NASA-TM-79232 19790023178

NASA Technical Memorandum 79232

# EVALUATION OF SILICON CARBIDE FIBER/TITANIUM COMPOSITES

R. W. Jech and R. A. Signorelli
Lewis Research Center
Cleveland, Ohio



July 1979

E-134

## SUMMARY

The potential usefulness of a composite composed of silicon carbide fiber in a titanium matrix (SiC/Ti) as a substitute for titanium alloys or stainless steel was evaluated. Composites were fabricated by hot pressing alternating layers of collimated silicon carbide fiber and unalloyed titanium foil.

Composites were evaluated for tensile strength and modulus of elasticity at room temperature and elevated temperature. Room temperature impact strength was determined for composites in the as-fabricated condition and after exposure in air at elevated temperature up to 1000 hours. The composites contained about 36 volume percent fiber.

Notched miniature Izod impact strength of SiC/A-70 Ti composites, in the as-fabricated condition, averaged 130 $kJ/m^2$ (60 $ft\text{-}lb/in^2$). This was increased to 190 $kJ/m^2$ (90 $ft\text{-}lb/in^2$) by changing the matrix to A-40 unalloyed titanium which was lower in oxygen content and higher in ductility. The impact strength of the A-40 titanium composites was equal to the titanium-6 aluminum-4 vanadium (6-4) alloy, 195 $kJ/m^2$ (95 $ft\text{-}lb/in^2$), but less than the unreinforced unalloyed (A-40) titanium, 515 $kJ/m^2$ (245 $ft\text{-}lb/in^2$).

SiC/A-70 Ti composites had a higher room temperature modulus of elasticity, 2.40 GPa ($35.0 \times 10^6$ psi), than either stainless steel, 2.10 GPa ($30 \times 10^6$ psi), or titanium, 1.20 GPa ($18 \times 10^6$ psi). This advantage persisted at test temperatures up to, and including, 870 K (1110° F).

The average room temperature tensile strength of the SiC/A-70 Ti composites was 650 MPa (95 ksi), which was nearly identical to the unreinforced A-70 titanium, 655 MPa (95 ksi). At temperatures above 700 K (800° F), the composites were superior in tensile strength to unreinforced unalloyed (A-70) titanium, but had lower tensile strength than the titanium-6 aluminum-4 vanadium (6-4) alloy. Although about 10 percent lower in density, the composites were not competitive with 6-4 titanium, either on the basis of absolute strength or specific strength.

The data emphasize both the promise and the problems of SiC fiber reinforced unalloyed titanium composites. The composites exhibit low density, high stiffness, and moderate tensile strength, but at the price of decreased ductility (<2%) and impact strength to the extent that their impact strength is approximately equal to currently available titanium alloys.

## INTRODUCTION

Temperatures encountered in gas turbine engines cover a wide range. Because of this, designers require a variety of materials for the various engine components, each compatible with its operating environment, in order to achieve powerful, lightweight, engines economical to operate. In the low temperature regions of the engine, up to 590 K (600° F), there is potential for the use of polymere matrix components and boron/aluminum composites. For application at temperatures in the intermediate range, to 810 K (1000° F), titanium alloys or stainless steel are used.

It is in the intermediate temperature region that silicon carbide/titanium (SiC/Ti) composites might be employed. In theory, SiC/Ti composites would be lower in weight and have higher tensile strength (especially at elevated temperature), greater creep resistance, and improved stiffness compared to either titanium alloys or stainless steel. Calculations indicate that titanium reinforced with 30 volume percent SiC fiber would have a density of about 4.1 grams/cc (0.148 $lb/in^3$) and a room temperature modulus of elasticity of about 2.10 GPa ($30 \times 10^6$ psi). Offsetting these advantages is the possibility of lowered impact resistance and decreased ductility.

The problem is to maximize the desirable properties of the composite while minimizing the undesirable ones. Past work on the SiC/Ti system (ref. 1) has shown that composites containing high strength SiC fibers in a matrix of titanium-6 aluminum-4 vanadium (6-4) alloy exhibited modest improvements in tensile strength compared to the unreinforced alloy. However, this alloy is less ductile than unalloyed titanium, 8 percent elongation versus 15 to 20 percent, and therefore lower in impact strength. Thus, when a brittle, high strength fiber, such as SiC, was used as reinforcement, the resulting composite had high tensile strength and stiffness in the major reinforcement direction, but at the cost of lowered impact strength (ref. 2).

It was believed possible to increase the impact strength of SiC/Ti composites by using a more ductile matrix than those previously employed. This assumption was based upon the results obtained in reference 3 where changing the matrix in a boron/aluminum composite from 5052 aluminum alloy to the more ductile 1100 aluminum alloy increased the notched Charpy impact energy from 24 to 64 J (18 to 47 ft-lb). This was accomplished with no decrease in modulus of elasticity in either the longitudinal or transverse direction.

The purpose of the present investigation was to evaluate the potential usefulness of composites composed of SiC fiber in a titanium matrix as a substitute for unreinforced titanium or stainless steel for certain stiffness critical applications. The requirements were: adaquate modulus, tensile strength and impact strength in both the as-fabricated condition and after exposure in air at 920 K (1200° F) for up to 1000 hours.

SiC/Ti composites containing 36 volume percent fiber were fabricated using the hot pressed foil-fiber mat technique. Notched Izod impact tests were conducted on composites in the as-fabricated condition and after exposure at 920 K (1200° F) in air for times of 100 and 1000 hours. Tensile data and modulus of elasticity measurements were obtained at room temperature and elevated temperature.

## MATERIALS, APPARATUS, AND PROCEDURE

### Matrix Selection

Four titanium alloys in bar form were screened for use as possible matrix materials. They were: unalloyed titanium (A-75), titanium-6 aluminum-4 vanadium (6-4), titanium-6 aluminum-2 tin-4 zirconium-2 molybdenum (6242), and titanium-5 aluminum-6 tin-2 zirconium-1 molybdenum-0.5 silicon (5621 S). Their complete chemical compositions are given in table I(a).

Screening was done by testing notched miniature Izod impact specimens machined from bar stock, figure 1(a), for impact strength using a modified Bell Telephone Laboratory type miniature Izod impact machine. The specimens were tested in the as-received condition and after exposure in air at 865 K ($1100^\circ$ F) or 980 K ($1300^\circ$ F) for 10, 100, or 1000 hours.

### Fiber

Commercially obtained SiC fiber made by chemical vapor deposition of SiC on a tungsten core was used in this investigation. The fiber diameter was 0.010 cm (0.004 in.).

### Process Selection

Processing variables such as hot pressing temperature and hot pressing pressure were investigated for a range of temperatures from 1090 K ($1500^\circ$ F) to 1200 K ($1700^\circ$ F) and pressures from 70 MPa (10 ksi) to 210 MPa (30 ksi). The composites were made of alternating layers of unalloyed titanium (A-70) foil, 0.008 cm (0.003 in.) thick and collimated SiC fiber mat using polystyrene as a binder to hold the fibers in position. The assembled layers of fiber mat and foil, 8 and 9 in number, were encapsulated in type 304 stainless steel cans. The polystyrene binder was removed by heating to 700 K ($800^\circ$ F) in vacuum ($\sim 10^{-3}$ torr). The composites were preheated for 15 minutes while a light clamping load was applied, and hot pressed in a channel die for 5 minutes.

The composites were air cooled to room temperature and decanned by etching away the stainless steel with $H_2O$-$HNO_3$-HCL. These particular composites were evaluated as nonstandard, thin-sheet, unnotched Izod impact specimens (fig. 1(b)) to determine an appropriate specimen fabrication process. The impact tests were conducted by striking the specimens normal to the pressing surface.

