COMPOSITE MATERIALS RESEARCH IN SUPPORT OF SUPERSONIC PROPULSION SYSTEMS

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SUMMARY

Two engine components, fan blades and exhaust systems, have been selected for composite materials development efforts in support of the supersonic cruise aircraft research (SCAR) engine program. The materials selected were boron/aluminum for fan blades and silicon carbide/superalloy sheet for the exhaust system. The current status of the research into applying these two composite materials to SCAR engines is reviewed in this paper.

Significant progress has been made in improving the impact resistance of boron/aluminum, and the improved material is being evaluated in prototype SCAR fan-blade rig tests. Reaction at the silicon carbide fiber - superalloy matrix interface has been identified as a problem area in fabricating composite sheet. Diffusion barriers appear to control this interfacial reaction, permitting composite development to proceed.

INTRODUCTION

Propulsion systems for supersonic cruise aircraft will require improved materials to achieve low ground noise on takeoff as well as efficient subsonic and supersonic flight. Some of the advanced-design engine components needed for this purpose can be achieved through the use of advanced composite materials. Composite materials offer the potential for better component performance than conventional materials because they have higher modulus, lower density, and greater strength. For example, using boron/aluminum fan blades for 275° to 375° C (500° to 700° F) service can reduce fan-blade stage weight by 25 to 40 percent from that of standard titanium alloy blades. In addition, aerodynamic performance is improved by the removal of midspan dampers, which is made possible by the greater stiffness of boron/aluminum. The lower blade weight also permits lower disk, shaft, bearing, and containment ring weights.

Silicon carbide/superalloy composite sheet will permit higher material operating temperatures than conventional superalloy sheet because the silicon carbide reinforcement retains its strength to above 1100° C (2000° F). Thus, trade-offs are possible between higher operating temperatures and decreased cooling-air requirements for the exhaust system. In addition, because the reinforcing filaments have less than half the density of conventional superalloys, the density of the composite is 20 to 25 percent lower than that of a conventional superalloy.

The current status of the research on boron/aluminum fan blades and silicon carbide/superalloy sheet for exhaust systems for SCAR engine applications is reviewed.

Values are given in both SI and U.S. customary units. The work was done in U.S. customary units.

BORON/ALUMINUM FAN BLADES

Composite fan blades have been fabricated in related programs and have shown excellent potential for fulfilling the requirements for advanced-engine fan blades. Fabrication processing of such blades generally involves production of monolayer composite tape by diffusion bonding two aluminum foils about a uniaxially oriented boron fiber array. Plies cut from the composite monolayer are stacked to fill a die cavity and are hot pressed to a blade shape such as that shown in figure 1. The desired blade properties are obtained by suitable orientation of the plies and selection of the stacking sequence. The relative advantages of boron/aluminum over titanium alloy, the standard fan-blade material, are also shown in the figure. The composite has better than a twofold strength/density and modulus/density advantage over titanium. Use temperature of the boron/aluminum is also greater than that of aluminum alloys (not shown in fig. 1). The boron fiber retains strength to well above 500° C (930° F) and increases the use temperature of boron/aluminum to 375° C (700° F).

While many properties of composite materials are superior to those of conventional materials, the impact resistance demonstrated has been inconsistent and, in many cases, inadequate for fan blades. Notched Charpy pendulum impact data for a titanium alloy and early boron/aluminum are compared in figure 2. The composite material has less than half the impact resistance of a typical titanium alloy used for fan blades.

Based on laboratory and rig tests of specimens and blades, it is probably safe to say that the impact resistance of boron/aluminum composites to small objects such as ice balls, gravel, rivets, and sand is acceptable. However, resistance to large objects such as birds has been less than adequate. Bird ingestion generally occurs at low altitudes because that is where most birds fly. Therefore, bird impact damage is most likely to occur during takeoff or landing of aircraft. Over half of the bird population is found at altitudes of less than 150 meters (ref. 1). Figure 3 clearly illustrates the potential danger of bird impact to aircraft engine fan blades. Even so, bird ingestion is rare, and usually does not cause severe operational changes in modern turbofan engines. However, as shown in figure 4, even standard titanium alloy fan blades can be damaged as a result of bird impact. The damage shown in this figure for a titanium alloy blade is representative of a severe impact condition. Also shown is an early boron/aluminum blade subjected to severe impact in a whirling-arm rig test. However, the poor impact resistance that led to the multiple failure of this early boron/aluminum blade does not represent the potential of this type of composite.

