Chapter 1

Metal matrix composites

1.1 Generality

A material composite can be defined as a material consisting of two or more physically and chemically distinct parts, suitably arranged, having different properties respect to those of the each constituent parts.

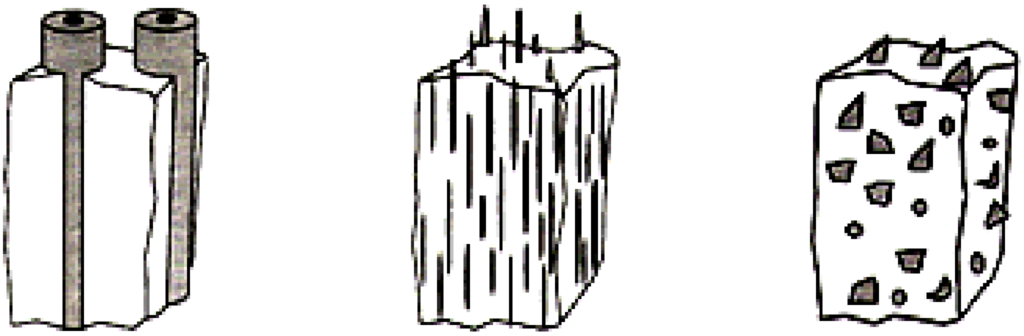
This is a very large family of materials whose purpose is to obtain certain property resulting by the combination of the two constituents (matrix and reinforcement), in order to to obtain the mechanical characteristics (and sometimes thermal) higher than that it is possible to have with their corresponding matrices. For this reason, about the wide range of new developed materials, composites are certainly those able to comply better the needs of most technologically advanced industries.

In a material composite, when the matrix is a metal or an its alloy, we have a "Metal Matrix Composite (MMC = Metal Matrix Composite). The performance of these materials, i.e. their characteristics in terms of physical and mechanical peculiarity, depend on the nature of the two components (chemical composition, crystalline structure, and in the case of reinforcement, shape and size), the volume fraction of the adopted reinforcement and production technology. In general we can say that metal matrix composites utilize at the same time the properties of the matrix (light weight, good thermal conductivity, ductility) and of the reinforcement, usually ceramic (high stiffness, high wear resistance, low coefficient of thermal expansion). By this way it is possible to obtain a material characterized, if compared to the basic metal component, by high values of specific strength, stiffness, wear resistance, fatigue resistance and creep, corrosion resistance in certain aggressive environments. However, cause to the presence of the ceramic component, ductility, toughness and fracture to the coefficients of thermal expansion and thermal conductivity decrease.

Generally MMCs are classified according to type of used reinforcement and the geometric characteristics of the same. In particular, the main classification groups these composites into two basic categories:

- continuous reinforcement composites, constituted by continuous fibers or filaments;
- discontinuous reinforced composites, containing short fibers, whiskers or particles.

The choice of reinforcement is related to the type of application, to the compatibility between the reinforcement and the matrix and to the interfacial resistance matrix/ reinforcement. As already mentioned, the ceramic reinforcement is usually in the form of oxides, carbides and nitrides, i.e. that elements with high strength and stiffness both at room temperature and at high temperatures. The common reinforcing elements are silicon carbide (SiC), alumina (Al_2O_3), titanium boride (TiB_2), boron and graphite. That particle type is the reinforcement most common and economical.



a) **b)** **c)**

Fig.1 Schematic illustration of the reinforcement type about MMC:
a) Long unidirectional fiber; b) Short fiber and whiskers; c) Particle

The continuous reinforcement composites have the possibility to incorporate a mix of properties in the chosen material as the matrix, as better wear resistance, lower coefficient of thermal expansion and higher thermal conductivity. The products are also characterized by high mechanical strength (especially fatigue strength) along the direction of reinforcement, so they are highly anisotropic.

Discontinuous reinforcement has a positive effect on properties as hardness, wear resistance, fatigue resistance, dimensional stability and compression resistance. This latter materials also show a significant increase in stiffness but to the disadvantage of ductility and fracture toughness. One of the biggest advantages of discontinuously reinforced composites is the possibility (especially in the case of reinforced aluminium alloy) to work with the usual techniques of rolling, extrusion and forging. The addition of the hard second phase however entails a fast tool wear, requiring sometimes diamond tools.

