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Ceramic and metal matrix composites: route and properties

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The paper presents a brief state of the art of advanced ceramics, metal matrix and ceramic matrix composites. The attention is focused on process technologies involved, applications and future of these “potential” materials. Some experimental results are included.

The future of advanced materials is related to systems solutions, economical manufacturing processing, diverse markets and new technologies. The new materials will provide the opportunity for growth to a new and healthier balance, with vibrant commercial sector delivering an improved quality of life and stronger technology base.

1. CERAMICS

With technological progress, natural materials become insufficient to meet increasing demands on product capabilities and functions.

There are many combinations of metallic and non-metallic atoms that can combine to form ceramic components, and also several structural arrangements are usually possible for each combination of atoms. This led scientists to invent many new ceramic materials to meet increasing requirements and demands in various application areas. Advanced furnaces and heat engines played important roles in the success of the industrial revolution, while ceramic materials were essential for thermal insulation of various types of furnaces and engines. Electrically insulating ceramic materials were developed as electrical and electronic technologies matured. As higher and higher frequencies and voltages were used, the demand on ceramic dielectrics became more stringent. Also, new specifications for the magnetic and optical properties of ceramics were developed as a part of the new electronic and electro–optical technology revolution.

The technology of ceramics is a rapidly developing applied science in today’s world. Technological advances result from unexpected material discoveries. On the other hand, the new technology can drive the development of new ceramics. Currently many new classes of materials have been devised to satisfy various new applications. Advanced ceramics offer numerous enhancements in performance, durability, reliability, hardness, high mechanical strength at high temperature, stiffness, low density, optical conductivity, electrical insulation and conductivity, thermal insulation and conductivity, radiation resistance, and so on. Ceramic technologies have been widely used for aircraft and aerospace applications, wear-resistant parts, bioceramics, cutting tools, advanced optics, superconductivity, nuclear reactors, etc.

Ceramics application could be categorised as structural ceramics, electrical ceramics, ceramic composites, and ceramic coatings. These materials are emerging as the leading class of materials needed to be improved to explore further potential applications. An Advanced Ceramics Application Tree, which classifies its current and potential application areas and related advantageous properties, has been developed and is shown in figure 1. Current and future advanced ceramic products derived from the application tree are indicated in table 1. Today, advanced ceramics have been widely used in wearing parts, seals, low weight components and fuel cells in transportation sectors, to reduce the weight of product, increase performance especially at high temperatures, prolong the life cycle of a product and improve the efficiency of combustion. As advances in ceramic technology offer potential and immediate opportunities, these materials will translate into greater market shares in transportation sectors. On the other hand, future application is still very limited if no breakthroughs are achieved in fundamental and applied research [1].

A study for new application. In the frame of a research project for the development of components to be used in critical environments, studies on the possibility of obtaining ceramic nuts and rods were carried out by the Centre for Study and Development of Metallurgy and Materials for mechanics at Politecnico di Torino in Alessandria.

The process of compacting and sintering powders, traditionally used in the field of P/M, was investigated with the aim of evaluating the behaviour of alumina based powder mixes.

Different prototype cylinders were obtained through uniaxial compaction, using a 50 t Komage press. Since high components were pressed in cold dies, particular care was taken to avoid the presence of density gradients, detrimental for the possibility of inducing differential shrinkages during sintering, thus leading to deformations in the final components. Other important considered aspects were the choice of the appropriate compacting speed, to minimise air trapping, and all what related to the extraction of the sample, in order to avoid the slip and stick phenomena which leads to the lamination of the component.

Different compacting pressures were investigated, but at the end, chosen values were in the range of 200 and 300 MPa. After cold compaction, part of cylinders were pre-sintered while others underwent directly secondary mechanical operations: drilling, internal and external trimming, milling and surface finishing.

This splitting was carried out in order to investigate the influence of the pre-sintering cycle on the machinability of compacted powders.
Examples of “green” final components are shown in the figures n. 2.

Mechanically worked samples then underwent pre-sintering and final sintering; this set of processes was performed to verify the previously calculated shrinkage, necessary to keep the final desired dimensions of threads and of the nuts.

Following the same scheme, the former pre-sintered samples underwent mechanical operations of drilling, trimming, etc… In this case different pre-sintering cycles had to be investigated to mediate between workability and fragility of components.

