Development and Application of Aluminum-Boron Composite Material

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Specific design studies of the application of aluminum-boron composites to structural components of the F-106 aircraft are presented and weight and performance improvements assessed. A summary of the current mechanical and physical properties, manufacturing, nondestructive test, and structural test evaluations of aluminum-boron are presented. Savings for components, which approach 50% in some cases, and the airframe weight saving for the F-106 are presented. The problems of high-temperature joining and cost of implementation are touched on briefly.

Introduction

RESEARCH into structural materials for aerospace uses has recently concentrated on filamentary composites. Of the almost endless number of possible matrix-filament combinations, the most advanced currently are those utilizing boron filament with either epoxy resin or diffusion-bonded aluminum matrix materials. For aircraft in the Mach 3 regime, hypersonic vehicles, or launch vehicles, external structure temperatures are in excess of the capabilities of current epoxy resins. For these applications, the aluminum-boron composite with its high strength and stiffness at temperatures up to 800°F is the more useful system. This paper outlines the state-of-the-art development of aluminum-boron material and also explores specific aircraft structural applications of the material in terms of design concepts and performance improvements over conventional materials.

The information presented on material development is largely drawn from completed research conducted by Convair under Air Force contract.‡ The studies relating to specific aircraft applications, however, have not been reported previously.

Aluminum-Boron Development

During the past three years, 26 different metal matrix composite material systems[1–5] were evaluated. These included boron, silicon carbide, graphite, metallic wires, whiskers, and coated filaments in combination with aluminum, titanium, and nickel matrices. Of the systems evaluated, one of the most promising composite materials is aluminum-boron. Al-B composite material has been developed to the point where it is believed ready for trial applications.[6]

The properties of most interest to the designer in the application of composite materials to structural hardware include availability, cost, strength, and fatigue properties, and fabricability. A summary of these properties is given here. Considerably more detail on these properties, as well as nondestructive testing, specifications, notched toughness, crack propagation, creep, elevated and low-temperature behavior, physical properties, corrosion, and compatibility may be found in Refs. 6–13.

Availability

Al-B composite material is presently available from at least four commercial suppliers. Methods of producing Al-B composite material include diffusion bonding of alternate layers of aluminum foil and boron filaments, casting or molten metal infiltration, plasma spraying, powder metallurgy techniques, and electroplating. Diffusion bonding and plasma spraying are the most commonly used methods. Sheet sizes up to 48 × 48 in. are presently being produced by diffusion bonding; however, the ability to step-press the Al-B composite material has recently been demonstrated, thus enabling sheets of nearly unlimited size with present processing facilities. An indication of the rapid growth in available sizes of Al-B composite sheet material is shown in Fig. 1.

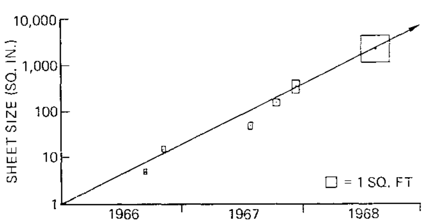

Fig. 1 Available sheet sizes of Al-B composites.

Cost

As can be seen from Fig. 2, the present cost is considerably less than in the past. Present costs for 50 volume percent (v/o) Al-B composite sheet material (including cost of the filaments) are \$500–\$1000/lb and are predicted to be as low as \$100–\$200/lb by 1972. This estimate is based on lower filament costs and quantity production.

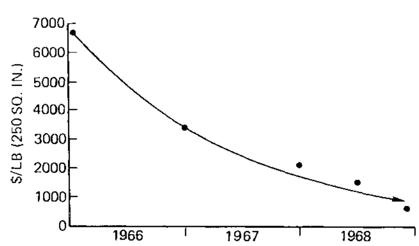

Fig. 2 Cost of Al-B composites.