Studies to understand and improve boron/aluminum impact resistance have been undertaken at several laboratories (refs. 2 to 8). The major variables that were investigated in a program undertaken by the Lewis Research Center to improve boron/aluminum fan-blade impact resistance were fiber diameter, matrix alloy ductility, fabrication processing, and fiber ply orientation. The choice of variables was influenced by efforts to minimize the embrittling effects of the low strain-to-failure boron fibers in an otherwise relatively ductile aluminum alloy. Large-diameter fibers ($\leq$ 0.2 mm) were selected to increase the interfiber distance in the composite and thereby reduce the volume of the matrix constrained by the high-modulus, low-strain boron fibers and permit greater strain in the composite upon impact. Fabrication processing was improved to obtain low-porosity, well-consolidated composites and a high degree of bonding between the fiber and the matrix and between matrix fiber plies. However, the bonding temperature was kept low to minimize reaction at the fiber/matrix interface since such reaction generally degrades composite properties. In addition, the fiber ply orientation was selected to provide a viable compromise between the properties required in the various directions and the impact resistance of the composite. Significant increases in impact resistance were obtained through these approaches (refs. 8 to 10). Only some of the results are included herein for brevity.

Increasing fiber diameter from 0.1 millimeter to 0.2 millimeter increased notched Charpy impact strength from less than 40 joules to 96 joules (fig. 5). These larger diameter fibers were incorporated in specimens that had the best combination of the other beneficial effects (such as better processing and a more ductile matrix) identified in the program. Increasing the ductility of the matrix by using commercially pure, 1100 alloy aluminum increased Charpy impact strength from less than 20 joules to 96 joules (fig. 6).

The marked improvement in impact resistance is illustrated in figure 7, which compares impact values of a typical titanium alloy fan-blade material, an early boron/aluminum composite, and an improved boron/aluminum composite. A tenfold increase in laboratory pendulum impact values, as shown in figure 7, is very encouraging but not necessarily indicative of satisfactory foreign-object-damage resistance at the high-velocity impact conditions that fan blades encounter in normal service. Fan and compressor blades of the improved boron/aluminum are being fabricated and tested, and preliminary results are encouraging. Composite J-79 blades containing improved boron/aluminum material are shown in figure 8 after bird impact testing in single-blade, rotating-rig tests. These blades were included in a joint Air Force - NASA program. Each of the three blades was impacted by a real bird under conditions simulating aircraft takeoff conditions. These blades showed evidence of some deformation and delamination at the tip of the airfoil near the impact point. However, no portion of the blade was broken off by the impact.

Improved impact-resistant boron/aluminum is currently being used in a prototype SCAR blade. Figure 9 shows one of the preliminary blades fabricated from boron/aluminum for evaluation, which includes rotating-rig impact tests. Additional blades are being fabricated for evaluation in the near future. The encouraging results obtained in this impact testing suggest that foreign-object-damage resistance, the remaining major technical impediment to successful flight demonstration of boron/aluminum blades, may have been overcome.

SILICON CARBIDE/SUPERALLOY COMPOSITE SHEET FOR EXHAUST SYSTEMS

Exhaust system components can be a significant portion of SCAR engine weight. The high-temperature portions of a SCAR engine, which operate at temperatures to 980° C (1800° F), have been estimated to weigh 550 kilograms (1200 lb) (private communication from R. A. Howlett, Pratt & Whitney Aircraft, East Hartford, Conn.). Substituting silicon carbide/superalloy composite sheet for the conventional superalloy could reduce that weight by about 20 to 25 percent or by about 120 kilograms (264 lb). This weight reduction is due to the lower density of the silicon carbide fiber. In addition to the lower density advantage, the silicon carbide fiber retains greater strength and stiffness at the operating temperature, 980° C (1800° F). The silicon carbide/superalloy composite sheet can be expected to have four times the tensile strength, twice the elastic modulus, and five times the 1000-hour rupture strength of conventional superalloy sheet at 980° C. These superior mechanical properties can be used to design more efficient systems that use less cooling air and to reduce weight by using thinner sections.