The matrix was considered for a long time simply a means to hold together the fibers or any other type of reinforcement: however this speech especially for a polymer matrix composite is effective. Over the years instead it has been increasingly clear that the microstructure of the matrix and consequently its mechanical properties, exerts a considerable influence on the overall composite performance. Among the most metal alloys used as a matrix in MMC, there are aluminium, titanium, magnesium and copper, with intermetallic compounds that are finding growing interest due to their excellent resistance at high temperature. The main combinations of MMC systems can be summarized as follows:

- Alluminium
  - Long fiber: boron, silicon carbide, alumina, graphite
  - Short fiber: alumina, alumina-silicon
  - Whiskers: silicon carbide
  - Particle: silicon carbide, boron carbide
- Magnesium
  - Long fiber: alumina, graphite
  - Whiskers: silicon carbide
  - Particle: silicon carbide, boron carbide
- Titanium
  - Long fiber: silicon carbide
  - Particle: titanium carbide
- Copper
  - Long fiber: silicon carbide, graphite
  - Particle: titanium carbide, silicon carbide, boron carbide
  - Filament: niobium – titanium
- Superaalloys
  - Filament: tungsten

Both reinforcement and matrix t are also selected on the basis of what will be the interface that unites them. In fact, cause to the fabrication and working conditions to which these materials are submitted, along the interface fiber/matrix special processes develop, capable in this zone of producing compounds and/or phases that can significantly influence the mechanical properties of the composite . This interface can be as a simple zone of chemical bonds (as the interface between the pure aluminium and alumina), but can also occur as a layer composed by reaction matrix/reinforcement products (type carbides produced between light alloy and carbon fibers) or as a real reinforcement coatings (for example, the C coating between SiC fibers and titanium matrix).

The mechanical and thermal MMC properties can be summarized by a quantitative way through the following table:

Density ρ	2,5 – 3,1 g/cm^3
Modulus of elasticity E	90-300 MPa
Specific resistance E/ρ	30-60
Tensile Strength, Ultimate σ_r	300-700 MPa
Thermal conductivity C	120-200 W/mK
C.T.E.	7-20 µm/K

Tab.1 Main mechanical properties for MMCs

In particular, note the fact that the E/ρ value for conventional metals usually is not more than 25.

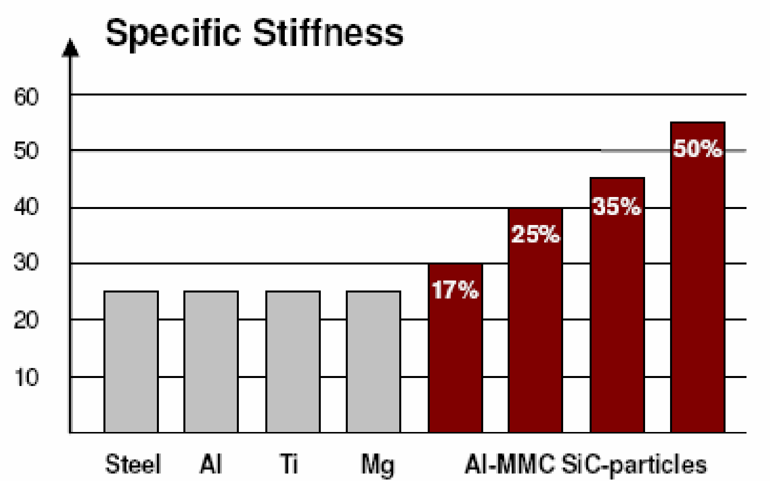


Fig.2 Graphic comparison of the specific stiffness (E/ρ) of conventional metal and MMC

About the possible disadvantages for the MMC production and application , these are based, comparing it to metals and polymer matrix composites, mainly on the following points:

- Expensive production system
- Technology still comparatively immature
- Complexity about the production processes (especially about the long fiber MMC)
- Limited experience of services dedicated to production

By this observation it is clear as major problems for the application of this technology are mainly related to the fact that, despite the first studies date back to the fifties, is still in the early development stages about many ways.

1.2 Production technologies

Fabrication processes result fundamental about the MMCs, to determinate their mechanical and phisical properties.

