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Development of a pneumatic spreading system for Kevlar-based SiC-precursor carbon fibre tows

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Abstract. A novel spreading system based upon the Venturi principle was designed and constructed. The system was used to spread Kevlar-based carbon fibres and to maintain that spread for sufficient time to facilitate chemical vapour deposition of an SiC coating. The Kevlar-based carbon fibres were shown to possess excellent thermal stability and a combination of properties that make them an ideal silicon carbide precursor fibre. Through a combination of pinch-rollers and two distinct axial Venturi spreaders, a highly chaotic and effective spread was achieved and maintained. This work provides a novel process for producing potentially excellent silicon carbide precursor fibres as well as providing a novel use for a high-performance polymer.

1. Introduction

Composite materials are rapidly displacing conventional metals and metallic alloys in high-performance aircraft manufacture. The leading edge of composite materials technology mainly revolves around rigid-rod aramid polymers and carbon fibres. Each class of fibre is capable of supporting significant tensile loads in composites and possesses strength-to-weight ratios far in excess of metals. However, rigid-rod polymers such as PBO (poly *p*-phenylene benzobisoxazole) and Kevlar (poly *p*-phenylene terephthalamide) are limited by comparatively poor compressive strengths. High-performance carbon fibres offer improved compressive strengths, but are expensive and cannot be used in high-temperature environments where oxygen is present. This limits the utility of carbon fibres in aircraft and aircraft engines.

The alternative to these polymeric and carbon fibres is the use of high-performance ceramic fibres such as silicon carbide. As table 1 shows, silicon carbide fibres possess tensile and compressive properties comparable to high-performance carbon fibres. However, the silicon carbide fibres are also oxidation resistant. Thus, continuous fibre ceramic composites can function in high-temperature oxidative environments without experiencing the brittleness problems associated with traditional ceramics [1].

The experimental challenge is to produce these high-performance silicon carbide fibres reliably and at a low cost. Currently, the majority of commercial silicon carbide fibres are produced by coating a suitable substrate using a chemical vapour deposition (CVD) process. The use of silicon carbide coatings is not new. Mesophase pitch fibres have long been coated to provide reactive barriers to oxidation [4]. The most common substrate used for silicon carbide manufacture is tungsten wire [5]. Unfortunately, tungsten wire is expensive and has a very rough surface that is not ideal for the deposition process. Thus, the manufacture of alternative

Table 1. Properties of high-performance fibres [2, 3].

Material	Tensile strength (GPa)	Tensile modulus (GPa)	Compressive strength (GPa)
Kevlar	3.5	125	0.39–0.48
PBO	5.7	306	0.20–0.40
Toray M60J carbon fibre	3.8	585	1.67
ARC Trimarc I SiC (tungsten core)	3.4	460	1.55–1.75

precursors would be advantageous provided that the precursors possess four fundamental properties:

(a) A smooth surface with a small uniform diameter.
(b) A low coefficient of thermal expansion (CTE) compatible with the silicon carbide coating.
(c) Sufficient tensile strength to withstand the coating process.
(d) A low cost.

An ideal solution to this problem would be to use a low-cost, low-modulus carbon fibre substrate [6, 7]. Because both mesophase pitch and polyacrylonitrile (PAN) based fibres have incompatible CTEs, the apparently logical choice would be to use a low-modulus isotropic pitch fibre. McHugh *et al* [8] attempted to create such a substrate, but found that the fibres lacked sufficient tensile strength to survive the rewinding process.

Carbon fibres made from high-performance polymers provide an alternative. High-performance polymers, including Kevlar and PBO, can be converted directly into carbon fibre without the need for the costly oxidative stabilization step required by traditional precursors [9–11]. Kevlar, shown in figure 1, carbonizes to form fibres that have diameters of less than 7 μm, moduli of less than 150 GPa, and tensile strengths of approximately 1 GPa. The only technical limitation inhibiting the use of carbonized Kevlar is the lack of an available monofilament.

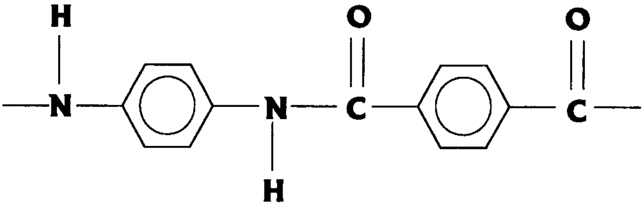

Figure 1. The molecular structure of Kevlar.

During the CVD process, each Kevlar-based carbon fibre filament in a tow must be unencumbered by its neighbours for long enough to receive the SiC coating. Without effective spreading, the effects of fibre bridging could become severe, as pictured in figure 2. Classical air-comb spreading technology fails to provide and maintain a suitable degree of spreading. Thus, developing an effective pneumatic spreading system capable of reducing potential bridging and enabling the conversion of Kevlar-based carbon fibre into silicon carbide is essential.