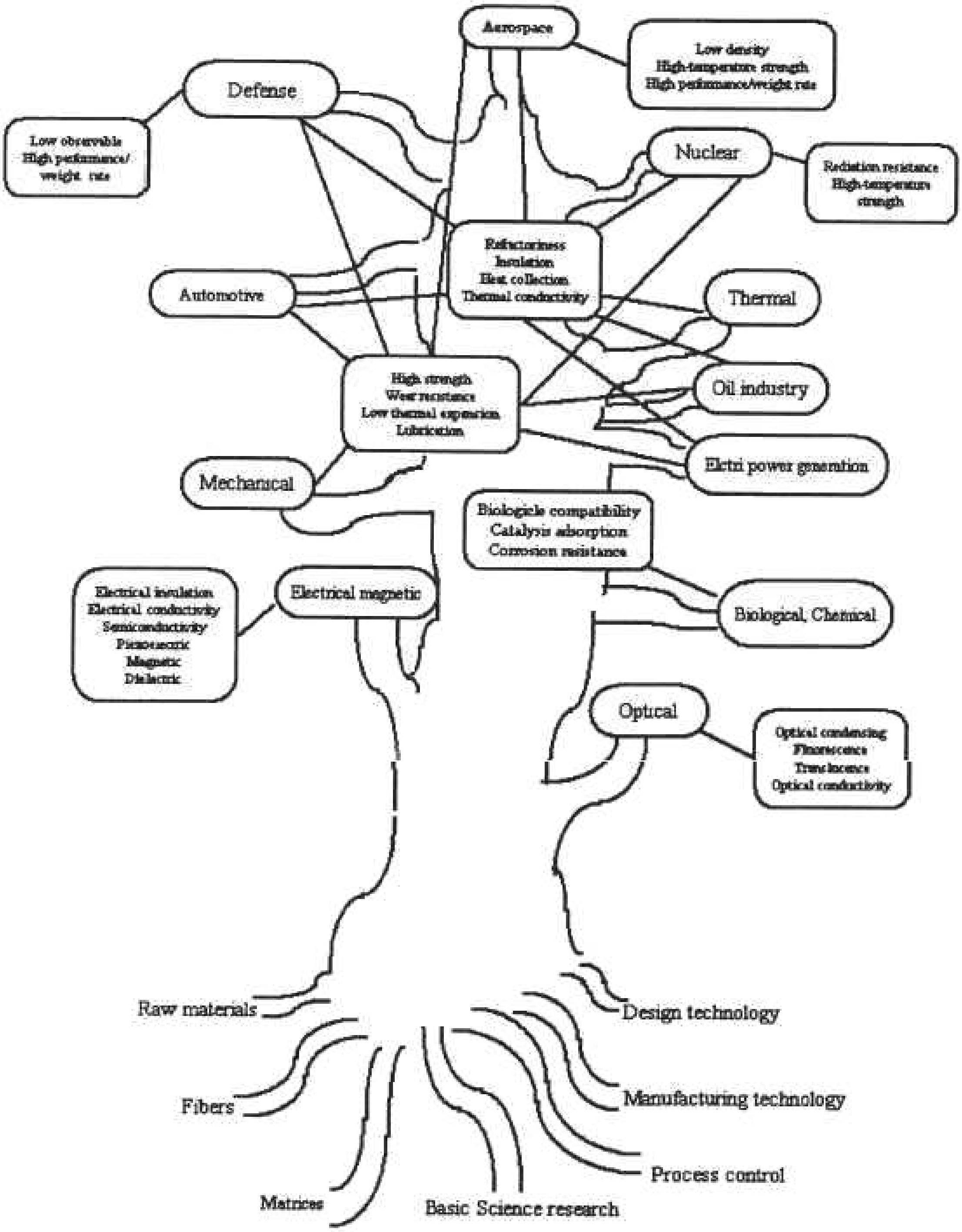


Figure 1. Advanced ceramic application tree [1].

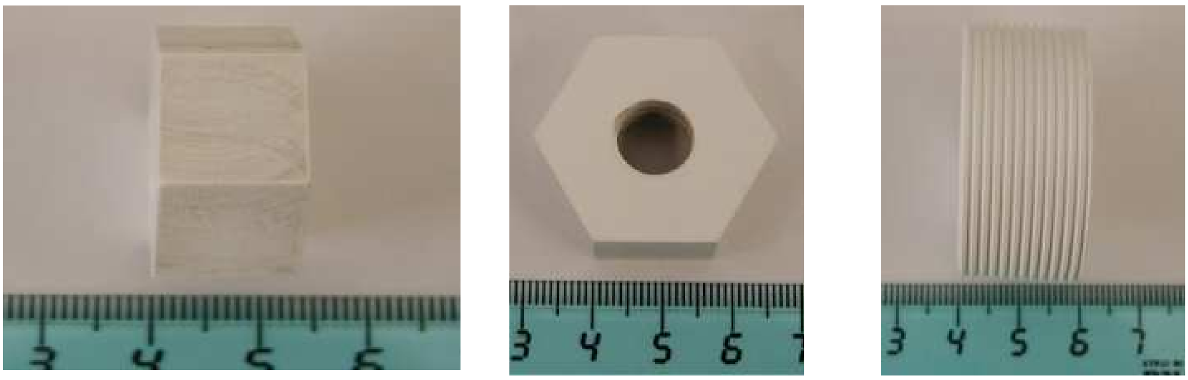
At the end, the length of the pre-sintering cycle (for both the cases, i.e: samples directly machined and machined after the thermal treatment) was of 74h with a peak T of 1000°C. Sintering was then carried out at 1600°C for 1h in air.

A general good response was obtained at the end of the whole process in terms of shapes and dimensions, in the sense that all the obtained shrinkages (approx 20%) followed a predictable equation in every area of the specimen.

As for the mechanical properties, hardness evaluations were carried out, as well as non standard tensile tests in order to verify the properties of the threads.

Table 1
Current and future products for advanced ceramics [1].

Mechanical Engineering	Aerospace	Automotive	Defense industry
Cutting tools and dies	Fuel systems and valves	Heat engines	Tank power trains
Abrasives	Power units	Catalytic converters	Submarine shaft seals
Precise instrument parts	Low weight components	Drivetrain components	Improved armors
Molten metal filter	Fuel cells	Turbines	Propulsion systems
Turbine engine components	Thermal protection systems	Fixed boundary recuperators	Ground support vehicles
Low weight components for rotary equipment	Turbine engine components	Fuel injection components	Military weapon systems
Wearing parts	Combustors	Turbocharger rotors	Military aircraft (airframe and engine)
Bearings	Bearings	Low heat rejection diesels	Wear-resistant precision bearings
Seals	Seals	Waterpump seals	
Solid lubricants	Structures		
Biological, Chemical processing engineering	**Electrical, Magnetic Engineering**	**Nuclear industry**	
Artificial teeth, bones and joints	Memory element	Nuclear fuel	
Catalysts and igniters	Resistance heating element	Nuclear fuel cladding	
Heart valves	Varistor sensor	Control materials	
Heat exchanger	Integrated circuit substrate	Moderating materials	
Reformers	Multilayer capacitors	Reactor mining	
Recuperators	Advanced multilayer integrated packages		
Refractories			
Nozzles			
Oil industry	**Electric power generation**	**Optical Engineering**	**Thermal Engineering**
Bearings	Bearings	Laser diode	Electrode materials
Flow control valves	Ceramic gas turbines	Optical communication cable	Heat sink for electronic parts
Pumps	High temperature components	Heat resistant translucent porcelain	High-temperature industrial furnace lining
Refinery heater	Fuel cells (solid oxide)	Light emitting diode	
Blast sleeves	Filters		



Figures 2a, 2b, 2c: Ceramic nuts and rods obtained through machining in the green state, work developed at Politecnico di Torino.

2. METAL MATRIX COMPOSITES

Metal matrix composites have many advantages over monolithic metals including a higher specific modulus, higher specific strength, better properties at elevated temperatures, lower coefficients of thermal expansion and better wear resistance. Because of these attributes metal matrix composites (MMCs) are under consideration for a wide range of applications. However, on the debit side, their toughness is inferior to monolithic metals and they are more expensive at present. In comparison with most polymer matrix composites, MMCs have certain superior mechanical properties, namely higher transverse strength and stiffness, greater shear and compressive strengths and better high temperature capabilities. There are also advantages in some of the physical attributes of MMCs such as no significant moisture absorption properties, non-inflammability, high electrical and thermal conductivities, and resistance to most radiations [2].

