Development of Metal-Matrix Composite Blading for Gas-Turbine Engines

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Metal-matrix composite materials are of interest for aircraft gas-turbine engine compressor blading because they offer significant weight savings, resulting in increased aircraft payload and range. Design of these lightweight blades requires development of analytical techniques to determine the stresses and behavior of these anisotropic structures for both steady-state and vibratory loadings. An initial survey of composite material systems indicated that the most promising system for study was boron filament in an aluminum matrix. Tensile specimens of this material with 30 to 40 vol. % boron demonstrated specific strengths which exceeded that of conventional titanium by better than 50%. A simulated boron-aluminum airfoil was produced containing unidirectional boron filaments which constituted 36 vol. % of the material. Testing indicated that the composite material airfoil had $1\frac{1}{2}$ times the torsional stiffness and better than twice the bending stiffness of a similar all-aluminum airfoil.

Introduction

THE design and development of high-performance gas-turbine engines have continually benefited from advances in component technology resulting from the application of new materials and fabrication processes. High-strength titanium, with a strength-to-density ratio which is 65% higher than that of steel, is just one example of a material which dramatically influenced engine design and performance by permitting greater thrust for less weight. Recent interest has been in the application of advanced filament-reinforced composite structures in engine hardware. The potential of these materials is evident when the theoretical strength-to-density and modulus-to-density ratios of these materials are compared with the experimental values for conventional engine materials (see Fig. 1). In view of this potential, a number of programs have been undertaken to develop the technologies required to translate these materials into engine hardware.[1–6]

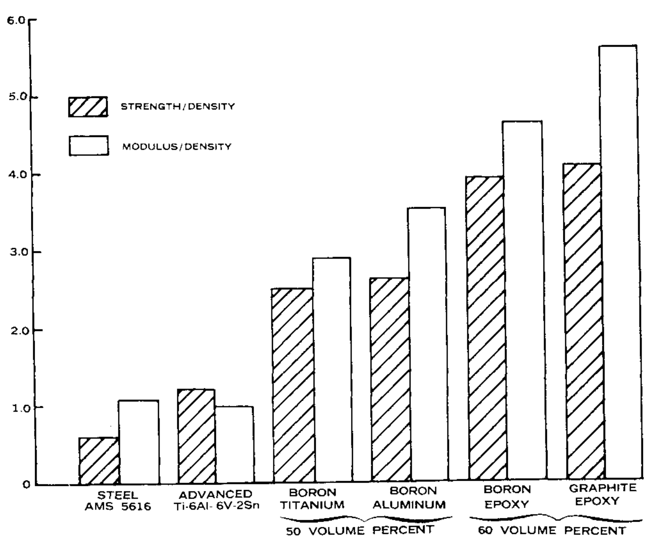

Fig. 1 Room-temperature strength-to-density and modulus-to-density ratios for conventional and unidirectional composite materials relative to Ti-6Al-4V alloy.

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Application Studies

Application studies for composite materials were initially performed as a part of an Air Force program[7] to assess the potential of advanced composites in propulsion systems. More recently, additional related studies were completed, and these results are summarized in Table 1. It is quite clear that a significant advantage of composite materials is realized in rotating components, particularly blading. For a given component, the weight savings are highest for subsonic engines with high bypass ratios and lowest for supersonic engines. The reason for this is that higher-bypass-ratio engines have a greater proportion of the weight represented by the fan stage and low-pressure compressor where the temperatures are relatively lower and the composite materials currently available are most suitable for low-temperature applications (on the order of 400°F or lower). In the supersonic engines, composite materials with a relatively high density are required to withstand the higher temperatures which exist in a greater portion of the engine.

Table 1 Potential engine weight advantages achievable with advanced composite materials in selected aircraft applications

	Approximate engine weight savings, %		
Engine component	Lift turbofan	Subsonic turbofan	Supersonic turbofan
Blades	7.0	6.0	1.5
Effect on disks	9.0	4.0	3.0
Disks	3.5	2.0	2.0
Stators	3.0	3.0	2.0
Cases	3.0	5.0	2.5
Other	4.5	5.0	4.0
Total	30.0	25.0	15.0

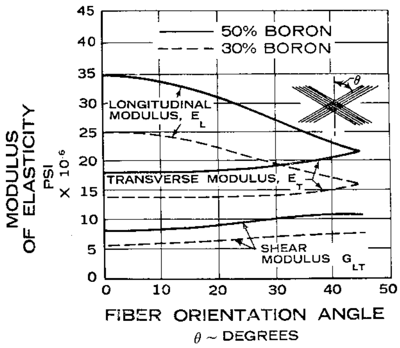


Fig. 2 Boron-aluminum composite moduli as functions of fiber orientation for material with 30 and 50 vol. % boron.

The use of composite materials in blades offers other advantages in addition to weight savings. These include reduced rotating mass, reduced blade tip clearance, the potential for higher blade tip speeds, and the possibility of eliminating the part-span shrouds presently needed to permit flutter-free blade operation.

