materials was accomplished in a high-pressure gas autoclave with a typical diffusion bonding cycle consisting of one hour at 900 F and 8000 psi pressure. Although no mechanical property tests were performed, visual observations and metallographic examinations indicated that good quality joints of Al-B-SS to itself and to other materials can be achieved by brazing, adhesive bonding, or diffusion bonding.

Table 2 Design Pay-Off Studies

Comparison of Structural Weights and Weight Savings for a

Material	Wing Box Weight (Arbitrary Units)	Wing Box % Savings	Longeron Weight (lbs.)	Longeron % Savings
Metal (Aluminum, Titanium)	100	-	44	-
Aluminum-Boron	85	15	31	30
Epoxy-Graphite	82	18		
Epoxy-Boron	78	22		
Aluminum-Boron-Stainless Steel	66	34	25	44

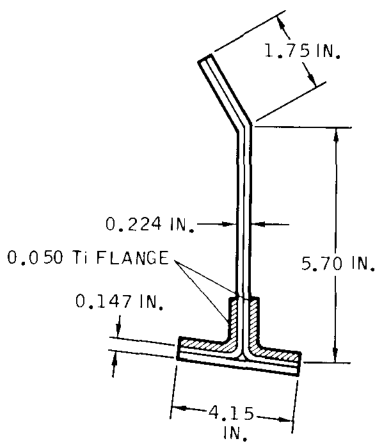

Fig.8 Composite Longeron design

APPLICATION STUDIES

Design studies were performed to determine the applicability and potential weight savings of the Al-B-SS composite material to various aerospace structural components. Aircraft components evaluated included a wing box, longeron, bulkhead, access door, and fitting. In addition, several space structures were studied. Typical weight savings of 30 to 45 percent as compared to conventional structural materials, and 10 to 20 percent as compared to other composite materials were obtained. Details of two typical design application studies are given for an aircraft wing box and longeron.

A comparison of optimized stiffened panel wing box covers was made for several advanced composites using computer program RJ4. The design requirements are typical of a subsonic military aircraft, and included bending and torsional loads and EI and GJ requirements. The wing box panels were constrained from buckling to ultimate load in this example. Results of the computer study on the wing box are summarized in Table 2 and show a 34 percent weight savings as compared to a conventional metal structure, and 15 to 22 percent weight savings as compared to other composite materials.

The longeron selected for study (shown in Fig.8) is typical of major fuselage longerons in high-performance military aircraft. The part is loaded axially by fuselage bending and thrust reactions, and is sized primarily by these axial load requirements. In the standard Al-B composite version, however, the rather minor flange bending reactions at the base of the longeron from panel pressure loads require the addition of considerable material. This is a result of the very low cross-tension strength (15,000 psi) of the standard Al-B unidirectional composite material. An efficient way to handle the flange bending requirements is to braze on 0.050-in. thick titanium reinforcing angles. These angles contribute very little to primary axial strength, but supply essentially all the transverse flange strength. This approach leads to a composite part weight of 31 lb for the 163-in. long longeron, which is a 30 percent weight saving.

The use of Al-B with 5 percent stainless-steel wire added allows us to eliminate the titanium doubler angles completely, providing we increase the base flange thickness by 0.090 in. The portion of the longeron loaded in tension, 111 of the 163 in., can be reduced in section elsewhere, since the added material is just as stiff and strong as the rest of the longeron. The net result with the application of Al-B-SS composite material is a longeron weight of 25 lb, yielding a 44 percent weight reduction over the original component (data summarized in Table 2). In addition to saving an additional six pounds, the improved Al-B-SS material greatly simplifies part fabrication, since the forming and brazing operations for the titanium doublers have been eliminated.

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