To make the silicon carbide/superalloy composite sheet a viable material system, certain problems must be addressed. The property advantages can be achieved only if fiber-degrading chemical interaction at the fiber/matrix interface can be minimized. Reaction rates at the 980° C (1800° F) service temperature are expected to be tolerable; however, reactions occurring during the higher temperature fabrication processing can be a problem. Typically, the composite is made by first hot pressing superalloy foils together with silicon carbide fiber arrays to form monotapes. A secondary diffusion bonding of stacked layers of the monolayer tapes forms the composite sheet. Limited fabrication processing techniques have been evolved to bend, cut, and join the composite sheet into exhaust system components.

Research has been underway to overcome the interfacial reaction through the use of diffusion barrier coatings on the silicon carbide fibers (ref. 11). Figure 10 shows the marked improvement provided by diffusion barrier coatings in reducing reaction during composite processing. The uncoated fiber has formed a thick reaction zone, but the tungsten-coated fiber has no visible reaction. Although tungsten is an effective coating, it requires a greater thickness than desired and incurs a weight penalty, being twice as dense as superalloys. Alternative carbide coatings are currently being deposited on silicon carbide fibers, and preliminary compatibility results suggest that the fiber/matrix reaction can be controlled. Composite test specimens also are being fabricated to assess the properties of the composite in high-temperature tensile and long-time rupture tests.

The properties of silicon carbide/superalloy and conventional superalloys are compared in figure 11. The data shown are projections expected from the composite currently being processed and evaluated.

In summary, considerable progress has been made, but much work remains before composite sheet can be applied to exhaust systems.

CONCLUDING REMARKS

Significant progress has been made in developing boron/aluminum and silicon carbide/superalloy sheet composites for application in SCAR propulsion systems. A marked improvement in boron/aluminum impact resistance has been obtained in laboratory tests, and this technology is currently being applied to fan blades. The progress made suggests that foreign-object-damage impact resistance, the remaining major technical impediment to the use of boron/aluminum blades in SCAR propulsion systems, may have been overcome.

Excellent progress has been made in studies of silicon carbide/superalloy sheet. Diffusion barrier coatings have been identified and applied to the silicon carbide fibers, and preliminary data suggest that these barriers can control interfacial reactions. While much work remains before silicon carbide/superalloy sheet can be used in SCAR engine exhaust systems, the potential appears promising.

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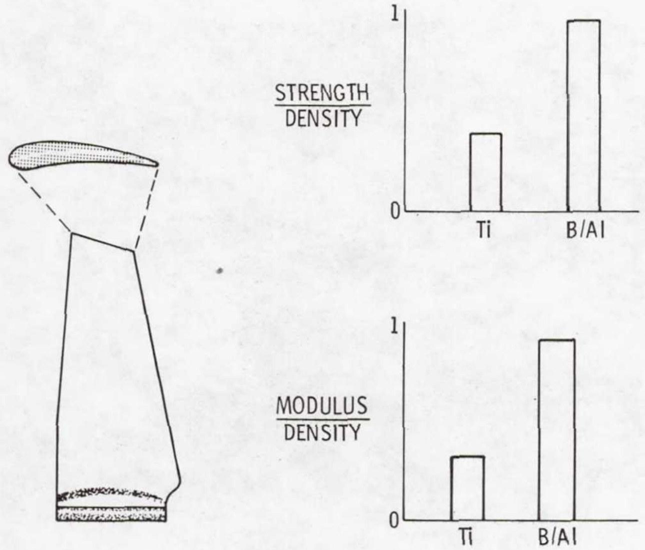

Figure 1.- Relative advantages of boron/aluminum composite blades over titanium alloy blades.

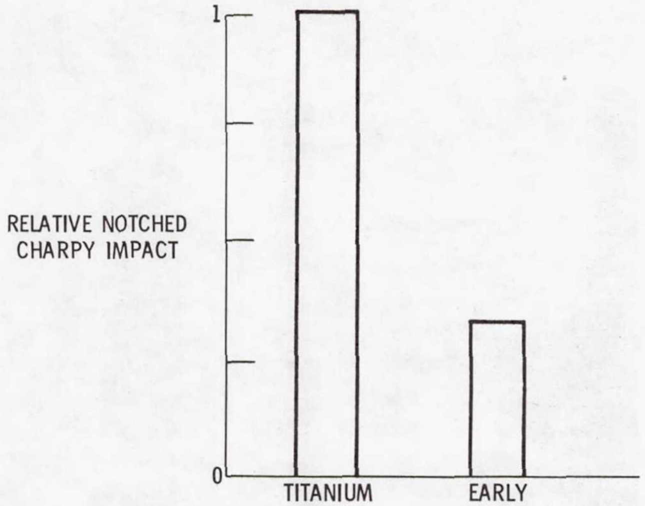

Figure 2.- Relative notched Charpy pendulum impact strength of titanium alloy blades and early boron/aluminum composites.