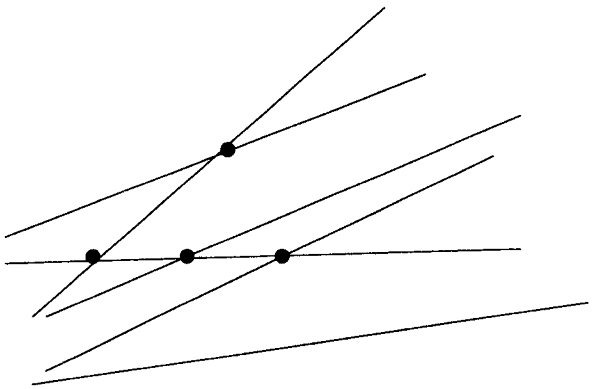

Figure 2. Illustration of potential fibre bridging during CVD.

2. Experiment

This research focused on the design and manufacture of an effective pneumatic spreading system for Kevlar-based carbon fibres tows. High-speed photography was used to evaluate the effectiveness of the spreaders. Gas flow rates were determined by measuring the exit velocity of the gas stream using an anemometer. All spreaders were constructed from commercial Lucite.

To characterize the mechanical properties of Kevlar-based carbon fibres, Kevlar fibres were carbonized by pulling them continuously through a tube furnace. Carbonization temperatures of 900, 1400 and 1600 °C were used. A positive pressure of argon was used to prevent oxidation of the fibres during heating. Fibre diameters were measured using a laser diffraction technique [12]. Tensile strengths and moduli of the fibres were measured using a modified Instron ultimate testing machine.

Fibre dimensional stability was characterized by comparing the diameters of two distinct processing trials. In the first trial, Kevlar was pulled through a tube furnace that had been heated to 1400 °C. The total soak duration of the fibre was approximately 40 s. A second length of Kevlar was pulled into a 1400 °C furnace, but remained in the heated region for 30 min.

3. Results and discussion

Table 2 summarizes the tensile properties of Kevlar-based carbon fibres. Even at relatively low carbonization temperatures, unstabilized Kevlar-based carbon fibres possess more than 500 MPa of tensile strength. This indicates that the fibres have sufficient strength to enable them to be pulled through the spreading system without breaking.

Table 3 indicates that no statistically significant differences exist between the diameters of fibres that were pulled quickly through the furnace and those that were allowed to dwell at high temperatures for 30 min. The dimensional stability shown by these Kevlar-based carbon fibres implies that they may be suitable for high-temperature chemical vapour deposition.

A fibre-spreading towline, pictured in figure 3, was constructed. During initial trials the tension required to advance the fibre along the towline had a tendency to reduce spreading. To alleviate this problem, a system of pinch rollers was constructed and used to create a loop of

Table 2. Tensile properties of Kevlar-based carbon fibres.

Carbonization temperature (°C)	Tensile strength (MPa)	Tensile modulus (GPa)
900	512 ± 36	78 ± 4
1400	749 ± 69	126 ± 9
1600	940 ± 76	143 ± 5

Table 3. Dimensional stability of Kevlar-based carbon fibres at elevated temperatures.

Soak duration at 1400 °C (min)	Mean fibre diameter (μm)
0.66	6.6 + 0.3
30	6.7 + 0.2

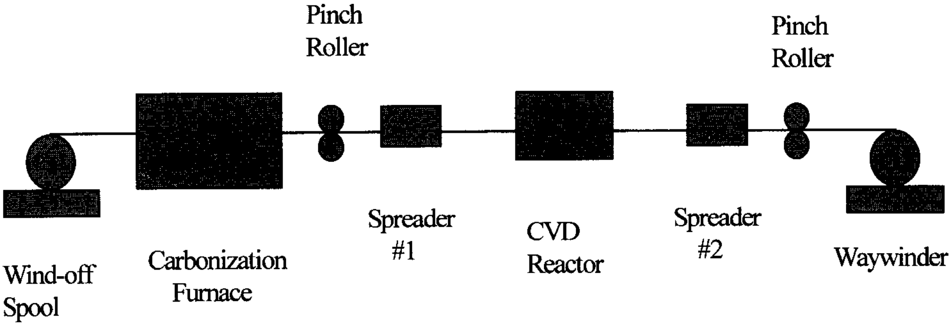

Figure 3. Spreading system configuration.

slack in which the spreading could occur. Fibres emerging from the carbonization step were pinched between rubberized rollers. Another pinch roller was placed beyond the last spreader before the traversing waywinder. The towline design priniciples were similar to those used in the continuous fibre coating system developed by Lackey *et al* [13]. The primary differences between these systems are that the Lackey system was oriented vertically and was constructed to continuously coat monofilaments. Thus, their paper focused on furnace design parameters and did not need to address spreading issues.

