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Evaluation of Low-Cost Aluminum Composites for Aircraft Engine Structural Applications

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SUMMARY

Panels of discontinuous SiC composites, with several aluminum matrices, were fabricated and evaluated. Modulus, yield strength and tensile strength results indicated that the properties of composites containing SiC whisker, nodule or particulate reinforcements were similar. The modulus of the composites was controlled by the volume percentage of the SiC reinforcement content, while the strength and ductility were controlled by both the reinforcement content and the matrix alloy.

The feasibility of fabricating structural shapes by both wire preforms and direct casting was demonstrated for Al_2O_3/Al composites. The feasibility of fabricating high performance composites into structural shapes by low pressure hot molding was demonstrated for B_4C-coated B/Al composites.

INTRODUCTION

The majority of effort in aluminum matrix composites has been directed toward the development of high performance composites for use in speciallized aerospace applications. For example, most of the aluminum matrix work at NASA-Lewis Research Center has been directed toward improving the impact resistance of boron/aluminum (B/Al) composites for possible application as rotating fan blades in aircraft engines. Due to the critical requirements of such applications, it could be cost effective to use high cost, high performance composites for these components. However, there are a number of other applications in aircraft engines and aerospace structures where metal matrix composites can also be used effectively and where the superior properties of high performance composites may not be required. For example, weight- and stiffness-critical components, such as engine static structures and compressor vanes and blades, do not require the superior properties of B/Al. Replacement of such current titanium/steel structures by composites offers the potential of significant weight and cost savings.

Therefore efforts were initiated to assess the potential of low cost composite materials and fabrication processes, including powder metallurgy, direct casting and hot molding techniques. As part of this assessment, low cost aluminum matrix composites containing silicon carbide (SiC) particulates, whiskers or nodules, and continuous aluminum oxide (Al_2O_3) fibers were fabricated under contract. Flat panels and simulated component shapes were obtained for in-house evaluation to assess the suitability of these composites for these potential applications. In addition, a potentially low cost hot molding process for fabricating boron carbide coated boron/aluminum (B_4C-B/Al) composites was examined.

The evaluation of the results from mechanical property testing of the composites indicated that these lower cost composites had significantly higher moduli than conventional aluminum alloys. It is the purpose of this paper to analyze and report these results and to compare the properties observed to those that would be needed to consider these composites as viable candidates to replace current monolithic materials, such as titanium and aluminum, for engine component and structural applications.

DISCONTINUOUS SILICON CARBIDE/ALUMINUM COMPOSITES

Materials and Fabrication

Four commercial wrought aluminum alloys were chosen as matrix alloys for the studies of properties of composites containing discontinuous SiC reinforcement. Alloy 6061 was chosen as the standard alloy for comparison since it represented a heat treatable alloy with high strength and ductility, combined with good corrosion resistance and weldability. Two typical very high strength aluminum alloys, 2024 and 7075, were chosen. These alloys are heat treatable and are used in high strength aerospace applications, in situations where corrosion resistance and weldability are of secondary importance. Alloy 5083 was chosen as being typical of a non-heat treatable alloy that draws its moderate strength from work hardening. This alloy has good formability, weldability and corrosion resistance.

Three types of low-cost, high-modulus aluminum matrix composites, containing discontinuous SiC reinforcement, have recently become commercially available. Two of these composites, containing SiC reinforcements produced from rice hulls, are being produced and marketed by ARCO Metals (formerly Silag Div. of Exxon Corp.). Two forms of reinforcement, β-SiC whiskers (containing a mixture of 80 percent whiskers/20 percent nodules) and β-SiC nodules (containing a mixture of 80 percent nodules/20 percent whiskers) are available. The whisker form has diameters in the 0.2 to 1.0 micron range (Ref. 2), an average aspect ratio of 75 and is a more effective reinforcement than the nodule form, which is basically a round platelet.

Another aluminum composite containing discontinuous SiC reinforcement is that developed by DWA Composite Specialties (Ref. 3). These composites are made with SiC reinforcements obtained from single crystals of α-SiC, typically used as abrasives, that are crushed into fine powder and separated by size.

The SiC particulates have an irregular platelet shape, with an average particle size between 1 and 10 microns.

Basically the same methods were used to fabricate composites containing all three types of SiC reinforcement (Refs. 3 and 4). In each case, the SiC reinforcement was blended with aluminum alloy powder, compacted into billets and sintered. The sintered billets were then rolled, forged or extruded into 2.54 mm thick flat plates for NASA evaluation. After receipt of the various SiC/Al plates from both fabricators, the plates were sheared into 12.8 mm wide strips in both the longitudinal and transverse directions. Test specimens were made from these strips by cutting a 28-mm-long reduced gage length in the midpoint of each strip. The density of each type of composite was measured by water immersion.

Tensile tests were used to evaluate the properties of the composites and to analyze the results to determine the effects of the type of SiC reinforcement, volume percent SiC reinforcement content and matrix alloy on the modulus of elasticity, yield strength, ultimate tensile strength and ductility of the composites. Composites with 2024, 6061 and 7075 Al matrices were tested in both the as-fabricated (F-temper) and the heat treated (T6 temper) condition. The heat treatments used are shown in Table I and were taken from Refs. 3 and 5. Composites with a 5083 Al matrix were tested in the F-temper only. Tensile tests were conducted at a constant crosshead speed of 2.54 mm/min and the stress-strain behavior and mechanical properties were determined using a 25.4 mm gage length extensometer.

Test Results

The effect of different types of SiC reinforcement on the strength and stress-strain behavior of the composites was examined by studying a series of specimens with an SiC content of 20 v/o in a heat treated 6061 Al matrix as a standard of comparison. The properties of the three types of composites with whisker, nodule and particulate reinforcement were very similar. Curves presented in Fig. 1 indicate the similarities of the stress-strain behavior of the three types of composites. Composites containing SiC whiskers had slightly higher tensile strengths than those with particulate reinforcement, while the nodule reinforcement gave slightly lower tensile strengths.

Results of tensile tests conducted on the three types of discontinuous SiC/Al composites showed that the moduli of elasticity of the various composites were similar at a given reinforcement content. The average modulus of the SiC whisker reinforced composites was about 3 percent higher than that of the composites containing nodule and particulate reinforcement. SiC-whisker reinforced composites exhibited some directionality in properties. Tensile strength and modulus values were about 5 percent higher in the transverse direction than in the longitudinal. Microstructures of these composites showed a mixture of whiskers and nodules. The whiskers that were present in the structure had an orientation generally in the transverse direction. This would indicate that the whisker orientation was basically set during the extrusion phase of fabrication. The extruded panels must have been cross rolled in the direction perpendicular to the extrusion direction, but the whisker orientation did not change appreciably during these subsequent reductions.

Composites with nodule and particulate reinforcement did not show any appreciable directionality in properties. Microstructures of composites containing particulate reinforcement indicated a coarser platelet structure with no significant preferred orientation. Composites with nodule reinforcement had a similar microstructure.

The effect of reinforcement content on stress-strain behavior and properties was examined using a series of specimens of different SiC whisker reinforcement contents in a heat treated 6061 Al matrix. Figure 2 shows that the modulus of elasticity increases with increasing reinforcement content. This increase, however, is not linear, as in the case of continuous fiber composites with fibers aligned in the longitudinal direction, and the modulus was below that expected from the fiber-composite rule of mixtures-type behavior. The modulus tended to follow a hyperbolic function with reinforcement content, similar to that observed for the transverse modulus behavior of fiber composites. This would be expected since, along a given plane in the transverse direction, the cross section of a round fiber would act in a manner similar to that of the discontinuous SiC reinforcement.