Figure 3.- Example of bird density near an airport.

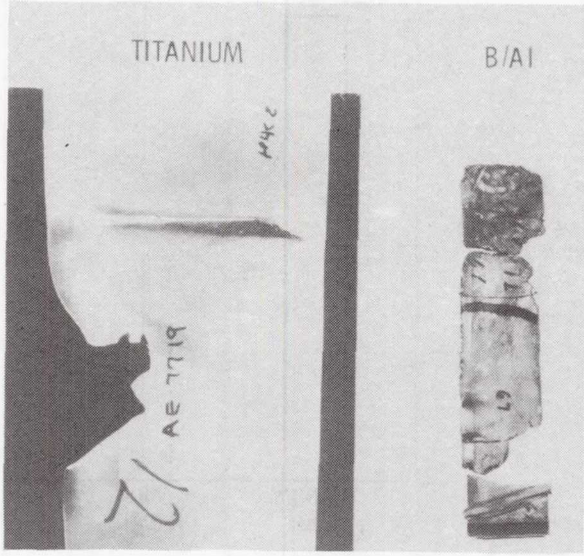

Figure 4.- Impact damage to representative fan blades.

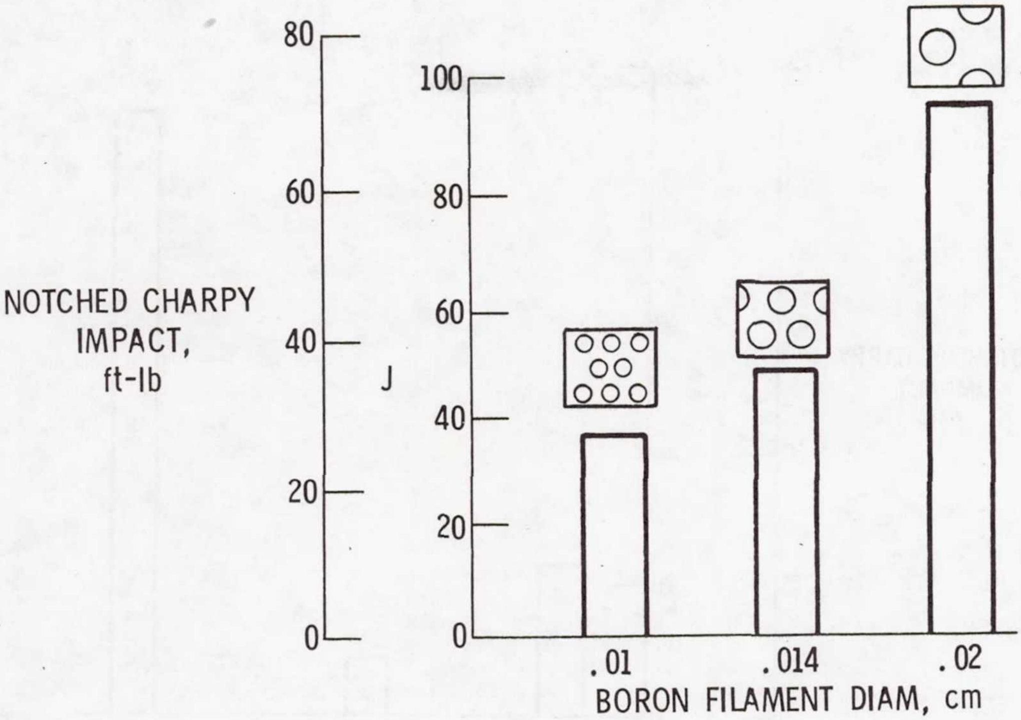

Figure 5.- Effect of filament diameter on impact strength of boron/aluminum composites. Matrix, 50-vol % 1100 aluminum.