Since the technology that concerns them is relatively young, the various manufacturing processes, especially as regards their history, are often customized by individual manufacturers to suit the specific necessity.
In general the most common manufacturing MMC technologies are divided primarily into two main part: the primary and the secondary, sometimes following from the “pre-processing” phases. About this latter, they are all steps which precede primary processing (surface treatment of ingredient materials, or preform fabrication for infiltration processing).

The primary processing is the composite production by combining ingredient materials (powdered metal and loose ceramic particles, or molten metal and fibre preforms), but not necessarily to final shape or final microstructure.

The secondary processing instead is the step which obviously follows primary processing, and its aim is to alter the shape or microstructure of the material (shape casting, forging, extrusion, heat-treatment, machining). Secondary processing may change the constituents (phases, shape) of the composite.

The choice of production processes, both primary and secondary, is very much determined by the type of reinforcement and the matrix, their mechanical and thermal properties, the shape, length and fibers packing from them than the matrix. Is essential to know the chemical properties of the constituents to analyze the possible evolution of kinetic and thermodynamic processes of reaction that could be to establish the interface fiber / matrix, especially if the compound is subjected to temperatures average -high.

A basic classification, about the technological methods for MMCs, take account of the state where the constituents during the primary cycle of production:

- Solid state processing
- Liquid metal processing

- Vapor state processing
- Plasma/spray deposition
- "In situ" processing

A schematic overview of the situation is well represented in Fig.3.