MMCs, in general consist of at least two components: one is the metal matrix and second is the reinforcement. In all cases the matrix is defined as a metal, but pure metal is rarely used: it is generally an alloy. Some classes of MMCs, like Cermets, Diamond tools and Hard Metals, have different and extensive applications and, even if they can be considered as traditional materials, they are in continuous evolution [3-6].

Metal matrix composites have been extensively studied since many years, the primary support has come from the aerospace industry for airframe and spacecraft components. More recently, automotive, electronic and recreation industries have been working diffusively with composites [7].

MMC reinforcements can be generally divided into five major categories: continuous fibres, discontinuous fibres, whiskers, wires and particulate (including platelets). With exception of wires, which are metals, reinforcements are generally ceramics. Typically these ceramics are oxides, carbides and nitrides which are used because of their excellent combinations of specific strength and stiffness at both ambient temperature and elevated temperature.

The two most commonly used metal matrices are based on aluminium and titanium. Both of these metals have comparatively low specific gravities and are available in a variety of alloy forms. Although magnesium is even lighter, its great affinity for oxygen promotes atmospheric corrosion and makes it less suitable for many applications. Beryllium is the lightest of all structural metals and has a tensile modulus higher than that of steel. However, it suffers from extreme brittleness, which is the reason for its exclusion as a potential matrix material. Nickel and cobalt-based super alloys have also been used as matrices, but the alloying elements in these materials tend to accentuate the oxidation of fibres at elevated temperatures.

Aluminium and its alloys have the most attention as matrix material for MMCs and the most common reinforcement is SiC. MMC engine applications are produced and used for automobile engine cylinders die-cast from carbon fibre-aluminium-Al_2O_3 material.

The titanium alloys that are most useful in MMCs are α, β alloys and metastable β alloys. These titanium alloys have higher tensile strength-to-weight ratios as well as better strength retentions at 400-500°C than those of aluminium alloys.

Titanium MMCs are used in applications where performance is demanded without regard to cost-effectiveness. This is where one obtains high-temperature performance unattainable with conventional materials [8].

Over the years a spectrum of processing techniques have evolved in an attempt to optimise the microstructure and mechanical properties of MMCs. The processing methods utilised to manufacture MMCs can be grouped according to the temperature of the metallic matrix during processing. Accordingly, the processes can be classified into five categories: (1) liquid-phase processes, (2) solid-liquid processes, (3) two-phase (solid-liquid) processes, (4) deposition techniques and (5) in situ processes.

1. Liquid phase processes. In liquid phase processes, the ceramic particulates are incorporated into a molten metallic matrix using various proprietary techniques. This is followed by mixing and eventual casting of the resulting composite mixture into shaped components or billets for further fabrication. The process involves a careful selection of the ceramic reinforcement depending on the matrix alloy. In addition to compatibility with the matrix, the selection criteria for a ceramic reinforcement include the following factors: (1) elastic modulus, (2) tensile strength, (3) density, (4) melting temperature, (5) thermal stability, (6) size and shape of the reinforcing particle and (7) cost. Since most ceramic materials are not wetted by molten alloys, introduction and retention of the particulates necessitate either adding wetting agents to the melt or coating the ceramic particulates prior to mixing. It is possible to individuate four methods:

- Liquid metal ceramic particulate mixing;
- Melt infiltration;
- Melt oxidation processing;
- Squeeze casting or pressure infiltration.

2. Solid-phase processes. Solid phase processes involve the fabrication of particulate-reinforced MMCs from blended elemental powders involves a number of steps prior to final consolidation. These processes are currently used for cemented carbides and for diamond tools, however they have good potentiality also for other systems, for examples Al based MMC [9]. Methods that fall in this category are:

- Powder metallurgy;
- High energy, high rate process;
- Diffusion bonding.

3. Two phase processes. Two phase processes involve the mixing of ceramic and matrix in a region of the phase diagram where the matrix contains both solid and liquid phases. Two phase methods are:

- Ospray deposition;
- Compocasting/Rheocasting;
- Variable codeposition of multiphase materials.

*4. Deposition techniques***.** Deposition techniques for MMCs fabrication involve coating individual fibres in a tow with the matrix material needed to form the composite, followed by diffusion bonding to form a consolidated composite plate or structural shape. Since the composite is composed of identical units, the microstructure is more homogeneous than that of cast composites. Several deposition techniques are available:

- Immersion plating;
- Electroplating;
- Spray deposition;
- CVD;
- PVD;
- Spray forming techniques.

*5. In situ processes***.** In these techniques the reinforced phase is formed in situ. The composite material is produced in one step from an appropriate starting alloy.

In table 2 there is a comparison of different MMCs techniques. The route, the related cost, the possible and most suitable applications, together with some comments are here presented. In particular the techniques are related to diffusion processes, to powder metallurgy, to casting techniques, as well as to spray processes.

The MMCs fabrication procedures with matrix-reinforcement best associations are shown in table 3, with distinction between continuous and discontinuous reinforcement, while the process routes for the production of continuous fibre-reinforced MMCs are shown in figure 3.

The wide choice between long and short fibers, as well as particulate reinforcement, figure 4, offers the possibility to design the composite with the best properties as a function of the application requirements. An example of microstructure of spray/wind Al-12Si reinforced composites is in figure 5 and the figure 6 describes the main process routes for the production of discontinuous fibre, whiskers and particulate-reinforced composites.

Table 2 : Comparison of MMCs tecniques [8].

Route	Cost	Application	Comments
Diffusion bonding	High	Used to make sheets, blades, vane shafts, structural components	Handles foils or sheets of matrix and filaments of reinforcing element
Powder metallurgy	Medium	Mainly used to produce small objects (especially round), bolts, pistons, valves, high-strength and heat-resistant materials	Both matrix and reinforcements used in powder form; best for particulate reinforcement; since no melting is involved, no reaction zone develops, showing high-strength composite
Liquid-metal infiltration	Low/Medium	Used to produce structural shapes such as rods, tubes, beams with maximum properties in a uniaxial direction	Filaments of reinforcement used
Squeeze casting	Medium	Widely used in automotive industry for producing different components such as pistons, connecting rods, rocker arms, cylinder heads; suitable for making complex objects	Generally applicable to any type of reinforcement and may be used for large scale manufacturing
Spray casting	Medium	Used to produce friction materials, electrical brushes and contacts, cutting and grinding tools	Particulate reinforcement used; full-density materials can be produced
Compocasting/ Rheocasting	Low	Widely used in automotive, aerospace, industrial equipment and sporting goods industries; used to manufacture bearing materials	Suitable for discontinuous fibres, especially particulate reinforcement

Table 3: MMCs fabrication procedures [8].