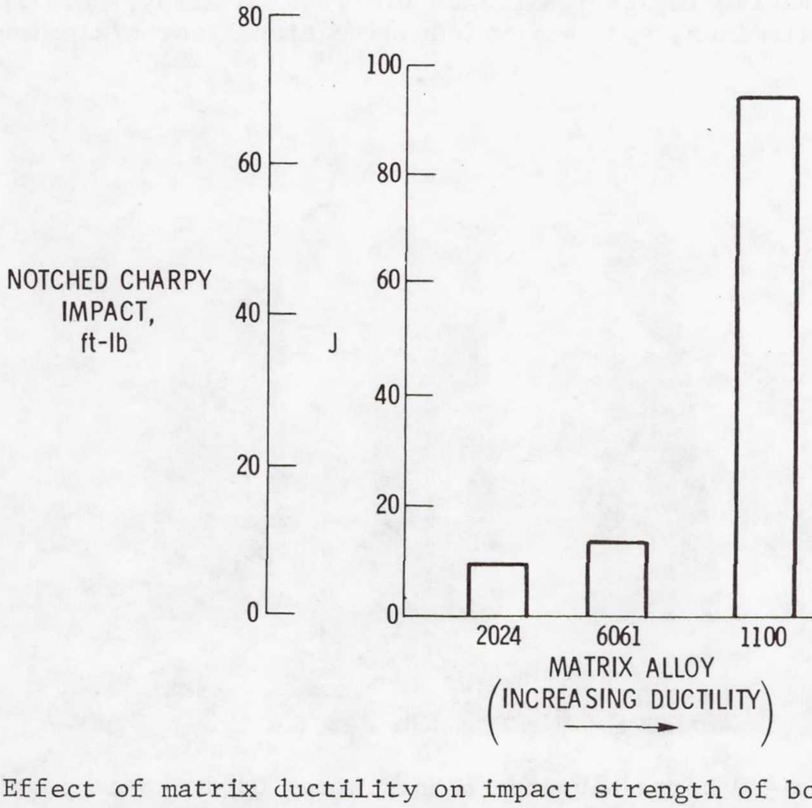

Figure 6.- Effect of matrix ductility on impact strength of boron/aluminum composites. Boron fiber content, 50 vol %; fiber diameter, 0.02 cm.