Theoretical Properties

Several investigators[8–12] have devoted extensive efforts to determine the properties of composite materials. Pratt & Whitney Aircraft has drawn on the techniques developed by these investigators where applicable and, in combination with original analytical and experimental work, developed computer programs for predicting the properties of laminated composite materials for various filament orientations and materials systems. Typical room-temperature properties determined in these programs are shown in Figs. 2 and 3.

Material Selection

A review of the material requirements for fan blades suggested the use of composite materials with metal matrices since these matrix materials provide the combined properties of high fatigue strength, high shear strength for root attachments, and good resistance to erosion and impact from ingested foreign objects. A boron-aluminum composite was selected, primarily because of the relative ease of fabrication and the good properties exhibited.

Polymer matrix systems are also being considered. These materials are potentially attractive, but the impact and erosion resistance as well as the shear properties must be improved.

Material Preparation

Three techniques were initially considered for incorporating boron filament into an aluminum matrix. These were liquid-metal infiltration, bonding with aluminum powder, and bonding with aluminum foil. Liquid-metal infiltration

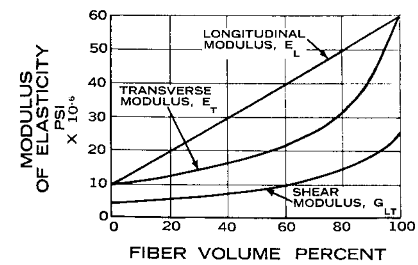


Fig. 3 Boron-aluminum composite moduli as functions of fiber volume percent for radial fiber orientation.

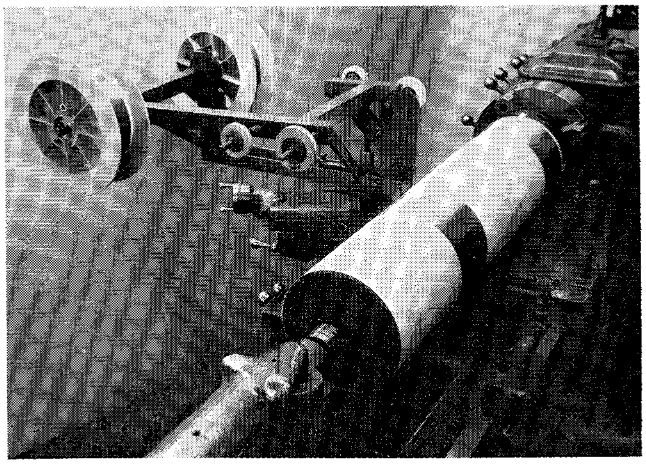


Fig. 4 Filament winding apparatus.

was immediately rejected because the boron filaments were attacked at the liquid-metal temperatures. Powder metallurgical methods also showed little immediate promise because of difficulty in maintaining the filament distribution and spacing and because of handling difficulties associated with atmospheric contamination.

It was soon evident that the fiber-foil hot pressing technique held the greatest promise, and a very effective technique was developed. Initially, single layers of filaments were produced by winding on a lathe, as shown in Fig. 4. A large cylinder, which was accurately machined and polished, was installed in the live head of a lathe to serve as a mandrel. The mandrel was then covered with a high grade of paper, and the filament ends were attached to the paper. The paper was required to ensure easy removal of the completed windings. Filament spacing and alignment was controlled by adjusting the lathe lead screw traverse adjustments, and a simple friction device was used to maintain the desired filament tension. When a complete traverse of the mandrel

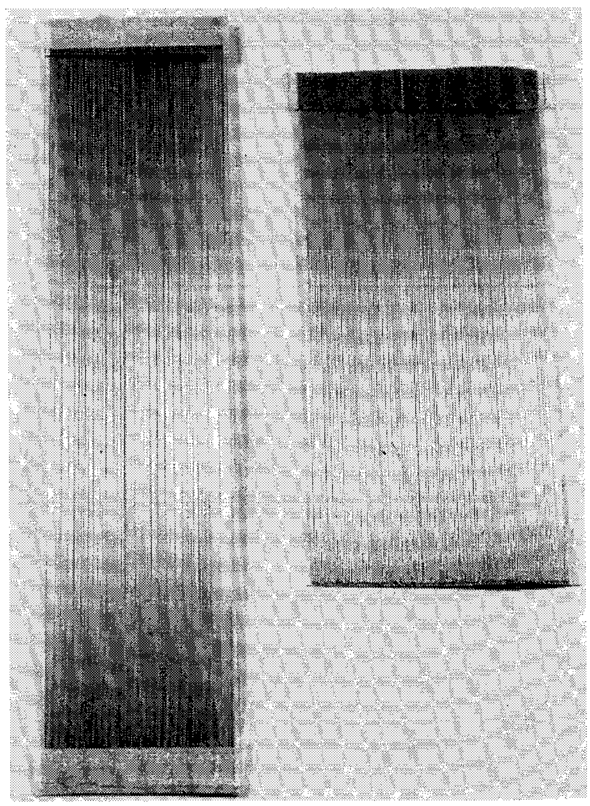


Fig. 5 Boron filament grills.