Processing route	**Continuous reinforcement**		**Discontinuous reinforcement**		
	Monofilament	**Multifilament**	**Staple fibre**	**Whiskers**	**Particulate**
Squeeze infiltrate preform	(√)	√	√	√	(√)
Spray coat or codeposit	√	√	x	x	√
Stir mixing and casting	x	x	(√)	(√)	√
Powder premix and extrude	x	x	√	√	√
Slurry coat and hot pressing	(√)	√	x	x	x
Intercleave and diffusion bonding	√	x	x	x	x

x: not practicable; (√): not common; √: current practice

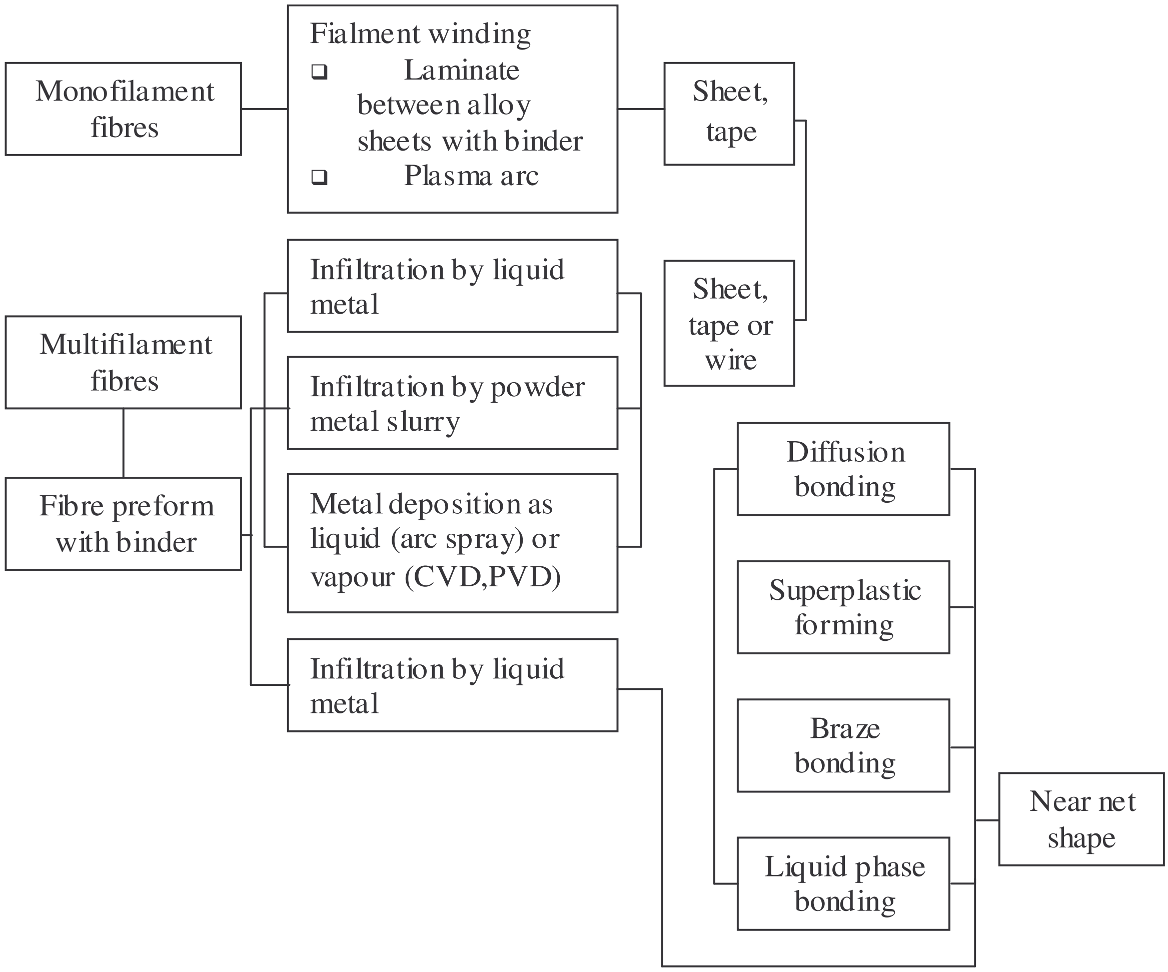


Figure 3. continuous fibre-reinforced MMCs process routes [8].

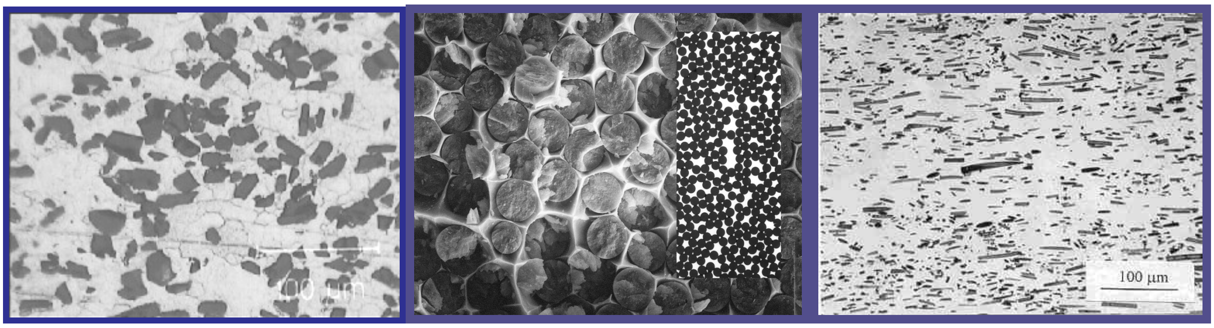


Figure 4: Long fibers, short fibers and paticulate reinforcement.