## Composite Fabrication

Fabrication of notched miniature Izod impact specimens was carried out using the appropriate parameters determined in the "Process Selection" portion of this paper. The hot pressing pressures and temperatures used were either 1200 K (1700° F)-210 MPa (30 ksi) or 1145 K (1600° F)-140 MPa (20 ksi). The notched Izod composite specimen blanks were thicker, 0.64 cm (0.25 in.) and contained more layers of fiber (71) and titanium foil (72) than the thin-sheet, unnotched specimens.

SiC/Ti notched miniature Izod specimens containing from 12 to 84 volume percent fiber oriented parallel to the longitudinal axis of the specimen were fabricated. Similar specimens, which contained 36 volume percent fiber angle-plied at ±10°, ±20°, or ±30° to the longitudinal axis were also fabricated.

Unreinforced titanium "control" specimens were made by hot pressing 90 layers of titanium foil encapsulated in a type 304 stainless steel can which had been evacuated and electron beam welded. The hot pressing pressure and temperature used was the same as that used to hot press the SiC/Ti composites.

## Testing

Tensile tests and sonic modulus of elasticity tests were conducted on SiC/Ti composites in the as-fabricated condition. The tensile tests were carried out in a standard constant crosshead speed tensile machine at a crosshead speed of 0.13 cm/min (0.050 in./min). Elevated temperature tests were performed in a vacuum chamber.

Modulus of elasticity measurements were made using the sonic method. The method employed and equations used are described in reference 4.

Izod impact tests of the SiC/Ti composites and unreinforced titanium control specimens were made using notched miniature specimens in the as-fabricated condition or after exposure in air at 920 K (1200° F) for 100 or 1000 hours. Both the composites and the unreinforced titanium specimens were notched in the surface normal to the pressing direction. The specimen configuration and notch orientation is shown in figure 1(a). The notch was transverse to the longitudinal axis of the specimen.

# RESULTS AND DISCUSSION

## Matrix Selection

Room temperature notched Izod impact test results for the titanium alloys considered as possible matrix materials are given in table II. As shown in figure 2, the impact strength generally decreased as the time at temperature increased. Increasing the exposure temperature also decreased the impact strength. The material with the highest impact strength was unalloyed titanium (A-75), followed by the 6-4, 6242, and 5621S alloys, respectively.

Selection of unalloyed titanium was predication upon its notched impact strength which was more than twice that of the next best titanium alloy, 6-4. This was true for samples in both the as-received condition and after air exposure at 865 K (1100° F) or 980 K (1300° F) for up to 1000 hours. The 6-4 alloy has higher tensile strength than the unalloyed titanium, it was anticipated that tensile strength could be "built into" composites made with unalloyed titanium by utilizing the high strength of the SiC fibers.

## Process Selection

A number of variables were considered when selecting suitable processing conditions for SiC/Ti composites. These variables were: hot pressing temperature, hot pressing pressure, preheat and hot pressing time, and the effect of possible contamination of the fiber and/or the matrix by the polystyrene binder used in the fiber mat.

Preheat and hot pressing time were arbitrarily set at 15 minutes and 5 minutes, respectively. Nothing occurred during the course of the investigation to require changing these times.

Contamination of the SiC fiber and A-70 titanium foil was investigated by tensile testing samples of each in the as-received condition, after polystyrene coating, and after coating and burn-off of the polystyrene. No change in the tensile strength of the SiC fiber, 3460 MPa (502 ksi) average, or the titanium, 702 MPa (102 ksi) average, was observed.

Chemical analyses showed no significant difference in the levels of oxygen, carbon, or nitrogen among the as-received foil; the hot pressed foil or the SiC/Ti composites (tables I(a) and (b)).

Hot pressing temperature and pressure were found to be important in their effect on the impact strength of the composites. The temperature had to be high enough to soften the titanium thus allowing it to flow around the fibers, but not so high as to cause thermal degradation of the fiber or reaction between the fiber and matrix. Hot pressing pressure had to be high enough to cause matrix flow, but not so high as to cause fiber breakage.

Hot pressing temperature and pressure were selected based upon the results presented in table III. These data are plotted in figure 3 and are the results of Izod impact tests on unnotched thin-sheet specimens. The results show that composites hot pressed at pressures of 70, 105, or 140 MPa (10, 15, or 20 ksi) exhibited their maximum impact strength when the hot pressing temperature was 1145 K (1600° F). As the hot pressing temperature was increased, the impact strength decreased. At a hot pressing pressure of 170 MPa (25 ksi), the maximum impact strength occurred when hot pressing temperature of 1170 K

(1650° F) was used. When the hot pressing pressure was 210 MPa (30 ksi), the impact strength was essentially constant regardless of the temperature. The two highest average impact strengths were achieved when composites were hot pressed at 1145 K (1600° F)-140 MPa (20 ksi) and at 1170 K (1650° F)-170 MPa (25 ksi). Because of the greater risk of reaction or fiber degradation at 1170 K (1650° F), the lower temperature was used in making most of the specimens subsequently fabricated. The specific hot pressing temperature-pressure combination utilized was 1145 K (1600° F) and 140 MPa (20 ksi).

## Impact Tests

In this investigation, major attention was directed toward determining the effects of processing parameters, matrix ductility, elevated temperature exposure, fiber content, and fiber orientation on the impact strength of SiC/Ti composites. These factors were examined in order to identify those areas which could be exploited to produce composites having good resistance to foreign object damage. Results of Izod impact tests on notched 36 v/o SiC/Ti composites are given in table IV(a), while table IV(b) contains impact data for unreinforced unalloyed titanium made from foil.

Influence of process parameters. - The influence of differing processing parameters on the impact strength of SiC/Ti composites was demonstrated using notched miniature Izod impact specimens. Previous results, described in the "Process Selection" section of this report, where unnotched thin sheet Izod impact specimens were used, showed that specimens made using different processing parameters had different impact strength. This was re-emphasized by the results shown in figure 4. Unalloyed (A-70) titanium, both reinforced with 36 v/o SiC fiber and unreinforced, exhibited greater impact strength when produced using 140 MPa (20 ksi) at 1145 K (1600° F), than when using 210 MPa (30 ksi) at 1200 K (1700° F).

Influence of matrix ductility. - SiC/Ti composites were made using either A-70 or A-40 unalloyed titanium as the matrix. The A-70 titanium contained 0.34 percent total interstitial impurities (carbon, oxygen, hydrogen, and nitrogen) and exhibited about 15 percent elongation when tested in tension at room temperature. Unreinforced notched miniature Izod impact specimens made from pressed A-70 foil, using 140 MPa (20 ksi) at 1145 K (1600° F), had an average impact strength of 245 $kJ/m^2$ (115 $ft\text{-}lb/in^2$). Incorporation of 36 volume percent SiC fiber into this matrix, using the same processing conditions, resulted in a composite whose average impact strength was 135 $kJ/m^2$ (65 $ft\text{-}lb/in^2$).

Composites made using the more ductile (20 percent elongation) unalloyed (A-40) titanium foil and the same processing conditions, had an average impact strength of 225 $kJ/m^2$ (105 $ft\text{-}lb/in^2$). Utilization of the higher purity (0.17 percent interstitials) unalloyed (A-40) titanium resulted in a 42 percent increase in impact strength. As was previously shown for boron/aluminum (ref. 3), the use of a more ductile matrix greatly improved the impact strength of composites. The impact strength of 36 v/o SiC/A-40 Ti composites was equal to unreinforced 6-4 titanium, 195 $kJ/m^2$ (90 $ft\text{-}lb/in^2$).