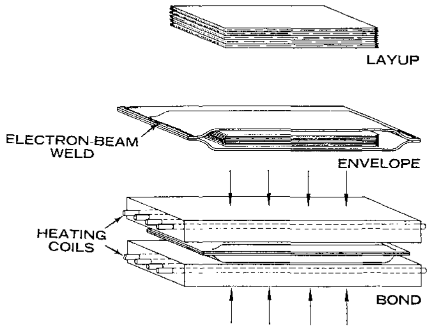


Fig. 6 Boron-aluminum composite-material fabrication process.

had been completed, the windings were secured with masking tape, which was positioned to provide the desired filament lengths between tapes. The windings were then removed from the mandrel and cut to size, forming monolayered filament elements or grills, as shown in Fig. 5. The slight helical angle produced in winding presented no problem once the grills were cut to size. This method provided the means of maintaining filament spacing, alignment, and volume percent of filament in the final composite sheet. The tapes secured the filaments and provided ease of handling during subsequent processing. The aluminum sheet selected in these first trials was commercially pure AA-1100. This material was selected because of ready availability, ductility, and ease of rolling to the required thickness.

Cleaning procedures are very important, and care was taken to ensure cleanliness of the bonding surfaces. The boron filaments were cleaned with alcohol to remove contamination introduced during handling. The aluminum sheet was cleaned by dipping in a sodium sulphate solution, rinsing in cold water, and then dipping in nitric acid, followed by cold and hot water rinsing. Brushing with stainless-steel wire brushes to break up the oxide layer on the aluminum just prior to bonding also contributed to the production of high-quality bonds. White-glove handling techniques were used where necessary in the layup procedures and vacuum jars or argon bags were used when storage was necessary.

The cleaned boron filament and aluminum sheets were then stacked in alternate layers in a jig that provided good alignment of the filaments. Steel or tantalum sheet was used to encase the layup, and clamps were installed to maintain the layup orientation while the masking tape was trimmed from the filament grills. The layup assembly was then sealed with electron-beam welding in a vacuum of about 1×10^{-5} torr. Finally, the vacuum-sealed assembly was hot-pressed in a simple calrod-heated die. The complete process is shown schematically in Fig. 6.

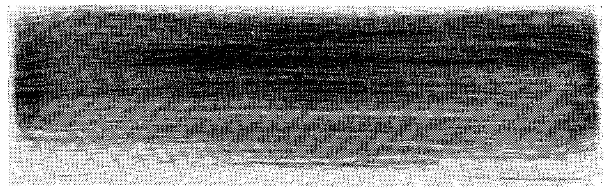


Fig. 7 X-ray photograph of boron-aluminum composite showing variations in filament density and alignment.

The die used in the initial fabrication trials did not completely encase the material. Consequently, the matrix material flowing perpendicularly to the filament direction caused variations in filament density and alignment (Fig. 7). Lack of proper filament alignment lowers the tensile strength below the value predicted by the rule of mixtures.[13,14] The die was changed to provide complete restraint during bonding, and satisfactory filament alignment control has been achieved.

The bonding parameters selected for composite fabrication were determined empirically by diffusion bonding small aluminum specimens without filaments. During these bonding studies, the deformation of the aluminum was observed to ensure that sufficient flow between the filaments would occur to bond the composite material. The results of these tests are shown in Fig. 8.

Having established the range of temperatures and pressures where adequate bonding could be expected, the authors then fabricated a number of composite specimens for tensile and impact testing. These specimens were flat with the original pressed thickness, but the edges were ground to the geometry shown in Fig. 9. The first attempts to machine the desired specimen geometry were unsuccessful because the hardness of the boron imbedded in the relatively soft aluminum matrix presented problems for the cutting tool alloys. Diamond grinding proved to be the most successful technique.

Initial tensile tests, made with specimens with shorter grip lengths than shown in Fig. 9, resulted in failures in the grip area. Increasing the grip length and bonding soft