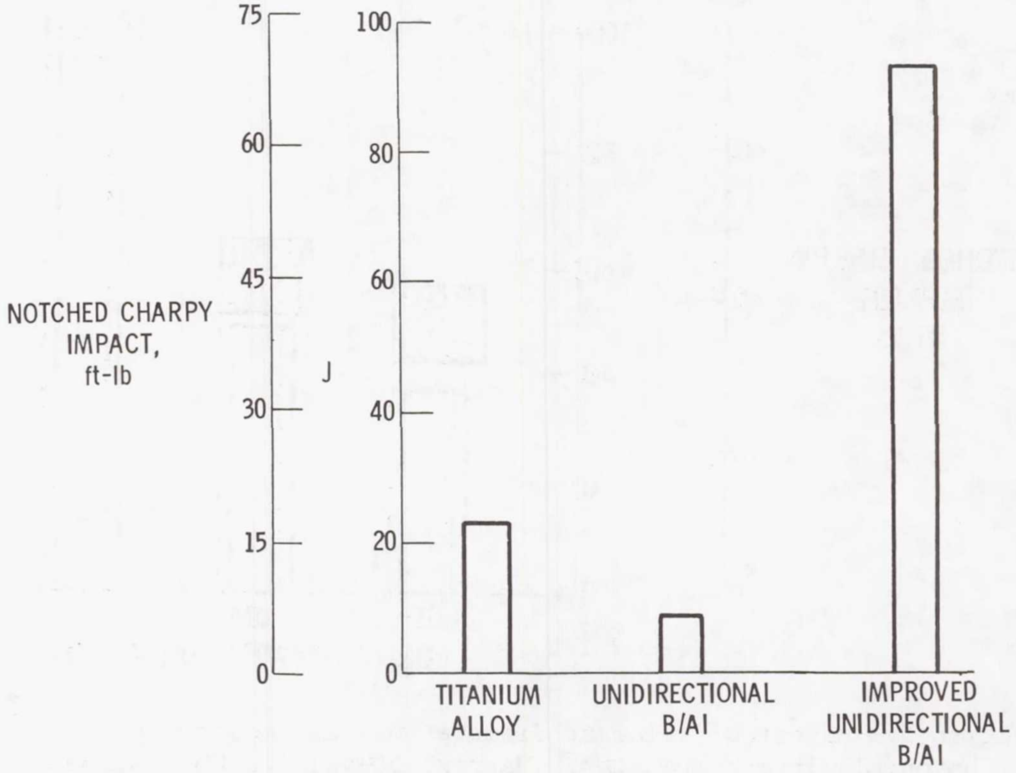

Figure 7.- Relative impact resistance of titanium alloy, unidirectional boron/aluminum, and improved unidirectional boron/aluminum.

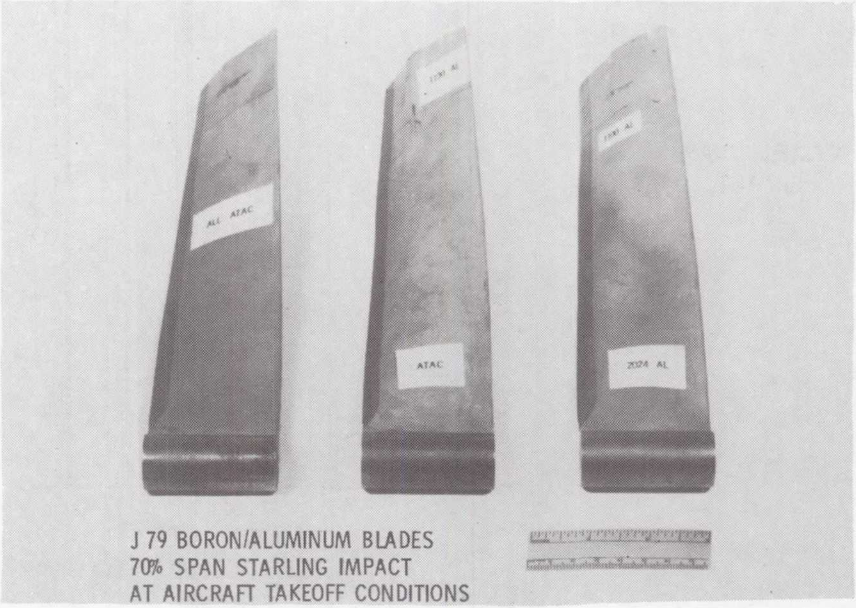

Figure 8.- J-79 boron/aluminum blades after bird impact testing at takeoff conditions. (Starling impact at 70 percent of span.)

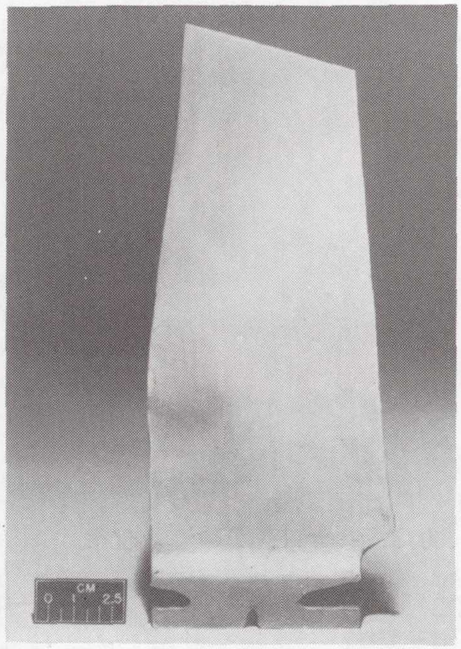

Figure 9.- Prototype SCAR boron/aluminum blade.

