

Metal-Matrix Composite Processing Technologies for Aircraft Engine Applications

D.R. Pank and J.J. Jackson

Titanium metal-matrix composites (MMC) are prime candidate materials for aerospace applications because of their excellent high-temperature longitudinal strength and stiffness and low density compared with nickel- and steel-base materials. This article examines the steps GE Aircraft Engines (GEAE) has taken to develop an induction plasma deposition (IPD) processing method for the fabrication of Ti6242/SiC MMC material. Information regarding process methodology, microstructures, and mechanical properties of consolidated MMC structures will be presented. The work presented was funded under the GE-Aircraft Engine IR & D program.

Keywords
exhaust nozzle components, induction plasma deposition, mechanical behavior, metal matrix composites, SiC-based fibers, titanium alloys

1. Introduction

1.1 *Background*

THE goal of doubling engine performance for the 1990s and beyond requires significant increases in the thrust-to-weight ratio. High-temperature titanium-base metal-matrix composites (MMCs) that incorporate high strength and high modulus fibers as continuous reinforcement offer up to a 50% weight reduction relative to monolithic superalloys in propulsion system components. Figure 1 illustrates the comparative properties and potential benefits anticipated with the use of these titanium-base metal-matrix composites.

For the past several years, GEAE has been working with the Ti-6Al-2Sn-4Zr-2Mo matrix reinforced with the SCS-6 SiC-based fiber and the induction plasma deposition (IPD) process to fabricate MMC structures for demonstration in aircraft engine components. GEAE's efforts to develop MMC components have included both rotating and static components divided into four critical areas: airfoils (blades and vanes), structural components (links, flaps, and ducts), shafts, and disks (rotors, blisks, and blings). Several different MMC geometries are associated with these various applications such as flat panels and tubes for the exhaust nozzle divergent flaps and compression links and hoop structures for compressor disks. Although the fabrication of MMC material by the IPD process is slightly different for each application, an exhaust nozzle divergent flap component represents a typical application and will be the focus of this article.

1.2 *Exhaust Nozzle Application*

Current nozzles have a two-dimensional, convergent-divergent (2DCD) geometry, in which both convergent and divergent sections of the nozzle are independently variable. This produces optimal engine performance as well as thrust vectoring capabilities. The nozzle controls the engine pressure ratio and the gross thrust by varying its convergent and divergent cross-sectional areas. Area control is, therefore, critical to properly controlling these engine parameters. For this reason, the stiffness of the mechanical members of the nozzle, both initial stiffness and retention of stiffness over time, is very important because mechanical deflection (lack of stiffness) can lead to aeromechanical problems. With the use of MMCs, the structural stiffness and strength of a nozzle can be enhanced at constant weight, or the weight of a nozzle can be reduced with the same level of stiffness and strength.

To assess the feasibility of using MMC structures in these and other components, Ti6242/SiC panels with from 2 to 72 plies were fabricated by GEAE for various component processing trials. The following sections describe those manufacturing trials and MMC evaluations.

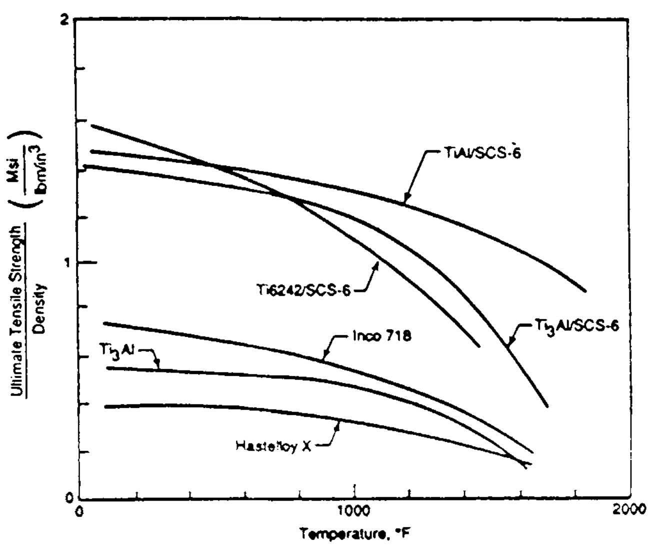

Fig. 1 Specific strength as a function of temperature for several high temperature-high strength materials.