The microstructure and the properties of MMCs with continuous reinforcement are quite homogeneous, in the case of discontinuous reinforcement the homogeneity of reinforcing particle distribution within the matrix must be evaluated in order to improve the mechanical properties. Moreover, for applications demanding high toughness, a proper choice of metal matrix, both in terms of chemical composition and percentage must be considered. In particular, a higher fracture toughness can be obtained owing to a continuous and regular ceramic network throughout the microstructure. Contrary, distributing the same volume of ceramic particles in a metal matrix rather frequently promote the formation of reinforcement clusters. These are weak zones that usually constitute fracture initiation sites [11].

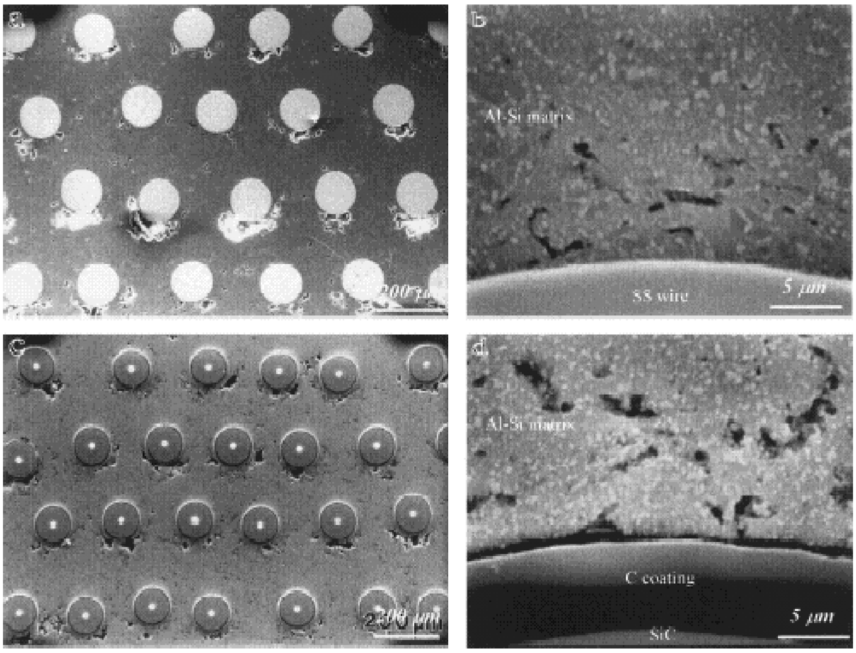


Figure 5. Spray/wind Al-12Si composites reinforced with (a) stainless wire and (c) Sigma 1140 + SiC. (b) and (d) shows the interface region of SS/Al-Si and SiC/Al-Si respectively [10].

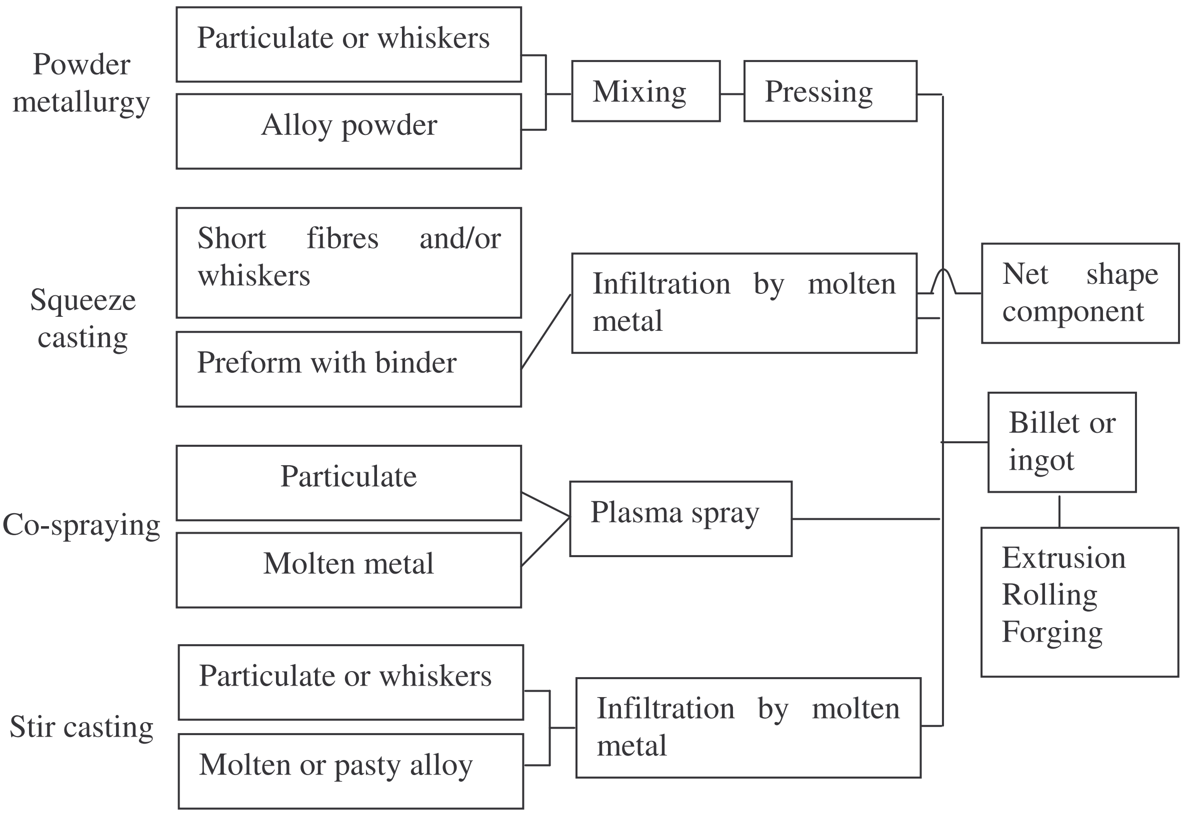


Figure 6. Discontinuous fibre, whiskers and particulate-reinforced composites process routes [8].