The most significant aspect of the data shown in Fig. 2 is the increase in modulus over that of unreinforced aluminum. Composites with 20 v/o SiC reinforcement showed a 50 percent increase in modulus, while with 30 v/o reinforcement, the increase was 70 percent. Data presented in Ref. 3 indicated that this same trend of increase continued up to 40 v/o reinforcement.

Figure 3 shows the effect of reinforcement content on the 0.2 percent offset yield and ultimate tensile strengths of SiC/Al composites. In this case, the results are also based upon tensile tests of the same heat treated 6061 Al composites with SiC whisker reinforcement as in Fig. 2. The yield and tensile strengths increased with increasing reinforcement. Part of the explanation of this increase observed in strength can be seen from the stress-strain curves presented in Fig. 4. As the reinforcement content increases, the slope of the stress-strain curve also increased as the composite entered plastic flow. This would indicate that the strength increase was related to interaction of dislocations with the SiC reinforcement, resulting in increased work-hardening with higher stresses being required to deform the composite.

These stress-strain curves also reflect a change in the fracture mode with increasing reinforcement content. Aluminum specimens, with no SiC reinforcement, exhibited failure strains of about 15 percent, and fractured with a 45-degree chisel-point shape across the thickness of the specimen. There was also a contraction in the width of the specimen at the fracture plane. Composite specimens with low reinforcement contents of 10-20 v/o in 6061 Al exhibited the same type of a smooth 45-degree chisel point type failure across the thickness, but without the width contraction. Failure strains of 6-12 percent were observed with this type of fracture. At higher reinforcement contents, the fracture underwent a transition, where one side had a smooth 45-degree chisel extending about half-way through the width of the specimen, but then became flat and granular for the remainder of the section thickness. This change in fracture behavior did not seriously affect the overall strain to failure. At reinforcement contents of 30 v/o, the fracture became flat and granular across the entire width, with no evidence of a chisel point. Composites exhibiting this type of fracture mode failed in a brittle manner, with a failure strain of 2 percent or less. As a result of the reduced strain to failure, increased scatter was observed in the tensile strength measured for composites with higher SiC contents. The composites failed while still in the ascending portion of the stress-strain curve, and a slight reduction in failure strain made a significant difference in the tensile strength obtained.

The effect of heat treatment on the stress-strain behavior and properties of the composites was examined by studying a series of specimens with various whisker-SiC reinforcement contents in a 6061 Al matrix. The composites were tested in both the as-fabricated (F-temper) and in the heat treated (T6-temper) condition. The heat treatments used (Refs. 3 and 5) are shown on Table I. Stress-strain curves of SiC-whisker reinforced 6061 Al composites are presented in Fig. 5 showing that heat treatment gave a significant increase in yield and tensile strengths of the composites at all reinforcement contents tested. In most cases, the heat treatment also gave a slight loss in ductility along with the strength increases.

The effect of different matrix alloys on the stress-strain behavior and mechanical properties of SiC/Al composites was examined using a series of specimens containing 20 v/o SiC-whisker reinforcement in each of the four alloys tested. Composites with heat treatable alloy matrices were tested in the T6-temper, while the composites with a 5083 Al matrix were tested in the F-temper. Stress-strain curves of 20 v/o SiC whisker composites with different matrices are presented in Fig. 6. These curves show that the use of higher strength aluminum alloys, such as 2024 or 7075 Al, resulted in higher strength, but lower ductility. Composites with a 6061 Al matrix showed good strength and higher ductility. Composites with a 5083 Al matrix failed in a brittle manner, at a strain of less than 1 percent.

The modulus of the SiC/Al composites was independent of matrix alloy or heat treatment. However, for a given reinforcement content, the failure strain and yield/tensile strength were controlled by the matrix alloy and heat treatment. Figure 7 shows a histogram summarizing the effects of matrix alloy and heat treatment on the 0.2 percent offset yield strength of composites containing 20 v/o SiC-whisker reinforcement, in both the F and T6 temper conditions where applicable. The heat treatments used for composites with each matrix alloy are shown in Table I. Figure 8 shows a similar histogram for ultimate tensile strength. The values shown for the unreinforced matrix alloys were taken from the values for maximum strength tempers listed in

Ref. 5. These plots show that the yield and ultimate tensile strength of the SiC/Al composites, with other conditions being constant, were controlled by the intrinsic yield/tensile strength of the matrix alloy. Figures 7 and 8 also show that, in general, the yield and tensile strengths of the composites, with 20 v/o reinforcement, were higher than those of the same heat treated matrix alloys without reinforcement. The same trends of increased yield/tensile strength were also observed for composites with these matrices using other SiC reinforcements and at other reinforcement contents. The largest increase in yield/tensile strengths was achieved by the SiC-reinforced 6061 Al composites, in which the strengths were increased by one-third over that of the unreinforced matrix alloy.

Figure 9 shows a comparison of the relative modulus/density ratios of the various matrix alloys used for the SiC/Al composites studied. Again, the modulus is basically dependent upon the reinforcement content, and is independent of reinforcement type and matrix alloy. These results show that at 20 v/o reinforcement, the modulus of elasticity of SiC/Al composites can be increased 50 percent above that of aluminum, to a value about that of titanium. This increase in modulus is achieved with a material having a density one-third less than that of titanium. The tensile strength of the SiC/Al composites is about the same as that of unreinforced aluminum alloys, and the composites showed a 4-12 percent strain to failure. At 30 v/o SiC, the modulus was increased by 70 percent, with about a 10 percent increase in yield and tensile strengths, but the strain to failure was reduced to <1-2 percent. Modulus and strength tended to be the highest for the whisker-reinforced composites, with values about 5 percent less for the particulate, and about 10 percent less for the nodule reinforcement.

The discontinuous SiC/Al composites also showed an advantage over conventional aluminum alloys at elevated temperatures. Figure 10 plots the results of tensile tests conducted on composites of 20 v/o SiC whiskers in a 6061 Al matrix at temperatures up to 316° C (600° F). The data at room temperature represent an average of several tests. The data for unreinforced 6061 Al are from Ref. 5. The composites continued to demonstrate a strength advantage over unreinforced 6061 Al over this entire temperature range and offer about a 109° C (200° F) increase in use temperature over conventional aluminum.

The results of this study showed that these low cost Al matrix composites, projected to sell for about $20/lb, demonstrate a good potential for application to aircraft engine components, such as compressor vanes and static structures. They merit additional work to determine their fatigue and thermal cycle behavior to more fully characterize their properties and allow their consideration for structural design. The composites are formable at warm working temperatures and can be made directly into structural shapes during fabrication, with a minimum of final machining required.

For applications where a high modulus, in the range of 103 GPa (15 Msi), a high strength and a good ductility are required, a composite with 20 v/o SiC in a 6061 Al matrix, could be substituted. These composites have a greater strain to failure and should offer a greater margin of safety under operating conditions. For applications where maximum stiffness is required, a 30 v/o SiC composite, with 6061 Al matrix, could be used (124 GPa -18 Msi). If maximum stiffness, 124-152 GPa (18-22 Msi), and strength 621 MPa (90 ksi) are required, then a 30-40 v/o SiC composite, with 2024 or 7075 Al matrix, would have the best potential.