Influence of elevated temperature air exposure. - Exposure in air at 920 K (1200° F) for up to 1000 hours generally caused a decrease in the impact strength of the SiC/Ti composites (fig. 5). This was true for the composites made with either A-70 unalloyed titanium or the lower interstitial, more ductile A-40 unalloyed titanium. The decrease in impact strength was probably due to interstitial contamination, primarily oxygen, which embrittled the titanium. This is supported by the fact that the oxygen content of the two composites, after exposure for 1000 hours, was similar (table I(b)). The A-70 composite contained 0.65 percent oxygen, an increase of 0.38 percent, while the A-40 composite contained 0.53 percent oxygen, an increase of 0.40 percent. However, after exposure for 1000 hours, the impact strengths of both the A-70 and A-40 composites were very nearly the same, averaging 75 $kJ/m^2$ (35 $ft\text{-}lb/in^2$) for the A-70 composites and 80 $kJ/m^2$ (40 $ft\text{-}lb/in^2$) for the A-40 composites.

Influence of fiber content. - Notched impact strength of SiC/A-40 Ti composites as a function of fiber content was also examined. These data, table V and figure 6, show a decrease in the impact strength of the composites as the fiber content increased. It would appear that at some fiber content between 42 and 74 volume percent, the impact strength reached a minimum. Such behavior agrees with the equations proposed in references 2 and 5 for fiber reinforced composites composed of a ductile, impact resistant matrix and brittle fibers.

The specimens containing greater than 40 volume percent fiber failed in shear, as shown by the series of steps along the ends of the specimen (fig. 7). The reason for the change in failure mode was not investigated.

Influence of ply angle. - Angleply specimens of 36 v/o SiC fiber in A-40 titanium were tested for impact strength using specimens containing fibers oriented at 0°, ±10°, ±20°, or ±30° to the major axis of the composite. These results are presented in table VI. As shown in figure 8, the notched impact strength decreased from 225 $kJ/m^2$ (120 $ft\text{-}lb/in^2$) to 110 $kJ/m^2$ (55 $ft\text{-}lb/in^2$) when the plyangle changed from 0° to ±10°. Increasing the plyangle resulted in further decreases in the impact strength although not nearly as drastically as the change in the first 10°.

## Tensile Strength

Modest increases in tensile strength at elevated temperature were achieved when A-70 unalloyed titanium was reinforced with 36 volume percent SiC fiber. Results of tensile tests carried out on 36 v/o SiC/A-70 Ti composites; unreinforced unalloyed titanium (A-70) hot pressed foil, A-75 bar stock, and 6-4 bar stock are listed in table VII. As shown in figure 9, the room temperature tensile strength of the SiC/Ti composites was about the same as for unreinforced unalloyed (A-70) titanium made from pressed foil. At test temperatures above room temperature, the tensile strength of the composites was greater than the unreinforced unalloyed titanium, either A-70 ro A-75, but lower than the 6-4 titanium alloy. In no case was rule-of-mixtures strength attained. The measured tensile strength at room temperature, 650 MPa (94.5 ksi), was less than one-half that expected from rule-of-mixtures, 1550 MPa (225 ksi). As the test temperature increased the discrepancy between calculated and observed tensile strength became greater. This was probably due to inadaquate bonding between the fiber and the matrix. An indication of this is seen in figure 10 which shows the appearance of the fracture surface of specimens tested at room and elevated temperature. Fiber pull-out at 920 K (1200° F) and 1035 K (1400° F) was much more pronounced than at room temperature which indicated a weak bond between fiber and matrix. As the test temperature was increased the bond and titanium lost strength more rapidly than the fiber, resulting in increased fiber pull-out.

## Modulus of Elasticity

Results of the sonic modulus of elasticity tests on the composite containing 36 v/o SiC in A-40 unalloyed titanium are presented in table VIII and figure 11. Figure 11 shows a plot of the ratio of the modulus at the test temperature ($E_T$) to the modulus at room temperature ($E_{RT}$). The room temperature modulus of elasticity of the composite was 2.41 GPa ($35.0\times10^6$ psi). This is 14 percent greater than type 403 stainless steel (ref. 6) and 48 percent greater than unalloyed (A-75) titanium bar (ref. 7).

The composite exhibited good retention of elastic modulus up to the final test temperature, 870 K (1110° F). At 870 K (1110° F), the composite had a modulus of 1.95 GPa ($28.5\times10^6$ psi), which was 0.81 of the room temperature modulus. In contrast, unalloyed titanium (A-75), at the same test temperature had a modulus of 1.24 GPa ($12\times10^6$ psi) (ref. 7). The composite exhibited rule-of-mixtures behavior over the entire range of test temperatures. Calculations indicate that at 810 K (1000° F) the modulus of elasticity would be 1.95 GPa ($28.0\times10^6$ psi), while the observed value was, in fact, 2.00 GPa ($29.0\times10^6$ psi). Unlike the tensile strength, the modulus of elasticity of the composite demonstrated rule-of-mixtures behavior over the entire range of test temperatures.

## SUMMARY OF RESULTS AND CONCLUSIONS

The purpose of this investigation was to evaluate the potential usefulness of SiC/Ti composites as a substitute for titanium alloys or stainless steel for stiffness critical applications in the compressor section of aircraft turbine engines.

The major results and conclusions were:

1. Composites of 36 v/o SiC/A-40 Ti exhibited notched Izod impact strength equal to unreinforced titanium-6 aluminum-4 vanadium (6-4) alloy. The composites averaged 190 $kJ/m^2$ (90 $ft\text{-}lb/in^2$) in the as-fabricated condition compared to an average of 195 $kJ/m^2$ (95 $ft\text{-}lb/in^2$) for the 6-4 alloy. Unreinforced unalloyed (A-40) titanium averaged 515 $kJ/m^2$ (245 $ft\text{-}lb/in^2$).

2. SiC/A-40 Ti composites containing 36 volume percent fiber had a higher room temperature modulus of elasticity than either stainless steel or unreinforced unalloyed titanium. At room temperature, the modulus of elasticity of the composite was 2.40 GPa ($35.0\times10^6$ psi) compared to 2.05 GPa ($30\times10^6$ psi) for stainless steel and 1.15 GPa ($17\times10^6$ psi) for A-75 unalloyed titanium. The composite retained a high fraction of its modulus at elevated temperature. At 870 K (1110° F), the modulus was 1.95 GPa ($28.5\times10^6$ psi), 81 percent of the room temperature modulus of elasticity compared to 66 percent for unreinforced unalloyed titanium.

3. Increasing the ductility of the unalloyed titanium used as the matrix in SiC/Ti composites resulted in an increase in the impact strength of the composites. Composites made with A-70 unalloyed titanium (15 percent elongation) had an average impact strength of 130 $kJ/m^2$ (60 $ft\text{-}lb/in^2$). When A-40 unalloyed titanium (20 percent elongation) was used as the matrix, the average impact strength was raised to 190 $kJ/m^2$ (90 $ft\text{-}lb/in^2$).

4. Hot pressing temperature and pressure affected the impact strength of the SiC/Ti composites. For example, composites of SiC/A-70 unalloyed titanium hot pressed at 140 MPa (20 ksi)- 1145 K (1600° F) averaged 115 $kJ/m^2$ (55 $ft\text{-}lb/in^2$) while composites of the same composition hot pressed at 210 MPa (30 ksi)- 1200 K (1700° F) had an average impact strength of 55 $kJ/m^2$ (30 $ft\text{-}lb/in^2$).

5. Use of 36 v/o SiC fiber to reinforce an unalloyed (A-70) titanium matrix resulted in composites having improved tensile strength at elevated temperature. The tensile strength of the composite was 405 MPa (58.5 ksi) at 810 K (1000° F) compared to 225 MPa (33 ksi) for unreinforced unalloyed (A-70) titanium. At room temperature the tensile strengths were 650 MPa (94.5 ksi) and 655 K (95 ksi), respectively. However, compared to unreinforced 6-4 titanium, the composite is lower in tensile strength over the entire range of test temperatures.

