Canada

ADVANCED COMPOSITES: OPPORTUNITIES AND OBSTACLES

REPORT No. 4/86

Office of Industrial Innovation

INNOVATION

Government of Canada
Gouvernement du Canada
Regional Industrial Expansion
Expansion industrielle régionale

ADVANCED COMPOSITES:

OPPORTUNITIES AND OBSTACLES

Office of Industrial Innovation
Department of Regional Industrial Expansion
May 1986

PU 2805

FOREWORD

Advanced industrial materials are a group of emerging technologies that are spurring the development of a wide range of high performance industrial products of importance to Canada's economic performance. Our ability to develop and use them will increasingly determine our industrial competitiveness.

We have already witnessed shifts in demand for traditional materials as innovative manufacturers introduce novel substitutes to improve the performance and competitiveness of their products. Optical fibres are replacing copper wire, composites are displacing aluminum in aircraft, and a variety of plastics and new alloys are supplanting steel in automobiles. Advanced industrial materials are at the leading edge of this transition. They are paving the way for even more dramatic changes.

The accelerating pace of change in the materials field offers unprecedented opportunities to develop new resources, processes and products. Our ability to recognize the changes while there is still time to take positive steps, and our readiness to face up to the challenges posed by the changes, will determine our potential to exploit fully these opportunities.

The traditional materials industry, long a major source of Canada's wealth, is facing severe economic problems. Most of the sources of its difficulties are beyond the influence of either the private sector or government. The rapid changes in advanced industrial materials might be viewed as a further threat. On the other hand, it is well within our combined ability to grasp the technological advances and use them to spur a rejuvenation of an otherwise stagnant sector.

This report is the second in a series on Advanced Industrial Materials. Its purpose, similar to Report No. 3/86 on Advanced Ceramics, is to demystify the field of Advanced Composites, outline from an international perspective the status of the technologies and markets, identify the players in Canada, and identify the opportunities and issues. It was prepared by the Ontario Research Foundation under contract with the Department of Regional Industrial Expansion and the opinions expressed are not necessarily endorsed by the department.

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EXECUTIVE SUMMARY

Although the technology of composites dates from the beginning of the century, large-scale commercial applications were developed only after World War II. Over the last 20 years consumption of composite materials has increased at an annual rate of 15 percent, and consumption of advanced composites has increased at a 30 percent annual rate over the last 10 years. Advanced composites are new, high-performance composites consisting of polymer, metal or ceramic matrix and high-performance reinforcements such as S-glass, Kevlar, graphite or boron fibres. These materials successfully compete with traditional materials due to their low density, high stiffness, high strength and vibration damping. Worldwide consumption of advanced composites was estimated to be valued at $1.3 billion (U.S.) in 1984, and is expected to reach $12 billion (U.S.) by the year 2000. Advanced composites are finding applications in such diverse fields as aerospace, sports and recreation, automotive industrial machinery, health care and others.

At present, polymer matrix advanced composites are by far the most commercialized of all advanced composites. Carbon/carbon composites have limited application in aircraft brakes and rocket nozzles where their high temperature resistance is important. Both metal matrix and ceramic matrix composites are still in the developmental state, with very limited market applications. With the improvement in manufacturing efficiency, applications for these materials are expected to increase rapidly.

Canada has strong auto parts, aircraft and sports equipment industries which create natural markets for advanced composites. Technical and manufacturing expertise in advanced polymer matrix composites, although somewhat limited at present, forms a good base on which the new industry may be built.

The new technologies pose both a threat and an opportunity. The threat is that the present products which do not utilize new materials will not be able to compete on the world markets. The opportunity lies in participation in the rapidly growing technology and new markets it creates.

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1. INTRODUCTION

Over the last 20 years, consumption of composites has increased at an annual rate of 15 percent, and the consumption of advanced composites has increased at a rate of 30 percent over the last 10 years. Worldwide consumption of advanced composites was estimated to be valued at $1.3 billion (U.S.) in 1984, and is expected to reach $12 billion (U.S.) by the year 2000.

Composite material may be defined as a synergistic assembly of two or more materials where the properties of the composite often exceed those of the individual components. The main mechanical properties of a composite are governed by the properties of the reinforcements. These reinforcements may be used in the form of fibres, flakes or irregular particles. Reinforcements are dispersed in another material known as matrix, whose main role is to transfer stress between individual reinforcements, protect them and form the shape. Composites are used for such diverse applications as printed circuit boards, tennis rackets, computer housings, automotive bodies, aircraft brakes and pressure vessels. Composites are often classified by type of matrix; thus, there are polymer, carbon or graphite, ceramic and metal composites.

The term "advanced composites" is not well defined but usually describes newer types of composites with properties exceeding those of more traditional composites. For the purpose of this report, the following composites are considered to belong to this category:

- organic matrix composites reinforced with carbon, Kevlar, boron and S glass (glass with higher strength than traditional E glass) fibres;
- carbon matrix with carbon fibres;
- ceramic matrix composites;
- metal matrix composites.

This report reviews technologies, applications and markets for these composites.

Although various composite materials (for example, wood-cellulose fibres in lignin matrix) have been used throughout history, the technology of modern composites dates from the beginning of the century when Beakeland discovered that the addition of wood fibres to phenolic resin results in a strong, hard and relatively tough material. This material has been manufactured under the trade name Bakelite.

During World War II the use of resin-impregnated paper as a substitute for aluminum in aircraft skins was investigated. The introduction of glass fibres at the end of World War II resulted in rapid growth of reinforced composites. The first applications were in housing for radar scanners but the use of composites rapidly spread to other industries such as transportation, electrical, construction and sports and recreation.

The introduction of composite materials was probably the most revolutionary development in the history of materials. For the first time material properties could be designed to suit engineering requirements. Since the end of World War II, the growth of composite materials has been spectacular. This growth is still continuing, opening business opportunities and threatening those industries unable to accommodate the change.

2. POLYMER MATRIX COMPOSITES

Polymer matrix composites are by far the best established synthetic composites with the market size of $1.3 billion (U.S.). A tremendous market growth rate of 30 percent per year for the last 10 years is due, in part, to the following properties:

- high specific strength (strength per unit weight, high strength and low density);
- high specific stiffness (stiffness per unit weight, high stiffness and low density);
- corrosion resistance;
- toughness (resistance to impact damage);
- ease of manufacturing.

Polymer matrix/glass fibre composites technology is well established. New reinforcement materials and matrix materials are being developed to further improve such properties as strength, stiffness, toughness and temperature resistance. At the same time, more efficient manufacturing processes are being introduced.

2.1 Matrix Materials

Plastics are divided into two distinct classes:

- thermosets - materials which permanently harden due to a chemical reaction at room temperature or higher (for example, epoxy and phenolic resins);
- thermoplastics - materials which melt when heated and solidify when cooled (for example, polyethylene and polyvinyl chloride).

The bulk of the polymer advanced composites utilize thermosetting resins as matrix materials. Although reinforced thermoplastics have been used for a long time, these materials use short fibres as reinforcements. The new class of reinforced thermoplastics referred to as Advanced Thermoplastics (ATPs) are now being commercialized. These composites utilize long or continuous fibres. At present there are only a few companies manufacturing advanced thermoplastic composites, but the applications of these products are expected to grow rapidly.

2.2 Thermosetting Resins

For Use at Ambient Temperature

Epoxies are the most widely used matrix resins. They offer ease of manufacturing, wide choice of forms, low shrinkage, good adhesion to fibres and good mechanical properties.

Polyesters are usually used with lower performance composites. They have a broad application in standard composites.

For Use at Intermediate Temperatures (150-250°C)

Epoxies which may be used in this temperature range are the novolacs, cycloaliphatics and standard epoxies cured with anhydrides. High temperature cured epoxies tend to be brittle.

Bismaleimides (BMI) process similarly to epoxies, but offer higher operating temperatures. These resins are finding applications in "hot" aircraft engine parts.

Phenolics offer a temperature resistance up to 250°C. Because of their poor mechanical strength their applications are limited.

Silicones are based on silicon rather than carbon chemistry. Some resins can operate even above 250°C. Their mechanical properties are poor and applications limited.

For Use at High Temperatures (250-400°C)

Polymers capable of operating above 250°C are based on an aromatic heterocyclic ring structure. Some of the high temperature polymers are:

- polyimides
- polybenzimidizoles
- polyquinoxalines
- polyamide-imides
- polybenzthiazoles.

Ambient temperature resins are used for sports equipment and aircraft interior components while aircraft exterior components are produced using intermediate and high temperature resins.

The selling price of these resins increases with increasing service temperature. Ambient temperature resins sell for approximately $2.20 to $8.80 per kilogram ($1 to $4 per pound), intermediate temperature resins for $6.60 to $44 per kilogram ($3 to $20 per pound) and high temperature resins for from $22 to over $220 per kilogram ($10 to over $100 per pound).

2.3 Thermoplastic Resins

The advanced composites technology was developed around thermosetting resins, because of the ease with which these resins may be used to impregnate the reinforcements. The disadvantages of thermosets are:

- long manufacturing cycles (because of the curing time of the resin);
- scrap cannot be re-used;
- poor toughness.

These disadvantages may be overcome by the use of thermoplastics. Resins used with advanced thermoplastics include:

- polyamideimide
- polyimide
- polyphenylene sulphide
- polyetheretherketone
- other resins including commodity and engineering resins.

Commodity resins such as polypropylene resins sell for approximately $2.20 to $4.40 per kilogram ($1 to $2 per pound), engineering resins such as polycarbonate and ABS for $4.40 to $22 ($2 to $10) and high-performance thermoplastics such as polyetheretherketone and polyphenylene sulfide for $11 to $44 per kilogram ($5 to $20 per pound). Mark-up in continuous fibre reinforced thermoplastics is high. Composites consisting of glass fibre (approximately $2.20 per kilogram -- $1 per pound) and polypropylene (approximately $2.20 per kilogram -- $1 per pound) are quoted at $44 per kilogram ($20 per pound).

Composites are produced by the impregnation of reinforcing fibres with the polymer. In the case of thermoplastics, the simplest system would utilize molten polymer to impregnate reinforcements. The viscosity of such a melt is high, making impregnation difficult.

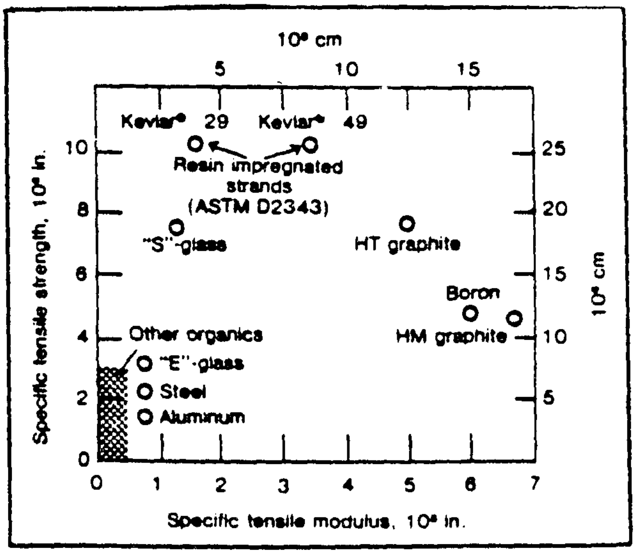
The main obstacle to the broader penetration of these materials is a lack of a low-cost process for impregnation of reinforcements with a high-viscosity melt. There is a considerable amount of R&D activity in this area and in the next few years advanced thermoplastic composites are expected to capture a considerable portion of the market for reinforced plastics.