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Table 1 Summary of room temperature tensile and shear data on Al-B composite sheet material

Filament orientation	Unidirectional						0_u–90° Cross-ply		±30° Cross-ply	
v/o filaments	25		37		50		45		50	
Thickness, in.	0.020	0.080	0.020	0.080	0.020	0.080	0.020	0.080	0.020	0.080
Tensile strength (long.)										
Avg., ksi	78.8	71.8	125	121	167	156	75.5	58.9	76.3	44.3
High, ksi	101	90.8	155	148	203	199	106	96.3	95.8	50.5
Low, ksi	60.3	45.6	104	63.7	128	134	33.7	24.2	45.4	40.3
No. of tests	27	17	24	20	107	35	54	8	15	4
Elastic modulus (long.), psi × 10^6	18.6	16.5	25.6	25.4	32.6	34.2	19.5	17.4	21.4	19.9
Tensile strength (trans.)										
Avg., ksi	14.5	15.6	13.2	15.4	12.1	15.1	68.3	42.2	17.2	15.0
High, ksi	16.1	16.7	15.7	16.3	18.1	17.0	96.6	47.9	19.1	16.3
Low, ksi	12.4	13.1	10.8	12.7	6.3	9.5	43.6	37.0	15.3	11.4
No. of tests	16	15	18	17	60	21	14	5	4	5
Elastic modulus (trans.) (psi × 10^6)	14.1	13.9	16.0	17.3	20.6	21.3	20.1	21.1	21.5	17.8
Shear strength										
Avg., ksi	12.2	12.8	12.4	15.1	13.0	18.6	14.9	13.1		
High, ksi	14.5	15.0	13.8	15.9	17.7	20.7	16.3	21.0		
Low, ksi	10.0	11.2	10.4	14.0	5.2	14.4	13.4	8.9		
No. of tests	10	19	5	12	33	25	10	9		

Tensile (Compression) Properties

Both tensile and compression properties are of considerable importance in the design of aerospace structures. However, only tensile properties are summarized here because of the limited amount of compression data available, and because all data indicate equal or superior strength and modulus values for Al-B composite material in compression as compared to tension. Therefore, tensile data are also used for compression values in design at this time.

Figure 3 indicates the considerable improvement made in tensile properties of Al-B during the past three years. The increases are believed to be the result of improvements in boron filament properties, in composite processing, and in mechanical property testing. Present typical tensile properties of 50 v/o Al-B sheet material are 175 ksi average, with a spread from about 150 to 200 ksi. There is reasonable assurance that minimum tensile strengths of 160 ksi, as shown in Fig. 3, can now be guaranteed.

Fatigue Properties

One of the desirable characteristics of composite materials for aerospace applications is their fatigue properties. The endurance limit (10^7 cycles) for composite materials ranges from 50 to 90% of the ultimate tensile strength, whereas for most structural materials the endurance limit is only about 20 to 50% of the tensile strength. Endurance limits for Al-B range from 50 to 80% of the tensile strength of the material, depending upon lay-up, v/o of filaments, test direction, and quality of the diffusion bond. Typical axial load fatigue test results are shown in Fig. 4.

Mechanical Properties

To provide design and engineering data, mechanical properties consisting of tension, compression, shear, creep, axial and flexural fatigue, notched tension, crack propagation, and thermal cycling have been determined. Tests were performed at room and at elevated (300°, 500°, and 700°F) temperatures. Typical tensile and shear data are summarized in Table 1 for various lay-ups (unidirectional and 0°–90° and ±30° cross ply), various volume percentages of boron filaments (25, 37, 45, and 50 v/o), and several sheet thicknesses (from 0.020 to 0.080 in.). Additional results are reported in Refs. 1–6. Based upon these results and literature data, preliminary structural design allowables were developed. These are reported in Table 2 and were used as the basis of Al-B properties for the design study.

Other Properties

Additional properties evaluated include thermal expansion and corrosion. Coefficients of thermal expansion from 75° to 700°F were determined for various lay-ups and volume percentages of Al-B. Coefficients are about 3.5 × 10^{-6} in./in.°F. These data indicate no significant incompatibility (i.e., large difference in coefficient of thermal expansion) of various lay-ups or volume percentages of Al-B composites by themselves; however, incompatibilities of Al-B with aluminum or other structural materials are apparent.