Trying to reduce this drawback, interpenetrating phase composites or co-continuous ceramic composites, called C^4, were developed [12, 13]. The production of this materials concerns with infiltration process of silica perform with molten aluminium alloy without the application of external pressure. The low production cost and the near net shape capability of C^4 materials are further advantages of co-continuous composites. The mechanical properties of these materials are very satisfying and their combination with thermal and electrical conductivity characteristics and with good tribological properties allows C^4 composites very promising for applications such as automotive disc brake rotors and callipers. To develop this application a project is under way in the frame of the bilateral cooperation between Italy and Slovenia [14].

There is a strong demand for the development of disc brake with improved resistance and properties and good result have been recently obtained at Politecnico di Torino using ceramic coatings applied on cast iron discs, as well as on Al based MMCs [15, 16].

6. Study of different ceramic coatings on cast iron and MMCs disk brakes

This work was an estimation of the possible automotive employment of a braking system with brake disks ceramic coated coupled with metal/ceramic based friction materials. The aim was to improve braking system performance, maintaining low production costs.

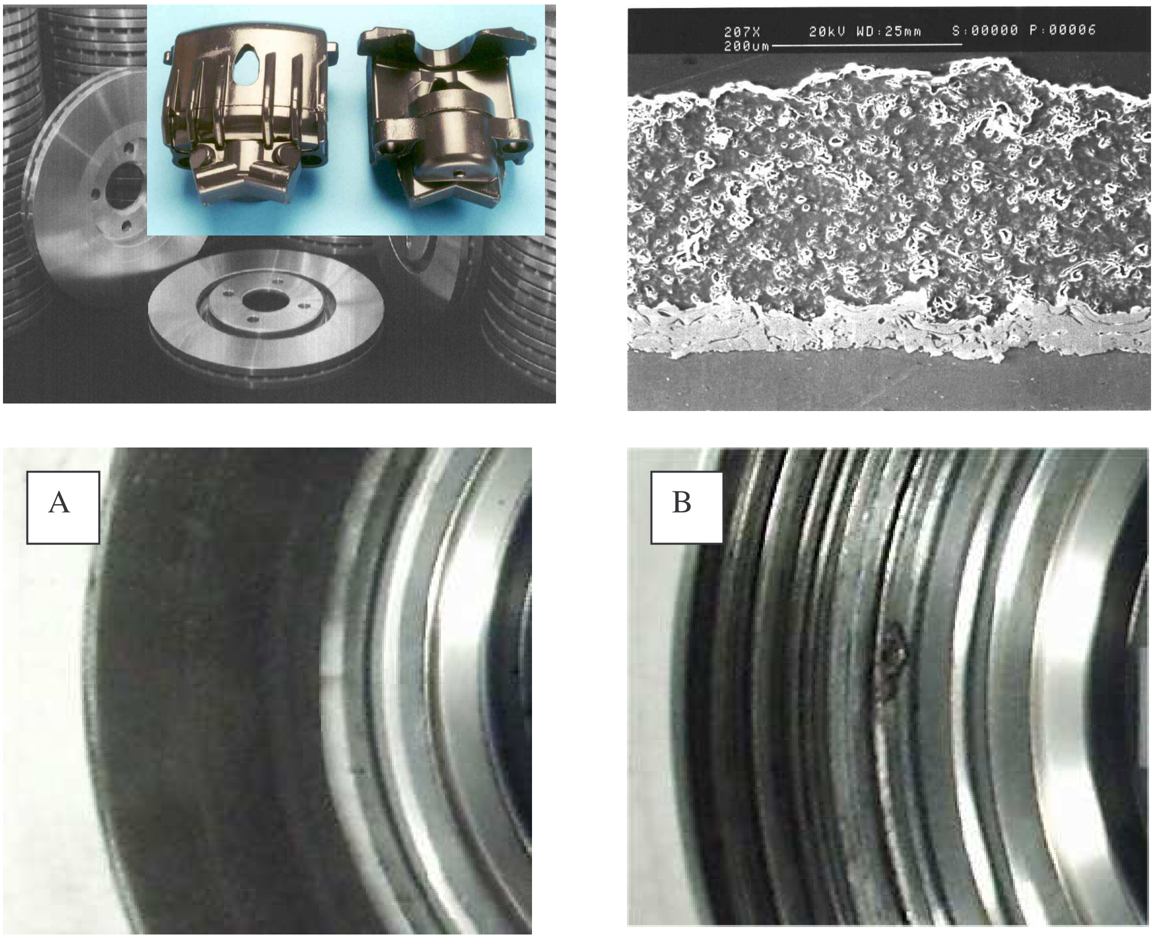


Figure 7: Brake components and coated discs; view of a ceramic coating layer. The surface appearance the coated disc (A) and of the MMC disc after the wear test at the bench.

In literature and already on the market there are braking disks entirely made of ceramic materials (excellent performances) but their prices are only competitive for special car production and not for mass production. Therefore the idea was to start from the same base concept (the employing of ceramic materials) but obtain a good performant, costs competitive solution.

The tested brake disks come from line production components and are employed on medium-high car sector and from sport cars. In figure 7 are shown the main aspects attained during the research.

The disks were plasma sprayed with different types of materials: Al_2O_3/TiO_2 of two granulometry range, ZrO_2/Y_2O_3. This coating technique is the best one with high melting point materials such as the previously indicated ceramic systems.

Ceramic coatings were tested with a thermal fatigue machine to simulate brakes work conditions and evaluate the coating adhesion. Coated samples were also tested with the FAST machine (friction assessment and screening test) to evaluate the friction coefficient. These tests took about one hundred of minutes and the results were plotted as friction coefficient vs time. Finally, coated discs were tested on the bench test apparatus and tested against a suitable pads, to check their behaviour, resistance and life. The test results very satisfying, the photo A and B in figure 7 show very important wear differences between the MMC coated disc (A) and the uncoated one (B). Both the coating materials given good results without significant differences about performances and they appear to be very profitable also for the MMC discs.

3. CERAMIC MATRIX COMPOSITES

Monolithic ceramics have reasonably high strength and stiffness but are brittle. Thus one of the main objectives in producing ceramic matrix composites is to increase the toughness. Naturally it is also hoped, and indeed often found, that there is a concomitant in strength and stiffness. Figure 8 compares typical stress-strain curves for composites with that for a monolithic ceramic; the area under the stress-strain curve is the energy of fracture of the sample and is a measure of the toughness. It is clear from this figure that the reinforcement with particulates and continuous fibres has lead to an increase in toughness but that the increase is more significant for the latter. Both the monolithic and the particulate reinforced composite fail in a catastrophic manner, which contrast with the failure of the continuous fibre composite where a substantial load carrying capacity is maintained after failure has commenced. therefore not only has the continuous fibre composite a better toughness but the failure mode is more desirable. However, fibres are a more expensive reinforcement than particles and the processing is more complex, therefore the improvement in toughness is associated with an extra cost burden.