2.4 Reinforcements

Reinforcements impart most of the mechanical properties to the composites; the role of the matrix is merely to transfer stress from one fibre to another. The most widely used reinforcements are:

- glass fibres (E and S glass)
- aramid fibres (Kevlar)
- graphite
- boron.

Figure 2.1 compares specific strength and specific modulus of these reinforcements.



<u>Figure 2.1</u>

Specific tensile strength and specific tensile modulus of reinforcing fibres (from <u>Rubber World</u>, May 1985)

Some materials are shown in two points depending on specific grades. Kevlar 29 is used mainly in tires while Kevlar 49 is used as reinforcing fibre. Graphite is available in high-tensile (HT) strength and high-modulus (HM) grades. The materials most desired by designers are located along the top and right-hand side of the graph. These materials are characterized by low density and high strength (top of the graph) or high stiffness (right-hand side of the graph).

Graphite fibres are used mainly when high specific tensile modulus, high thermal conductivity and low thermal expansion are required. A disadvantage of graphite is the rather poor impact strength of the composite. Kevlar provides high specific strength and toughness. Its compressive strength, however, is rather poor. Boron composites offer excellent tensile and compression strength.

Although the tensile strength of high-strength graphite composites is similar to that of boron composites, the compressive strength of boron composites is considerably higher. Glass fibres offer good mechanical properties at lower cost than either carbon, Kevlar or boron. In order to optimize the cost/performance characteristics of composites, a combination of two or more reinforcements is often used.

Reinforcing fibres vary considerably in cost from approximately $3.30 per kilogram ($1.5 per pound) for E glass and $15.40 per kilogram ($7 per pound) for S glass, to $44 per kilogram ($20 per pound) for Kevlar and some grades of graphite, to $815 per kilogram ($370 per pound) of boron fibres.

Reinforcements are available in a variety of forms. These include:
- continuous strand
- fabric
- woven roving
- chopped strand
- three-dimensional reinforcements
- mat
- prepreg.

Prepregs (reinforcements impregnated with a partly cured resin or with thermoplastic resin) are widely used in manufacturing high-performance components.

2.5 Manufacturing

The manufacture of advanced composite products involves a chain of activities performed by various manufacturing companies:

- production of raw materials (resins, additives, reinforcing agents). These activities are carried out mainly by large corporations and require considerable technical know-how;

- production of reinforcing fabrics. This activity may be carried out by medium-sized companies with an expertise in textile manufacturing;

- production of prepregs. This activity may be carried out by a medium-sized company and involves impregnation of reinforcements with resin;

- fabrication.

A variety of manufacturing processes are being used to produce advanced composite components:

- Contact moulding. Reinforcements are placed in the mould, resin is spread on it and allowed to harden. Mainly low-performance parts are manufactured by this method.

- Vacuum bag moulding. This method is used with wet lay-up to extract the air entrapped in the resin. Reinforcement impregnated with resin is positioned in the mould, covered with plastic film and vacuum is drawn between the product and the film. Atmospheric pressure compacts the reinforcements.

- Pressure bag moulding. This method is somewhat similar to the vacuum bag moulding except that the part is covered by rubber sheet and positive pressure is applied.

- Autoclave moulding. This is a modification to the pressure or vacuum bag moulding. The whole assembly is placed in the autoclave where the resin hardens under elevated temperature and pressure.

- Filament winding. Reinforcement in the form of strand is impregnated with the resin and wrapped on a rotating mandrel. Prepreg tapes may be used instead of the strand.

- Pultrusion. Reinforcements are impregnated with the resin and pulled through a heated die where the resin hardens. This method is used mainly to produce continuous profiles but has also been modified to produce glass fibre leaf springs for the automotive industry.

- Stamping. Reinforced thermoplastic sheet may be formed by stamping using high-speed metal forming equipment with some modifications.

Fabrication may be carried out by large or medium-sized companies (e.g., aircraft components, sports equipment) or small companies (e.g., dish antennas).

2.6 Markets

Over the last 20 years, consumption of reinforced plastics has increased at an annual rate of 15 percent, and the consumption of advanced composites has increased at an annual rate of 30 percent over the last 10 years. This has been achieved while the growth of basic metals, such as steel or aluminum, was increasing at approximately 4 percent per year.* Worldwide consumption of advanced composites in 1984 was estimated to be 48.5 million kilograms (22 million pounds) valued at $1.3 billion (U.S.). The market breakdown was as follows:**

(a) Reinforcements:

Aramid	27%
Carbon	30%
S-glass	42%
Other	1%

* Rubber World, May 1985.

** Reinforced Plastics, March 1985

(b) Resins:

Epoxy	80%
Other thermosets	12%
Thermoplastics	8%

Through the next decade the market is expected to grow 16 percent a year achieving sales of slightly more than $12 billion by the year 2000. The aerospace industry will show the highest growth (22 percent per year) and other industrial applications will account for the annual growth of 10 percent per year.* Similar data for Canadian markets are not available.

The main markets for advanced composites are:**

- Aerospace	38%
- Recreational	31%
- Industrial	23%
- Autos and trucks	3%
- Others	5%

The United States is a major market for advanced composites, with both the U.S. and Japan being important suppliers of reinforcements and composite components. This is illustrated in Figure 2.2 using graphite fibres as an example.

There is no Canadian manufacture of graphite fibres or of any of the reinforcements used in advanced composites.

* Reinforced Plastics, March 1985.

** D.S. Brown, C.H. Eckert, Ch. H. Kline, Advanced Polymer Composites, Five Keys to Success, Material and Design, Vol. 6, No.5, 1985.

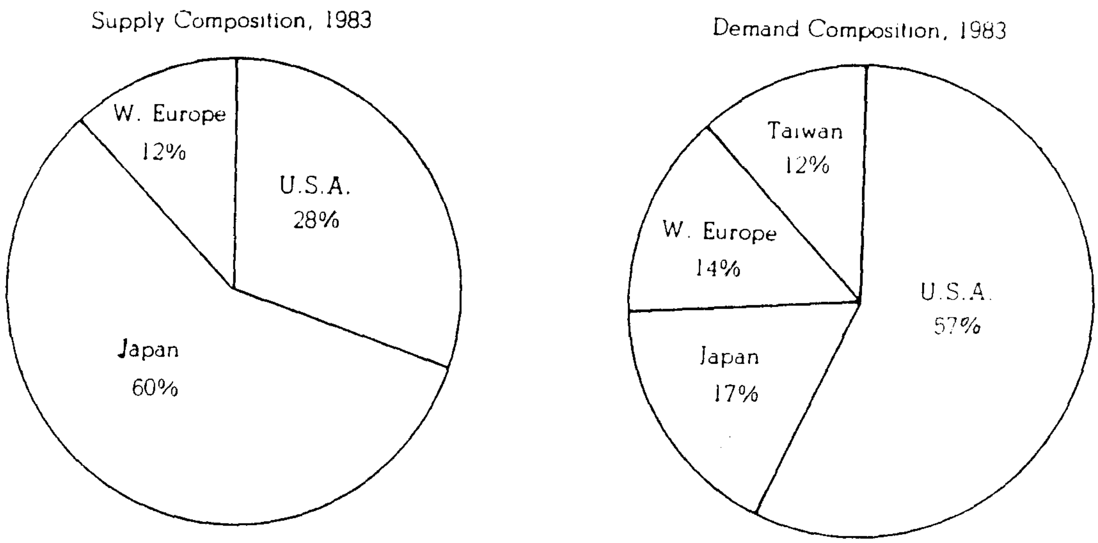


Figure 2.2

World Carbon fibre Supply/Demand
(from Japan's New Materials Industries,
Japan Strategy Resources, Vol. X, No.20,
International Business Information Inc.)

Some specific markets for advanced polymer matrix composites are:

AEROSPACE AND SPACE EXPLORATION. Aerospace is the single largest market for advanced composites. The main reason for use of composites in the aircraft structure is the weight saving of 20 to 30 percent compared to aluminum plus a substantial reduction in the number of parts. The obstacles to an even more widespread usage are a high material cost ($110 to $154 per kilogram [$50 to $70 per pound] compared to $4.40 to $11 per kilogram [$2 to $5 per pound] for aluminum) and labour-intensive manufacturing. A future space station may be manufactured of advanced composites, possibly formed in space.

Moisture absorption and subsequent reduction of mechanical properties is a serious problem for exterior aircraft applications.

Commercial Transport Aircraft. The high cost of fuel has created a demand for lighter structures. At present, cost of fuel constitutes approximately 60 percent of the operating costs. One kilogram of dead weight on the airplane consumes 1000 gallons of fuel per year. Now, all the major manufacturers of commercial transport aircraft are incorporating large numbers of composite parts. Examples of composite components on Boeing 767 are shown in Table I.

TABLE I

Composite Components used on Boeing 767 (from Composites Use in Aircraft with Emphasis on Kevlar Aramid, P.R. Langston, Composites in Manufacturing 5, LA, Jan. 1986)

Weight Summary Advanced Composites

Material	Application	Weight Estimate Lb.	Weight Savings Lb.
Graphite	Inboard Aileron	89	
	Outboard Aileron	75	
	Inboard and Outboard Spoilers	182	
	Rudder	280	
	Elevator	326	
	Sub Total	952	(-160)
Hybrid (KEVLAR)	Fixed Panels - Wing T. E.	325	
	Cowls - Thrust Reverser, and Fan	326	
(Graphite)	Fairing - T. E. Flap Linkage	59	
	Cove Panels - Inbd. T. E. Flap	9	
	Wing/Body Fairing	298	
	Landing Gear Doors - Body	298	
	Fixed T. E. Panels	114	
	Seal Plates - Stabilizer	17	
Hybrid (Fibreglass/Graphite)	Nose Landing Gear Doors (Graphite Weight Only)	25	
	Sub Total	1471	(-542)
KEVLAR aramid	ECS Ducts	328	
	Cargo Liner	276	
	Outboard Stowage Bins and Center Stowage Supports	314	
	Emergency Escape System	60	
	Lavs, Closets and Partitions	84	
	Fairings - Engine Pylon	77	
	Outboard Flap - L. E. and T. E.	33	
	Inboard Flap - Debris Protection	24	
	Fairing - Thrust Reverser	14	
	Sub Total	1210	(-548)
	TOTAL	3633	(-1250)

Commuter Aircraft. The de Havilland Dash 8 commuter plane has probably the highest percentage of composites of any other similar plane flying today. Interior applications of composites include cabin floor panels, overhead baggage compartment, lavatory compartment, wardrobe and buffet, air-conditioning ducts. The exterior composite components are illustrated in Figure 2.3.

Wide application of composites in the Dash 8 contributed to fuel economy by more than 25 percent better than that of other similar planes made with aluminum parts.