6. Exposure at elevated temperature in still air decreased the impact strength of the SiC/Ti composites. After exposure for 1000 hours at 920 K (1200° F), the SiC/A-40 Ti composites had an average impact strength of 80 $kJ/m^2$ (40 $ft\text{-}lb/in^2$) compared to the original 190 $kJ/m^2$ (90 $ft\text{-}lb/in^2$) for the as-fabricated composites.

## CONCLUDING REMARKS

Impact results obtained in this investigation were encouraging from the standpoint that those trends observed in boron/aluminum composites were also observed in the SiC/Ti composites. The variation in impact properties of SiC/Ti due to both matrix ductility and processing variables were similar to boron/aluminum. Other changes such as increasing fiber diameter and hybridizing which have been successful in boron/aluminum, were not investigated. However, there is reason to expect that the results of such changes would also be similar in the SiC/Ti system. Furthermore, the impact properties observed for the SiC/Ti composites in this investigation may not be the best which can ultimately be achieved. It is therefore suggested that further investigation of fabrication variables would be useful for achieving optimum properties.

Although the processing of the SiC/Ti composites may not have been optimum, their properties compare well, in certain areas, to those of 403 stainless steel and 6-4 titanium. The composites had higher moduli of elasticity and these moduli were retained to a greater degree at elevated temperature than the monolithic materials. The composites exhibited room temperature impact strengths equal to that of unreinforced titanium 6-4 alloy. Composite tensile strength was lower than that of 6-4 titanium both at room temperature and elevated temperature. In order to provide a full fledged comparison with currently used monolithic materials, additional data would be required in other areas such as high and low cycle fatigue, erosion, and oxidation resistance.

## REFERENCES

1. Ahmad, I.; et. al.: Metal Matrix Composites for High Temperature Applications. WVT-7266, Watervliet Arsenal, 1972. (AD-756867)

2. Winsa, E. W.; and Petrasek, D. W.: Factors Affecting Miniature Izod Impact Strength of Tungsten- Fiber- Metal-Matrix Composites. NASA TN D-7393, 1973.

3. McDanels, D. L.; and Signorelli, R. A.: Effect of Fiber Diameter and Matrix Alloy on Impact Resistant Boron-Aluminum Composites. NASA TN D-8204, 1976.

4. Roberts, M. H.; and Nortcliffe, J.: Measurement of Young's Modulus at High Temperatures. J. Iron Steel Inst., vol. 157, pt. 3, Nov. 1947, pp. 345-348.

5. Cooper, R. E.: The Work-to-Fracture of Brittle Fibre Ductile-Matrix Composites J. Mech. Phys. Solids, vol. 18, 1970, pp. 179-187.

6. Metals Handbook. Vol. 1. Eighth ed. American Society for Metals, 1961.

7. Jech, R. W.; and Weber, E. P.: Development of Titanium Alloys for Elevated Temperature Service by Powder Metallurgical Techniques, Clevite Research Center, Contract NOas-55-953-c, Final Report, July 15, 1957.

8. Crane, R. L.; and Krukonis, V. J.: Strength and Fracture Properties of Silicon Carbide Filament. Am. Ceram. Soc. Bull., Vol. 54, Feb. 1975, pp. 184-188.

TABLE I. - CHEMICAL COMPOSITION AND INTERSTITIAL CONTENT OF SiC/Ti COMPOSITES, HOT PRESSED TITANIUM FOIL, TITANIUM BAR, AND TITANIUM FOIL

(a) Titanium Alloys - Supplier's Analysis

| Designation | Form | Composition, wt % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Al | V | Sn | Zr | Mo | C | H | O | N | Other |
| 6-4 | Bar | 6.3 | 4.1 | --- | --- | --- | 0.026 | 0.003 | 0.18 | 0.012 | 0.17 Fe |
| 6242 | ↓ | 5.9 | --- | 2.2 | 3.9 | 2.0 | .019 | .006 | .09 | .008 | .06 Fe |
| 5621S | ↓ | 4.8 | --- | 6.1 | 1.9 | 1.0 | .024 | .003 | .13 | .010 | .5 Si<br>.13 Fe |
| A-75 | ↓ | --- | --- | --- | --- | --- | .028 | .002 | .17 | .010 | .15 Fe |
| A-70 | Foil | --- | --- | --- | --- | --- | .026 | .003 | .30 | .012 | .12 Fe |
| A-40 | Foil | --- | --- | --- | --- | --- | .022 | .004 | .13 | .015 | .07 Fe |

(b) Pressed Foil and SiC/Ti Composites

| Type | Condition | Composition, wt % | | | |
|---|---|---|---|---|---|
| | | C | H | O | N |
| Pressed foil (A-70) | As fab - 1200 K (1700° F) | 0.019 | 0.009 | 0.35 | 0.015 |
| | Exposed 100 hr at 920 K (1200° F) | .008 | .007 | .50 | .023 |
| | Exposed 1000 hr at 920 K (1200° F) | .008 | .005 | .67 | .021 |
| SiC/A-70 | As fab - 1200 K (1700° F) | [a]ND | [a]ND | .28 | [a]ND |
| | Exposed 100 hr at 920 K (1200° F) | [a]ND | [a]ND | .35 | [a]ND |
| | Exposed 1000 hr at 920 K (1200° F) | [a]ND | [a]ND | .65 | [a]ND |
| SiC/A-40 | As fab - 1145 K (1600° F) | [a]ND | [a]ND | .13 | [a]ND |
| | Exposed 100 hr at 920 K (1200° F) | [a]ND | [a]ND | .24 | [a]ND |
| | Exposed 1000 hr at 920 K (1200° F) | [a]ND | [a]ND | .53 | [a]ND |

[a]ND - Not determined.

TABLE II. - ROOM TEMPERATURE NOTCHED IZOD IMPACT STRENGTH OF UNREINFORCED TITANIUM AND TITANIUM ALLOYS AFTER EXPOSURE IN AIR AT 865 K (1100° F) OR 980 K (1300° F)