A series of spreaders that focused on axial spreading effects was found to be the most effective. First, the tow is passed through an axial type I Venturi spreader, shown in figure 4. In this spreader, the inner channel widens, much like the nozzle of a Venturi flow meter. The resultant Venturi effect aligns the streamlines of the spreading gas in a favourable fashion. The divergent nozzle moves the tow through a pressure differential as described by the Bernoulli equation, resulting in a chaotic motion of filaments within the tow. At the same time, the Venturi throat minimizes the formation of undesirable vortices and eddies. Although this spreader alone provides a reasonably effective short-duration spreading, a second spreader is required to maintain adequate separation between filaments.

At the opposite end of the spreading region, the tow is passed into an axial type II Venturi spreader. This device, pictured in figure 5, is conceptually similar to the type I spreader. However, the tow is fed into the spreader through a narrow hole drilled at a 30° angle to the channel and the gas inlet is positioned at the rear, rather than the middle, of the spreader. In this design, the entire gas flow could be biased to one end of the spreader only.

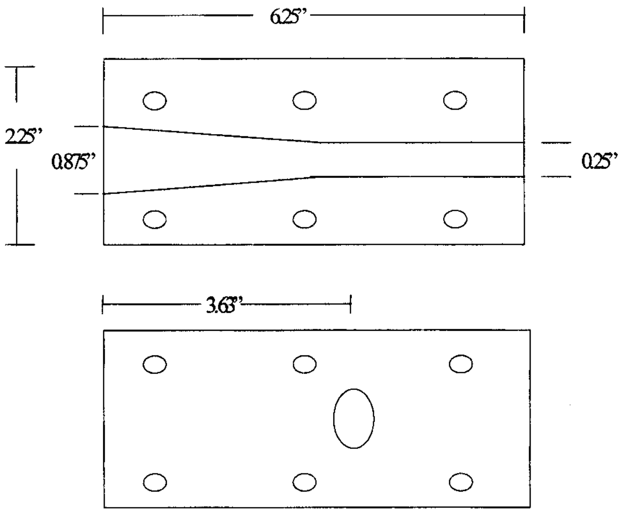

Figure 4. The axial Venturi type I spreader.

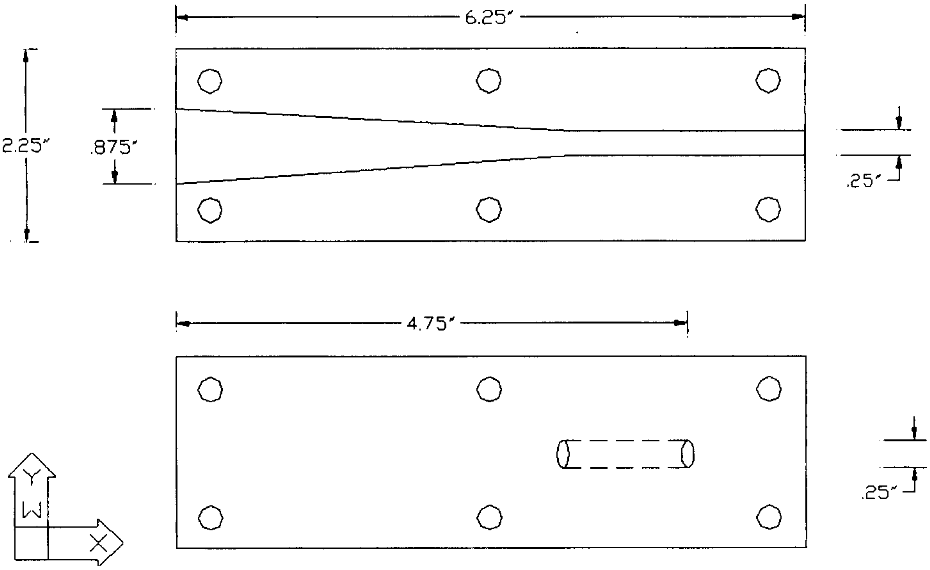

Figure 5. The axial Venturi type II spreader.

Using this system of pinch rollers and Venturi spreaders in series, a highly chaotic, three-dimensional spread was achieved and maintained through a linear distance of 3 ft. With gas velocities of 25 cfm (12 $\mathrm{cm}^3\ \mathrm{s}^{-1}$), a chaotic spread with a total diameter of 3–4 in was maintained across the entire 3 ft. Figures 6–8 show stop action photos of this spreading. It is important to note that a two-dimensional photograph cannot perfectly capture the entire three-dimensional nature of the spreading; however, they do show that the fibre is widely dispersed.