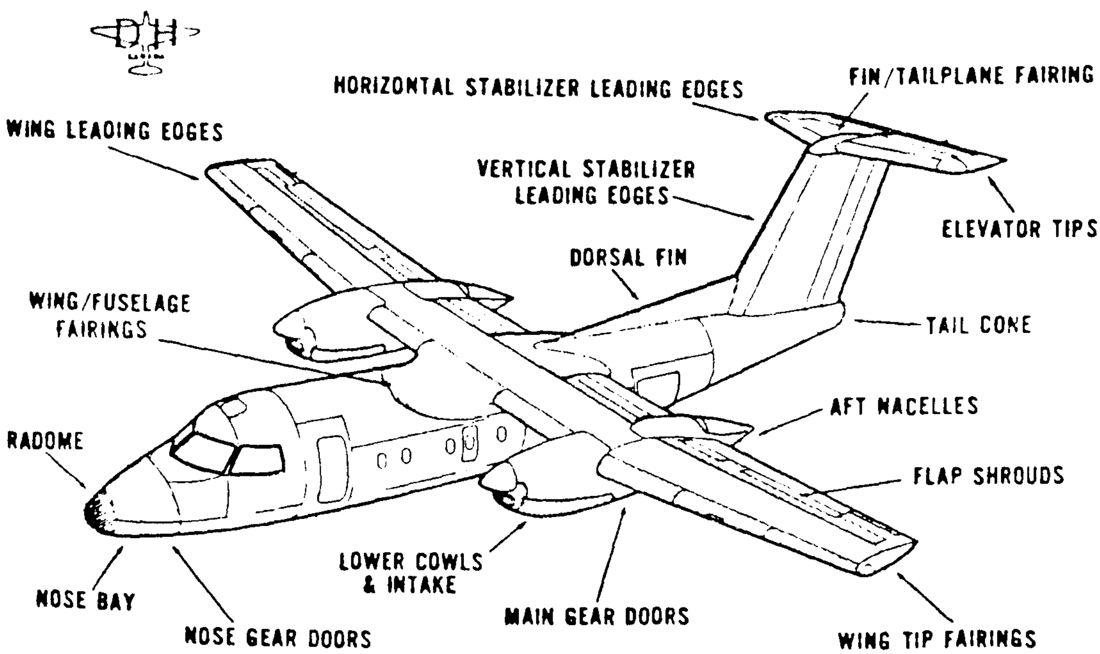


Figure 2.3

Exterior Composite Structures on Dash 8
(L.K. John, de Havilland Aircraft of Canada, Aramid Composite Applications at de Havilland).

Aircraft for General Aviation. The first all composite aircraft, the Windecker Eagle, was certified in 1968 generating baseline experience in the use of composites in small aircraft. Two composite planes, Avtek 400 and Beech Starship are undergoing FAA certification procedures.

Helicopters. The use of advanced composites in the helicopter structures results in both cost and weight savings. Sikorsky predicts that composite airframe will result in a cost saving of 25 percent and weight saving of 23 percent. Cost reduction is achieved by parts consolidation and reduction of assembly cost*. Typical composite helicopter parts include rotor hub, rotor blades, tail assembly and landing gear.

Military Aircraft. Use of composites in military aircraft allows weight reduction and increased range and size of the payload. A typical new fighter aircraft uses about 400 kilograms (900 pounds) of composite structures. A good example is the AV8B Harrier II, built by McDonnell Douglas, which uses 638 kilograms (1400 pounds) of graphite/epoxy composites (28 percent of the total weight). The resulting weight reduction of 20 percent is critical to the performance of this vertical take-off and landing aircraft.

Typical composite components include fuselage sections, empennage, doors, internal structures, control surfaces, vertical and horizontal stabilizers.

AUTOMOTIVE. In spite of the wide application of reinforced plastics in cars, the use of advanced composites is rather limited because of their high cost. For example, in order to find wider use for graphite fibres in cars, the price would have to fall below $11 per kilogram ($5 per pound). The price history of graphite fibres is shown below as Figure 2.4.

Initial rapid price reduction in the 1960s and 1970s was followed by rather stable prices in the 1980s. Price reduction needed by the automotive industry is not expected to happen in the near future.

Although advanced composites are not expected to achieve high penetration into general automotive market, there are some components where high cost of advanced composites is justified by their performance.

Hybrid graphite/glass composite air-conditioner compressor mounting brackets have been installed on some Ford Mustangs and Mercury Capri models. These units weigh 0.7 kilograms (1.7 pounds) compared to 3 kilograms (6.7 pounds) for the metal brackets they replace. A graphite/glass drive shaft was first used on a race car participating in Daytona Challenge race. Since then, composites drive shafts have been incorporated in some trucks such as 1985 Econoline Van. Composite drive shafts not only reduce weight but also improve riding comfort by reducing vibrations.

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* R.R. Irving, Advanced Composites, They are Now Stronger and Cheaper from Iron Age, Oct. 3, 1983.

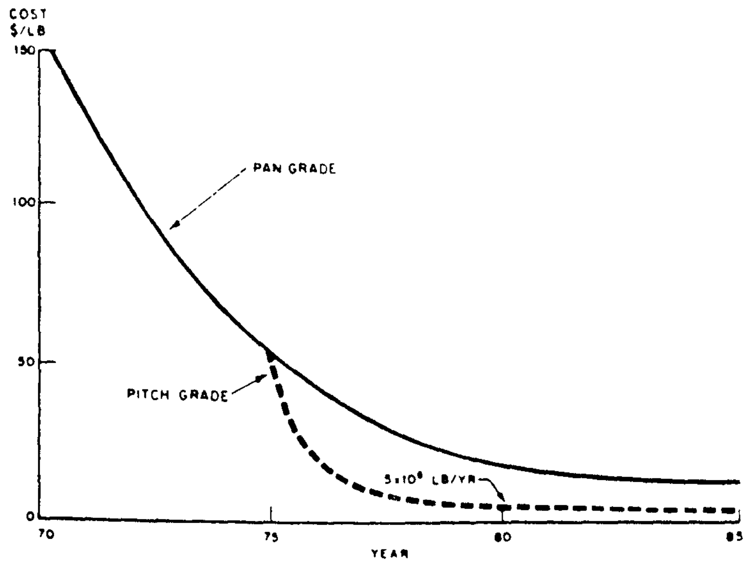

Figure 2.4

Price History of Graphite Composites (U.S. dollars), from Commercial Opportunities for Advanced Composites, ASTM, 1980
(* shows the lowest actual 1986 price of graphite fibres)

SPORTS AND RECREATION. The largest portion of this market is in water craft. Aramid fibres are used to provide high-stiffness and low-weight structure. Graphite fibres are occasionally used as local stiffeners.

A large number of tennis racket manufacturers use graphite and, to a lesser extent, boron reinforced composites. The use of composites allows designers to produce rackets with larger "sweet spots", less vibration and better bounce. The endurance life of the product is also increased.

Shafts for golf clubs were some of the early applications of composite materials in sport equipment. Since the weight of the shaft may be reduced by as much as 40 percent, additional weight may be built into the club head, resulting in improved driving distance.

Advanced composites have largely replaced fiberglass and bamboo in fishing rods. Vibration damping of graphite composites improves both casting distance and accuracy. Other products incorporating advanced composites include bicycle components, archery equipment, sailplanes, kayaks, racketball rackets.

ENGINEERING APPLICATIONS. Graphite fibre reinforced composites are used when high specific stiffness and strength, low coefficient of thermal expansion and surface lubricity are required.

Because of these properties, carbon fibre composites are widely used in the components of textile manufacturing machines where high-speed reciprocation, oscilation and rotation require materials with low inertia and excellent fatigue resistance. Weaving looms incorporating graphite composites operate faster and generate lower noise levels. Because of their low coefficient of thermal expansion, graphite composites have found applications in precision micrometers where measurement error due to temperature changes must be minimized. Lubricity of graphite is utilized in manufacturing composite gears which, with graphite, require lower torque, generate lower noise levels than metal gears and do not require lubrication.

MEDICAL EQUIPMENT. Low X-ray absorption of graphite composites has various applications in X-ray equipment such as tables and film cassettes. Because of low X-ray absorption, the level of radiation to which the patient is exposed could be significantly reduced.

2.7 Future Trends

MATRIX MATERIALS. Although epoxy is expected to be a dominant material, new materials which are stable at higher temperatures will be introduced and commercialized. Thermoplastics are expected to capture a certain portion of advanced composites and offer perhaps the greatest potential for growth. Advanced thermoplastic composites are potentially more suited for mass production and offer advantages in toughness and resistance to moisture over thermoset-based composites. Although these materials have been introduced only recently for military applications, they are already finding applications in such mundane products as toe caps in safety boots.

REINFORCEMENTS. The market is dominated by S-glass, graphite and aramid fibres, a situation which will probably continue for the next five to 10 years. Other fibres are being commercialized and will find new applications or capture portions of the market from other products. The new fibres will be based on:

- ceramics (such as silicon carbide, silicon nitride, alumina);
- polymeric liquid crystals;
- ultradrawn polymers (such as ultradrawn polyethylene introduced by Allied).

MANUFACTURING. Higher speed, more reliable manufacturing processes are being developed and commercialized. In the area of reinforced thermosets the trend is toward automation of processes which reduces labour requirements and improves accuracy.

Higher speed processing will be accomplished with reinforced thermoplastics. The standard processes, such as filament winding or pultrusion, are being modified to accommodate reinforced thermoplastic. Wider use of high-speed stamping processes can also be expected to form advanced thermoplastics. The advantages of such processes are shown in Figure 2.5. In spite of the often higher tooling costs, these processes are more suitable for high production volumes.

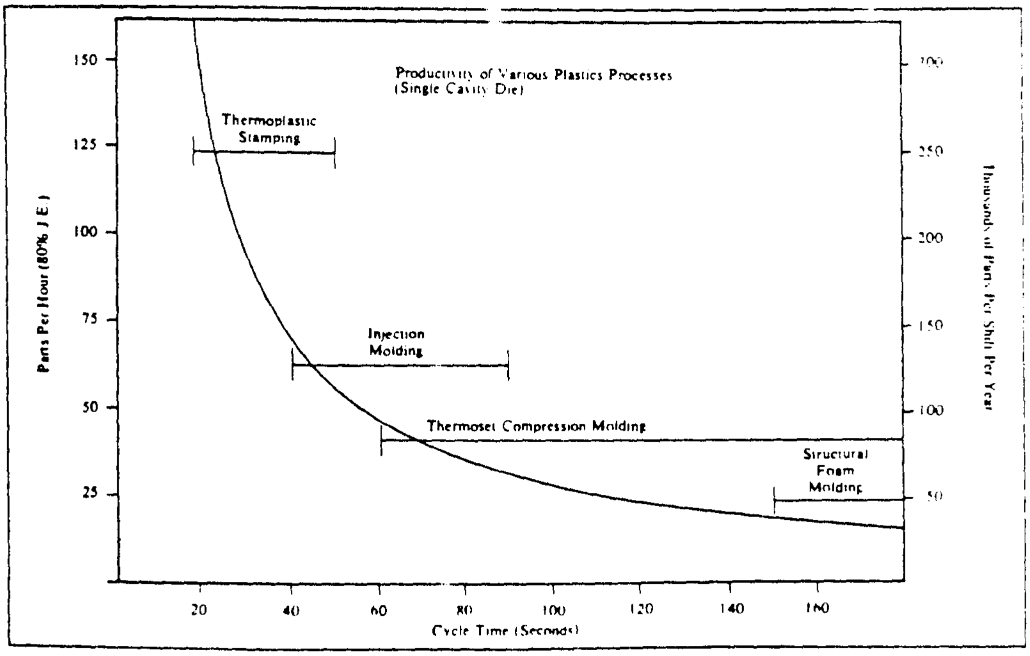

Figure 2.5

Productivity of various plastics processes (from F. Studer, Automotive Applications of Stampable Reinforced Thermoplastics Development Prospects, Materials and Design, Vol. 4, Aug/Sept. 1983)

2.8 Summary

Consumption of polymer matrix advanced composites are expected to grow at 16 percent per year and reach $12 billion by the year 2000. Important properties such as ease of manufacturing, low density, high strength and stiffness, fatigue resistance, corrosion resistance and vibration damping make these materials ideally suited for application in aerospace, machine components, chemical equipment, transportation and sport equipment. A variety of manufacturing technologies are available ranging from very sophisticated ones requiring considerable know-how and high capital investment to relatively simple ones which may be implemented with a minimum know-how and capital investment.