D.R. Pank and **J.J. Jackson**, GE Aircraft Engines, Lynn, Massachusetts, 01910.

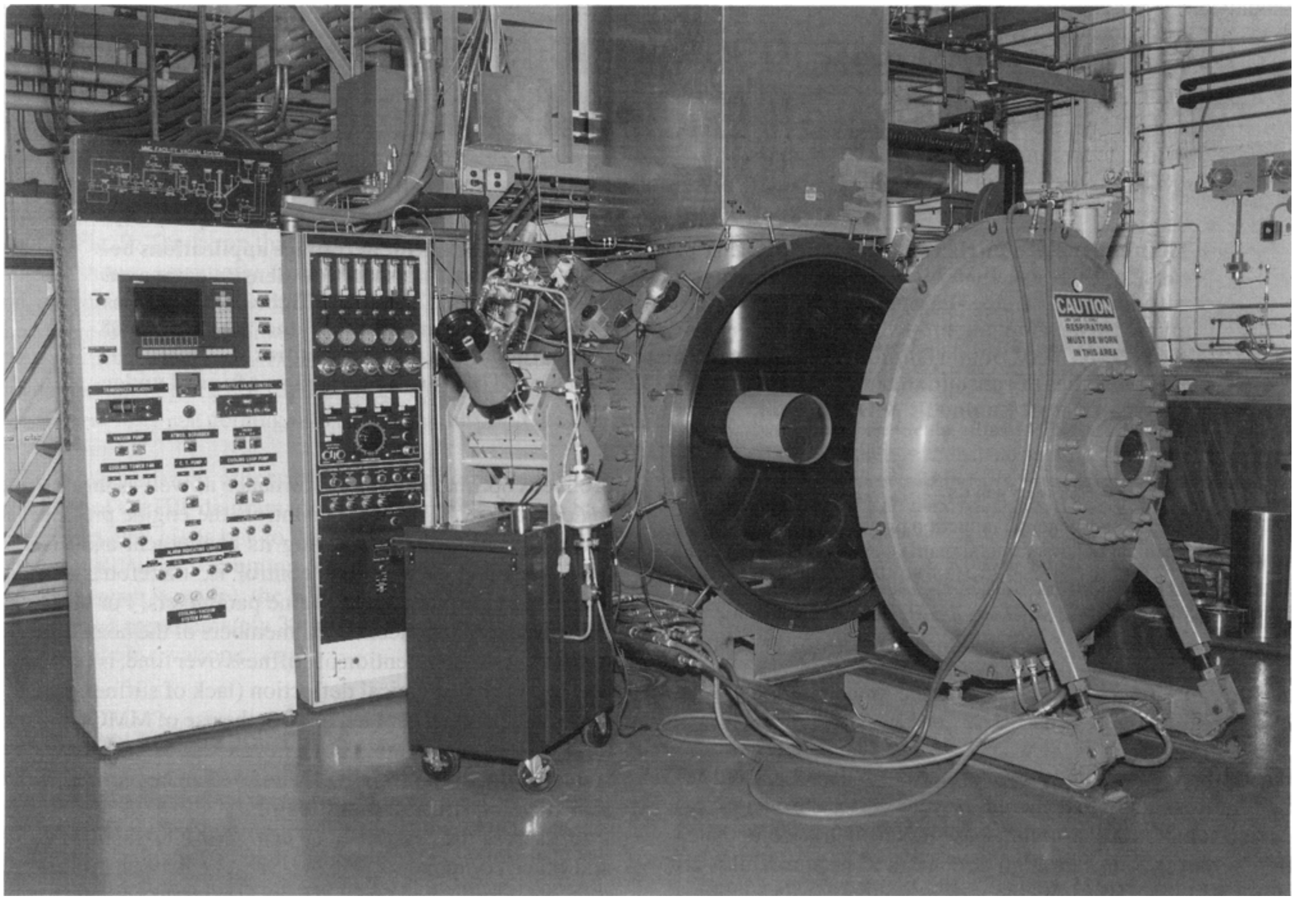

Fig. 2 The GEAE induction plasma deposition facility for the manufacture of metal matrix composite materials.