ALUMINUM OXIDE/ALUMINUM COMPOSITES

Along with the SiC/Al evaluation, NASA-Lewis has also evaluated Al_2O_3/Al composites to determine their potential as low cost aluminum matrix composites for structural applications. Aluminum oxide fiber is being experimentally produced by duPont as a continuous, polycrystalline α-Al_2O_3 yarn and marketed under the name of FP fiber (Ref. 6). The yarn contains 210 filaments, with each filament being round in cross section, and with each filament having an average diameter of 20 microns. The fiber has a density of 3.90 g/cc (0.141 pci). The projected cost of this fiber is about $25/lb. The fiber has a high modulus of 345–379 GPa (50–55 Msi) and a reasonable tensile strength of 1380 MPa (200 ksi). Two methods were investigated for fabricating Al_2O_3 fiber into Al_2O_3/Al composites: Wire Preforms and Direct Casting.

NASA-Lewis awarded a series of contracts to Fiber Materials Inc. (FMI), and their subsidiary, Materials Concepts Inc. (MCI) to fabricate Al_2O_3/Al composites (Refs. 7 to 9). The intent of these contracts was to utilize the existing fabrication technology available for graphite/aluminum composites to produce Al_2O_3/Al composites. After being given a thermal treatment, the fiber yarn was passed through a molten bath of 1100 Al with 0.3 w/o Mg added to improve the wettability of the molten matrix to the fiber. These yarns were infiltrated by capillary flow of the molten aluminum and were in the form of wire preforms after cooling.

These wire preforms were consolidated into plates by hot pressing or by hot drawing through shaping dies (pultrusion) to fabricate composites with 20-40 v/o fiber. Figures 11 and 12 summarize the modulus and tensile strength results obtained in these studies. The reduced properties of the pultruded material were caused by fiber breakage during the drawing process. Hot pressing eliminated this breakage and higher moduli and tensile strengths were obtained. Additional wire preforms were consolidated into structural "hat" and channel shapes by hot pressing (Ref. 9). A photograph of these structural shapes is presented in Fig. 13. Hot pressing caused the wire preforms to tend to merge together and gave a fairly uniform fiber distribution throughout the structure (Fig. 14). The outer surfaces of the structural shapes tended to be matrix-rich because additional Al foils were added at the outer surfaces to give a smoother surface and avoid roughness from fiber replication.

Results from Refs. 7 to 9 indicated that the effective tensile strength of the Al_2O_3 fiber in the composite had been reduced to about 841 MPa (122 ksi), a degradation of about 39 percent from the strength of the starting fiber. An additional contract was awarded to FMI to study various mechanisms of increasing the strength of the Al_2O_3 fiber (Ref. 10). A detailed study of the properties of the Al_2O_3 fiber showed considerable variation in strength along its length and from spool to spool. Attempts at hot-stretching the fiber were unsuccessful, but high temperature heat treatments and deposition of a glassy carbon coating did increase the effective fiber strength in the composite from 841 MPa (122 ksi) to 1117 MPa (162 ksi).

A contract also was awarded to the duPont Pioneering Research Laboratory to fabricate Al_2O_3/Al composite simulated compressor vanes by direct casting to net shape. This direct casting process was similar to that described in Ref. 6, which also reported an effective fiber strength of about 1103 MPa (160 ksi) in the composite. Small lithium additions (2 w/o) were made to the pure aluminum melt to promote wettability of the matrix to the Al_2O_3 fiber. The fibers were positioned in the mold to give proper fiber loading and orientation. The simulated compressor vane chosen by NASA-Lewis for this study was a demonstration shape that incorporated a rounded leading edge, flat chordal surfaces, and taper to a sharply pointed trailing edge. The demonstration vane-like shapes were cast in both solid and hollow configurations to determine the feasibility fabricating of both geometries. A standard fiber content of 35 v/o was used although one simulated vane was cast with 55 v/o to demonstrate process flexibility. Fiber orientations of either unidirectional (0 degrees) or ±15 degrees were used to demonstrate the feasibility of angle-plying to resist multiaxial loads.

Photographs of these demonstration vanes are shown in Fig. 15. Cross sections of the solid demonstration vane-shapes are presented in Fig. 16, showing good fiber distribution for both the unidirectional and ±15 degree plies. The individual yarns tended to keep gathered together, but the fiber distribution is good. The Al-infiltrated individual ±15 degree angleplied yarns tended to form an aluminum boundary between plies, but again show a good overall fiber distribution. Figure 17 shows photographs of hollow blades with unidirectional and ±15 degree angleplied fibers. The fiber distribution in the shank of the taper and along the flat by the hollow chord section is good, however the distribution became somewhat uneven for the angleplied fiber yarns at the curved leading edge and at the radius at each end of the hollow section. This unevenness was probably caused by ply shifting within the mold, and further development should alleviate this problem.

Other NASA work, reported in Ref. 11, indicated that cast Al_2O_3/Al and Al_2O_3/Mg composites showed a strength and modulus degradation after isothermal exposure of 120 hours at 350° and 425° C (662°-797° F) which was attributed to matrix softening. Further work (Ref. 12) reported that cast Al_2O_3/Mg composites showed no strength or modulus degradation after 3000 thermal cycles between 50°-250° C (122°-482° F). It would be expected that the Al matrix composites would show similar or improved behavior to that of the Mg matrix composites.

The feasibility of fabricating high modulus Al_2O_3 composites by both the wire preform and direct casting processes was demonstrated in these programs. The modulus properties are very attractive and the strength is acceptable. Composites may be fabricated by either method, but the direct casting probably offers the lower cost commercial practice. On the basis of these results, it appears that Al_2O_3/Al composites offer good potential for use as engine components and structures that are cost-, weight- and stiffness-critical, at service temperatures up to 250° C (482° F).

BORON CARBIDE-COATED BORON/ALUMINUM (B_4C-B/Al) COMPOSITES

Another phase of this effort was the investigation of reducing fabrication costs of high performance composites. Avco Corp. has recently started marketing a B_4C-coated boron fiber. The B_4C-B fiber is currently being produced only in a diameter of 0.149 mm (5.6 mils). The B_4C coating is deposited by CVD on the surface of conventional boron fiber during fiber production. A coating thickness of about 5 microns was found to increase the tensile strength of the boron fibers and also to act as a diffusion barrier to inhibit reaction with aluminum. Decreased reaction at temperatures near and above the melting point of aluminum allowed much high fabrication temperatures to be used in composite fabrication without degradation of fiber properties.

Because of the increased tolerance to higher fabrication temperatures exhibited by B_4C-B fibers, NASA-Lewis awarded contracts to demonstrate the feasibility of low-pressure/high-temperature bonding of B_4C-B/Al composites by fabricating and testing a subscale prototype of an instrument mounting platform typical of that required for a sensor mounting panel in an orbiting spacecraft. Avco Specialty Metals Division was awarded a contract to develop a low-pressure hot molding composite fabrication process, to fabricate the components and to assemble the platform structure. General Electric Space Systems Division was awarded a contract to design and test the prototype structure.