Ceramic matrix composite (CMC) development has lagged behind other composites for two main reasons. First more of the processing routes for CMCs involve high temperatures and can only be employed with high temperature reinforcements. It follows that it was not until fibres and whiskers of high temperature ceramics, such as silicon carbide, were readily available was there much interest in CMCs. The high temperature properties of the reinforcement are also of importance during service. A major attribute of monolithic ceramics is that they maintain their properties to high temperatures and this characteristic is only retained in CMCs if the reinforcements also have good high temperature properties. Hence, there is only limited interest in toughening ceramics by incorporation of reinforcements of materials, such as ductile metals, that lose their strength and stiffness at intermediate temperatures.

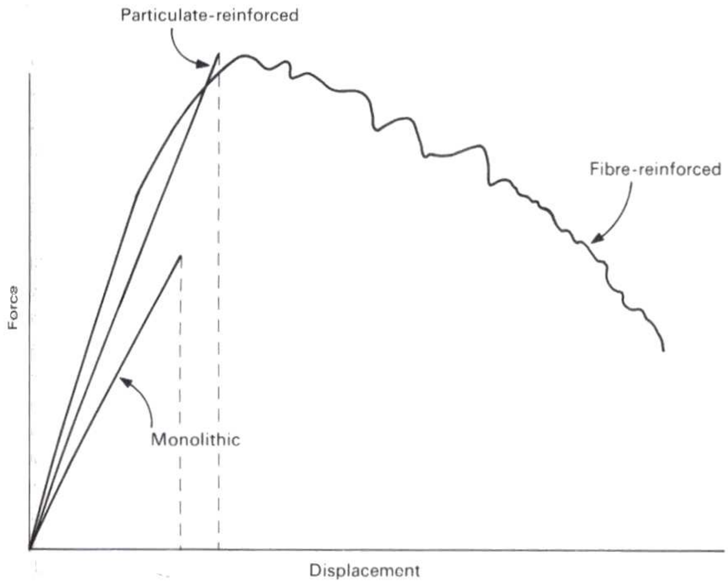


Figure 8. Schematic force-displacement curves for a monolithic ceramic and CMCs illustrating the greater energy of fracture of the CMCs [2].

The second factor that has hindered the progress of CMCs is also concerned with the high temperatures usually employed for production. Differences in coefficients of thermal expansion, α, between the matrix and the reinforcement lead to thermal stresses on cooling from the processing temperature. However, whereas the thermal stresses can generally be relieved in metal matrix composites by plastic deformation of the matrix, this is not possible for CMCs and cracking of the matrix can result. The nature of the cracking depends on the whether the reinforcement contracts more or less than the matrix on cooling as their determines the character (tensile or compressive) of the local thermal stresses. If α_R for a particulate reinforcement is great than that for the matrix α_M then the circumferential cracks may be produced in the matrix, and for $\alpha_R < \alpha_M$ radial cracks may be found. With a fibre reinforcement, when $\alpha_R > \alpha_M$ the axial tensile stresses induced in the fibres produce an overall net residual compressive stresses in the matrix and, as the fibres contract, there is a tendency for them to pull away from the matrix. The stress situation is reversed when $\alpha_R < \alpha_M$ and cracking of the matrix due to the axial tensile stresses may occur. Clearly there has to be some matching of the coefficients of thermal expansion in order to limit these problems.
Ceramic fibres such as SiC and Si_3N_4 use polysilane as the base material. CMCs, in which ceramic or glass matrices are reinforced with continuous fibres, chopped fibres, whiskers, platelets or particulates, are emerging as a class of advanced engineering structural materials. They currently have limited high-temperature applications but a large potential for much wider use in military, aerospace and commercial applications such as energy-efficient systems and transportation.

There are also other specialty CMCs such as nanocomposites (made from reactive powders) and electroceramics. CMCs are unique in that they combine low density with high modulus, strength and toughness (contrasted with monolithic ceramics) and strength retention at high temperatures. Many have good corrosion and erosion characteristics for high temperature applications. CMCs have been used in jet fighters. Industrial uses of CMCs include furnace materials, energy conversion systems, gas turbines and heat engines.

Processing methods can be broken down into two broad groups: powder consolidation and chemically based methods. The latter class consists of:

- Melt processing;
- Hot pressing;
- Slip casting and low-pressure sinter;
- Reaction sinter;
- Pressureless sinter;
- Slurry;
- Chemical vapour infiltration;
- Directed melt oxidation;
- Sol-gel processing;
- Self-propagated high temperature synthesis or combustion synthesis.

Figure 9 is an example of sintered glass/spinel composite.

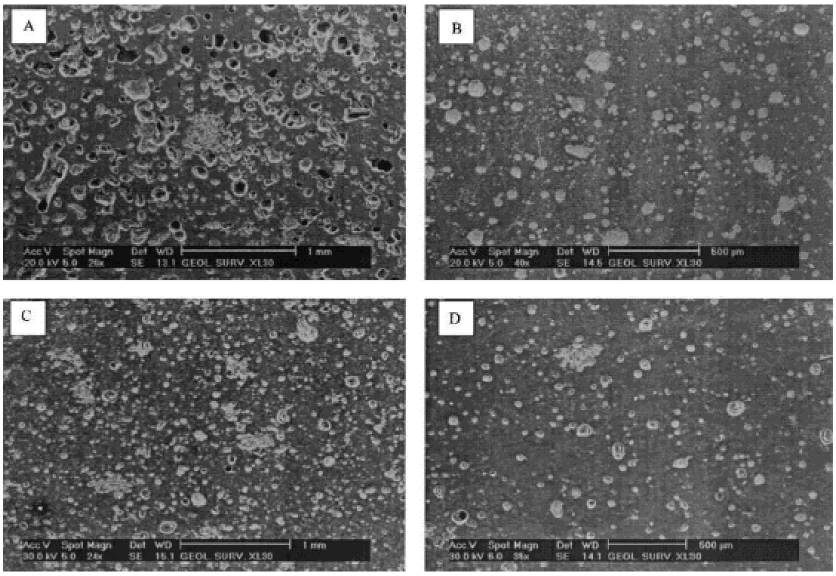


Figure 9. Photomicrographs of glass/spinel composites [17].