2. Experimental Procedure

2.1 *Input Materials*

Powders for the IPD process can be produced by any process that meets required composition and interstitial limits. Currently, the Nuclear Metals Inc. Plasma Rotating Electrode Process (PREP) and the Crucible Materials Corp. Gas Atomization (GA) process are the primary sources of titanium powder. The preferred powder mesh size is –80+140; however, spray parameters have been established for many particle size ranges including titanium powders as coarse as –60+80 mesh (180 to 250 μm). Current powder specifications for IPD input material require total interstitial oxygen, nitrogen, hydrogen, and carbon levels to be less than 1500 ppm. Interstitial pickup during IPD of conventional titanium alloys is typically 200 to 300 ppm.

The primary MMC reinforcement used in this study was the Textron Specialty Materials 0.0056 in. (0.014 cm) diameter SCS-6 silicon carbide fiber. The SCS-6 fiber is supplied with certified tensile strengths of greater than 500 ksi (3500 MPa) and diameters to within ±0.0002 in. (0.00051 cm). Other SiC fibers such as those produced by BP Sigma and Amercom can also be IPD processed, as described below. Prior to use for IPD processing, all input fiber lots are evaluated to ensure that they meet tensile and surface coating quality requirements. The IPD process uses high-purity argon and helium gases that contain less than 1 ppm and less than 5 ppm oxygen, respectively.

2.2 *IPD Process Description*

The GEAE IPD system for MMC manufacture is shown in Fig. 2. The IPD process uses an inductively coupled radio frequency (RF) plasma generator to melt and spray deposit a fine-grained uniform microstructure of titanium matrix onto a fiber-wound drum. Virtually any matrix alloy that can be produced as powder can be deposited to produce MMC monotapes and neat (unreinforced) foils. During IPD processing, fiber spacing is positively maintained (fixed in place by the solidified metal), and the resultant monotape is flexible and easily handled during further processing into multilayer composites without fear of fiber movement.

2.3 *Monotape Fabrication*

Prior to fiber winding for the MMC monotape used in this study, special surface preparation was completed on the nominally 12 in. (30.5 cm) diameter by 14 in. (35.6 cm) long low-carbon steel mandrels. This special technique provides a guide

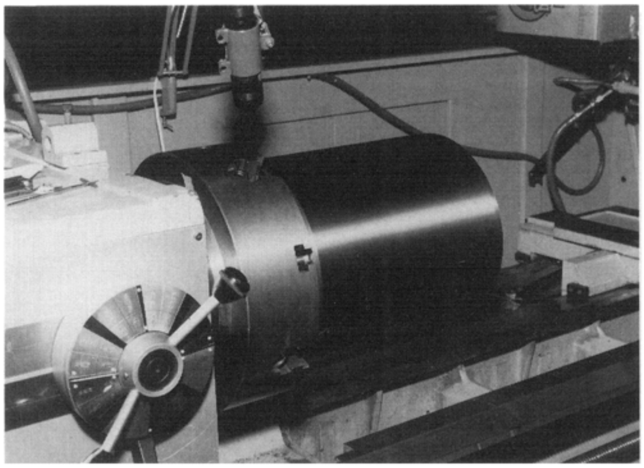

Fig. 3 A 12.7 in. (32.2 cm) diameter low carbon steel mandrel wound with SCS-6 fiber.

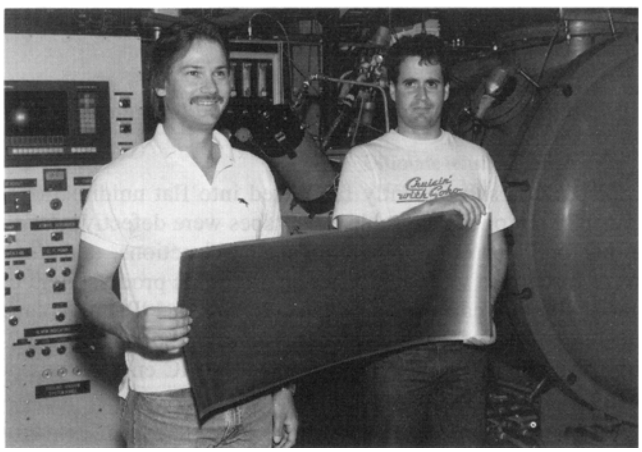

Fig. 4 An example of a typical Ti6242/SCS-6 plasma sprayed monotape produced by the induction plasma deposition process.