| Alloy | Exposure | | | Impact energy | | Impact strength | |
|---|---|---|---|---|---|---|---|
| | Time | Temperature | | J | in-lb | kJ/m$^2$ | ft-lb/in$^2$ |
| | Hr | K | °F | | | | |
| A-75 | As received | | | 6.55 | 58.0 | 365 | 170 |
| | As received | | | 5.94 | 52.5 | 330 | 155 |
| | 10 | 865 | 1100 | 7.92 | 70.0 | 340 | 210 |
| | 100 | 865 | 1100 | 7.04 | 62.5 | 390 | 185 |
| | 1000 | 865 | 1100 | 7.47 | 66.0 | 415 | 195 |
| | 10 | 980 | 1300 | 7.65 | 67.5 | 425 | 200 |
| | 100 | 980 | 1300 | 8.85 | 78.5 | 490 | 230 |
| | 1000 | 980 | 1300 | 6.99 | 62.0 | 390 | 185 |
| 6-4 | As received | | | 3.27 | 29.0 | 180 | 85 |
| | As received | | | 3.72 | 33.0 | 210 | 100 |
| | 10 | 865 | 1100 | 3.47 | 30.5 | 190 | 90 |
| | 100 | 865 | 1100 | 3.27 | 29.0 | 180 | 85 |
| | 1000 | 865 | 1100 | 3.22 | 28.5 | 180 | 85 |
| | 10 | 980 | 1300 | 3.32 | 29.5 | 180 | 85 |
| | 100 | 980 | 1300 | 3.83 | 34.0 | 215 | 100 |
| | 1000 | 980 | 1300 | 2.78 | 24.5 | 155 | 75 |
| 6242 | As received | | | 3.42 | 30.0 | 190 | 90 |
| | As received | | | 3.02 | 26.5 | 165 | 80 |
| | 10 | 865 | 1100 | 2.93 | 26.0 | 160 | 80 |
| | 100 | 865 | 1100 | 2.54 | 22.5 | 140 | 65 |
| | 1000 | 865 | 1100 | 2.03 | 18.0 | 110 | 55 |
| | 10 | 980 | 1300 | 3.02 | 26.5 | 165 | 80 |
| | 100 | 980 | 1300 | 2.83 | 25.0 | 155 | 75 |
| | 1000 | 980 | 1300 | 1.94 | 17.0 | 110 | 50 |
| 5621S | As received | | | 1.89 | 16.5 | 110 | 50 |
| | As received | | | 2.19 | 19.5 | 120 | 60 |
| | 10 | 865 | 1100 | 1.37 | 12.0 | 75 | 35 |
| | 100 | 865 | 1100 | 1.76 | 15.5 | 95 | 45 |
| | 1000 | 865 | 1100 | 0.63 | 5.5 | 35 | 15 |
| | 10 | 980 | 1300 | 1.59 | 14.0 | 90 | 40 |
| | 100 | 980 | 1300 | 1.01 | 9.0 | 55 | 25 |
| | 1000 | 980 | 1300 | 0.89 | 8.0 | 50 | 25 |

TABLE III. - ROOM TEMPERATURE IZOD IMPACT STRENGTH OF UNNOTCHED THIN-SHEET 36 V/O SiC/A-70 TITANIUM COMPOSITES

| Hot pressing | | | | Impact energy | | Impact strength | |
|---|---|---|---|---|---|---|---|
| Pressure | | Temperature | | | | | |
| MPa | ksi | K | °F | J | in-lb | kJ/m$^2$ | ft-lb/in$^2$ |
| 70 | 10 | 1090 | 1500 | 0.34 | 3.0 | 95 | 45 |
| | | | | .23 | 2.0 | 65 | 30 |
| | | 1115 | 1550 | .23 | 2.0 | 65 | 30 |
| | | | | .23 | 2.0 | 65 | 30 |
| | | 1145 | 1600 | .28 | 2.5 | 80 | 35 |
| | | | | .40 | 3.5 | 110 | 55 |
| | | 1170 | 1650 | .23 | 2.0 | 65 | 30 |
| | | | | .17 | 1.5 | 45 | 25 |
| | | 1200 | 1700 | .17 | 1.5 | 45 | 25 |
| | | | | .17 | 1.5 | 45 | 25 |
| 105 | 15 | 1115 | 1550 | .28 | 2.5 | 80 | 35 |
| | | | | .34 | 3.0 | 95 | 45 |
| | | 1145 | 1600 | .28 | 2.5 | 80 | 35 |
| | | | | .34 | 3.0 | 95 | 45 |
| | | 1170 | 1650 | .17 | 1.5 | 45 | 25 |
| | | | | .23 | 2.0 | 65 | 30 |
| 140 | 20 | 1090 | 1500 | .34 | 3.0 | 95 | 45 |
| | | | | .28 | 2.5 | 80 | 35 |
| | | 1145 | 1600 | .34 | 3.0 | 95 | 45 |
| | | | | .40 | 3.5 | 110 | 55 |
| | | 1200 | 1700 | .11 | 1.0 | 30 | 15 |
| | | | | .11 | 1.0 | 30 | 15 |
| 170 | 25 | 1115 | 1550 | .23 | 2.0 | 65 | 30 |
| | | | | .28 | 2.5 | 80 | 35 |
| | | 1170 | 1650 | .40 | 3.5 | 110 | 55 |
| | | | | .40 | 3.5 | 110 | 55 |
| 210 | 30 | 1090 | 1500 | .17 | 1.5 | 45 | 25 |
| | | | | .11 | 1.0 | 30 | 15 |
| | | 1145 | 1600 | .11 | 1.0 | 30 | 15 |
| | | | | .11 | 1.0 | 30 | 15 |
| | | 1200 | 1700 | .17 | 1.5 | 45 | 25 |
| | | | | .17 | 1.5 | 45 | 25 |

TABLE IV. - ROOM TEMPERATURE NOTCHED IZOD IMPACT STRENGTH OF 36 V/O SiC/TITANIUM COMPOSITES AND UNREINFORCED UNALLOYED TITANIUM AS-FABRICATED AND AFTER AIR EXPOSURE AT 920 K ($1200^{\circ}$ F)

(a) Composites

| Matrix alloy | Condition | Impact energy | | Impact strength | |
|---|---|---|---|---|---|
| | | J | in-lb | $kJ/m^2$ | $ft\text{-}lb/in^2$ |
| A-70 | As fabricated[a] | 1.36 | 12.0 | 75 | 35 |
| | | 1.36 | 12.0 | 75 | 35 |
| | | 1.13 | 10.0 | 65 | 30 |
| | | 1.41 | 12.5 | 80 | 35 |
| | Exposed 100 hr | 1.36 | 12.0 | 75 | 35 |
| | | 1.41 | 12.5 | 80 | 35 |
| | | 1.19 | 10.5 | 65 | 30 |
| | | 1.24 | 11.0 | 70 | 35 |
| | Exposed 1000 hr | 1.36 | 12.0 | 75 | 35 |
| | | 1.53 | 13.5 | 85 | 40 |
| | | 1.07 | 9.5 | 60 | 30 |
| | | 1.07 | 9.5 | 60 | 30 |
| | As fabricated[b] | 2.26 | 20.0 | 125 | 60 |
| | As fabricated[b] | 2.54 | 22.5 | 140 | 65 |
| | Exposed 100 hr | 1.80 | 16.0 | 100 | 45 |
| | Exposed 100 hr | 2.03 | 18.0 | 115 | 55 |
| | Exposed 1000 hr | 1.58 | 14.0 | 90 | 40 |
| | Exposed 1000 hr | 1.19 | 10.5 | 65 | 30 |
| A-40 | As fabricated[b] | 4.52 | 40.0 | 250 | 120 |
| | As fabricated[b] | 3.56 | 31.5 | 200 | 95 |
| | Exposed 100 hr | 1.75 | 15.5 | 95 | 45 |
| | Exposed 100 hr | 1.70 | 15.0 | 95 | 45 |
| | Exposed 1000 hr | .85 | 7.5 | 45 | 20 |
| | Exposed 1000 hr | 2.09 | 18.5 | 115 | 55 |

[a]Hot pressed at 1200 K ($1700^{\circ}$ F) and 210 MPa (30 ksi).
[b]Hot pressed at 1145 K ($1600^{\circ}$ F) and 140 MPa (20 ksi).

TABLE IV. - CONCLUDED.