Table 2 Preliminary structural design allowables

Material	Property	Direction	Temperature Room	300°F	500°F	700°F
Al-B, 50 v/o, UD	F_{tu}, ksi	Long.	160	155	150	120
		Trans.	12	10	5	2
	E, msi	Long.	32	31	29	26
		Trans.	19	11	6	4
	Endurance Limit, ksi	Long.	90			
Al-B, 45 v/o, 0–90° CP	F_{tu}, ksi	Long.	70	60	55	50
		Trans.	60	45	35	30
	E, msi	Long.	19	18	17	16
		Trans.	19	18	17	16
	Endurance Limit, ksi	Long.	50			

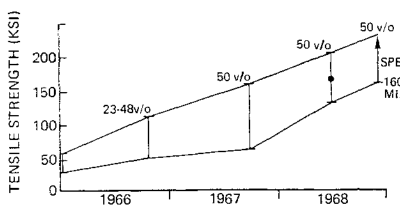


Fig. 3 Tensile strength of Al-B composites.

Corrosion tests on bare and coated Al-B were performed in several environments, including salt spray and industrial sea coast atmospheres, and under various stressed conditions. Results indicate that standard aluminum coatings provide adequate protection for the Al-B material.

Fabrication Development

A program has been performed to develop and evaluate acceptable means for fabricating structural hardware from Al-B. The fabrication development investigation included various techniques for machining, cutting, forming, and joining. Several methods have been demonstrated to be acceptable. These methods have already been used to fabricate a number of structural elements and subcomponents, and were used in manufacturing a large (60 in. in diameter × 42 in. high) piece of aerospace hardware.

Machining and Cutting

A large number of methods and techniques for machining and cutting were evaluated. Although some were found to be completely unacceptable (e.g., high-speed steel drilling and band sawing), several methods were found to be acceptable under certain conditions. These methods and their limitations are summarized in Table 3.

Forming

Techniques have been developed for successfully roll forming and bending Al-B composite sheet material. Both unidirectional and cross-ply material has been roll formed at room temperature to as small as 8-in. radii without any damage to the composite material. By use of elevated temperatures and/or compression fixtures, the Al-B sheet material has been successfully bent to a 4.5-t bend radius. Examples of parts formed from Al-B are shown in Fig. 5.

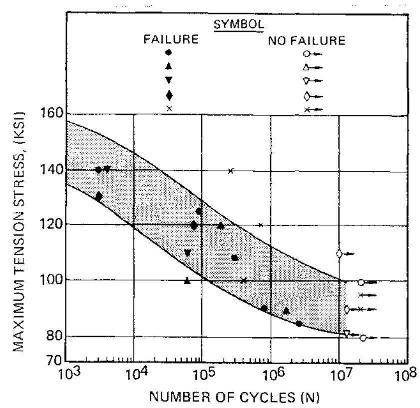


Fig. 4 Axial-load fatigue test results of Al-50 v/o boron, UD, longitudinal direction, $R = +0.10$.

Joining

The joining of Al-B composite material, both to itself and to other structural materials, has been most successful. One of the more promising methods is resistance welding (spot and roll seam) which results in very high joint strengths, since full benefit of the filaments is realized. Typical strengths of individual resistance spot welds are shown as a function of nugget diameter in Fig. 6. Other successful joining methods include mechanical joints, brazing, and adhesive bonding. A comprehensive presentation on joining of Al-B composite material can be found in Ref. 8.