The B_4C coating allows the boron fiber to be exposed to molten aluminum for short periods of time with little or no degradation of properties. This allowed processing temperatures to be increased, which in turn allowed processing pressures to be decreased. Standard diffusion bonding processing for B/6061 Al composites is 530° C (980° F), for 30 minutes at a pressure of 34 MPa (5000 psi). In the low-pressure hot molding process (Ref. 13), a two-phase aluminum matrix alloy was heated to a temperature above the solidus temperature and pressures from 0.7 to 10.3 MPa (100 to 1500 psi) were used to consolidate the composite at temperatures of 527°-627° C (980°-1160° F). Three types of fiber preforms were used. It was found that the B_4C/Al interface was weak when relying on the bond formed by hot molding the aluminum matrix into fugitive binder green tape or dry woven tape preforms, leading to reduced transverse strength of the composites. Plasma spraying a thin layer of matrix onto the tape layup eliminated this problem and allowed an intimate, but not degrading, bond to be formed between the coating and the matrix. Composites with modulus and tensile strength comparable to those of conventionally fabricated B/Al were produced by hot molding of 6061 Al foil/plasma sprayed 6061 Al preforms at pressures under 6.9 MPa (1000 psi).

Flat plates were fabricated to evaluate bonding conditions from tensile test results. After optimization of the bonding parameters, "Zee" member structural shapes were fabricated in an autoclave under low-pressure hot molding conditions. The "Zee" members were tested and a demonstration structure was assembled by spot welding "Zee" members onto a flat plate. A photograph of this structure is shown in Fig. 18. Crippling tests run on this preliminary prototype structure were encouraging. The structure failed in the anticipated manner at 80 percent of the theoretical prediction. A slight misalignment of the plates during spot welding prevented attainment of full properties.

The feasibility of fabricating flat panels and preliminary prototype structures by low pressure hot molding was successfully demonstrated. The method offers the potential of fabricating large composite structures by low pressure autoclave consolidation. Hot molding gives the potential of reducing fabrication costs by using lighter, less expensive tooling, and by using smaller, lower capital cost, press capability to consolidate B/Al high pefor-mance composites.

CONCLUSIONS

Studies were undertaken to assess the potential of low cost materials and fabrication processing methods for applying aluminum matrix composites to air-craft engine components and structures. Panels and structural shapes were fabricated and delivered to NASA-Lewis Research Center for evaluation. The properties obtained on these materials led to the following conclusions:

1. Low-cost, light-weight aluminum matrix composites containing dis-continuous SiC reinforcement show very good potential for application to aircraft engine structures. The properties of composites containing whisker, nodule or particulate SiC reinforcement are similar and tend to be isotropic.

2. The discontinuous SiC/Al composites offer a 50-100 percent increase over the modulus of unreinforced aluminum and offer a modulus equivalent to that of titanium, but at a third less density. For a given weight, they offer twice the modulus of titanium.

3. The modulus of SiC/Al composites is controlled by the amount of SiC reinforcement. The yield and tensile strengths are controlled by the proper-ties of the aluminum matrix and heat treatment used, at a given reinforcement

content. The overall strength and ductility of the composites are controlled by the matrix alloy and the amount of reinforcement.

4. The feasibility of fabricating structural shapes was demonstrated for Al_2O_3/Al composites. These composites are suitable for applications requiring low-cost, light-weight materials with directional very high modulus requirements.

5. The feasibility of fabricating structural shapes of B_4C-coated boron fibers in an aluminum matrix by low pressure hot molding was demonstrated. High performance aluminum matrix composites can be fabricated at low autoclave pressures offering the possibility of lower cost fabrication of large aerospace structures.

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TABLE I. - HEAT TREATMENTS OF ALUMINUM MATRIX COMPOSITES

Alloy	Solution treatment	Artificial aging
2024	482° C (900° F) - 2 hr W.Q.	177° C (350° F) - 24 hr A.C.
6061	527° C (980° F) - 2 hr W.Q.	177° C (350° F) - 18 hr A.C.
7075	482° C (900° F) - 2 hr W.Q.	121° C (250° F) - 24 hr A.C.

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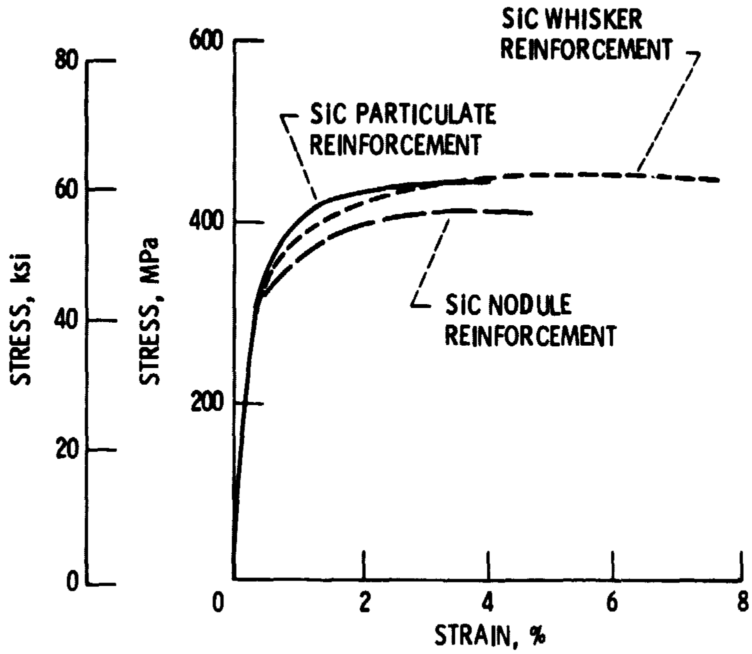

Figure 1. - Effect of different types of discontinuous SiC reinforcements on stress-strain behavior of heat treated 6061 Al matrix composites.

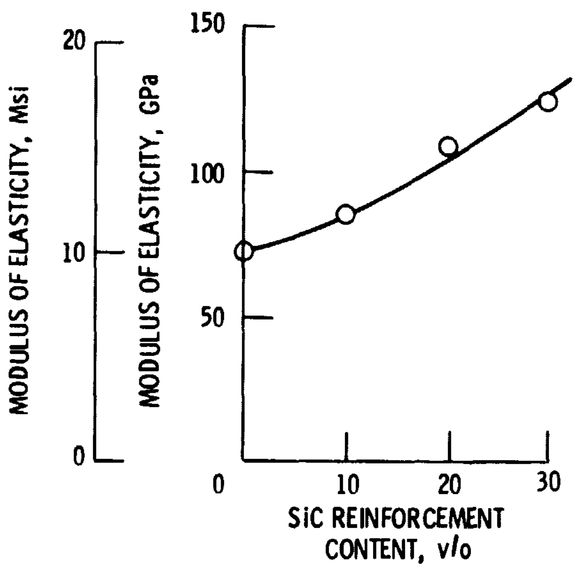

Figure 2. - Effect of SiC-whisker reinforcement content on modulus of elasticity of 6061 Al matrix composites.

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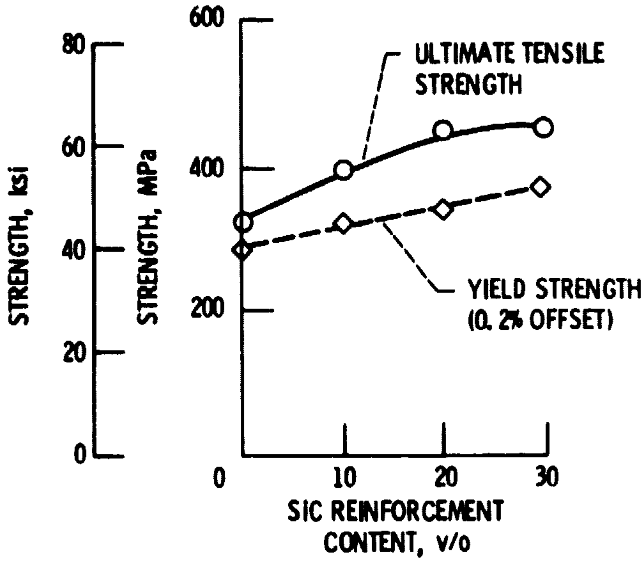

Figure 3. - Effect of SiC-whisker reinforcement content on yield strength and tensile strength of heat treated 6061 Al matrix composites.