(b) Hot pressed unreinforced titanium foil

| Alloy | Condition | Impact energy | | Impact strength | |
|---|---|---|---|---|---|
| | | J | in-lb | $kJ/m^2$ | $ft\text{-}lb/in^2$ |
| A-70 | As fabricated[a] | 4.07 | 36.0 | 225 | 105 |
| | As fabricated[a] | 1.98 | 17.5 | 110 | 50 |
| | Exposed 100 hr | 2.03 | 18.0 | 110 | 50 |
| | Exposed 1000 hr | 2.71 | 24.0 | 150 | 70 |
| | As fabricated[b] | 4.41 | 39.0 | 245 | 115 |
| | As fabricated[b] | 4.41 | 39.0 | 245 | 115 |
| | Exposed 100 hr | 3.90 | 34.5 | 215 | 100 |
| | Exposed 100 hr | 4.12 | 36.5 | 230 | 110 |
| | Exposed 1000 hr | 4.52 | 40.0 | 250 | 120 |
| | Exposed 1000 hr | 4.52 | 40.0 | 250 | 120 |
| A-40 | As fabricated[b] | 9.32 | 82.5 | 515 | 245 |
| | As fabricated[b] | 7.63 | 67.5 | 420 | 200 |
| | Exposed 100 hr | 8.59 | 76.0 | 475 | 225 |
| | Exposed 100 hr | 8.72 | 72.0 | 485 | 215 |
| | Exposed 1000 hr | 5.93 | 52.5 | 330 | 155 |
| | Exposed 1000 hr | 6.72 | 59.5 | 370 | 175 |

[a]Hot pressed at 1200 K (1700° F) and 210 MPa (30 ksi).
[b]Hot pressed at 1145 K (1600° F) and 140 MPa (20 ksi).

TABLE V. - ROOM TEMPERATURE NOTCHED IZOD IMPACT STRENGTH OF SiC/A-40 TITANIUM COMPOSITES CONTAINING VARIOUS AMOUNTS OF FIBER

| Fiber content, vol % | Impact energy | | Impact strength | |
|---|---|---|---|---|
| | J | in-lb | $kJ/m^2$ | $ft\text{-}lb/in^2$ |
| 0 | 9.32 | 82.5 | 515 | 245 |
| 0 | 7.62 | 67.5 | 420 | 200 |
| 12 | 6.27 | 55.5 | 345 | 165 |
| 23 | 5.65 | 50.0 | 310 | 145 |
| 25 | 4.40 | 39.0 | 245 | 115 |
| 36 | 3.39 | 30.0 | 250 | 120 |
| 36 | 3.62 | 32.0 | 200 | 95 |
| 37 | 2.03 | 18.0 | 110 | 55 |
| 38 | 1.92 | 17.0 | 105 | 50 |
| 42 | [a]1.53 | 13.5 | 85 | 40 |
| 74 | [a]1.24 | 11.0 | 70 | 30 |
| 84 | [a]1.53 | 13.5 | 85 | 40 |

[a]Shear failure.

TABLE VI. - ROOM TEMPERATURE NOTCHED

IZOD IMPACT STRENGTH OF ANGLEPLY

36 V/O SiC/A-40 TITANIUM COMPOSITES

| Ply angle, (θ) deg | Impact energy | | Impact strength | |
|---|---|---|---|---|
| | J | in-lb | $kJ/m^2$ | $ft\text{-}lb/in^2$ |
| 0 | 4.52 | 40.0 | 250 | 120 |
| 0 | 3.56 | 31.5 | 200 | 95 |
| 10 | 1.92 | 17.0 | 105 | 50 |
| 10 | 2.15 | 19.0 | 115 | 55 |
| 20 | 1.75 | 15.5 | 95 | 45 |
| 20 | 1.52 | 13.5 | 85 | 40 |
| 30 | 1.52 | 13.5 | 85 | 40 |
| 30 | 1.64 | 14.5 | 95 | 45 |

TABLE VII. - ROOM TEMPERATURE AND ELEVATED TEMPERATURE TENSILE STRENGTH OF 36 V/O SiC/A-70 TITANIUM COMPOSITES, HOT PRESSED A-70 TITANIUM FOIL AND A-75 AND 6-4 TITANIUM BAR STOCK

(a) Composites

| Test temperature | | Tensile strength | |
|---|---|---|---|
| K | °F | MPa | ksi |
| RT | RT | 650 | 94.5 |
| 645 | 700 | 550 | 80.0 |
| 810 | 1000 | 405 | 58.5 |
| 865 | 1100 | 265 | 38.5 |
| 920 | 1200 | 225 | 32.5 |
| 1035 | 1400 | 110 | 16.0 |

(b) Unreinforced Titanium

| Alloy | Test temperature | | Tensile strength | |
|---|---|---|---|---|
| | K | °F | MPa | ksi |
| A-75 Bar | RT | RT | 770 | 112.0 |
| | 810 | 1000 | 190 | 28.0 |
| | 865 | 1100 | 145 | 21.0 |
| | 920 | 1200 | 60 | 8.5 |
| | 1035 | 1400 | 30 | 4.0 |
| A-70 Foil (Hot pressed) | RT | RT | 655 | 95.0 |
| | 810 | 1000 | 225 | 33.0 |
| | 865 | 1100 | 125 | 18.0 |
| | 920 | 1200 | 70 | 10.0 |
| | 1035 | 1400 | 30 | 4.5 |
| 6-4 Bar | RT | RT | 1125 | 163.0 |
| | 420 | 300 | 880 | 128.0 |
| | 535 | 500 | 780 | 113.5 |
| | 675 | 750 | 710 | 103.0 |
| | 740 | 875 | 635 | 92.0 |
| | 810 | 1000 | 520 | 75.5 |
| | 865 | 1100 | 410 | 59.5 |
| | 920 | 1200 | 295 | 43.0 |
| | 980 | 1300 | 170 | 25.0 |
| | 1035 | 1400 | 100 | 14.5 |

TABLE VIII. - SONIC MODULUS OF ELASTICITY OF 36 V/O SiC/A-40 TITANIUM COMPOSITES AT ROOM AND ELEVATED TEMPERATURE

| Test temperature | | Modulus of elasticity | | Ratio: $E_T/E_{RT}$ |
|---|---|---|---|---|
| K | $^oF$ | GPa | psi | |
| RT | RT | 2.40 | $35.0\times10^6$ | 1.00 |
| 325 | 110 | 2.40 | 35.0 | 1.00 |
| 370 | 210 | 2.35 | 34.0 | .97 |
| 420 | 295 | 2.25 | 33.0 | .94 |
| 480 | 415 | 2.25 | 32.5 | .93 |
| 535 | 500 | 2.20 | 32.0 | .91 |
| 590 | 600 | 2.15 | 31.5 | .90 |
| 645 | 700 | 2.10 | 30.5 | .87 |
| 700 | 805 | 2.10 | 30.0 | .86 |
| 755 | 900 | 2.05 | 29.5 | .84 |
| 810 | 1000 | 2.00 | 29.0 | .83 |
| 870 | 1110 | 1.95 | 28.5 | .81 |

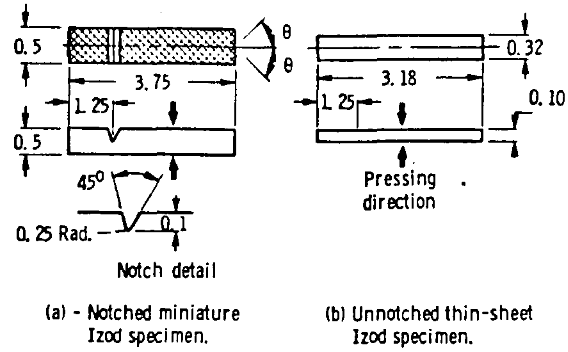



Figure 1. - Configuration and dimensions of notched, miniature Izod impact specimens and unnotched, thin-sheet Izod impact specimens. (All dimensions in centimeters.) Note: Ply angle θ is the angle between the fiber and the longitudinal centerline of the specimen.