to keep the fiber in place during winding and IPD processing. An example of a fiber-wound mandrel is shown in Fig. 3. The spacing was selected to achieve the desired volume percent fiber, which in this study was a spacing of 0.008 in. (0.02 cm), to produce approximately 40 vol% MMC monotapes. The fiber ends were attached to the mandrel under cap screws, and a 0.010 in. (0.025 cm) thick by 0.5 in. (1.27 cm) wide molybdenum strip was secured along the mandrel length (Fig. 2) to produce an uncoated region for easy monotape cutting and removal after plasma spray. The fiber-wound mandrels were mounted on a rotating and translating sting and instrumented with thermocouples to monitor mandrel temperature during IPD processing. After evacuation and backfilling the IPD chamber with argon to a pressure of 250 torr, the mandrel was plasma sprayed with –80+140 mesh Ti6242 to produce a nominally 0.015 in. (0.038 cm) thick MMC monotape. An example of a typical plasma sprayed monotape produced by the IPD process is shown in Fig. 4.

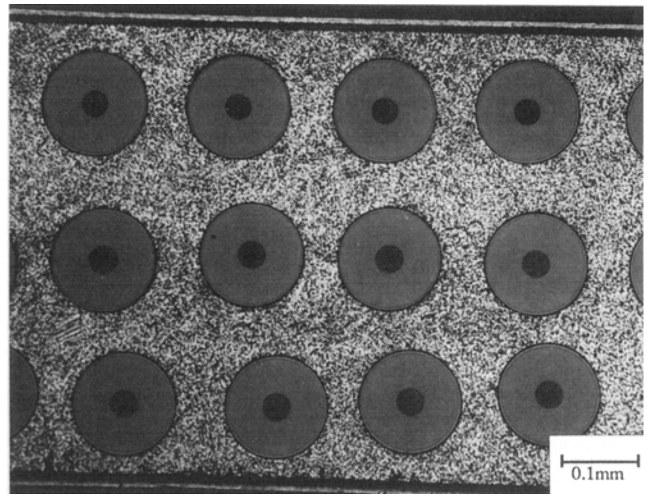

Fig. 5 Typical microstructure of a 3-ply unidirectional Ti6242/SCS-6 composite panel manufactured by the IPD process.

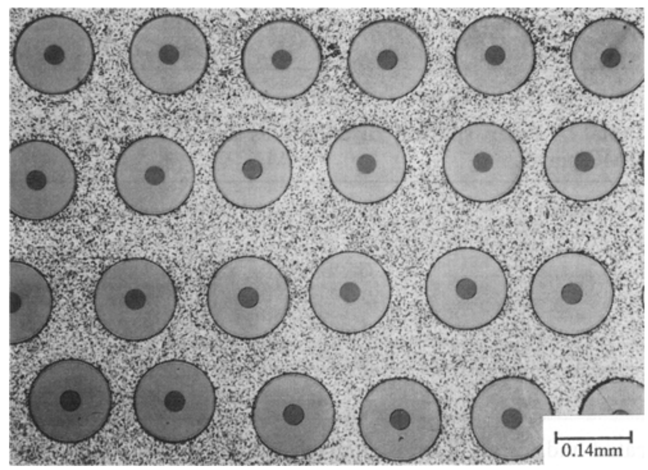

Fig. 6 Typical microstructure of a 4-ply unidirectional Ti6242/SCS-6 composite panel manufactured by the IPD process.