3. CARBON/CARBON COMPOSITES

This chapter reviews technology, applications and markets for carbon/carbon composites. Carbon is an attractive engineering material. It exists in a variety of forms such as conventional hot pressed carbon, densified graphite, pyrolytic graphite and vitreous graphite. It has good lubricity, high electrical and heat conductivity and in pyrolytic and vitreous forms high strength and resistance to oxidation. Carbon/carbon composites utilize these properties while overcoming the brittleness of carbon.

3.1 Manufacturing

Carbon/carbon composites are manufactured by repeated impregnation of graphite fibres with an organic resin followed by pyrolysis of the resin. The initial step in the manufacturing process is similar to that in the manufacturing of polymer matrix composites. Graphite fibres, in the form of strands, unidirectional, two- or three-dimensional tape, are impregnated with phenolic resin or hydrocarbon pitch and formed to the final shape by hot pressing. In the next step, the resin is pyrolyzed which converts it to carbon. Pyrolysis results in porous system and, in order to densify the product, it has to be impregnated and pyrolyzed a number of times. Each pyrolysis step may take up to 70 hours resulting in a high cost of carbon/carbon parts. A schematic of the process is shown in Figure 3.1. For application in oxidizing environments the surface must be coated and sealed, for example, with silicon carbide.

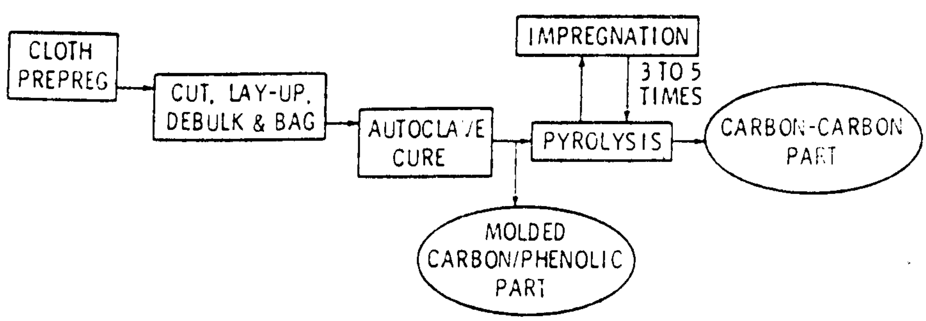

Figure 3.1

Schematic of a Process for Manufacturing of Carbon/Carbon Composite (from D.R. Rummler Recent Advances in Carbon-Carbon Materials Systems NASA Conf. Publication No. 2251, 1982)

3.2 Properties

The most important properties of carbon/carbon composites are:

- low density (approximately 70 percent of that of aluminum);
- low coefficient of thermal expansion;
- high thermal conductivity;
- resistance to thermal shock;
- constant tensile strength at high temperatures.

The last point is illustrated in Figure 3.2. The three carbon/carbon composites shown here differ in the type of graphite reinforcement.

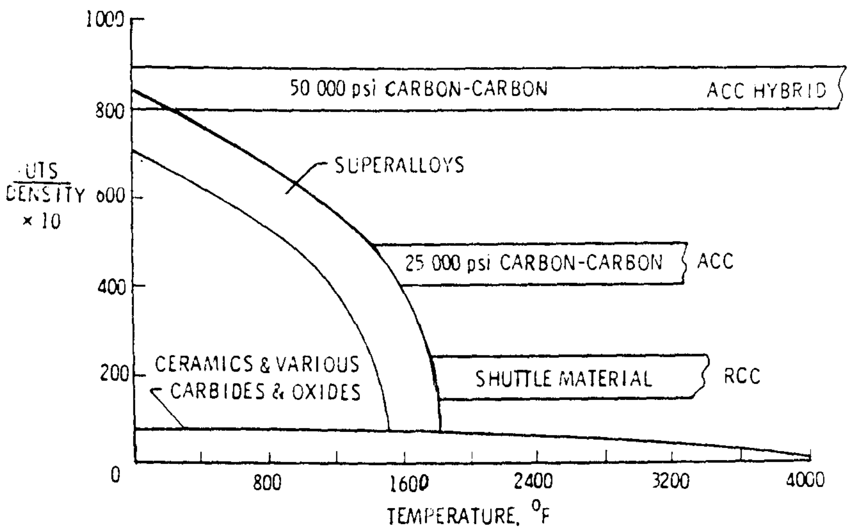

Figure 3.2

High Temperature Properties
of Carbon/Carbon Composites (from D.R. Rummler,
Recent Advances in Carbon-Carbon Materials Systems
NASA Conf. Publication No. 2251, 198

3.3 Markets

Since this product is still very specialized and produced worldwide by about half a dozen companies and because the information on this technology is restricted by the United States, it was impossible to assess actual market size.

Carbon/carbon composites are very expensive to manufacture ($330 to $440 per kilogram [$150 to $200 per pound]) which results in rather limited applications. Some applications include:

- thermal protection of the space shuttle in the areas exposed to temperatures up to 1650°C (the nose cap and leading edges);
- braking rotors and pads for airplanes and racing cars;
- nozzle cones of space rockets.

The largest present application for carbon/carbon composites is in aircraft brakes. These have a stable frictional performance up to 2000°C (steel melts at 1600°C). The brakes developed by Goodyear for F-15 planes weigh about 27 kilograms (60 pounds) as opposed to 90 kilograms (200 pounds) for the steel product and perform three to five times better. These brakes are now used on F-14, F-15, F-16, B-1B as well as on commercial aircraft. Some of the racing cars use carbon/carbon composite brakes. The U.S. supplier of carbon/carbon aircraft brake discs, HITCO, also carries out development work on motorcycle brakes, while Nissan Spinning Company and Toho Rayon in Japan are developing automotive carbon/carbon brakes.

Because of the generally excellent biocompatibility of carbon, carbon/carbon composites may also have a future in various prosthetic and cardiovascular applications.

3.4 Future Trends

The cost of manufacturing is probably the main barrier to the more widespread use of carbon/carbon composites. The main technological challenge at present is to cut the manufacturing cost by reducing the time needed for pyrolysis of the resin.

3.5 Summary

Because of their high manufacturing costs, carbon/carbon composites are finding only limited use where their high temperature resistance and low density justify cost. Their main application is in aircraft brakes. However, because of the excellent biocompatibility of graphite, these composites should find various prosthetic and cardiovascular applications.

4. METAL MATRIX COMPOSITES

Metal matrix composites (MMCs) consist of metal alloys reinforced with fibres, whiskers, particulates and wires. Development of metal matrix composites began over 20 years ago; however, early MMC systems found few applications. The first major MMC structural system was boron/aluminum, developed in the late 1960s. With the recent development of new MMC systems, offering superior mechanical properties and unique physical characteristics such as low coefficients of thermal expansion, insensitivity to moisture and high temperature properties, interest in MMC has been revived.

4.1 Matrix Materials

The present dominant metal matrix materials are aluminum, magnesium, titanium and their alloys. Aluminum and magnesium and their alloys are known to have a low density, and are useful for applications in which weight saving is important. However, titanium and its alloy have a high melting temperature and are used where high temperature capability is required. Compared to the more popular polymer matrix, metal matrix has other advantages such as higher temperature capability, higher transverse stiffness and strength, higher shear moduli, higher electrical and thermal conductivities, better radiation and fire resistance, and no moisture absorption.

4.2 Reinforcements

For reinforcements, the key fibres used at present are boron, beryllium, graphite, alumina and silicon carbide. All of these fibres have high tensile strength of around 2000 MPa and modulus of roughly 350 GPa, which make them extremely suitable as reinforcing agents for composites in structural applications. While whiskers and particulate reinforcements are normally inferior in mechanical properties than their fibre counterparts, more isotropic properties are attained. In areas where electrical conductivity is important, metal fibre or metal-coated fibre reinforcements are employed. The popular wire reinforcements include tungsten, beryllium and titanium, while the common coated fibres are carbon fibres coated with silver, copper and gold.

4.3 Composites

The properties of metal matrix composites are impressive. Generally, in comparison to monolithic metals, metal matrix composites have higher strength-to-density and stiffness-to-density ratios, better fatigue resistance, lower coefficient of thermal expansion and better wear resistance. For example, 6061 aluminum has an ultimate tensile strength of roughly 344.8 MPa; when reinforced with SiC, an ultimate tensile strength of 1462 MPa is attained.

4.4 Manufacturing

Fabrication methods of MMC generally can be divided into two major steps, primary and secondary. In the primary fabrication step, the main objective is to assure proper bonding between fibre and matrix and to create the metal matrix composite from its constituents. In the secondary fabrication step, processes such as forming, rolling, metallurgical bonding and machining are involved to make the raw composite into the desired final configuration. The selection of a primary fabrication technique depends very much upon the choice of fibre and matrix.

In many cases, pretreatment of fibre prior to fabrication is necessary. Pretreatment, often involving coating of fibre, is to prevent deterioration in fibre stiffness and strength at elevated temperatures and to enhance the fibre/matrix wettability and adhesion. Various techniques have been developed for coating fibre including chemical vapour deposition, physical vapour deposition, plasma spraying and electrochemical plating.

The primary step of fabricating composites, with either pretreated or untreated fibre, can be achieved by solid-phase or liquid-phase methods. In solid-phase fabrication, the common techniques are diffusion bonding, cold isostatic pressing, hot rolling, hot isostatic pressing, extrusion, drawing and explosive welding. In liquid-phase fabrication methods, infiltration is the most commonly used technique, even though there has been a substantial amount of work on the developing unidirectionally solidified eutectic alloys.

The application of the secondary fabrication step is mainly to change the shape of composites already fabricated. Currently, techniques employed in the machining, joining and forming of conventional metals are used for MMC. For example, electrical discharge and laser beam cutting are used for cutting; soldering or brazing for joining; and press forming for forming operations. However, with the increasing use and development of advanced metal matrix composites, many conventional technologies used in secondary fabrication are unsuitable or incapable of handling materials with such superior mechanical properties. Consequently, revolutionary changes are under way in many of the above related technologies to meet this growing MMC development.

4.5 Markets

The initial development of metal matrix composites 20 years ago was applied strictly to the aerospace industry. However, with the unique properties generally found in MMC, there are now applications in such industries as marine, automotive, electronics, recreational and orthopaedics.

Because of its unique properties, the potential for MMC products is tremendous. The technology, however, is still in its infancy and the present commercial applications are still extremely limited. The total market size is not available but the table below gives some indication of production volumes and prices of the prouduct.

Company	Product	Annual Production or Production Capability*	Price ($ U.S.)
DWA	SiC/Al Al_2O_3/Al	20 000 lb./year 100 lb./year	$50/lb.-1000 lb. basis $20/lb.-10 000 lb. basis
ARCO Chemical	SiC/Al	Not available	$70-100/lb.
American Inc.	SiC/Al Al_2O_3/Al	Research Quantity Research Quantity	$300-400/lb. Not available
AVCO	SiC/Al Al_2O_3/Al	Research Quantity	No available
Superior Graphite Co	SiC/Al	200 000 lb./yr*	$1-15/lb. depending on grade
Mitsubishi Al.Co.	SiC/Al	Research Quantity	$200/lb.