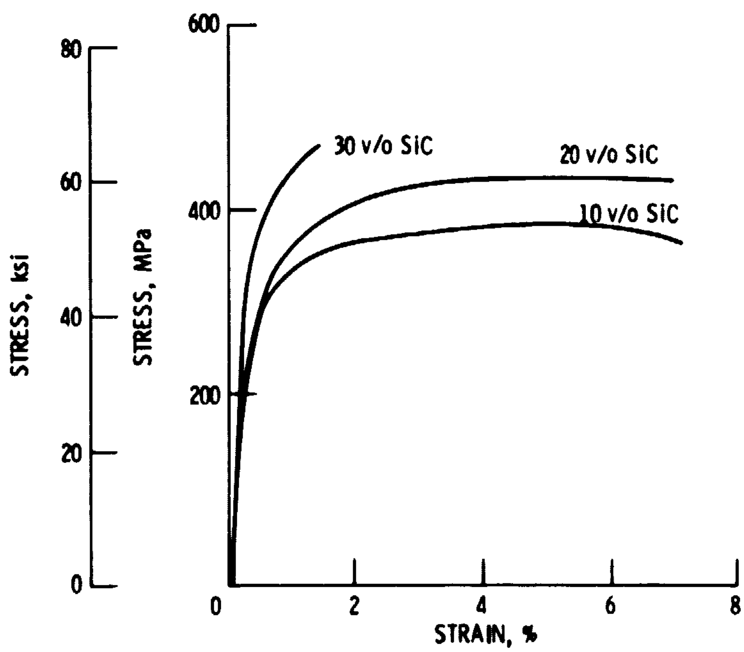

Figure 4. - Effect of SiC-whisker reinforcement content on stress-strain behavior of heat treated 6061 Al matrix composites.

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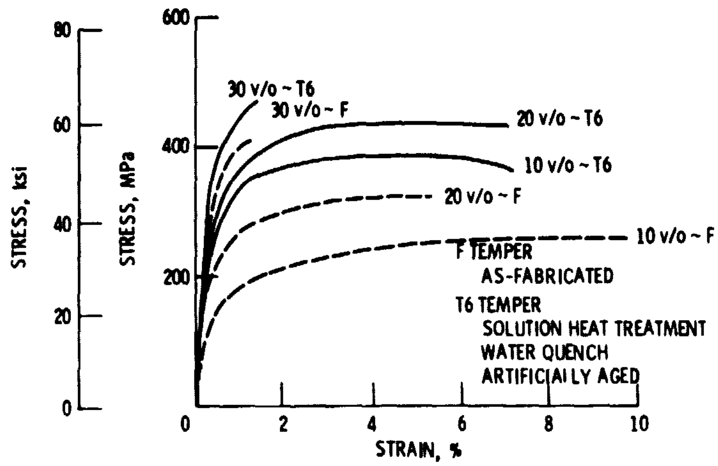

Figure 5. - Effect of heat treatment on stress-strain behavior of SiC-whisker reinforced 6061 Al matrix composites.

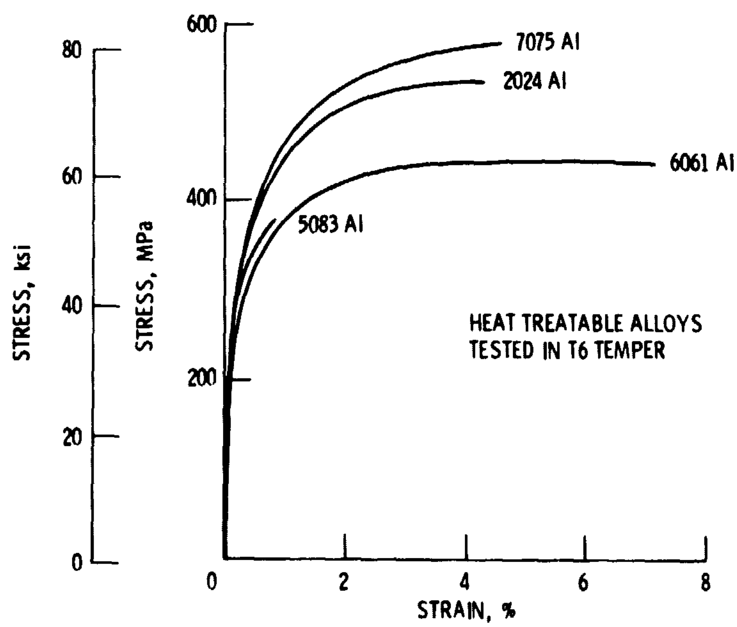

Figure 6. - Effect of Al matrix alloy on stress-strain behavior of heat treated composites with 20 v/o SiC-whisker reinforcement.

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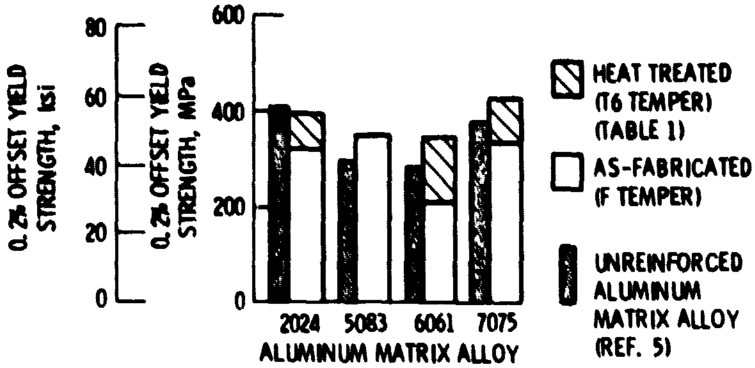

Figure 7. - Effect of Al matrix alloy and heat treatment on yield strength of 20 v/o SiC-whisker reinforced composites.

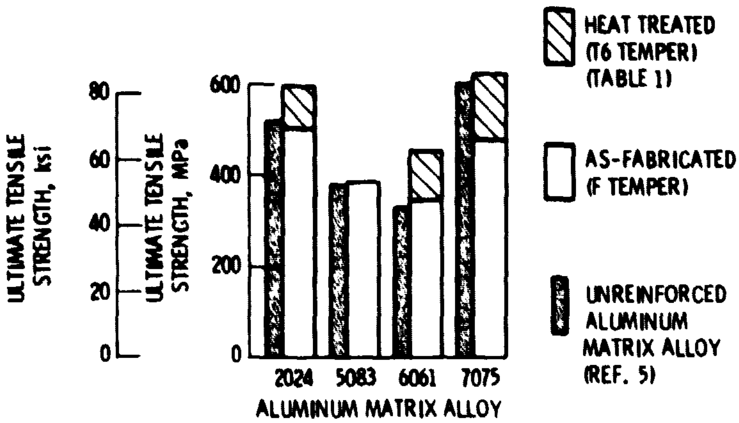

Figure 8. - Effect of Al matrix alloy and heat treatment on tensile strength of 20 v/o SiC-whisker reinforced composites.