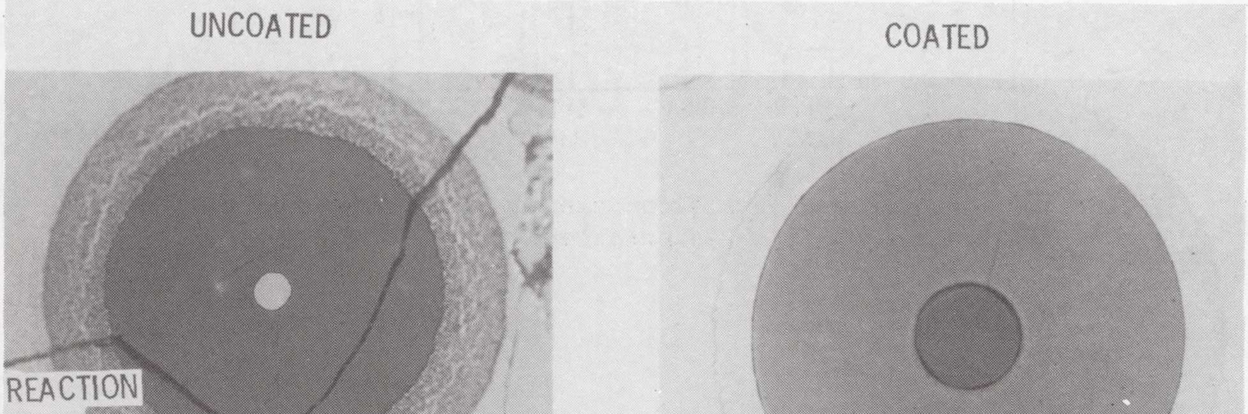

Figure 10.- Relative interfacial reactions of coated and uncoated silicon carbide fibers in a superalloy matrix.

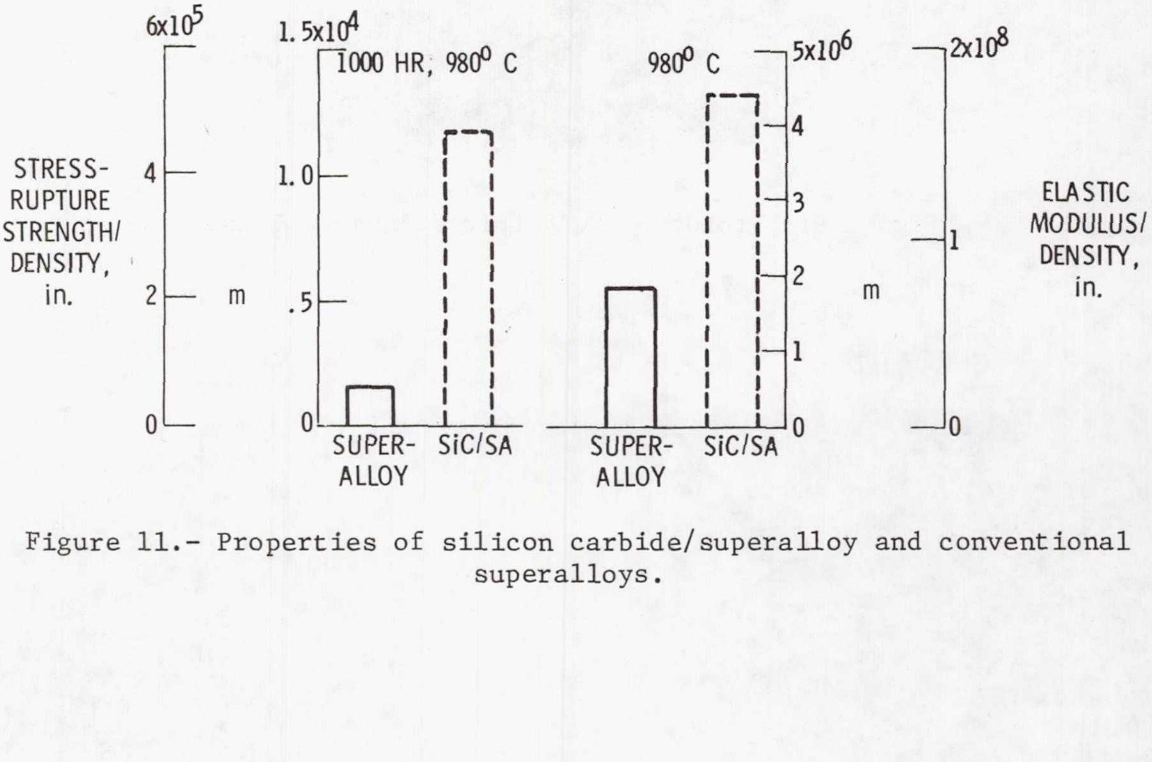

Figure 11.- Properties of silicon carbide/superalloy and conventional superalloys.

NASA- Langley, 1977