2.4 *Panel Manufacturing*

The hot isostatic pressing (HIP) consolidation procedure for producing titanium MMC panels for this study used low-carbon steel HIP cans. Molybdenum separator sheets were used to isolate the monotapes from the steel can. The HIP can assemblies were TIG welded and helium leak inspected to ensure can integrity. The cans were then loaded with MMC monotapes and hot degassed prior to sealing under vacuum. HIP consolidation was performed at Howmet Corp., Whitehall, MI, using a controlled HIP cycle designed to prevent fiber breakage. During this study, various Ti6242/SCS-6 MMC panel sizes and thicknesses were HIP consolidated and evaluated. Unidirectional panels ranging from 2 to 72 plies and from 5×6 in. (12.7×15.2 cm) to 12×18 in. (30.5×45.7 cm) were fabri-

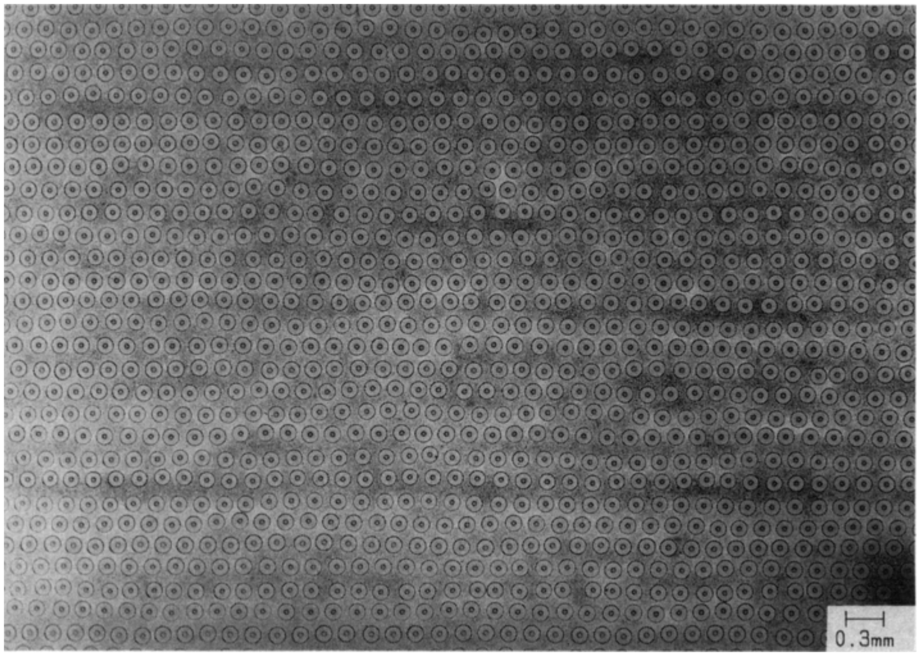

Fig. 7 Typical microstructure of a 36-ply unidirectional Ti6242/SCS-6 composite panel manufactured by the IPD process.

Table 1 Fiber spacing distributions for the Ti6242/SCS-6 MMC panels

No. of plies	Panel ID	Average spacing, mils
3	GE"A"	7.83 ± 0.29
4	GE"B"	7.88 ± 0.44
8	VHP 264	7.85 ± 0.30
36	1-36B	8.02 ± 0.25
72	2-72	7.96 ± 0.35

cated and tested. Representative sections of several of these panels are shown in Fig. 5 to 7.

2.5 *Evaluations*

Composite panels were examined metallographically to determine the volume fraction of fibers, reaction zone thickness, and fiber spacing distributions. Fiber spacing was measured using an Omnimet 1 Image Analyzer, which consisted of 20 to 50 fiber center-to-center measurements along the *x*-axis of selected 3-, 4-, 36-, and 72-ply panels. Tensile and fatigue specimens were machined from several of the composite panels and tested per appropriate ASTM specifications.

3. Results and Discussion

3.1 *Process Control/Yield*

Sixty-eight monotapes were manufactured during this study to demonstrate a "best practices," reproducible MMC monotape fabrication process. After inspection to ensure no fiber bunching or breakage, 61 of these monotapes were found acceptable and subsequently fabricated into flat unidirectional panels. Four of the unusable monotapes were defective due to either operator error or equipment malfunctions, and three were associated with poor fiber quality. This process yield of about 90% indicates that a properly established IPD monotape manufacturing procedure can consistently produce high-quality MMC precursor material for use in MMC engine components.