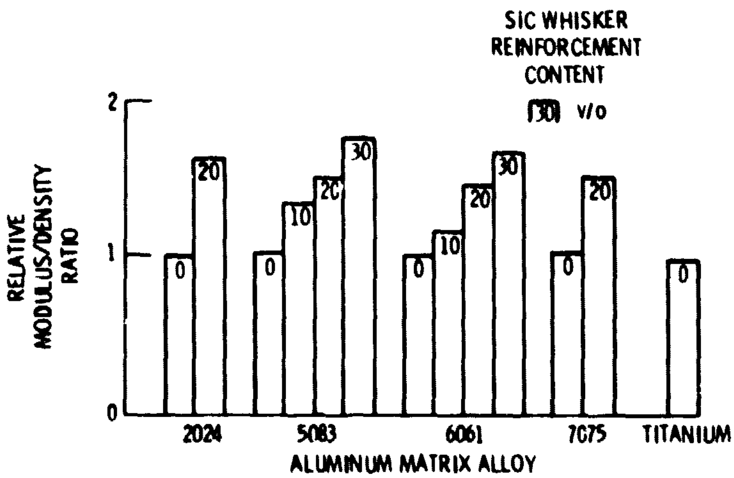

Figure 9. - Comparison of relative modulus/density ratios of whisker reinforced SiC/Al composites.

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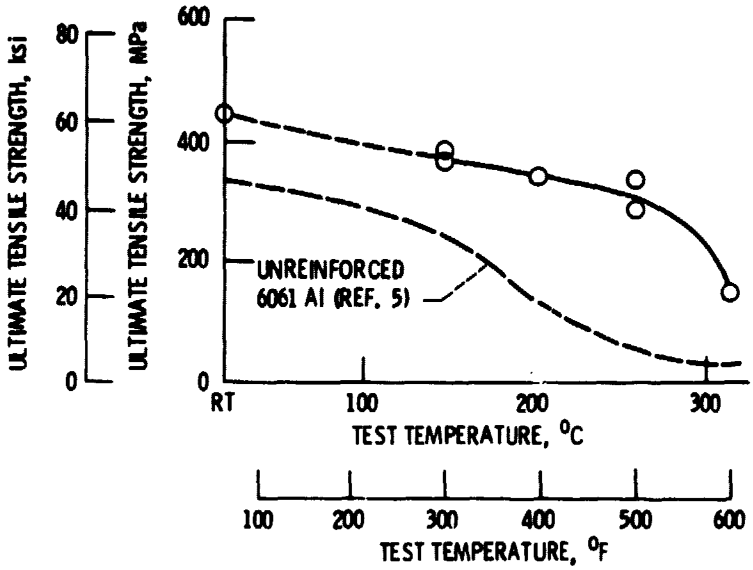


Figure 10. - Effect of test temperature on tensile strength of 20 v/o SiC-whisker reinforced 6061 Al matrix composites.

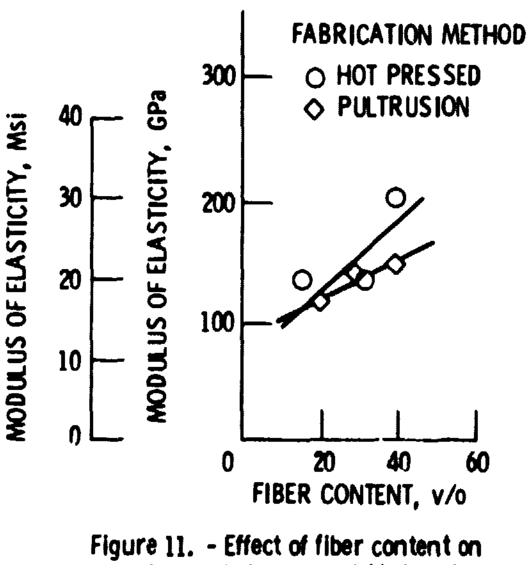


Figure 11. - Effect of fiber content on modulus of elasticity of Al_2O_3/Al composites fabricated by hot pressing or pultrusion of wire preforms.

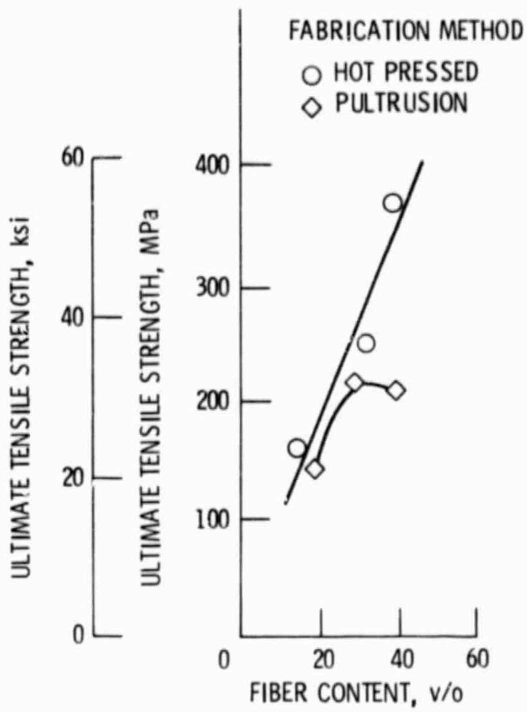


Figure 12. - Effect of fiber content on tensile strength of Al_2O_3/Al composites fabricated by hot pressing or pultrusion of wire preforms.

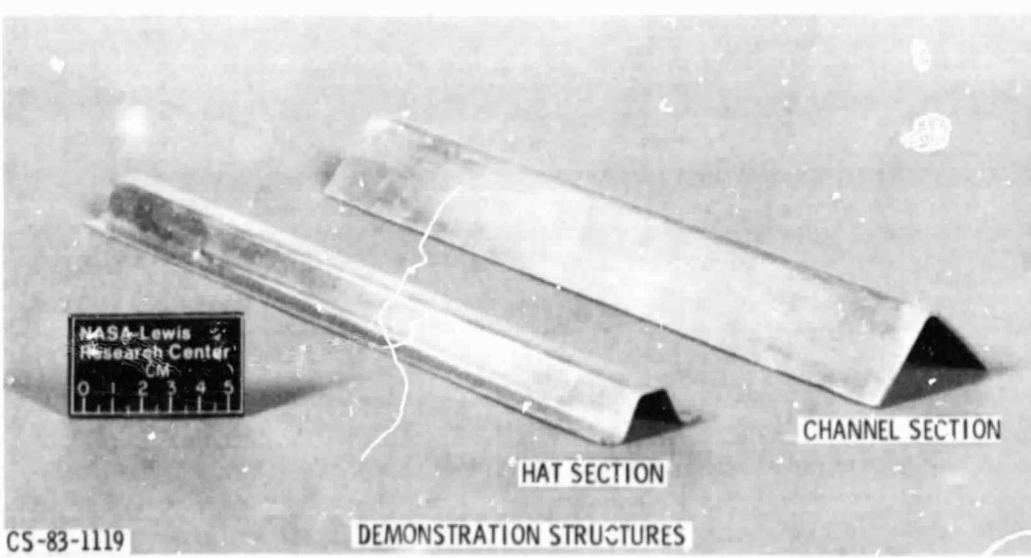
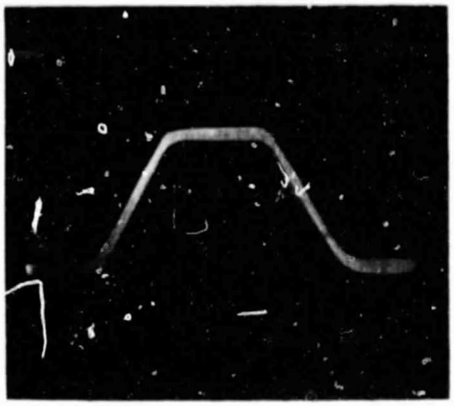
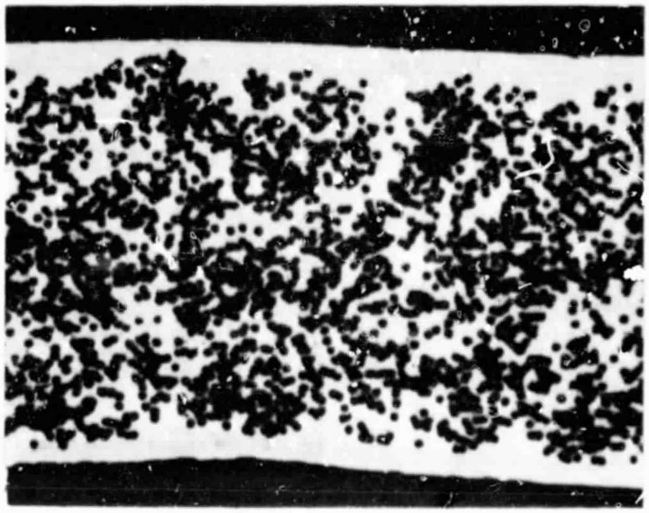