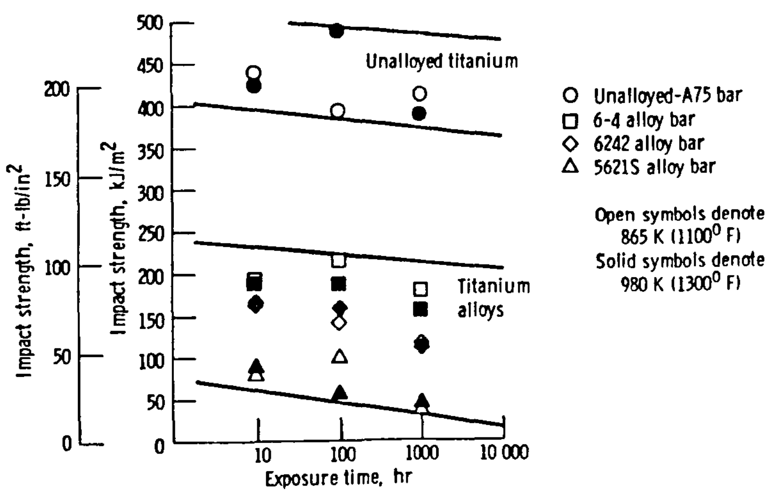



Figure 2. - Room temperature notched, Izod impact strength of unreinforced titanium and titanium alloys after air exposure at 865 K (1100° F) or 980 K (1300° F).

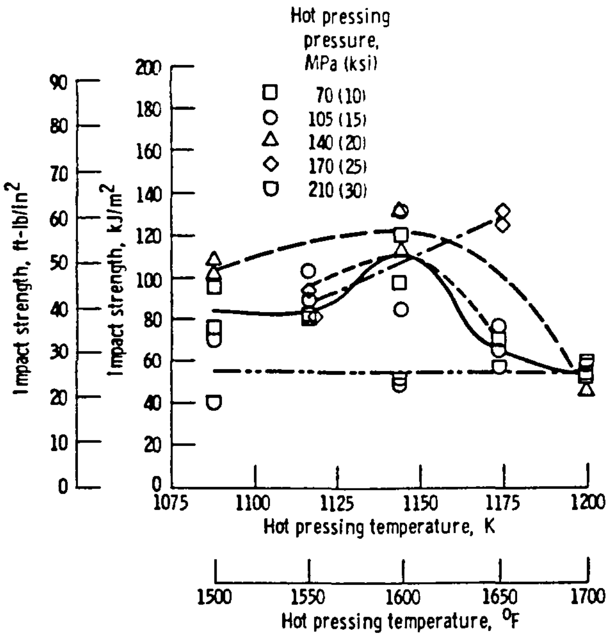



Figure 3. - Room-temperature Izod impact strength of unnotched thin-sheet 36 vol % SiC/A-70 Ti composites hot pressed at various temperatures and pressures.

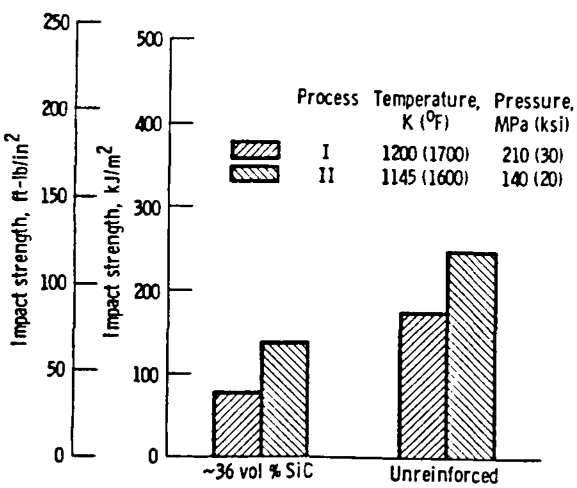



Figure 4. - Room temperature notched Izod impact strength of as-fabricated SiC/A-70 Ti composites and hot pressed unreinforced titanium foil made using different processing conditions.

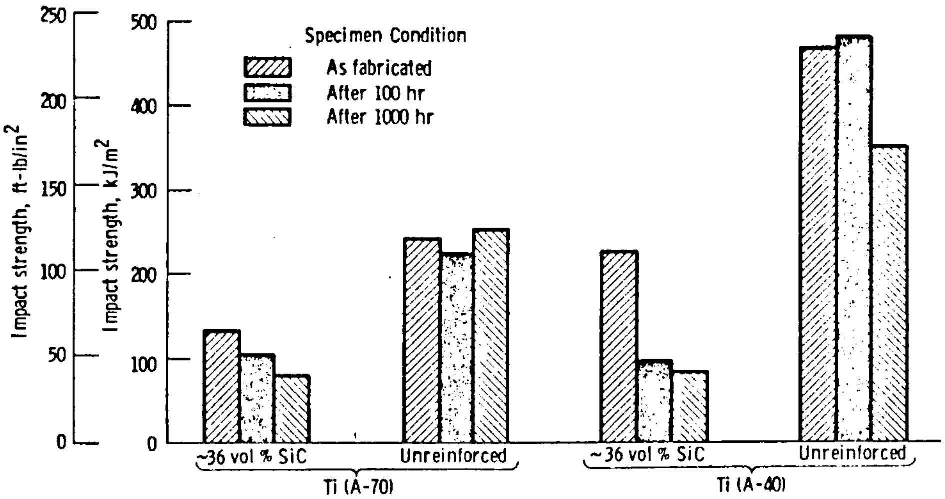



Figure 5. - Room temperature notched Izod impact strength of SiC/Ti composites and unreinforced hot-pressed titanium foil in the as-fabricated condition and after air exposure at 920 K (1200° F).

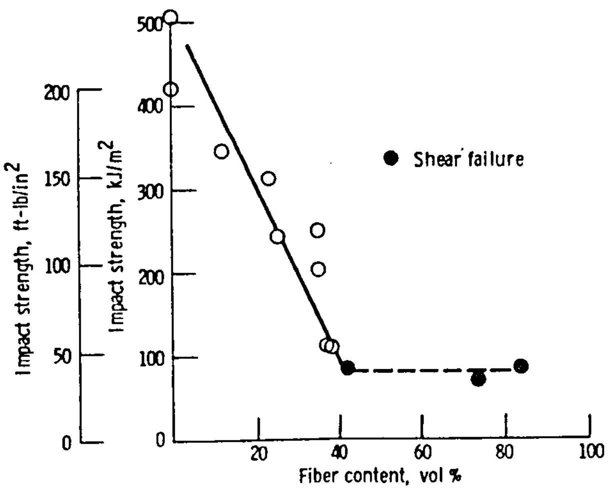
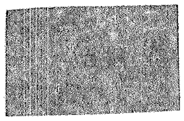
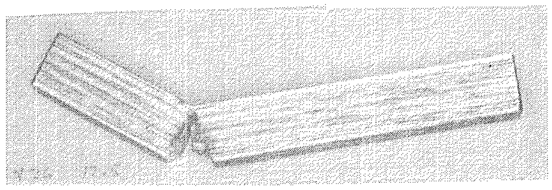
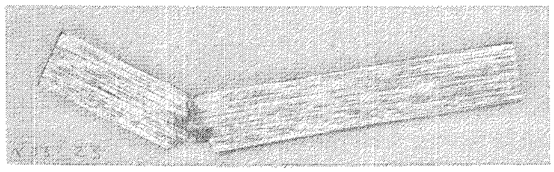



Figure 6. - Room temperature notched Izod impact strength of SiC/A-40 Ti composites containing various amounts of fiber.