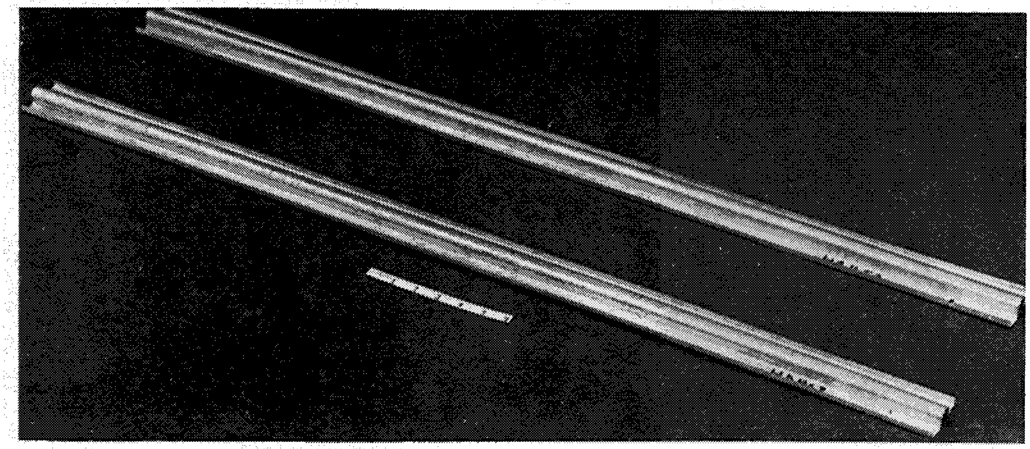
Structural System Selection

Aluminum-boron composite is a highly anisotropic material with very high strength and stiffness along the filament direction and significant ductility across the filament direction. In order to fully utilize the properties of this material, the designer must select a structural system in which the primary load paths have preferred, discrete directions. The filaments in the composite can then be oriented in the direction of load to match material properties and the structural system in a design of superior efficiency. This simple philosophy is, of course, very complex in actual application.

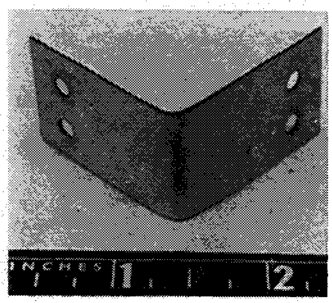
Since the primary loads in most airframe structures are compression loads, the designer is faced with the dual problems of strength and stability limitations imposed by material properties. Two structural systems have been found to produce efficient compression structures: 1) sandwich construction using lightweight core and 2) a biaxially stiffened

Table 3 Visual comparison of machining processes on 0.020-in. thick 50 v/o Al-B (ranked in order of least damage first)

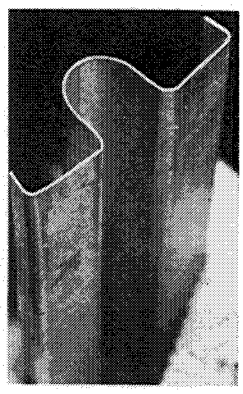
Rating	Process	Observation	Remarks
1	Electrodischarge machining	Almost complete absence of filament damage. Caused least damage to filaments of all the processes tried	Slow feed rate used on machine
2	Electrolytic grinding	Small amount of filament damage consisting of chipped filament ends	Slow feed rate
3	Shearing	Practically no crushing of filament ends observed. Uneven profile of cut filaments when compared with above processes	Damage to filaments increases rapidly with increase in sheet thickness
4	Abrasive cutoff	Slight chipping of filament ends	Minimum damage, fast and acceptable process
5	Grinding	Some filament edge crumbling and broken filaments	Acceptable process
6	Diamond routing	Broken and chipped filaments	Acceptable process, but needs further development
7	Punching	Crushed and chipped filaments	Acceptable process for sheet material, but wears punch rapidly
8	Diamond drilling	Broken and chipped filaments, uneven filament profile	Acceptable process, but needs further development



a) 42-in.-long stringers from Al-B composite containing selectively placed filaments



b) 45 v/o Al-B 0°-90° crossply material formed to $4\frac{1}{2}$ t



c) Closeup of Al-B stringer

Fig. 5 Examples of formed parts from Al-B composites.

panel construction using a thin shear skin that is allowed to buckle or relax under load. The stiffened panel construction is generally lighter than the sandwich construction for strength-critical designs; however, the design criteria for certain materials (primarily fiberglass, epoxy-boron, epoxy-graphite) do not allow buckling and these materials cannot, therefore, be used in relaxed skin designs. Sandwich and other forms of buckle-resistant panels are required with these resin matrix materials.

Aluminum-boron, on the other hand, has been shown to have post buckling shear strength similar to conventional aircraft alloys. Significant buckling has been induced both in Al-B shear webs and in curved panels under negative pressure without filament breakage, matrix cracking, disbonding, or severe permanent distortion. The preferred structural system for strength-critical compression structures using Al-B is, therefore, the stiffened panel construction with thin shear skins that are allowed to buckle.

F-106A Application Study

A rather detailed applications study of Al-B for the F-106A aircraft structure was conducted. This work indicates significant weight savings potential and also performance increases resulting from the substitution of major amounts of Al-B material for existing aluminum components. The F-106A is a twin inlet, single engine, delta wing jet with the characteristics shown in Fig. 7.