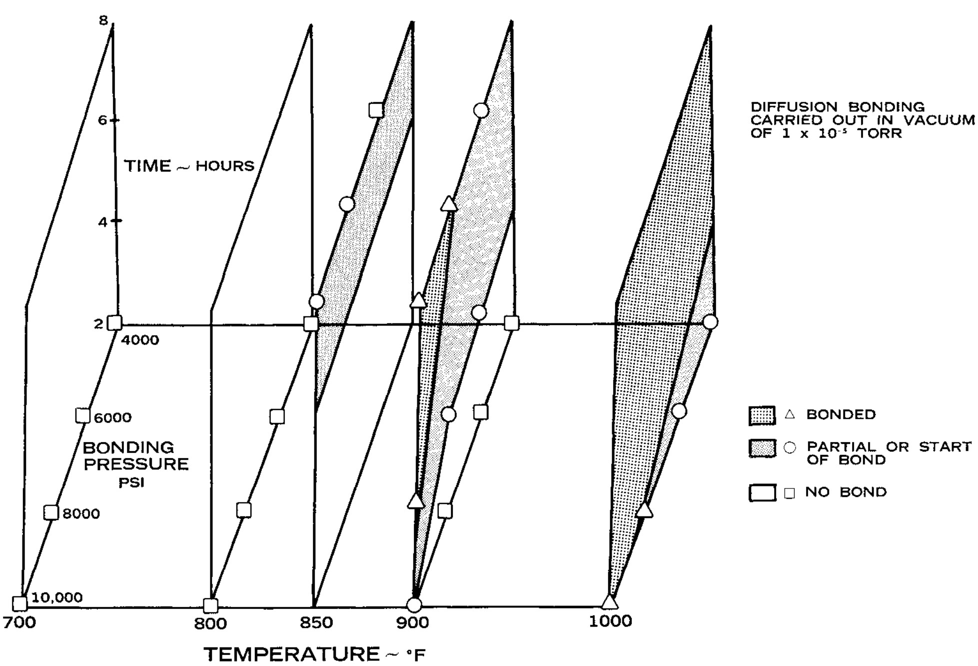


Fig. 8 Summary of diffusion bonding parametric study for AA-1100 aluminum.

Table 2 Ultimate tensile strength and bonding parameters of boron-aluminum composite specimens

Specimen no.	Bonding parameters at 1 × 10^{-5} torr: Temperature, °F	Bonding parameters at 1 × 10^{-5} torr: Pressure, psi	Time, hr	Fiber, vol. %	Ultimate tensile strength, psi	Remarks
1	900	10,000	1	15[a]	31,800	
2	815	15,000	1	15[a]	33,500	
3A	900	15,000	2	15[a]	47,000	
3B	900	15,000	2	15[a]	37,400	
4A	950	15,000	1	15[a]	39,300	
4B	950	15,000	1	15[a]	27,800	
5	1,000	15,000	1	15.7	44,000	
6A	1,000	10,000	1	15[a]	40,800	
6B	1,000	10,000	1	15[a]	39,500	
7	980	15,000	1	35.0	...	Ballistic impact
8A	1,000	15,000	1	33	156,200	
8B	1,000	15,000	1	33	146,500	
9A	1,000	15,000	1	42.5	123,000	
9B	1,000	15,000	1	42.5	116,000	
10A	1,000	15,000	1	30.0	112,000	
10B	1,000	15,000	1	30.0	133,000	
11A	1,000	7,000/ 15,000	1/1	31.0	77,500	Poor machining
11B	1,000	7,000/ 15,000	1/1	31.0	131,000	
12	1,000	15,000	1	35.0	...	Ballistic impact

[a] Estimated from specimen 5.

aluminum tabs to the grips resulted in specimen failures within the gage area. Special care was also taken to align the specimen properly during tensile testing to minimize, if not eliminate, any bending stresses. As a result of these precautions, the tensile test results obtained are believed to be representative of the material strength.

The results of the tensile tests are shown in Table 2, together with the corresponding fabrication parameters. In most instances, the low strengths obtained during the tensile tests were attributed to improper filament alignment, mechanical and metallurgical filament damage during hot pressing, strength variations in the early manufacture of the boron filament, improper fabrication parameters, and improper material cleaning prior to bonding.

The impact resistance of the boron-aluminum composite material was investigated using small flat panels containing 35 vol. % boron filament. The test panels were subjected to the impact of a 0.7-g steel pellet fired at 90° to the panel surface with velocities of 600 and 800 fps. Typical results are shown in Fig. 10. Some matrix cracking in the filament direction is apparent, but the cracks did not propagate beyond the immediate region of impact. Further study of this problem is needed to define the extent of the impact energy damage properly.

The rapid deterioration of the boron filaments which was observed during evaluation of the liquid-metal infiltration technique caused concern over the possibility of filament-matrix interactions in the diffusion-bonded foil material. Consequently, several composite foil specimens were fabricated and thermally soaked at temperatures between 400° and 1000°F for periods from 100 to 5000 hr. The results of these tests, shown in Fig. 11, indicate that attack of the boron filament occurs at high temperatures but does not occur at temperatures in the range of 400°F. Additional quantitative tests are required to determine the exact temperature limits of this system for compressor blading applications. The development of silicon-carbide-coated boron (BORSIC$_{TM}$) by United Aircraft Corporation allows the fabrication temperature as well as the temperature at which the boron-aluminum system is suitable for use to be raised.