In satellite applications and space-borne parabolic antennas where thermal distortion or high specific stiffness is a major consideration, graphite/aluminum and graphite/magnesium have proved to be most effective. In the marine industry, silicon carbide/aluminum shows promise for ship superstructures, torpedoes and underwater structural applications.

In the automotive industry, Toyota has already employed alumina/aluminum as connecting rod material in its newest show car (FX-1). This material has strength equivalent to that of steel plus low density. For battery plates, graphite/lead composites are now used and are stronger and more resistant to creep than lead. Statistically, it has been shown that the lifetime of battery plates has doubled with the composite plate.

In sports applications, boron/aluminum, graphite/aluminum and silicon carbide/aluminum are used in making tennis rackets, skis, golf clubs, bicycle frames and fishing rods. And in the electronics industry, carbon fibre reinforced copper matrix composites are used in areas where chemical stability, electrical and thermal conductivity are required.

4.6 Future Trends (MMC)

The current technological trend of MMC, of either a short- or long-term nature, can generally be classified in four main directions:

- development of new applications;
- improvement of design efficiency and reduction of production costs;
- generation of engineering data;
- improvement of fabrication methods.

Research is continuing on improving the physical and mechanical properties of reinforcements, and to develop new MMC systems. New technology, such as rapid solidification, is being considered to improve properties to an even greater extent. For example, rapidly solidified silicon carbide/aluminum produces a uniform distribution of non-shearable dispersoids such as Al_3Ti, which stabilizes grain boundaries and strengthens grains, providing better high-temperature properties.

Other new systems include "hybrids", which use either more than one type of reinforcing fibre in a single matrix, or a foil on the MMC of a different composition to that of the matrix. Foils are considered to provide improved transverse properties of some MMC systems. Other types of hybrid systems include graphite/aluminum cross-plied with boron/aluminum, and graphite and Al_2O_3 fibres that have been formed into a single yarn and infiltrated with Al. In the latter example, the graphite provides increased specific modulus while the Al_2O_3 provides increased compressive strength.

Production efficiency is achieved through improvements or developments in automated winding, weaving, moulding, lay-up, forming and bonding procedures. Future trends in this direction will gear towards process monitoring, on-line inspection and data processing. These procedures will enable the manufacture, at a lower cost, of high-quality, reliable composite parts and structures.

The principal applications of composite materials, at present, are associated with military and space equipment and systems. A barrier to the increase use of MMC in the commercial sector is the lack of in-service experience and performance data. The availability of engineering data to characterize the behavior of MMC is invaluable for increasing commercial applications.

In addition, cost is another prime factor inhibiting use of MMC in other areas. It is anticipated that, as the technology of fabricating MMC is advanced to the stage where the cost of fabrication is comparable to that of conventional material, MMC will certainly find more applications.

5. CERAMIC MATRIX COMPOSITES

Most of the research and development of ceramic matrix composites (CMC) has occurred very recently. Over the past 20 years, the level of interest has fluctuated widely as various technical problems were encountered and then solved. The technology is still very much in the research stage.

Advanced ceramics are now being considered for existing and emerging applications because of their performance properties, abundance of raw materials supply and potential low costs. Their value is further enhanced by their ability to perform under severe physical and chemical environments in which conventional materials fail. Nevertheless, contemporary ceramics suffer from one major flaw, brittleness, that renders service life unpredictable. The impetus of the development of ceramic matrix composites stems largely from the need to improve the fracture toughness and strength of monolithic ceramics while retaining all their intrinsic merits.

Theoretical advances are being made to address the complicated issue of interrelating the size of dispersed particles or fibres, their spacing in a ceramic matrix, the property differences between matrix and reinforcement, and the typical flaw-size that affects strength. However, systematic research work is directed toward demonstrating these concepts with material systems that show high promise for selected applications. All in all, the technology of ceramic matrix composites is largely based on the research done on reinforced metal and resin matrix materials.

Ceramic matrix composites are still largely in the development stage with only extremely limited commercial applications and markets.

5.1 Matrix Materials

The use of monolithic ceramics has been established in a wide range of areas owing to their technical and/or cost advantages over other classes of materials. The constituent ceramic materials include a large group of oxides and complex oxides, carbides, nitrides, borides, silicides and halides. In the field of advanced materials technology, these materials are being used, or show high promise of use, for electrical and magnetic components, or for mechanical parts which must be strong and wear-resistant at ambient or moderate temperatures. In addition, ceramics are being examined for high-temperature mechanical applications. All these materials, in principle, can be utilized as matrix materials for the fabrication of composites, depending on the intended applications.

5.2 Reinforcements

The choice of reinforcement material is as diverse as that of the ceramic matrix. Basically, there are two forms of reinforcement, fibre and particulate, which are frequently used.

Common fibre materials include graphite (carbon); metals such as boron, tungsten, niobium and stainless steel; glass and ceramics such as fused silica, borosilicates, alumina and silicon carbide. Most of these materials are at least as strong as the ceramic matrix and are normally incorporated into the matrix to improve its mechanical strength and fracture toughness through a load transfer mechanism and by inhibiting crack propagation. Typical properties of some fibres are listed in Table II.

Table II

Typical Properties of Common Fibre Reinforcement Material for CMC (From Fabrication of Composites, North-Holland, 1983)

Fibres	Young's modulus (GPa)	Tensile strength (MPa)	Thermal expansion coeff. α (10^{-6} °C^{-1})	Density e (g × cm^{-3})	Fibre diameter d (μm)
High modulus carbon[a]	360	2400	radial 8 axial 0	1.8	8
Silicon carbide yarn from organo-metallic polymer[b]	220	2060	4.8	2.7	10
Silicon carbide deposited on carbon filament[b]	415	3450	4.8	3.2	140
α-alumina[c]	385	>1400	8.5	3.9	20
Alumina–borosilicate[d]	152	1550		2.5	11
Boron	420	3000	8.2	3.4	100
Tungsten	340–410	2900–3800	4.8	19.3	
Niobium	83–124	500–1030	8.1	8.6	
Stainless steel	150–210	2050–2550		7.7–8.0	

Particulate materials are usually glass and ceramics but, in certain cases, metals or polymers are also used. Incorporated into structural, high-strength ceramics, their function is to increase the fracture toughness and wear resistance of the matrix. In other applications, such as in electronics, the inclusion of particulates in a monolithic ceramic component serves to expand the range of useful properties, such as electrical resistance, conductivity and capacitance, or to impart new properties to those of the matrix to meet the overall application requirements.

5.3 Composites

A typical ceramic matrix composite (CMC) is made up of very fine fibres or particulates embedded in an otherwise monolithic ceramic body. The fibre or particulate reinforcement may be arranged randomly or in a partially or completely oriented manner, depending on the design requirements.

Examples of ceramic matrix composite systems currently under development for high-temperature structural applications include partially stabilized zirconia, alumina reinforced with zirconia or boron nitride particulates, and silicon carbide fibre reinforced lithium aluminium silicates. All these systems show substantially improved strength, fracture toughness and thermal shock resistance as compared with their monolithic ceramic counterparts. A brief comparison is presented in Table III.

Examples of electronic CMC systems are high-capacitance barium titanate-metal laminate, SiC-glass varistors, and piezoelectric lead zirconate titanate reinforced with elastomer. The first example is typical of the multilayer capacitor design in which the dielectric barium titanate tape layers provide the high capacitance. In the second example, the glass component serves to bond the SiC particles together to give the body shape, handleability and stability, while the SiC particles provide the nonlinear resistance characteristics. The last example is basically a macro-composite in which the elastomer imparts new properties to the composite, such as flexibility and shock resistance, and at the same time improves the piezoelectric response and sensitivity of the ceramic matrix.

Based on these examples, the versatility of CMC designs and the wide variety of matrix-reinforcement combinations can perhaps be adequately illustrated.

Table III

A Comparison of Typical Room Temperature Properties of Structural Ceramics and CMC Systems (From Chemtech 13 (4) (April, 1983))

Material	Strength (10^3 psi/MPa) [a]	Fracture toughness (K_{1C}, MPa $m^{1/2}$) [b]	Thermal shock resistance (ΔT °C) [c]
Conventional ceramics			
SiO_2-based (e.g., borosilicate glasses)	10/70	0.5	300
Al_2O_3	50–100/350–700	4	225
B_4C	50/350	4	225
ZrO_2 (fully stabilized)	20–50/140–350	2.5	225
Si_3N_4 (hot pressed)	100–125/700–860	5	450
Ceramic composites			
ZrO_2 crystals (partially stabilized)	200/1400	6	450
Al_2O_3 (10 vol % ZrO_2)	100/700	8	>900
Al_2O_3 (30 vol % BN)	50/350	6–9	500
B_4C (50 vol % C)	30/200	3.5	1100
Glass–SiC fiber composite	50–100/350–700	20	>900

[a] Tensile strength measured in flexure.
[b] While strength and fracture toughness are basically related, they do not always vary in a parallel fashion due to dependence on crack sizes associated with the different tests used to measure the two properties.
[c] Thermal shock is given here by the common test of the temperature difference (ΔT) over which a test bar must typically be quenched in order to measurably degrade its strength.

5.4 Manufacturing

A fair number of techniques for the fabrication of CMC parts has been attempted and reported by researchers. In principle, CMC components can be produced in two stages. First is the incorporation of the reinforcement to the unconsolidated ceramic matrix material, followed by consolidation of the reinforced matrix, usually involving heat treatment and pressurization. In some cases, these two stages can be combined in one process.

Random short fibre and particulate reinforcements normally can be incorporated into the ceramic matrix by blending the reinforcement with the matrix powder. Methods for making aligned short fibre composites generally involve alignment of the fibres through shear during flow in some carrying media such as glycerine and ammonium alginate. The addition of the matrix powder into the flowing medium effects intimate co-deposition of fibres and powder into an unbound, aligned mat or felt. Aligned continuous fibre composites are usually made by forming a fibre tape impregnated with the matrix powder in a slurry form. Final products of all these composites are consolidated by sintering or hot pressing after the fibre mat or tape is dried, cut into shape and stacked to desired thickness. Random short fibre and particulate composites can also be injection moulded.

5.5 Applications

Very few applications of the ceramic matrix composite technology have been commercialized up to date. Of these, the most publicized example is the SiC whisker reinforced ceramic inserts for cutting tools. However, a large number of potential applications exists. In the military sector, they include radomes, re-entry space vehicle antenna windows and nosetips, armour, engine components such as heat exchangers, gas turbine parts, bearings and nozzles.

Other prominent areas of intended uses of CMC are in the energy-related technologies, such as semi-structural components for nuclear fission and fusion reactors, large-scale solar energy conversion systems, coal liquefaction and gasification, high-energy-density batteries, and electrodes for MHD generation units. The focus of the current R&D efforts is on composites with ceramic fibre reinforcement and ceramic or glass matrix. There is also a wide range of potential applications for CMC in the field of electronics encompassing dielectrics, piezoelectrics and pyroelectrics.