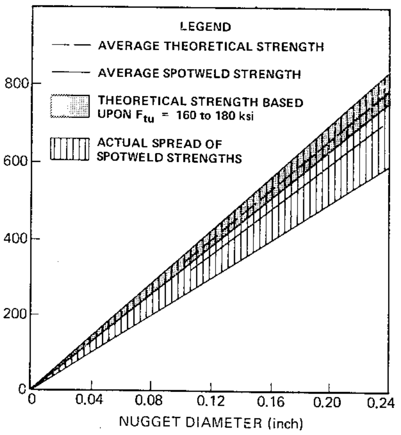


Fig. 6 Resistance spot weld strength (0.020-in., 50 v/o Al-B composite).

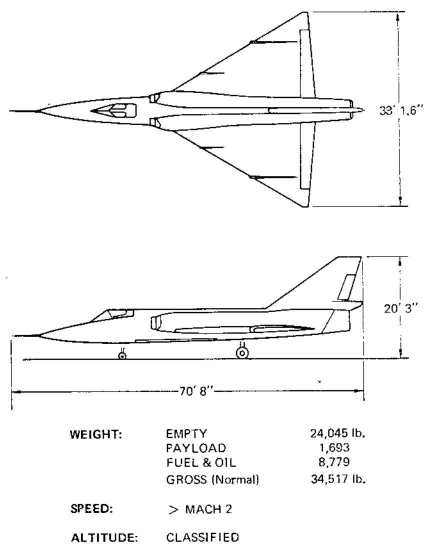


Fig. 7 F-106A characteristics.

Typical components selected from the wing, fuselage, and fin area were redesigned for Al-B. Redesigned components included skins, spars, ribs, longerons, bulkheads, and frames. One of the most significant savings was found in the bulkhead application. Figure 8 indicates the design of the built-up aluminum bulkhead, which weighs 97 lb. Also indicated is the redesigned bulkhead using unidirectional Al-B caps over a titanium carrier. The redesigned bulkhead weighs only 55 lb, a 43% wt saving.

Figure 9 shows another component studied, one of the wing spars, and the Al-B redesign. Again, unidirectional caps of Al-B are used with a titanium carrier. The combination of titanium with its high shear capacity for the webs, and unidirectional Al-B with its high strength and stiffness for the caps, results in a 42% spar weight saving. Titanium was selected for the carrier because of its very high shear capacity and bearing strength (for local attachment loads) and the similarity of its coefficient of thermal expansion to that of Al-B. It also offers the advantage of good elevated temperature strength and therefore does not impose an artificial limit on the useful range of the Al-B.

Aluminum can also be used as a carrier, as shown in Fig. 10 which indicates the construction of a typical Al-B longeron section. The particular longeron shown runs through the pilot compartment area, which is pressurized, and is critical in bending resulting from the lateral pressure loads. The redesigned section results in a 28% wt saving. In other areas, where the longerons are loaded in axial compression with low bending stresses, the weight savings are over 30%. Titanium carriers are a little more efficient than the aluminum ones shown, but are more costly than the simple aluminum extrusion used. A disadvantage of the aluminum carriers is their high thermal expansion relative to Al-B. Thermal stresses on the order of 15,000 psi are induced in the aluminum at 200°F. This condition is especially undesirable where the skin-to-longeron rivets must resist relatively high skin shear flows in conjunction with engine compartment heating. Fuselage temperatures reach 260°F in some areas of the aft body structure. As a result, the aluminum carriers are recommended primarily for the forward fuselage area.

Although the basic longeron weight saving of 30% is excellent, even more substantial weight savings accrue in the intermediate frames as a combined result of changing the longerons and the skins to aluminum-boron. The intermediate frames serve to prevent column buckling of the longerons, and to delay buckling of the skin panels. Because of the increased stiffness of Al-B over aluminum, the fuselage frame spacing can be doubled, resulting in a weight saving of 50% in frames. A similar argument holds for the wing, fin, and elevon ribs, where weight savings of 35 to 50% result from increased spacing.