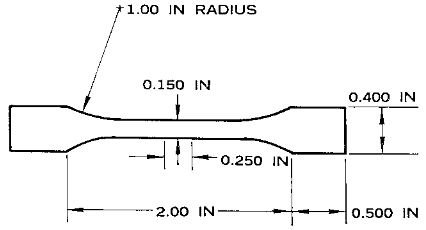


Fig. 9 Boron-aluminum composite-material tensile specimen.

Fabrication

Small-scale fan blades were fabricated from the composite material on the basis of the fabrication trials. Simple configurations were made initially. The first blade produced is shown in Fig. 12. This blade was produced by diamond grinding a block of composite material containing 33 vol. % boron filament. Close examination of the surface of the finished part revealed that grinding was not an entirely satisfactory method of producing the blade contours because it damaged the surface filaments. The damaged surface filaments represent almost 10% of the bulk material in blades having a small airfoil thickness. In addition, the broken filaments on the surface tended to lift away from the surface

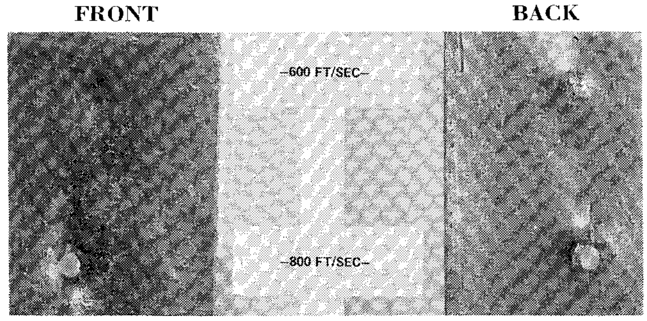


Fig. 10 Ballistic-impact-tested boron-aluminum composite specimen with 35 vol. % boron (specimen thickness = 0.075 in., pellet weight = 0.70 g).

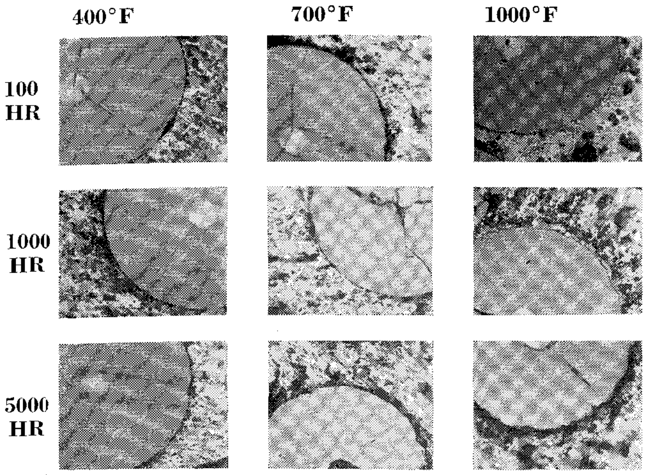


Fig. 11 Summary of boron-aluminum compatibility tests.

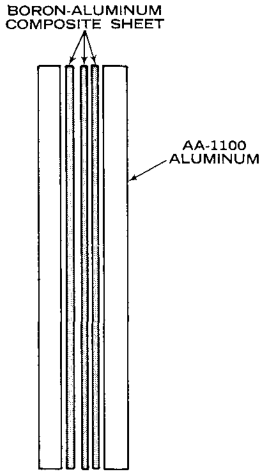


Fig. 13 Design of simulated composite blade with straight filament root.

and could cause undesirable high-stress concentration areas at engine operating conditions. These results indicate that every attempt should be made to form the airfoil to the final dimensions in the initial pressing operation, allowing only for clean up.

Of greatest concern in the fabrication of composite-material blades is the airfoil-to-root transition section. This section of the blade must provide a smooth path for the filaments into the blade root, and it must also be capable of withstanding severe and highly complex stresses. Two methods of fabricating the root section were evaluated. The first, and simpler, of these permitted the filaments to remain straight through the root. This blade was produced by sandwiching three sheets of composite material between two plates of aluminum, as shown in Fig. 13. After being suitably prepared for bonding, the assembly was placed in a simple box die, vacuum sealed, and pressed. Subsequent grinding of the aluminum airfoil contours and machining of the aluminum root produced the simulated compressor blade shown in Fig. 14.

The second method for fabricating the root is shown in Fig. 15. In this design, the outer boron-aluminum sheets were creep-formed at the root at a temperature of 900°F. Slots were machined into the outer aluminum plates to receive the composite material. This assembly was prepared, bonded, and machined in the same manner as the simulated blade with the straight filaments. The completed part is shown in Fig. 16.