The development of CMC technology is critically related to the contemporary advances in the ceramic science and fibre fabrication technology, as the versatility and performance of CMC components are limited by the properties of the two major constituents - matrix and reinforcement materials. The current diffusion of CMC technology to industries and other technologies is gradual, but several issues are readily noticeable. Successful commercial applications of the CMC technology and products will require substantial innovative developments in engineering design, quality assurance, manufacturing processes and tooling. The latter three are particularly important for high-volume production of parts with consistent quality and reasonably low costs. In addition, the need of novel joining technology for CMC parts with components made of other materials will be dictated by engineering designs.

5.6 Future Trends

Since the CMC technology is still in early stages of development, with only a handful of commercialized applications, any prediction of its trends in terms of technological advances or application developments other than for the immediate future will be necessarily speculative. Nevertheless, some useful insight can be gained from the experience of more matured organic matrix composite technology and, to a lesser extent, the metal matrix counterpart.

In the medium term, CMC technology development is expected to be centred on broadening the understanding in the designing, processing and reliability testing of this class of materials to effect optimum performance properties. At the same time, this progress will be applied to specific future product developments, typical of which are the high-temperature gas turbine mechanical components and electric-electronic devices.

One mechanical system that will likely enjoy much attention is the silicon carbide fibre reinforced glass-ceramic matrix composites. Although information on the development of this technology, mostly made in the military sector, is virtually unavailable, it is understood that continuing, large funding and efforts will be allocated and, as a result, much progress is expected to be made over the next five years but will remain confidential.

In the long-term perspective, as ceramic matrix composite technology reaches a more matured state, interest will likely focus on two fronts - development of new generation of CMC and application development. Efforts in the first area will be closely correlated with the availability of higher quality and/or lower cost fibre reinforcement. Higher quality fibres will enhance the overall performance of composites and thus allow new, special applications of more demanding nature to become viable.

Application development will encompass all existing areas as well as those currently unexplored. An integral part of these efforts is expected to be in the development of cost-effective, mass-production techniques and equipment. The availability of low-cost materials such as the fibre reinforcements will also be a vital factor. The CMC applications will be diffused to industries and consumer sectors where other materials traditionally dominate. In fact, the replacement market where CMC is expected to supplant the traditional materials is seen to be a major area for long-term expansion. Nevertheless, the extent of this expansion will very much depend on the cost-competitiveness of the future CMC materials.

6. INTERNATIONAL PERSPECTIVE

Originally, the main impetus for the development of composites was the need for better materials for defence applications. Although by now the use of advanced composites has spread to non-military products, the defence and aerospace needs are still the major driving force behind further development. In terms of technical accomplishment and the level of effort, the United States is probably the leader followed by Japan. Other countries, such as U.K., Germany, France and the Soviet Union, are also involved although their level of effort is far less than that of the U.S.

6.1 United States of America

The U.S. government supports a considerable R&D effort in the area of composite materials. The main area of support is for high-performance polymer matrix composites with considerably less financial support available for metal, ceramic and carbon matrix composites. Three main funding agencies are, the Department of Defense (through the Defense Advanced Research Project Agency and agencies of the U.S. Army, Navy and Air Force), NASA and the Department of Energy.

The main emphasis of the defence-related work is on:

- development of composite structures for aircraft, missiles and ships;
- development of more efficient manufacturing procedures;
- generation of engineering data needed in designing composite structures.

The Department of Energy supports work on advanced composites related to the ceramics engine, energy storage and alternate energy sources.

In addition to major concentration on composites for defence applications, the U.S. is also concerned that the domestic industry is losing out in international competition in the advanced composites. In particular, Japan has been making inroads into U.S. markets at home and abroad mainly in the area of reinforcements. Under such circumstances, the National Science Foundation has granted $7.5 million to the University of Delaware to establish a Centre for Composites Manufacturing Science and Engineering. Besides government support, the centre is also sponsored by 30 major corporations. The primary research programs are:

- manufacturing and processing science;
- mechanics and design;
- computation, software and information transfer;
- materials design;
- materials durability.

Most of the industrial research in advanced composites is carried out by defence suppliers. Companies with excellent R&D as well as manufacturing capabilities include Lockheed, Pratt & Whitney, Boeing, Sikorsky, Rockwell and Martin-Marietta. Some suppliers of reinforcing fibres or matrix materials, such as Hercules, DuPont, and Allied-Signal, are also manufacturing composite components.

DuPont has recently launched a major program for developing the technology and markets for advanced composites. The company will not only expand the range of fibres and matrix materials but will also supply standard and custom prepregs based on Kevlar, graphite and glass and will fabricate high-performance structural components and assemblies.

6.2 Japan

The driving forces behind Japan's composites program are national need and economic opportunity. The country is lacking of natural resources, is small and densely populated. Thus, saving materials, energy and a rational use of resources have been the underlying themes. Recognition of the potential of composites in structural applications, aerospace systems as well as their economic advantages, has encouraged an intensive effort of R&D.

The Japanese government has already started to sponsor long-term projects aimed at the needs of the next century. The main thrust of all the Japanese materials projects is under the Basic Technologies for New Industries. It has been established to last 10 years with annual funding of initially $40 million (U.S.), of which about half is being spent on materials research.

In 1981, the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry started eight national R&D projects for future industry in Japan. Among them, there was an eight-year R&D project on advanced composite materials, the aim of which is to create advanced composite materials for aerospace applications, jet engines and automobiles.

Japan is currently in the forefront of reinforcing fibre technology supplying, for example, 60 percent of the world's demand for graphite fibres. Indeed, there are sufficient reasons for its dominance in this technology.

- First, there is an intensive effort by all fibre research organizations to develop a cheaper means of manufacturing fibres.
- Second, Japan is venturesome enough to manufacture fibre tailored specifically for the U.S. market.
- Third, in terms of implementing new fibre applications, co-ordinated effort from other industrial sectors within the country is always available. The list of Japanese companies manufacturing reinforcing fibres is shown in Table IV.

TABLE IV

Japanese Companies involving in fibre development

Company	Type of Fibre
Tokai Carbon Co.	Carbon
Nippon Carbon Co.	Carbon
Kureha Chemical Industries	Carbon
Mitsubishi Chemical Industries	Carbon
Toray	Carbon
Toho Beslon	Carbon
Nippon Carbon Co.	Silicon Carbide
Mitsubishi Aluminum	Silicon Carbide Whiskers
Unitika	Amorphous Metal
Nippon Seisen	Stainless Steel

Among the government laboratories under the supervision of the Agency of Industrial Science and Technology (Ministry of International Trade and Industry), two are heavily involved in composite research. In the Research Institute for Polymers and Textiles (RIPT), the main emphasis is on the development of a system for weaving three-dimensional fabric reinforcement for composite materials. At the National Research Institute for Metals (NRIM), the function is to develop materials for the aerospace, nuclear and semi-conductor industries.

The ceramic-matrix-composites-related activities in Japan are primarily geared towards supporting the domestic uncooled diesel engine and heavy-duty power programs. Although the Japanese effort in CMC development is relatively new and in a lower profile compared to the U.S. counterpart, the situation may change in the near future once the significance of this new class of materials is more universally perceived.

Automotive companies, such as Toyota and Honda, are taking leading roles in developing metal matrix composites. Companies in other fields, such as Hitachi, the largest manufacturer of electrical and electronic products, and Kobe Steel, one of the largest steel-making companies in Japan, are also actively developing metal matrix composites.

6.3 Europe

The objective of participation of European countries in advanced composites research and development is quite different from those of U.S. and Japan. First, none of the European countries has a large aerospace industry like the U.S. (although several countries in Europe have been involved in the Airbus and Ariane programs and they became competitors to the U.S. aerospace industry). Nor do they have a huge automotive industry like Japan, where high technology has to be implemented to overcome performance limits of conventional materials.

Rather, the participation is due to recognition of the potential of composites to provide economic opportunities for their industries. Other factors of concern, like the impact of development of composites in the U.S. and Japan and the availability and cost of imported strategic raw materials, have also contributed in motivating European countries in joining research and development.

The European Community has proposed spending an estimated $120 million over the next four years on research into new technologies used in mining, processing and developing raw and advanced materials. More than one-third of the funds ($40 million) would be spent on research into developing advanced materials like metal alloys, technical ceramics and composites, of which composites are considered to be the key factor in the future development of the Community. The Community acknowledges that it is essential for Europe to remain among the forefront in this field and hold its position in such varied sectors as transportation, electronics and biomedical technology.

The United Kingdom, France and Germany are considered to have placed relatively more effort in composites R&D than other countries in the European Community.

<u>United Kingdom</u> -- Similar to the University of Delaware in U.S., a Centre for Composite Materials has been established at Imperial College in London to serve the industrial users of composites. It is envisaged as an advisory centre for industrial consultancy on design analysis and testing of composites. Research in private companies is usually product-oriented.

ICI manufactures advanced thermoplastic composite prepregs mainly for aerospace applications. A number of companies are involved in manufacturing composite components for military aerospace and naval applications.

<u>France</u> -- In France considerable R&D activity exists in universities, government laboratories and industry. Major emphasis is weaponry and structural components for aeronautical and automotive applications.

The development of CMC materials and applications is mostly carried out by industries under contract with the defence agencies. Aerospatiale and La Société Européenne de Propulsion are two companies specializing in the production of ceramic composites using continuous fibre and multidirectional reinforcements. The composite systems are C-SiC, SiC-SiC, C-Al_2O_3, and SiO_2-SiC with a primary emphasis on the weapon market and those of missiles, civil aeroplanes and racing cars. Marcel Dassault Co. is also known to produce high-performance CMC materials for its own use in the production of jet fighters.

In the R&D of CMC technology, companies such as Ceratech, Desmarquest and Aerospatiale are conducting a number of projects. Ceratech has been involved in ceramic and glass matrix composites reinforced with continuous SiC fibres, while both Desmarquest and Aerospatiale are interested in short fibre reinforced ceramics.

Pechiney Aluminum is speculating on the properties of reinforced aluminum foundry alloys for automotive industry, while the Université de Bordeaux is investigating the interfacial chemistry and mechanical behaviour of composite systems. And Université de Technologie is focusing on fracture mechanics aspect of composite materials. At CNRS (the French equivalent of the National Research Council), considerable basic research on metal matrix composites is also conducted.

The French government and its industry have perceived its handicap in composite development due to the lack of domestic fibre production capability. As a result, Société Européenne de Propulsion and Desmarquest have initiated substantial work to develop manufacturing technology for SiC and Al_2O_3 fibres, respectively. A joint venture between Pechiney and ELF, with the participation of Toray of Japan, has led to the setting up of a factory to produce carbon fibres. Narmco and Hexel of the U.S. have set up joint ventures with French company to produce prepregs in France.

West Germany -- West Germany is quite systematic in its R&D activity. Similar to Japan, it has launched a 10-year program on advanced materials, with a budget allocation of DM 70 million for fiscal 1985. The advanced materials include composites, powder metallurgy, high-temperature materials and ceramics. Besides government programs, private companies are engaged in product-oriented research.

In the area of advanced composites, the U.S. is a leader in fabrication of composite parts, mainly due to the requirements of its aerospace and armanents industries. Japan leads in manufacturing of reinforcing fibres and is expected to establish a strong, if not leadership, position in the emerging ceramic and metal matrix composites.

7. CANADIAN PERSPECTIVE

Japan has amply demonstrated the importance of high technology to the national economic well-being. The technology based on ceramic matrix composites is an emerging one which offers substantial future commercial opportunity to industrial countries, including the U.S., Japan and members of the European Community. At this point, Canada is at a crossroad, hard pressed to examine what advanced composites technology can do for its scientific and business communities, and to decide on its future commitments.