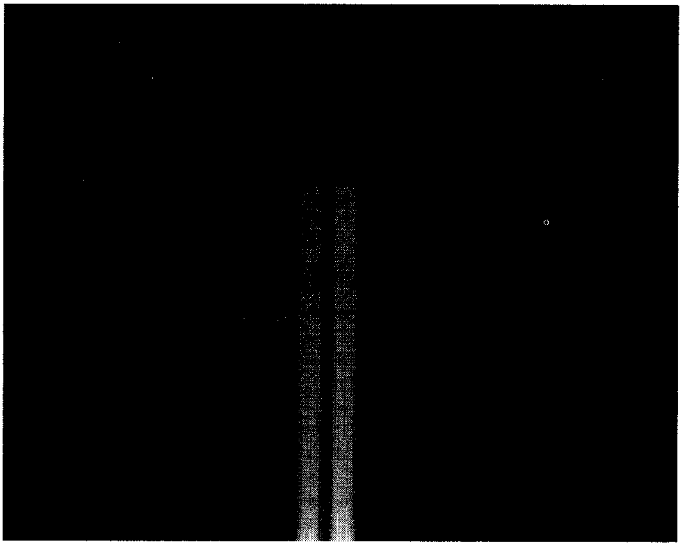

Figure 6. Unspread Kevlar tow.

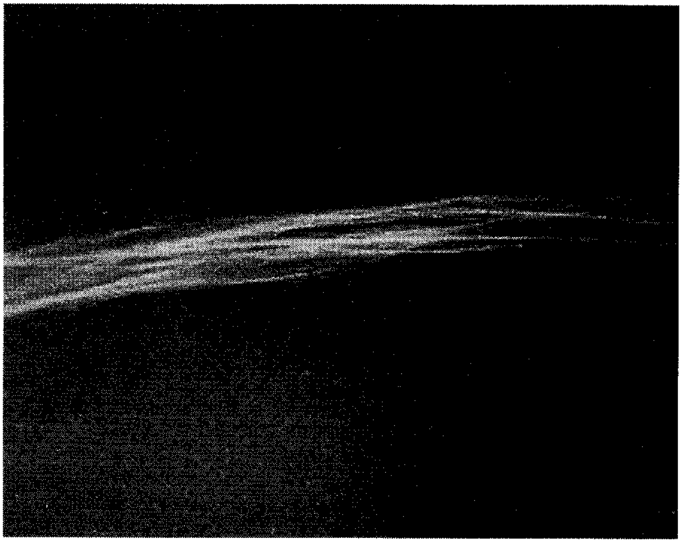

Figure 7. Stop-action spreading photo (perspective is identical to figure 6).

4. Conclusions

Significant spreading between individual fibres was achieved using the axial Venturi spreading system. Enough spreading is achieved to make CVD coating possible. This spreading can be maintained for a linear distance of 3 ft. The use of shallow rectangular channels prevents the vorticular twisting effects experienced in round channels. Finally, Kevlar-based carbon fibres seem to possess considerable potential as a silicon carbide precursor fibre.

Figure 8. Spread Kevlar tow (1.6×magnification).

Acknowledgments

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References

[1] Chin K and Wessel J 1996 *Chem. Eng.* **103** (10) 80
[2] Kumar S and Helminiak T E 1990 *SAMPE J.* **26** (2) 51
[3] Atlantic Research Corporation 1996 *Trimarc I Silicon Carbide Fibre Specifications Sheet*
[4] Emig G, Popovska N and Schoch G 1993 *Thin Solid Films* **241** 361
[5] Bustamante W J 1996 Private communication (Amercom Inc.)
[6] Aggour L, Fitzer E, Ignotowitz E and Sahebkar M 1974 *Carbon* **12** 358
[7] Fitzer E, Kehr D, Morin D and Sahebkar M 1975 *Proc. Fifth Int. Conf. Chemical Vapour Deposition* (Princeton, NJ: The Electrochemical Society) p 623
[8] McHugh J J and Edie D D 1995 Unpublished data
[9] Newell J A, Rogers D K, Edie D D and Fain C C 1994 *Carbon* **32** 651
[10] Newell J A, Edie D D and Fuller E L Jr 1996 *J. Appl. Polym. Sci.* **60** 825
[11] Jiang H, Desai P, Kumar S and Abirahman A 1991 *Carbon* **29** 635
[12] Hayes G J 1993 Analysis of the single filament recoil test *PhD Dissertation* Clemson University
[13] Lackey W J, Hanigofsky J A, Gorves M T and Heaney J A 1991 *Ceram. Eng. Sci. Proc.* **12** 1048