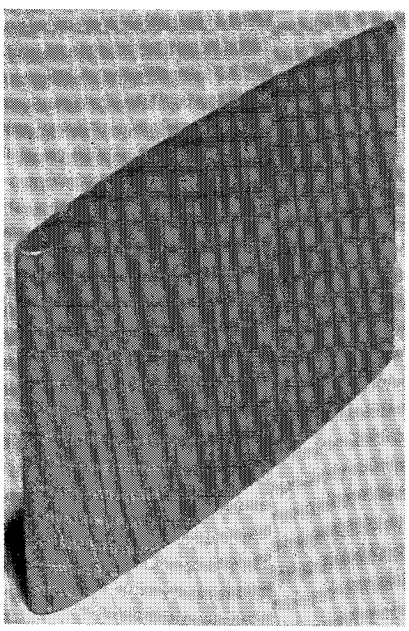


Fig. 12 Boron-aluminum composite airfoil.

Although the straight-through filament root concept would depend almost completely on shear strength at the composite-aluminum interface and on the shear strength of the aluminium, it is the simplest concept to fabricate. Not only does it eliminate the need for the extra forming and machining steps, but examination of both parts indicated that the splayed concept resulted in more filament breakage during bonding than the straight-through concept. This breakage indicated that additional development would be necessary to ensure filament integrity in subsequent trials. Further, attaching a root to a preformed airfoil would be relatively simple using the straight-through filament concept, whereas the splayed filament root concept provides better shear strength at the root through wedging of the filament at the cost of more complicated fabrication procedures.

Test

The previous material properties tests had provided a means for evaluating fabrication techniques, but they did not define the behavior of the material under the loading it would receive in a compressor blade. Consequently, a simple test program was conducted to determine some of the more important blade properties including bending, torsional stiffness, and natural frequencies. The tests were performed on the small airfoil shown in Fig. 17. This airfoil contained 36 vol. % boron filament and between the blocks had a nominal length of 4.25 in., a nominal width of 1.125 in., and a nominal thickness of 0.100 in.

Initially, strain gages were installed and the airfoil was subjected to static bending and torsion tests. The static bending tests were performed by clamping the root end of the airfoil and then adding weights to a load pan attached to the tip end while the deflections at the tip were recorded (see Fig. 18). For torsion testing, the airfoil was secured ver-

Table 3 Elastic properties of boron-aluminum composite material with 36 vol. % boron

	Young's modulus, psi	Shear modulus, psi
Experimental		
Static bending	28.24×10^6	...
First-harmonic bending	28.20×10^6	...
Second-harmonic bending	28.60×10^6	...
Static torsion	...	8.06×10^6
First-harmonic torsion	...	7.45×10^6
Theoretical	28.13×10^6	6.80×10^6

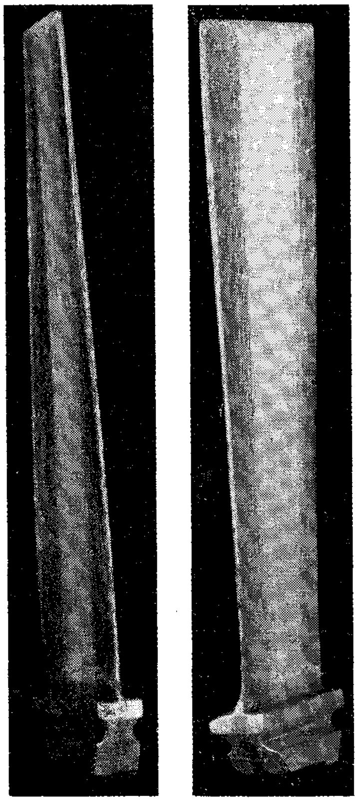


Fig. 14 Boron-aluminum composite simulated compressor blade with straight filament root.

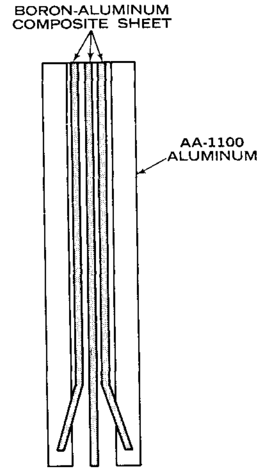


Fig. 15 Design of simulated composite blade with splayed filament root.

tically at the root and fitted with a torsion disk at the tip, as shown in Fig. 19. Two small cables with dead weight pans were attached at opposite positions on the disk diameter to provide the torsion moment. Weights were then applied to the loading pans and the strain produced was measured with the strain gages. Dial gages were mounted at various positions on the disk diameter to insure that no cantilever bending occurred.

After the static test, the small block of material at the tip was removed, and the airfoil was vibrated as a cantilevered airfoil at the first- and second-harmonic bending frequencies and the first-harmonic torsional frequency. Damping characteristics were also determined. The same tests were performed on a similar airfoil fabricated entirely from aluminum.

Evaluation

The results of the static tests are shown in Figs. 20 and 21. These results and the results of the dynamic tests were analyzed to determine the elastic constants of the material. These are shown in Table 3 together with the predicted values.