A cross-ply arrangement running 0°–90° to the main structural members has been used for the fuselage, wing, and elevon skins. Direct weight savings through gage decreases amount to 13% in the wing skins, where ultimate and fatigue strength properties of the Al-B, rather than shear strength, control the gage requirements. In the fuselage skins there is an actual direct weight increase in the skins of about 9% over-all as a result of the lower shear allowable of the Al-B. However, the secondary stiffness and temperature advantages of the Al-B skins make the stiffener savings already discussed feasible, so the cross-ply skins do offer performance advantages.

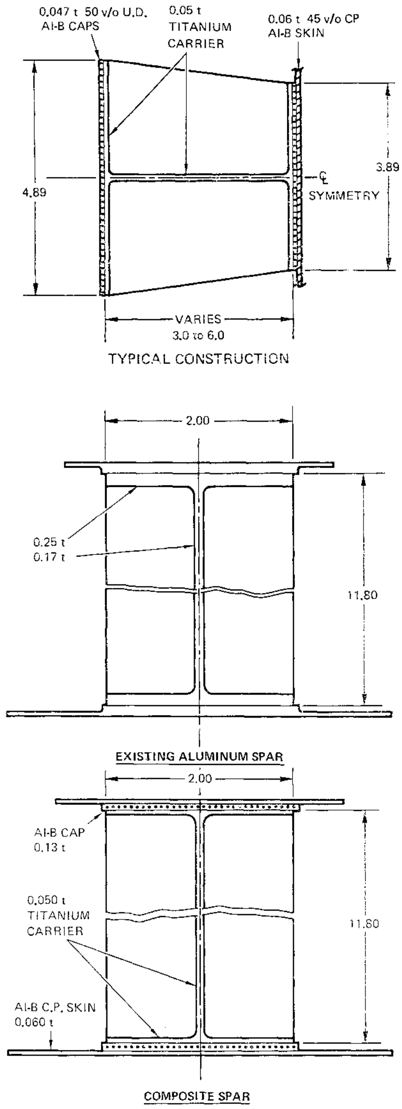


Fig. 9 Typical spar.

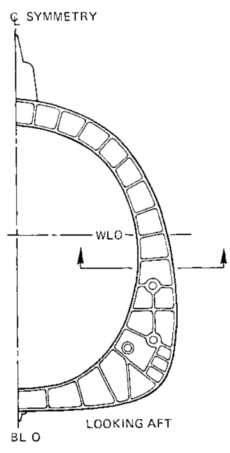


Fig. 8 Fuselage bulkhead at wing spar No. 5.

Some significant weight advantages in joints and fasteners result from the application of Al-B to the major primary structure. The reduction in number of frames and ribs eliminates many splices and rivets. Spot welding can be efficiently used to attach the remaining frames and ribs to the skin panels, eliminating additional rivets. Other savings in joints result from the increased bearing and shear strength of the titanium carriers. Although not investigated in this study, others [6,19] have found weight savings as high as 70% possible through the use of Al-B for major tension fittings. However, techniques for manufacturing such fittings are in the very early stages of development.

Over-All Performance Gain

Table 4 summarizes the results of the applications study in terms of total and percentage weight savings for each type of

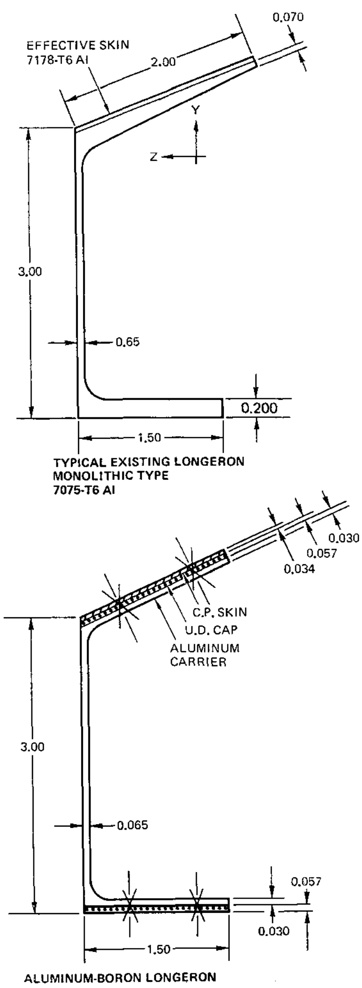


Fig. 10 Typical fuselage longeron.

component of the F-106A structure. Over-all structural weight has been reduced from 8538 lb to 6593 lb. This amounts to a total saving of 1945 lb, or 23% of the original structure. It is interesting to note the percentage saving by weight group: fuselage, 28%; wing, 25%; fin, 18%; elevon, 11%.