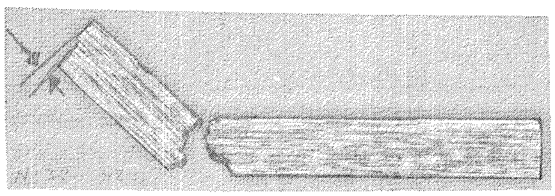




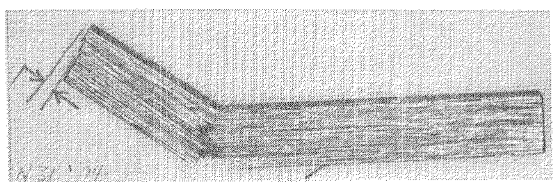
12.5 v/o



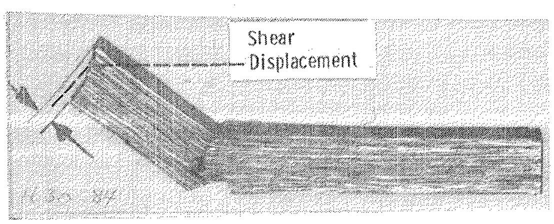
23 v/o



42 v/o



74 v/o




84 v/o

Figure 7. - Notched Izod impact specimens of SiC/A-40 Ti composites showing change from fibrous to shear displacement failure.

C-77-2348

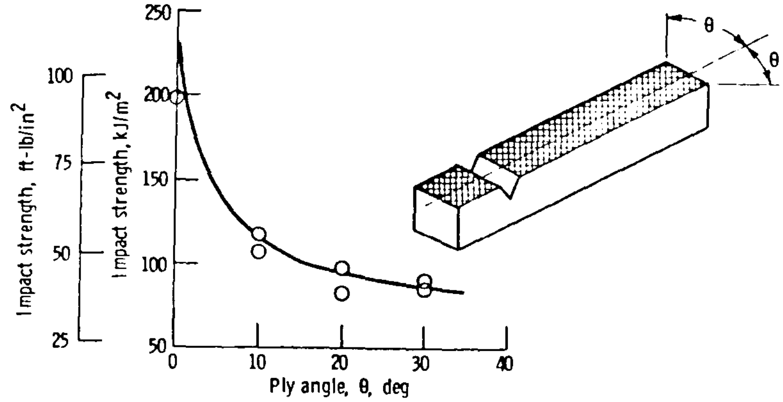



Figure 8. - Room temperature notched Izod impact strength of 36 vol % SiC/A-40 Ti composites containing alternate layers of fibers crossplied at various angles.

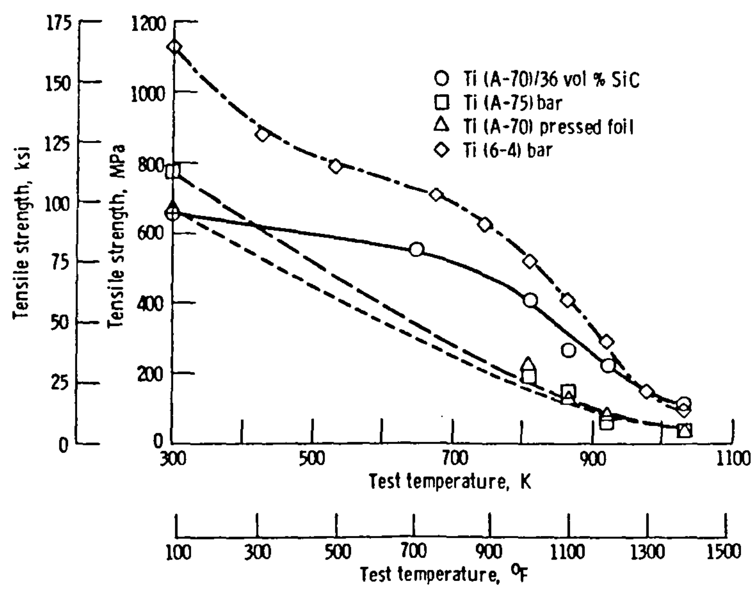
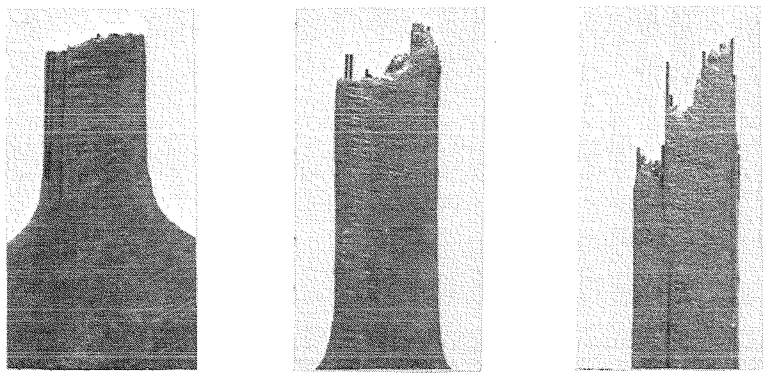



Figure 9. - Room- and elevated-temperature tensile strengths of 36 vol % SiC/A-70 Ti composites, hot pressed A-70 foil, and A-75 and titanium 6-4 bar stock.



Room Temperature | 920 K (1200 F) | 1035 K (1400 F)

Figure 10. - Tensile specimens of 36 $^{V}/o$ SiC/A-70 Ti composites showing fiber fracture and fiber pull-out failure.

C-78-1037

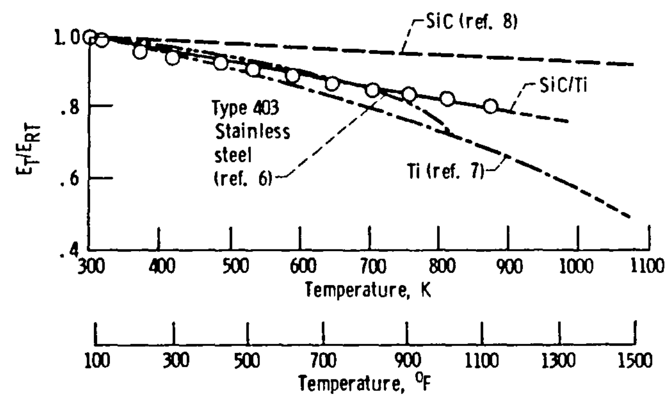



Figure 11. - Modulus of elasticity ratio for SiC fiber, 36 vol % SiC/A-40 Ti composite, unalloyed (A-75) titanium bar, and 403 stainless steel at various temperatures.

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM-79232 | | |
| 4. Title and Subtitle<br>EVALUATION OF SILICON CARBIDE FIBER/TITANIUM COMPOSITES | | 5. Report Date<br>July 1979 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>R. W. Jech and R. A. Signorelli | | 8. Performing Organization Report No.<br>E-134 |
| | | 10. Work Unit No. |
| 9. Performing Organization Name and Address<br>National Aeronautics and Space Administration<br>Lewis Research Center<br>Cleveland, Ohio 44135 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered<br>Technical Memorandum |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | | 14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract

Izod impact, tensile, and modulus of elasticity were determined for silicon carbide fiber/titanium composites to evaluate their potential usefulness as substitutes for titanium alloys or stainless steel in stiffness critical applications for aircraft turbine engines. Variations in processing conditions and matrix ductility were examined to produce composites having good impact strength in both the as-fabricated condition and after air exposure at elevated temperature. The impact strengths of composites containing 36 volume percent silicon carbide (SiC) fiber in an unalloyed (A-40) titanium matrix were found to be equal to unreinforced titanium-6 aluminum-4 vanadium alloy; the tensile strengths of the composites were marginally better than the unreinforced unalloyed (A-70) matrix at elevated temperature, though not at room temperature. At room temperature the modulus of elasticity of the composites was 48 percent higher than titanium or its alloys and 40 percent higher than that of stainless steel.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Composites; Silicon carbide fiber; Titanium; Modulus of elasticity; Impact strength | Unclassified - unlimited<br>STAR Category 24 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | | |

* For sale by the National Technical Information Service, Springfield, Virginia 22161

**End of Document**