The test results indicated that the composite-material blade had a greater resistance to torsion than had been predicted and that the shear yield limit had been exceeded. With unidirectional filaments, the shear strength of a composite material is strongly dependent on the shear strength of the matrix material. Pure aluminum has a very low yield point in shear (about 1500 psi according to ALCOA). Consequently, the composite blade started to yield under torque loads at a maximum shear stress of about 1600 psi.

The yield point in shear could be raised in two ways. First, a reinforcing layer of filaments at an angle of 45° to the blade

Table 4 Natural frequencies and damping constants of composite boron-aluminum and all-aluminum airfoils

	All-aluminum[a] airfoil	Boron-aluminum composite airfoil
Natural frequency, cps		
First-harmonic bending	185	320
Second-harmonic bending	1040	1640
First-harmonic torsion	1450	2220
Airfoil damping constant	0.0169	0.0295

[a] Aluminum alloy used was 6061-T6.

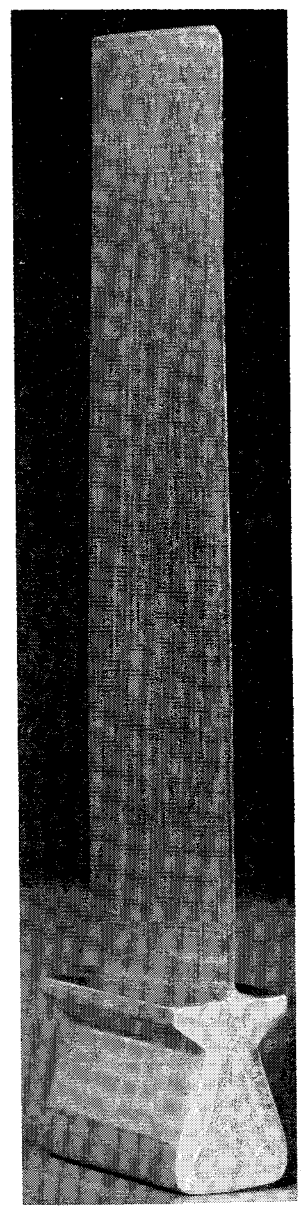


Fig. 16 Boron-aluminum composite simulated compressor blade with splayed filament root.

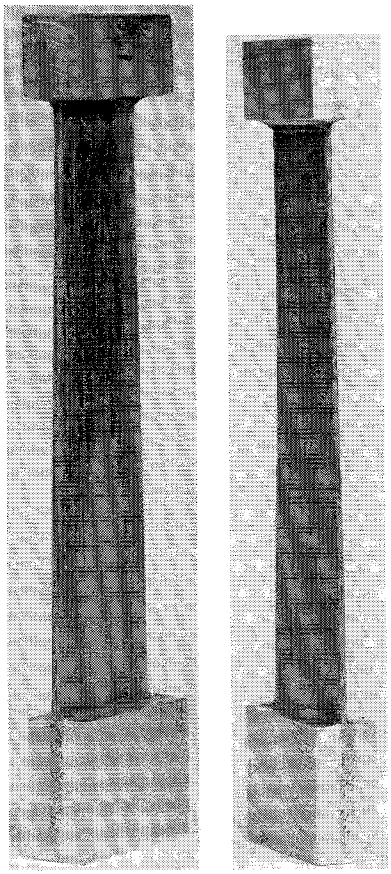


Fig. 17 Boron-aluminum composite simulated airfoil.

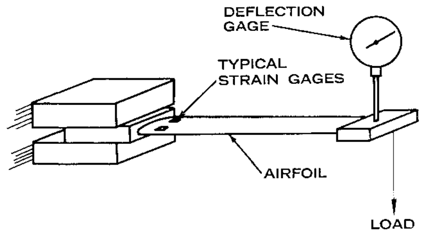


Fig. 18 Static bend test procedure used for boron-aluminum composite simulated airfoil.

axis could be added. This would both raise the shear yield point and also raise the natural torsional frequency. However, the centrifugal load-carrying capability of the blade would be lowered, as would the natural bending frequencies. The second approach would be to use an aluminum alloy with a higher shear strength for the matrix. This would achieve the desired result without complicating the fabrication process.

The natural frequencies of the boron-aluminum airfoil in bending and torsion are shown in Table 4 together with those of the identical airfoil fabricated entirely of aluminum. As shown, the composite airfoil exhibited both higher natural frequencies and a higher damping constant than the all-aluminum airfoil.

Conclusions

The results of the program for developing boron-aluminum composite material for use in gas-turbine engine compressor blades has been quite encouraging to date. The program has demonstrated that blade structures can be designed and fabricated to take advantage of the high strength and modulus of boron filaments. Diffusion bonding has been shown to be the most attractive method for producing metal-matrix blading. The boron-aluminum system is suitable for structures operating at temperatures up to 400°F, and this temperature range can be extended even higher with the use of silicon carbide coated boron ($BORSIC_{TM}$). The experience gained during this program in the handling of boron filament and the fabrication of composite structures has laid the foundation for the design and fabrication of the more complex shapes typical of blading in advanced engines. The good agreement between the test results and the analytical predictions for unidirectional structures has verified that the techniques used are suitable for predicting the behavior of composite blading and can account for the directional properties of the materials.