The very substantial savings in fuselage and wing do not carry through to the elevon and fin. This results primarily from the use of minimum gage sandwich construction for much of the original structure of these items.

The 1945-lb wt saving obtained can be converted into increased performance in any of several ways: 1) a 115% increase in payload weight capability without loss of speed or range; 2) a 22% increase in fuel capacity without loss of payload or speed; 3) an increase in intercept performance (time-to-altitude) without loss of payload, range, or loiter time.

In addition, the basic structure of the aircraft with Al-B on titanium carriers is now suitable for speeds in the Mach 3 regime. As noted in previous paragraphs, the strength and modulus of Al-B are essentially unchanged to 300°F, and show relatively small decreases to 700°F. Use of spot welding, high-temperature adhesives, and titanium fasteners produces low-creep joints up to 500°F.

In order to achieve the full 23% weight savings, about 3300 lb of Al-B must be employed in the structure. At the currently quoted prices for orders of this size, Al-B is about $600.00/lb. Assuming a reasonable fabrication cost of $50.00/lb, the added cost per aircraft then amounts to about $1.9 million. Thus, at current material prices, the weight saved would have to be valued at almost $1000/lb for the substitution to be cost effective. If the material price can be reduced to $100/lb, however, the cost of implementation is less than $200/lb of weight saved—making the substitution effective for almost all supersonic aircraft.

Table 4 F-106A structure weight comparison

Item	% saving	Conventional aircraft	Composite aircraft
Wing group			
Spars	42	716.5	423.0
Skins	13	1130.5	985.0
Ribs	35	480.3	314.0
Leading edge	20	154.4	123.5
Tip	20	114.5	91.5
Joints & fasteners	25	268.8	202.0
Doors & fairings	20	81.6	65.4
Miscellaneous	0	14.4	14.4
Elevon group			
Spars	42	16.2	9.4
Ribs	50	28.8	14.4
Skins	10	77.4	69.5
Trailing edge	10	59.1	53.3
Joints	0	7.0	7.0
Hinges & miscellaneous	0	138.5	138.5
Fin group			
Spars	42	184.4	108.6
Skin panels	0	254.6	254.6
Ribs	50	38.5	19.8
Leading edge	20	26.8	21.4
Tip	20	76.1	61.0
Rudder	20	75.0	60.0
Joints	0	40.6	40.6
Miscellaneous	0	7.0	7.0
Fuselage group			
Bulkheads	43	923.1	525.0
Intermediate frames	50	610.5	305.3
Skins	−8.9	712.5	775.0
Longerons	30	515.6	361.0
Floor	20	64.5	51.5
Small doors	20	316.3	253.0
Joints & fasteners	50	51.5	26.0
Major missile bay doors	30	470.7	330.0
Canopy, radome, mechanical, etc.	0	882.3	882.3
Total	23	8538.0	6593.0

Conclusions

Al-B has been developed sufficiently so that it is now possible to speak in terms of actual fabrication techniques, material properties, and structural behavior in relation to specific aircraft applications. Using the shear buckled skin structural concept common to many modern aircraft, weight savings of about 25% in structure can be obtained. This value has also been substantiated by F-111 and missile adapter studies.[6,19] Furthermore, only two basic laminate layups are required—unidirectional and 0°–90° cross-ply. The substitution can also be cost-effective, providing material priced at about $100/lb can be obtained. This material offers distinct advantages for very high performance, Mach 3 aircraft. Al-B appears to be an ideal material for a relatively small, lightweight, air-superiority type aircraft capable of operating at or above Mach 3.

The next step in the development process is to obtain flight experience and additional, systematic, structural test data so that the next generation of military aircraft can take full advantage of the performance of this material.

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