Figure 13. - Photograph of structural shapes fabricated by hot pressing of Al_2O_3/Al composite wire performs.



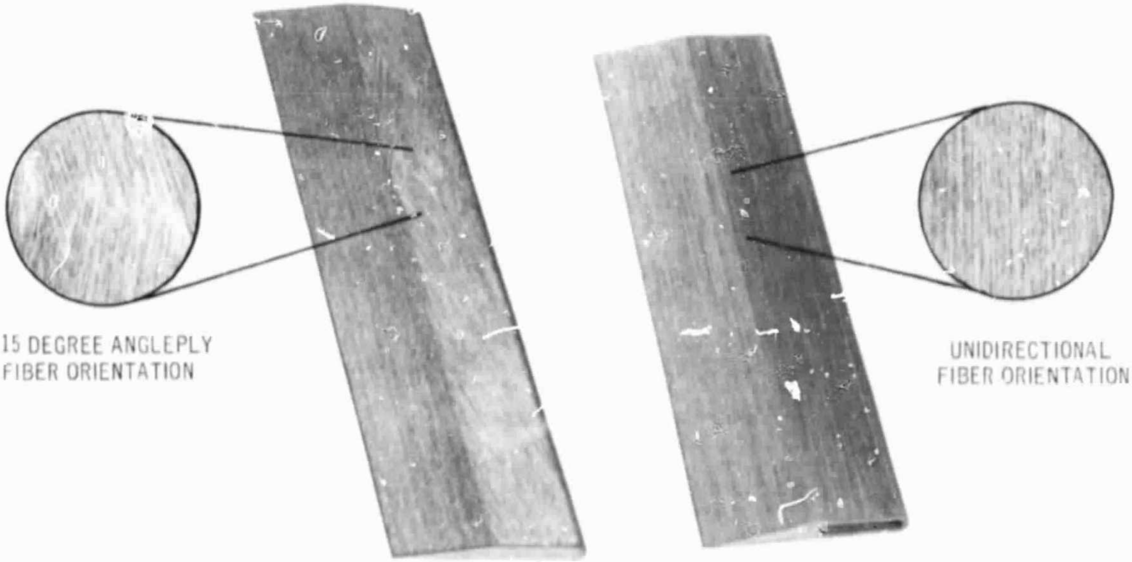
DEMONSTRATION HAT SECTION

FP ALUMINUM OXIDE FIBER
UNIDIRECTIONAL FIBER ORIENTATION



1 mm

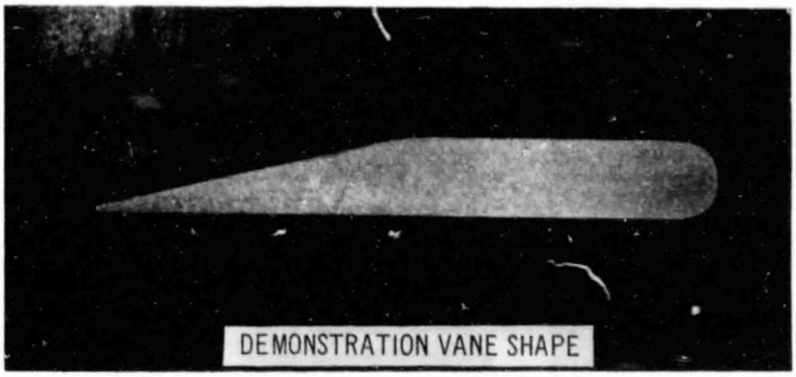
Figure 14. - Photographs of Al_2O_3/Al composite structure fabricated by hot pressing of wire preforms.



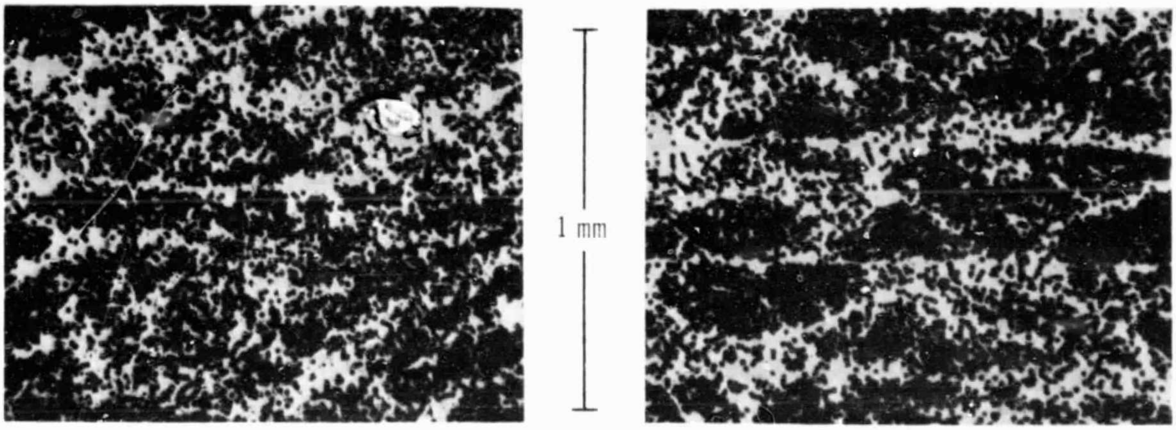
SOLID CONFIGURATION HOLLOW CONFIGURATION

DEMONSTRATION VANE SHAPE

Figure 15. - Photographs of demonstration vane shapes fabricated by direct casting of Al_2O_3/Al composites.



SOLID CONFIGURATION
35 v/o FP ALUMINUM OXIDE FIBER



UNIDIRECTIONAL
FIBER ORIENTATION

15 DEGREE ANGLEPLY
FIBER ORIENTATION

Figure 16. - Photographs of cross section of solid configuration demonstration vane shape fabricated by direct casting of Al_2O_3/Al composites.