Future Developments

The success of this program represents a first step toward the eventual acceptance and use of metal-matrix composite

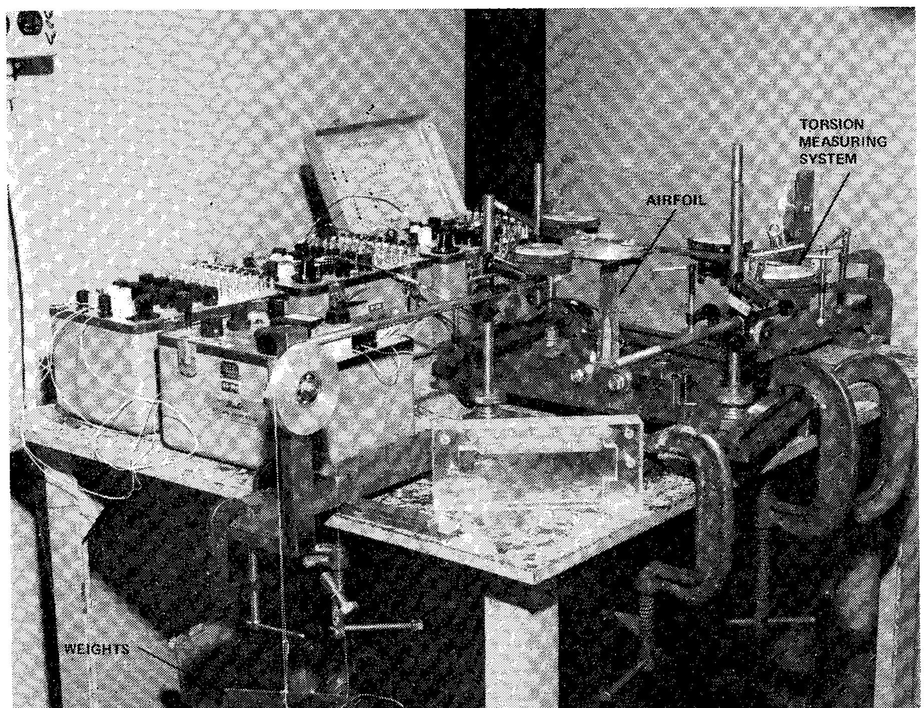


Fig. 19 Apparatus used for simulated airfoil.

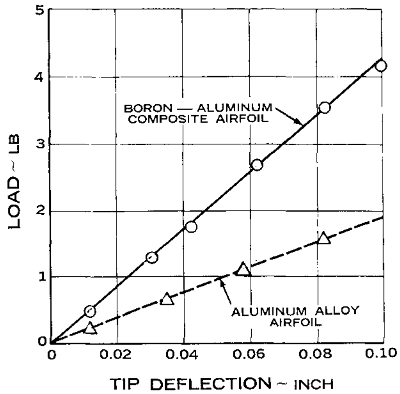
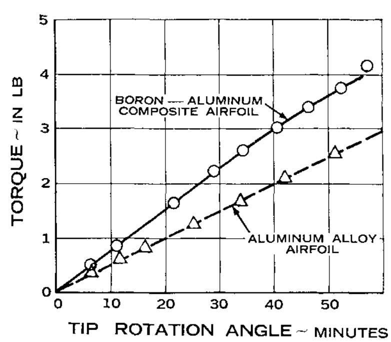


Fig. 20 Static bend test results for boron-aluminum airfoil.

blading in gas-turbine engines. The development of fabrication techniques that are both reproducible and economical for the complex shapes and large sizes of fan blades for advanced engines is required, and the temperature limits of the BORSIC$_{TM}$-aluminum material system in this application should be determined. The effect of erosion and impact from foreign-object ingestion must be fully assessed, and protective measures must be taken where required. Methods for repairing damage should also be investigated to prolong the life of blades and to help in reducing operational costs.

To qualify these materials and the methods of their construction for early application in gas-turbine engines, the development of a BORSIC$_{TM}$-aluminum fan blade for the JT8D engine is in process. This effort consists of the design, analysis, and fabrication of a sufficient number of composite blades to permit a thorough material and structural evaluation. Successful completion of this effort will be followed by engine testing of a complete set of composite blades and possibly by field service evaluation.

Fig. 21 Static torison test results for boron-aluminum simulated airfoil.



Beyond the development of composite BORSIC$_{TM}$-aluminum material lies the development of other systems with higher temperature capability, such as BORSIC$_{TM}$-titanium or graphite-reinforced material. Eventually, systems are required which will perform effectively at temperatures in excess of 2000°F.

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