Basically, just like many other emerging advanced technologies, the possible influence of advanced composites technology to Canada is most evident in the industrial sector. This new technology offers potential opportunities to the existing domestic industry in growth and diversification, so that existing market shares can be secured or expanded, and new markets entered. It also provides a key to the development of new industries, both in the materials and user sectors.

Similar to the situation in the U.S., most of the Canadian R&D on advanced composites and manufacturing activities are concentrated at the aerospace companies and most are related to the polymer matrix composites. At present, there is no commercial manufacturing of metal, ceramics or carbon matrix composites in Canada and only a limited amount of R&D on those materials.

7.1 Polymer Matrix Composites

Canadian activities in advanced polymer matrix composites are listed below:

ACTIVITIES OF CANADIAN GOVERNMENT AGENCIES IN ADVANCED POLYMERIC MATRIX COMPOSITES

NAME OF AGENCY	R&D ACTIVITIES
Defence Research	Advanced composite studies in connection with the F-18 Hornet (graphite-epoxy). Studies concern long-term maintenance and the critical effects of battle and accidental damage. Specimens are being prepared and performance tests carried out. There are also studies in progress on the chemical aspects of resin matrix composites: - properties of resins and how they are related to chemical environmental factors; - adhesive bonding, particularly the development of adhesives that will eliminate the need for surface preparation and high temperature repairs; - F-18 Hornet project - The effects of light, heat and water on the chemistry of graphite epoxy systems are being studied;

ACTIVITIES OF CANADIAN GOVERNMENT AGENCIES IN ADVANCED POLYMERIC MATRIX COMPOSITES (CONT'D)

NAME OF AGENCY	R&D ACTIVITIES
	- looking for thermoset and thermoplastic replacements for epoxies that will withstand higher temperatures, e.g., PEEK, PPS.
National Aeronautical Establishment	A small program on the development and characterization of materials began about 18 years ago. This involved new higher strength resins, and resulted in the development of an epoxy fortifier. The program was expanded three years ago to include the development of resin matrix composites for structural purposes, especially utilizing newly emerging epoxy-graphite prepreg systems. Studies are being done on low- and high-impact tolerance, effects of the environment, fatigue, effects of processing, lay-up and manufacturing techniques, acoustic qualifications. The work is sponsored by various government departments.
Industrial Materials Research Institute	Organize annual symposium on composites. R&D Work on non-destructive testing, tolerance evaluation and composites for industrial applications.

ACTIVITIES OF CANADIAN CONSULTING AGENCIES IN ADVANCED POLYMER MATRIX COMPOSITES.

COMPANY NAME	R & D ACTIVITIES
Composites Development International	The company was started in 1979 by Dr. Leone Dyke. CDI does consulting in resin matrix composites.
Engineering Research Associates (ERA)	The company, a division of Tennyson, Hansen, Mabson and Uffen Associates Limited, was incorporated in 1979 for the purpose of performing research in structures and materials. It has worked with graphite, Kevlar, glass and boron-epoxy composites in contracts involving both experimental and analytical capabilities. Clients have included all the aircraft companies in Canada, the various Canadian defence research establishments and NASA.

ACTIVITIES OF CANADIAN COMPANIES IN ADVANCED POLYMER MATRIX COMPOSITES

NAME OF COMPANY	PRODUCTION ACTIVITIES	R & D ACTIVITIES
Allied Canada Inc. Mississauga, Ontario (Parent company US)		Sponsors programs at Canadian Aircraft Products and University of B.C. on selection of resins and evaluation of composites using Spectra 900 fibre.

ACTIVITIES OF CANADIAN COMPANIES IN ADVANCED POLYMER MATRIX COMPOSITES (CONT'D)

NAME OF COMPANY	PRODUCTION ACTIVITIES	R & D ACTIVITIES
Bay Mills Midland, Ontario	Manufactures industrial cloth consisting of mixed glass and carbon fibres in U.S. It is currently setting up a plant in Midland to make prepregs with this cloth.	R&D programs on the use of the cloth aircraft are just beginning.
Boeing of Canada Winnipeg, Manitoba	Aircraft and spacecraft components using graphite and Kevlar-epoxy systems.	Carrying out R&D on high-temperature-resistant composites using high-temperature epoxies, and on automated filament winding.
Bristol Aerospace Winnipeg, Manitoba	Epoxy-bonded composites; parts for the Dash 7 & 8, CL215; rocket casings Lay-up and oven curing under vacuum	R&D in glass fibre, Kevlar, graphite with polyester and epoxy matrices.
Canadair Limited Montreal, Quebec	Composite parts for aircraft interiors and exteriors using epoxy graphite, glass and Kevlar fibres. Radomes using polyester composites.	It has been experimenting with epoxy systems in an attempt to improve fracture toughness.
Canadian Aircraft Products Richmond, B.C.	It uses composites to produce aircraft components: stabilizers, cowlings, fairings, elevator tips.	Proprietary work on resin composites. R&D laboratory has been open about 1 year and is self-supporting. Clients include Boeing, Bristol, Allied, de Havilland, Canadair.
Composite Technology Canada Limited Winnipeg, Manitoba	Repair tail and main rotor blades on helicopters made by Bell, Hughes and Aerospatiale.	No R&D
English Plastics Brampton, Ontario	Components and prepregs using epoxy glass, Kevlar for de Havilland, and glass fibre prepregs for Litton Industries.	No R&D
Enheat Inc. Aircraft Division Amherst, N.S.	Fiberglass, Kevlar and graphite prepregs for most of the major aircraft companies in North America.	No R&D
Fleet Industries Fort Erie, Ontario	Produces blade portions for Sikorsky Black Hawk helicopter; doors for F18 Antennas for Raytheon, Lockheed Electronics, LIT Gilfillan.	Started R&D in the 1950s. It is currently increasing its R&D efforts to develop composite seats for aircraft and also landing gear.

ACTIVITIES OF CANADIAN COMPANIES IN ADVANCED POLYMER MATRIX COMPOSITES (Cont'd)

NAME OF COMPANY	PRODUCTION ACTIVITIES	R & D ACTIVITIES
Lindhall Composite Materials Burnaby, B.C.	Prepregs for the aircraft industry using woven and unidirectional glass with epoxy matrices. Planning to include Kevlar and graphite.	Darcy Lindhall, president, is a consultant to Uniroyal's epoxy fortifier program. His specialty is epoxy formulation.
Relmech Manufacturing Elmira, Ontario	Cold moulding synthetic stone used in the high-voltage electrical industry. This product uses asbestos reinforcement.	The company has been doing R&D for past year Projects include: development of asbestos free products, new product development, increased temperature resistance.
Uniroyal Limited Research Department Guelph, Ontario	Epoxy fortifiers	Working since 1981 with NRC on epoxy fortifiers that improve properties of epoxy resin matrices.
Universal Insulation Aurora, Ontario	Tapes for electrical industry, prepegs for gear cases.	R&D activities are market-driven, and their direction is determined by the firm's production facilities. It has an IRAP grant to evaluate the use of epoxy fortifiers with curing systems other than the amine type.

ACTIVITIES OF CANADIAN UNIVERSITIES IN ADVANCED POLYMER MATRIX COMPOSITES

NAME OF UNIVERSITY	R & D ACTIVITIES
British Columbia	Metallurgical Engineering Department: Studies on fatigue, friction and wear of composites. Standard epoxy, Kevlar and glass systems are employed in the studies. The university is also working on fracture toughness of graphite-epoxy composites. Since about 1980, it has worked for Allied on the ultra-high-strength polyethylene fibre "Spectra 900". Resins used with the fibre are vinyl ester and polyester. Staff: two faculty, two engineers, five technical, five graduate students.
Concordia	Mechanical Engineering Department: Working on resin composites for the chemical processing industry (e.g., pressure vessels), some aircraft work and a small amount of automotive work. Supported by government grants and contracts from the various companies. The university has been doing this R&D for six to seven years, some of its major sponsors being NRC, Spar Aerospace, Quebec government and Imperial Oil. Working with glass-polyester, Kevlar-epoxy and graphite-epoxy, using pressure vacuum moulding. Staff: 10, consisting of faculty, graduate students and research assistants.

ACTIVITIES OF CANADIAN UNIVERSITIES IN ADVANCED POLYMER MATRIX COMPOSITES (CONT'D)

NAME OF UNIVERSITY	R & D ACTIVITIES
Ottawa	Mechanical Engineering Department: Flywheel Project - Composite rotors are designed and manufactured using epoxy-S-2 glass and carbon fibre combinations. Pressure vessels - Fibres are filament-wound S-2 glass, Kevlar 49, Grafil E-XA-F carbon. The matric is epoxy with amine cure. Design programs include multiple layers, different materials, various wind angles. Currently fabricating prototypes and in 1986 will start on robot-filament winding.
Sherbrooke	Mechanical Engineering Department: There are five professors working on polymer composites, two in mechanical engineering and three in civil engineering. Currently they have four contracts: - Canadair - Three-year study (one year has been completed) of the damage tolerance of carbon-epoxy composites. Staff: Prof. Roy, one research engineer, three graduate students, one technician. - Canadian Department of Communications: Study of acoustic emission, damage under stress, fundamental research frequency signatures of various mechanisms, signal analysis. - Hydro-Québec: Study of fibreglass booms on Hydro trucks by the acoustic method. - Department of Defence (Canadian Arsenals Limited): Development of suitable composites for ammunition shells.
Toronto	Mechanical Engineering Department: Some composite work has been going on at a low level of activity for the past four to five years. This involves carbon and Kevlar in epoxy matric, concentrating on fracture behaviour and nondestructive testing. Institute of Aerospace Studies: Current projects include work on the abrasion resistance of composites in connection with the space shuttle arm; effort of space environment on composites; atomic oxygen erosionl effect of thermal vacuum cycling. The university is developing fracture models and fatigue models for the F-18 fighter and doing work for the Communications Research Centre on joint design. It is also developing composites for cryogenic storage, and designing for NASA strength models for aircraft. For automotive applications they have developed chopped fibre-reinforced sheet moulding compounds. There is no materials development, but structures are made up and analytical modelling and space simulation carried out. Chemical Engineering: Work on toughness improvement of graphite fibre composites and on ultradrawn polymers.

Canada has a manufacturing base for producing polymer matrix composites. The domestic market for aircraft components is limited and market expansion may only be achieved by diffusion of technology into non-aerospace markets, such as sports equipment, and by improving access to the foreign, mainly U.S., markets.

7.2 Metal Matrix Composites (MMC)

The current MMC R&D activity in Canada is restricted to a small community of university, industrial and government researchers. There are few factors causing the inactivity of MMC research in Canada. At present, no professional organization for this technology has been established. And with the U.S. imposing an export restriction on this technology, a large amount of technical information has become unavailable. In addition, technical discussion on the subject, even within the country, is greatly discouraged due to the proprietary nature of the MMC manufacturing processes.

Among the major universities in Canada, no large-scale program is being launched on MMC. However, a fair number of universities (as listed in Table V) have expressed interest. Major MMC systems being researched at the University of British Columbia and McMaster University are SiC/aluminum and alumina/aluminum. At the University of Waterloo, carbon/aluminum is being investigated. The only form of government funding available in this area of research is through NSERC, but the amount is almost insignificant. Universities interested in MMC research are providing their own funding in the investigation, while others would consider engaging in research only if funding becomes available.