3.2 *Microstructures*

The chemical reactions between the SCS-6 fiber and the Ti6242 matrix can lead to the formation of a brittle reaction layer that can be detrimental to the properties of the composite. Studies have shown that the effective tensile strength of SCS-6 fiber in the titanium matrix decreases as the thickness of the reaction zone increases.[1] Therefore, controlling the extent of the interfacial chemical reaction during processing and service is crucial.

Typical microstructures of several Ti6242/SCS-6 composite panels that underwent HIP processing at 1650 °F (900 °C) are shown in Fig. 5 and 6. The matrix consists of ultrafine αTi grains containing plates of βTi. The average thickness of the reaction zone that forms between the matrix and fiber coating in these IPD fabricated and HIP composites is approximately 0.6 μm. Previous work[2] has shown that the reaction zone consists of three different regions; a fine-grained zone of TiC next to the fiber coating, a central zone of larger grained TiC which contains Zr, and a band of elongated $(Ti,Zr)_5Si_3$ silicides adjacent to the matrix. A small amount of silicide precipitate may also be present in the fine-grained TiC. These reaction layers are observed in Ti6242/SCS-6 MMCs after HIP, regardless of the fabrication technique used, and do not appear to be any thicker in

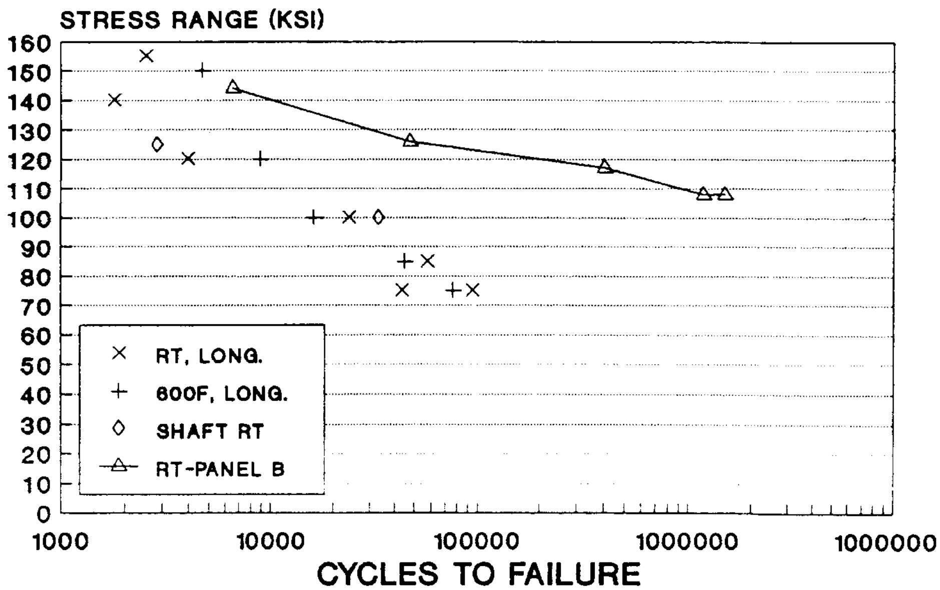

Fig. 8 RT fatigue properties of IPD processed Ti6242/SCS-6 MMCs with well-controlled fiber spacing exhibit a 2× improvement over material with poor spacing or touching fibers. (Load control, R = 0.05, 30 CPM)

Table 2 Longitudinal room-temperature tensile test results for Ti6242/SCS-6 MMC panels

Panel	Ultimate tensile strength, ksi	*E*, msi	Fiber, vol%	%*e*	Panel size, in.	No. of plies	No. of tests
GE"A"	255	...	40	...	12 × 18	3	1
GE"B"	261	...	38	...	12 × 18	4	2
GE"C"	232	...	40	...	12 × 18	4	1
GE"D"	246	31.4	38	0.83	12 × 18	3	1
GE"E"	244	30.7	35	0.88	12 × 18	3	1
GE"F"	260	31.2	35	0.95	12 × 18	3	1
GE"G"	220	31.4	35	0.72	12 × 18	3	1
GE"H"	256	31.1	36	0.81	12 × 18	3	1
VHP 264	276	32.8	39	0.95	5 × 6	8	1
1-24A	...	32.8	39	...	5 × 18	24	2

the plasma sprayed MMCs than in foil/fiber or powder-processed composites. The effect of these layers on mechanical properties other than tensile strength has yet to be determined.