Table 4 shows the main processing routes for CMCs and their matrices and table 5 is a detailed scheme of continuous fibre reinforced CMCs.

Table 4.
Main processing routes for CMCs [8].

Processing route	**Matrices**
Chemical vapour infiltration	Carbides, nitride carbon, oxides, borides
Viscous phase hot pressing (2D performs)	Glasses, ceramic-glasses
Sol-gel route (2D, 3D performs)	Oxides
Polymer precursor route (3D performs)	SiC, Si_xN_y, $Si_xC_yN_z$
Liquid metal infiltration	Si→SiC
Gas-metal reaction	Oxide (Al, nitrides [Al, Zn, Ti])
Solid-state hot pressing	SiC, Si_3N_4
Prepreg curing and pyrolysis	SiC, Si_3N_4
Hot pressing (2D preforms)	Oxides

Table 5
Some processes for continuous fibre-reinforced CMCs [8].

Processing method	Advantages	Disadvantages	Fibre	Matrix	T range [1]
I. SLURRY INFILTRATION a) Glass ceramic matrix	Commercially developed. Good mechanical properties.	Limited max. temperature due to matrix. Needs to be hot pressed, expensive. Formations of complex shapes is difficult	Graphite Nicalon	Glass-ceramic Glass-ceramic	800-1000°C 800-1000°C
b) Ceramic matrix 1. Sintered matrix	Potentilally inexpensive. Could produce complex shapes.	Shrinkage during sintering cracks matrix. Temperature limit due to glassy phase.		Alumina SiC Si_3N_4	800-1400°C 800-1600°C 800-1500°C
2. "Cement bonded matrix"	Inexpensive. Ability to produce large complex shapes. Low temperature processing.	Relatively poor properties to date.	Graphite Nicalon "New" fibres	Cements	400-1400°C
3. Reaction bonded matrix	Good mechanical properties. Pressureless densification.	Has required hotpressing of Si powder in silicon nitride system prior to reaction bonding. Simple shapes only.	Nicalon "New" fibres	Si_3N_4 SiC	800-1500°C 800-1600°C
II. SOL-GEL & POLYMER PROCESSING	Good matrix composition control. Easy to infiltrate fibres. Lower densification temperature.	Low yields. Very large shrinkage. Woul require multiple infiltration/densification steps. No promising results reported.	Nicalon	Nonoxide Alumina Silicates	800-1200°C 800-1400°C
III. MELT INFILTRATION a) Ceramic melt	Potentially inexpensive. Should be easy to infiltrate fibres. Lower shrinkage on solidification.	High melting temperatures would damage fibres.	Graphite Nicalon "New" fibres	Alumina Oxides	800-1100°C 800-1100°C
b) Metal melt, followed by oxidation	Potentially inexpensive. Cermet type material.	Difficult to control chemistry and produce all ceramic system. Difficult to envision in use for large, complex parts for aerospace applications.	Graphite Nicalon "New" fibres	Alumina B_4C SiC	800-1200°C 800-1200°C 800-1200°C
IV. CHEMICAL VAPOUR INFILTRATION a) General approach	Has been commercially developed. Best mechanical properties. Considerable flexibility in fibres and matrices. High quality matrix, very pure. Little fibre damage. In situ fibre surface trestment. Ability to fill small pores.	Slow and expensive. Requires iterative process. Never achieved full density. Capital intensive.	Nicalon Nextels	SiC HfC Nitrides Oxides Borides	800-1600°C 800-1800°C
b) Lanxide	Ability to produce complex shapes. Properties dominated by ceramic. Very pore grain boundaries. Systems include: AlN/Al, TiN/Ti, ZrN/Zr.	Slow reaction and growth kinetics. Long processing time & high temp. limits chemistry. Wetting and reaction are limitations	Graphite Nicalon	Alumina AlN TiN ZrN	800-1200°C 800-1200°C 800-1200°C 800-1200°C

[1] Temperature limit depends on fibre. Currently all systems are limited to ≈ 1200°C available fibres.

CONCLUSIONS

There are four recurring principles that will shape the future of advanced materials: systems solutions, economical manufacturing processing, diverse markets and new technologies.

Systems solutions

The industry must drive systems solutions for even the most down-to-earth markets. For maximum return, development of composite systems must be approached as an integrated process. Decisions regarding designs, processes and materials must be made synergistically to ensure peak product performance.

Economical manufacturing processes

For composite material systems to grow successfully in the next century, manufacturing process must be made more economical, productive and efficient. Efforts in this area are already under way.

Composite technology has now matured to the point where larger and more complex structures can be produced with predictable, reliable mechanical properties. The next logical step in the evolution of this technology is toward thin, complex sections with forming, joining and inspection all being carried out simultaneously [18]. This will demonstrate the potential of this technology to dramatically streamline and simplify the manufacture of complex composite structures.

Diverse markets

To obtain the best return on technology investment, systems solutions and more economical processes must be applied to new and diverse markets. There are many applications where existing technology might be successfully applied to commercial markets. It is foreseen that in the next two decades airframe and engine materials will change from monolithic, metal-base alloy to ceramic, both monolithic and composite.

New technologies

The final key to success for advanced materials will involve taking experience from both military and commercial applications and seeking out new technologies that are appropriate to the future of the industry. The challenge is to identify and focus on the right problems and opportunities that will facilitate a successful shift from basic science to functioning technologies.

The procedures for materials selection and bounding of composite properties using selection charts and merit indices provide powerful general tools for matching materials to the needs of a design. Implementation of the approach in software greatly facilitates these procedures. The methodology gives:

1. quick, visually straightforward methods of exploring the potential of a new material for a given application
2. vectors for the development of new materials to meet a specific design need.

To successfully drive all four principles – systems solutions, economical manufacturing processes, diverse markets and new technologies – active cooperation is need among industry, government and academia. It is a formidable challenge, but the stakes are enormous and well worth the effort.

The future provides the opportunity for growth to a new and healthier balance, with vibrant commercial sector delivering an improved quality of life and stronger technology base possessing the agility and responsiveness to support both commercial and national defence needs.

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