TABLE V

Canadian Universities engaging or showing interest in MMC R&D

University of British Columbia
University of Waterloo
Queen's University
McMaster University
University of Ottawa
Technical University of Nova Scotia
University of Windsor

Similar to the universities' situation, no large-scale MMC program is currently conducted in Canadian government laboratories or non-profit organizations. Programs on MMC performed in the past were mainly product-oriented and MMC investigations are speculative in nature. In the past, NRC had worked jointly with Westinghouse Canada on MMC gas turbine material, and its present interest is on a graphite/aluminum system. Industrial Materials Research Institute is conducting research on metal matrix composites made by powder metallurgy techniques.

Energy, Mines and Resources Canada (EMR) worked on MMC roughly 10 years ago, but is not now conducting any projects on MMC. Nonetheless, EMR's interest has been revived by the U.S. aggressive move into this technology. Ontario Research Foundation (ORF) is currently developing MMC fabrication technology under an in-house program. The technical know-how achieved is expected to be used to encourage and assist Canadian industries in the utilization of MMC.

At Defence Research Establishment Pacific (DREP), test programs are being conducted exclusively for polymer matrix composites. However, interest in the development of MMC is expressed at Defence Research Establishment Valcartier (DREV).

The companies engaging in MMC research and development in both U.S. and Japan can roughly be classified into two categories. The first includes fibre suppliers, while the second includes MMC manufacturers and end-users. In Canada, there is neither a fibre supplier nor an MMC manufacturer and end-user. Alcan is one of the few potential MMC manufacturers now active in MMC R&D.

The attitude towards this technology by potential MMC users is quite different. In the aerospace industry, companies like Canadian Astronautic Limited (CAL), Fleet Industries, Bristol Aerospace Ltd. and Applied Space Mechanics Communications have expressed a strong interest in implementing this technology in their products. However, initiating an MMC development program with their own funding is deemed not economically viable. As with companies in the U.S., R&D programs would be much encouraged if government assistance was provided.

Responding almost in the same way as the aerospace industry, the automotive industry in Canada is unfamiliar with MMC and is curious about this technology. Again, no company is aggressive enough to take on MMC development work.

Application of MMC in other industries, like semiconductors and recreational goods, is considered relatively new even in the U.S. and Japan and it is not surprising that no program of this nature is found in Canada.

At present, metal matrix composites have only limited commercial applications, mainly in aerospace and millitary products. However, judging from the amount of R&D work conducted, this technology will penetrate more general markets such as automotive parts and sports equipment. Unfortunately, present Canadian involvement in this area of materials technology is minimal and inadequate to capitalize on commercial opportunities posed by the emerging technology. Because the U.S. restricts MMC technology transfer, Canadian manufacturers should be looking to transfer of technology from Japan and/or developing Canadian technology.

7.3 Ceramic Matrix Composites (CMC)

The research and development activities in the area of CMC technology in Canada are very much in the nascent state. Neither the government nor the industry is known to have participated in this new technology on any appreciable scale. As it stands, Canada is perhaps five to 10 years behind the major participants such as the U.S. and Japan in direct experience as well as technological capability. This estimate does not take into consideration the vast differences in industrial capability between Canada and these two countries.

At present, a small number of Canadian organizations are pursuing R&D of CMCs, mostly in particulate reinforced ceramics. The relevant efforts are small and the focus is usually scientific in nature. Additionally, there is virtually no co-ordination of the activities, as organizations co-operate with each other only on project basis, or work individually to enhance their in-house capability and to meet their own specific needs. Government-supported R&D programs in advanced structural ceramics are all at early stages of studies, and CMCs are not emphasized.

Typical of these programs are the ceramics for engines projects under the Department of National Defence and the National Research Council of Canada.

A list of Canadian organizations in the government, industry and research sectors involved in CMC-related work is given in Table VI. It is to be noted that the level of effort involved is generally very low, even by domestic standards. Of the large number of government, industrial and academic organizations surveyed for this report, only those appearing on the list are known to have CMC-related work in progress. Also, only one company, Alcan International Ltd., is reported to have had comprehensive in-house work for the last four years. Electrofuel Manufacturing Co. has worked for about one year on an R&D project for boron nitride fibre composites with the assistance of government funding, while B.M. Hi-Tech, also with government support, is involved in the development of piezoelectric ceramic-polymer composites.

TABLE VI

R&D OF CMC RELATED TECHNOLOGY IN CANADA

Government Laboratories	
Defence Research Establishment Pacific, Victoria, B.C.	Non-destructive testing
National Research Council Division of Mechanical Engineering Ottawa, Ontario	Ceramics for engines (zirconia based ceramics)

Government Laboratories (Cont'd)

National Research Council National Aeronautical Establishment Ottawa, Ontario	Non-destructive testing of advanced composites
National Research Council Atlantic Research Laboratories Halifax, Nova Scotia	Alumina-based ceramics
National Research Council Industrial Materials Research Inst. Boucherville, Québec	Non-descructive testing of ceramics, piezoelectric composites

Universities and Provincial Research Organizations

McMaster University Hamilton, Ontario	Oxide-based, toughened ceramics, property evaluation
University of Toronto Toronto, Ontario	Fibre technology
Ontario Research Foundation Mississauga, Ontario	Al_2O_3-ZrO_2 composites, long fibre reinforced glass and glass-ceramics
Nova Scotia Research Foundation Halifax, Nova Scotia	Al_2O_3-ZrO_2

Companies

Electrofuel Manufacturing Co. Toronto, Ontario	BN fibre composites
Home Technics Ltd. Peterborough, Ontario	ZrO_2O_3-based ceramics
Alcan International Ltd. Kingston, Ontario	Alumina matrix and other ceramic matrix composites
B.M. High Tech. Inc. Collingwood, Ontario	Piezoelectric composites
Almax Industries (1980) Ltd. Lindsay, Ontario	Particulate composites, piezoelectric composites

To date, there are few CMC products in the domestic market and all are foreign imports for cutting tool and electronic applications.

7.4 Carbon/Carbon Composites

Except for a small R&D project recently initiated at the Ontario Research Foundation (ORF), there are no other R&D or manufacturing programs in this field. The present market for carbon/carbon composites is fairly limited and consists mainly of aircraft brakes and rocket components. However, opportunities exist in other areas such as prosthetic devices and components for aircraft engines. At present, there is no Canadian technology available to pursue these opportunities. Since most of the work carried out in this field in the U.S. and Japan is either proprietary or classified, the flow of information is limited.

8. CANADIAN ISSUES

There are barriers confronting the development of advanced composites despite the growing interest expressed by some sectors of Canadian industrial community. Some of these barriers are:

- The branch plant mentality;
- Access to know-how. Information on new materials is often restricted usually for strategic reasons;
- Lack of awareness of business community;
- Fragmented R&D and lack of information about R&D. Inadequate linkages between industry and universities;
- Small domestic market. The total Canadian market for prepregs, for example, is less than $1 million per year. No market-oriented pull or national strategic thrust. Canada has traditionally exported raw materials, a tradition that discourages innnovation especially in advanced materials;
- Lack of innovative entrepeneurs and incentives for innovation;
- Cost of introducing new materials in some industries (e.g., aerospace) is very high due to stringent specifications;
- Limited pool of skilled personnel due to the present lack of employment opportunities.*

International competition from the U.S., Japan and Western Europe is intense. Both the U.S. and Japan have achieved leadership in composite technologies and it is apparent that they will be maintaining that position by committing huge resources in terms of human resources and R&D funding. Intense national programs are being implemented by the U.S. and Japan and this is widening the technological gap between them and Canada.

On the positive side, Canada has a strong polymer matrix composites industry which, in 1985, produced approximately 64 million kg of products. Expertise existing in this industry may be applied to advanced composites. Large automotive parts and aerospace industries, if properly encouraged, may produce strong market pull.

Because technology and applications of advanced composite materials are rapidly expanding, opportunities for business entries exist. A number of areas may be listed as examples:

Aerospace. This is the area of largest growth for advanced composites. Since Canadian market is limited, market opportunities in the U.S. and Europe should be pursued. Depending on future developments, this industry may produce a market pull for advanced composites.

* Based on Advanced Materials: A National Opportunity, Plastics Business, Jan/Feb 86.

Sports and recreation. This is an area where high-performance products can be marketed at a premium price. Canada has a credible reputation in this market and application of advanced composites would further improve penetration of Canadian products into world markets.

Machine components. There is a market for advanced composite components for specialized (e.g., high-speed) equipment. Canadian machine manufacturing industry should be encouraged to explore the potential of advanced composites.

Reinforcements. At present, there is no Canadian manufacturing of reinforcements for advanced composites. Since markets for graphite fibres (especially low-cost, pitch-based fibres) expand, Canadian entry into this market is possible.

"Niche" products. Opportunities exist for composite components in various "niche" markets. One example might be prosthetic devices where composite materials might successfully compete with currently used products. Another example of "niche" market are toe caps for safety boots. Here, advanced composites are an alternative to less expensive steel products providing advantages in low weight, better strength and in being non-magnetic. For those opportunities to be exploited better dissemination of information to the business and technical communities on advanced composites is needed.

Automotive. Canada has a large automotive industry. Various advanced composites (especially metal/metal) may find applications as substitutes for currently used components resulting in higher performance parts. Because of the relatively high cost of materials and manufacturing, the utilization of advanced composites in automobiles is limited. Even minor components, however, constitute considerable business opportunities in such a large volume product.

Ceramic matrix composites should probably be considered as part of modern ceramic technology. It is impossible to imagine development of CMCs without establishing advanced ceramic technology first. It is the development in that area that has to be stimulated first with CMCs assuming only secondary importance for the time being.

The development of metal matrix composites technology in Canada is definitely perceived to have an impact on Canadian industrial structure as well as its economy despite the barriers that must be overcome. The successful development of MMC technology would require simultaneous development of many supporting technologies such as fibre development, MMC fabrication, joining, machining and designing. The growth in this industry, therefore, means a growth in many related industries by introducing MMC technology in Canada. This will certainly vitalize the existing material industry and automatically stimulate the development of many pheripheral industries. Considering the existing and growing industries in Canada, e.g., automotive, aerospace and semiconductor, MMC technology has demonstrated its beneficial applications.

Consequently, this potential market alone makes it very favourable to introduce MMC technology into Canada. In addition, the application of MMC is not only restricted to the above mentioned industries. In recreation, communication and even oil and gas industries its potential has been demonstrated in the U.S., Japan and European countries.

In Canada, even though applications of MMC in the major industries of automotive, oil and gas and aerospace have not been realized, the presence of these industries is a strong indication of the huge market potential for this technology.

Because of their present high cost, carbon/carbon composites are of only limited commercial importance. That may soon change due to the intense R&D programs in the U.S. and Japan. If the manufacturing cost is reduced, carbon composite brakes might replace asbestos brakes. Another area of opportunity is in the application of these composites in the prosthetic devices where they are expected to perform better than present metal devices.

Since most of the work carried out in the U.S. on carbon/carbon composite is classified, the only way for Canada to enter this field is through government-supported research.

Advanced composite materials are rapidly replacing standard materials in a variety of applications. Canada has strong auto parts, aircraft and sports equipment industries which create natural markets for advanced composites. The Canadian composites (non-advanced) industry is strong and technologically competent. Technical and manufacturing expertise in advanced polymer matrix composites, although somewhat limited at the present time, form a good base on which the new industry may be built. The new technologies pose both a threat and an opportunity. The threat is that the present products which do not utilize new materials will not be able to compete on the world markets. The opportunity lies in participation in the rapidly growing technology and new markets which it creates.