3.3 *Fiber Spacing Control*

Control of fiber spacing and volume fraction is one of the strongest features of IPD processing. Excellent fiber spacing control can be maintained in IPD processing. This is an extremely important feature because various studies have shown that longitudinal tensile[3] and fatigue[3,4] properties of titanium MMCs can be lowered significantly due to fiber contact. Internal studies at GEAE[5] have also shown that transverse creep of MMC can be severely reduced with inadequate fiber spacing.

The fiber spacing distributions for panels fabricated in this study were determined for 3-, 4-, 8-, 36-, and 72-ply panels. The average fiber spacing for each of these panels is listed in Table 1. With a goal of obtaining an 0.008 in. (0.02 cm) fiber spacing in the *x*-axis direction (plane of fiber winding), the average values measured for the various panels ranged from 0.00783 to 0.00802 in. (0.0199 to 0.0204 cm). Fiber spacing in the *y*-axis direction, which is dependent on control of the amount of matrix deposition during IPD, is also very uniform as evident in Fig. 7, which shows the 36-ply panel. These results indicate that excellent fiber spacing control can be maintained in IPD-processed MMCs.

3.4 *Mechanical Property Data*

Room-temperature tensile testing was performed on longitudinal specimens from several panels manufactured in this study as listed in Table 2. The ultimate tensile strengths for these Ti6242/SCS-6 composites ranged from 220 to 276 ksi (1540 to 1932 MPa), and the modulus values ranged from 30.7 to 32.8 msi (215 to 230 GPa). Initial room-temperature fatigue test results for panel GE"B" are plotted in Fig. 8 and are compared with prior IPD MMC material fabricated with less-well controlled fiber spacing.[4] These data indicate a nearly 2× (stress basis) improvement over the earlier data and clearly illustrate the importance of preventing fibers from touching and the benefits of achieving good spacing control.

4. Conclusions

Large-scale nominally 40 volume fraction Ti6242/SCS-6 MMC monotapes can be fabricated with precisely controlled fiber spacing using the GEAE developed IPD process. Longitudinal room-temperature tensile results for Ti6242/SCS-6 MMCs fabricated by IPD yield ultimate tensile strength values between 220 to 276 ksi (1540 to 1932 MPa) and modulus values in the range of 31 msi (217 GPa). Fatigue properties for IPD-processed Ti6242/SCS-6 MMCs with well-controlled fiber spacing exhibit a 2× improvement over material with poor spacing or touching fibers.

Acknowledgments

The authors would like to acknowledge the contributions of M. Murray, J. Alexa, E. Ardini, and J. McGovern for their effort in the fabrication and evaluation of the composite material; R. March and L. Squillacioti for helpful discussions on processing issues; K. Bain for conducting the mechanical property testing and analysis of these materials; and D. Blatt and J. Larsen for additional composite testing.

References

1. J.-M. Yang, S.M. Jeng, and C.J. Yang, Fracture Mechanisms of Fiber-Reinforced Titanium Alloy Matrix Composites, Part I: Interfacial Behavior, *Mater. Sci. Eng.*, Vol A138, 1991, p 155-167
2. A.M. Ritter, "Reaction Zone Formation in Ti-Base/SiC Composites," GE-CRD Report No. 89CRD173, Jan 1990
3. M.L. Gambone and K.R. Bain, "Fractography of Titanium Aluminide Metal Matrix Composites," Proc. 2nd Int. SAMPE Metals Conference, Dayton, OH, Aug 1988, p 487
4. K.R. Bain, private communication, 1992
5. P.K. Wright, "Creep Behavior and Modeling of Titanium/SCS-6 MMC," Proc. Titanium Aluminide Composite Workshop, Orlando, FL, Nov 1991