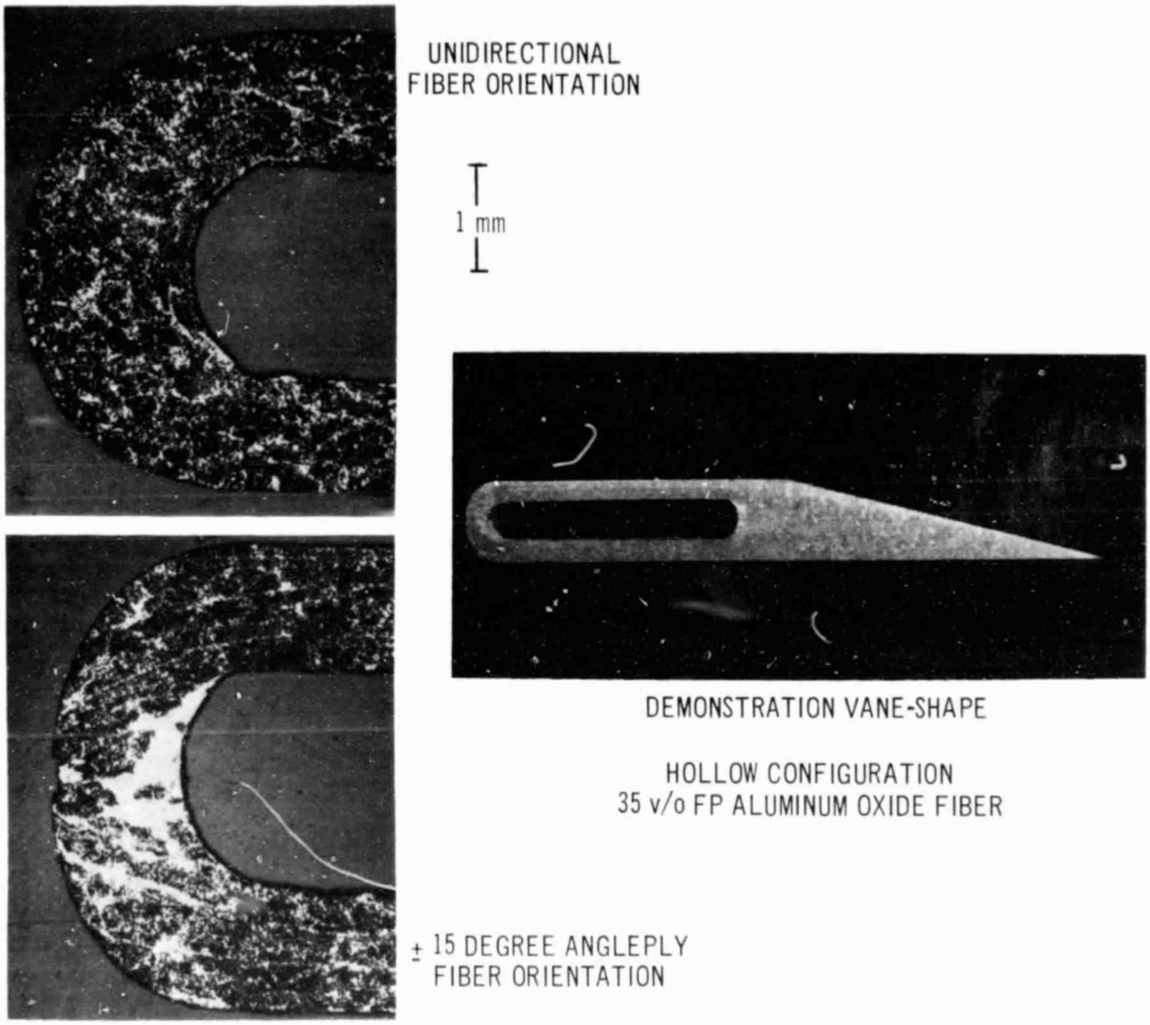


Figure 17. - Photographs of cross section of hollow configuration demonstration vane shape fabricated by direct casting of Al_2O_3/Al composites.

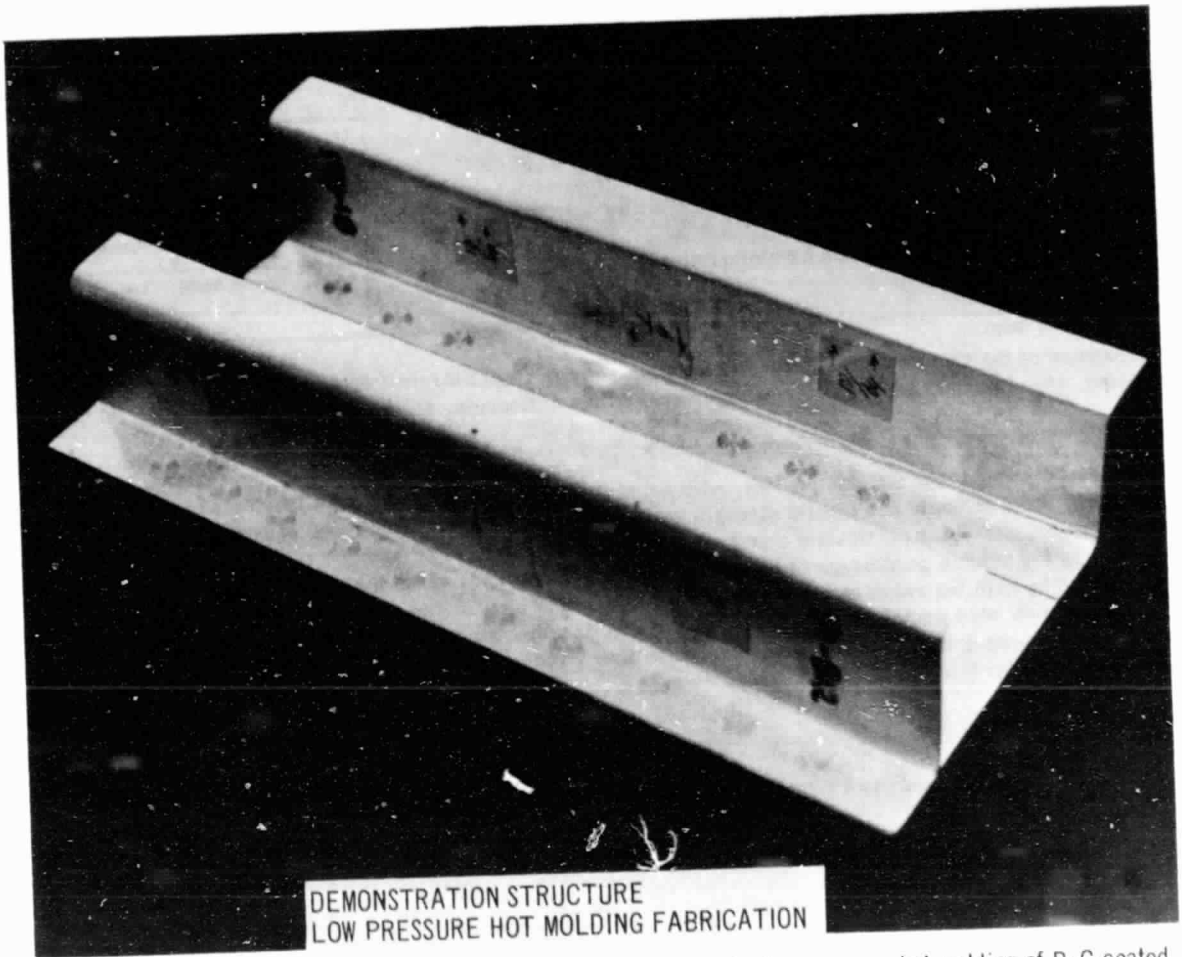


Figure 18. - Photograph of structural prototype structure fabricated by low pressure hot molding of B_4C-coated B/Al composites.