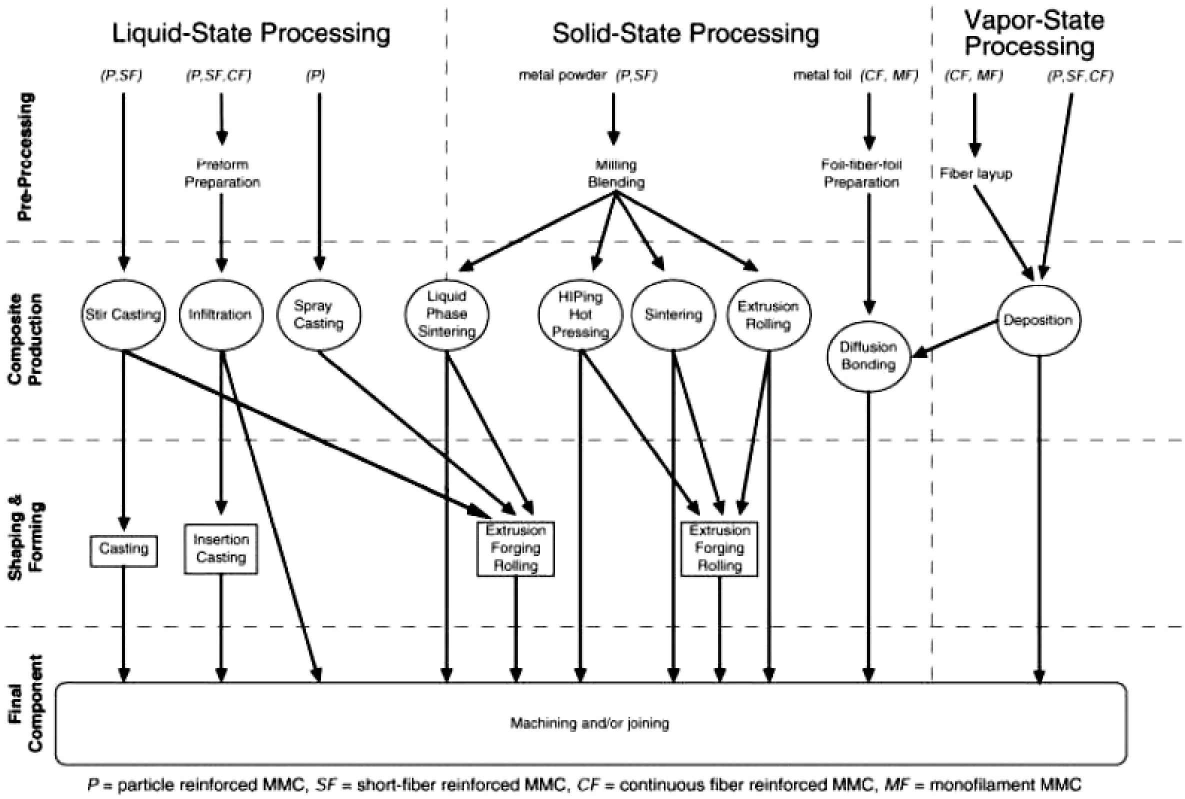


Fig.3 Schematic overview of the production processes about MMCs

1.2.1 Solid state processing

About the solid state production reinforcement is embedded in the matrix through diffusion phenomena produced at high pressures and high temperatures. In this case it appears crucial monitoring of the diffusion phenomena to avoid the growth of undesirable phases or compounds species on interfaces. That is why the various steps of processing are usually preceded by a "pre-processing" having the purpose of preparing the surfaces before they are subject to the concerned bonds. Moreover about the primary process a method is that to reduce the time of this diffusions for example carrying out extrusion of a sandwich fiber/matrix. In these cases a hot-rolling can be also used, but the matrix deformation should be limited to minimize the reinforcement movement and thus the formation of voids. The high temperatures are used to facilitate the flow of reinforcement in the matrix, but the risk of harmful chemical attack must be considered on the fibers, for which generally solid state processes should be made in a vacuum or inert atmosphere.

Diffusion bonding

The technique of diffusion forming, particularly for the typical composite fiber long, consists of mechanical application of pressure and high temperature causing processes that would bind tightly matrix and fiber.

One of these techniques is such that the “foil-fiber-foil” where alternating sheets of reinforcement (usually a long fiber) and matrix are stacked one over the other, and then be united together. The consolidation of the foil together and with the fiber, with the penetration of the metal among the interlacing of these, happens through a process of sintering, which is implemented by the two main phenomena.

The first phenomenon is the creation of the matrix sheets deformation due to the mechanism of viscous or plastic flow at high temperature (creep), responsible for the penetration among the layers of fibers and their winding. Another phenomenon that completes the production is the a jointing mechanism that occurs at the interfaces when the layers come in contact.

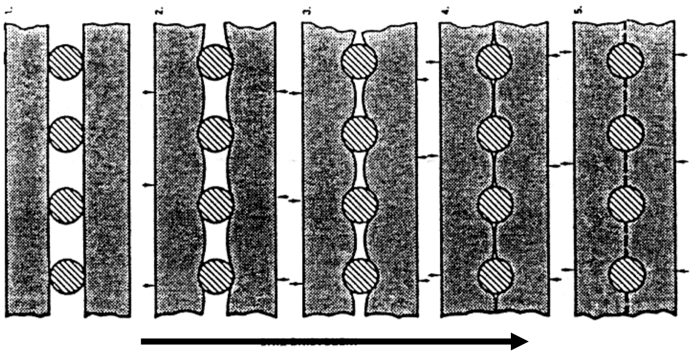


Fig.4 Diffusion bonding process and the consolidation steps Foil/Fiber/Foil

One of the biggest problems concerning the management and ordering fibers about the preparation of intermediate layers of reinforcement between the matrix foil is the control of their mutual position and maintaining this until the end of consolidation. The fibers, lined the next one another, can be consolidated using different methodologies, in order to compose the layers of reinforcement. One of these is, for example, to prepare an enveloping layer of reinforcement fibers on a cylinder so as to control the spacing. Here the fibers are fixed in their position through the deposition of a temporary polymeric binder, as polyester, which is removed successively by vacuum degassing or during consolidation.

However many problems occur during consolidation: not vaporized binder inclusion may be remained in the final microstructure, and occurrence of contamination phenomena with a upsetting into fibers.

The use of polymer binder can be avoided by wire or strips arranged across the fibers. Logically, the wires used to weave the fiber cross must be so small as to allow the desired spacing between the fibers, but at the same time strong enough to be able to endure the stresses that replaced during the fibers "texture". All these difficulties and these parameters construction that must be observed limit the range of choice and availability for suitable wires, so that the best results have been obtained with pure titanium wires, certainly not easy to find or manufacture.

An alternative procedure to produce the composite tape is to spray the matrix directly on fibers using plasma, when they are on the cylinder fasteners. This avoids the use of polymer binders and composite sheets are ready for the step of junction and compaction (Fig. 5).

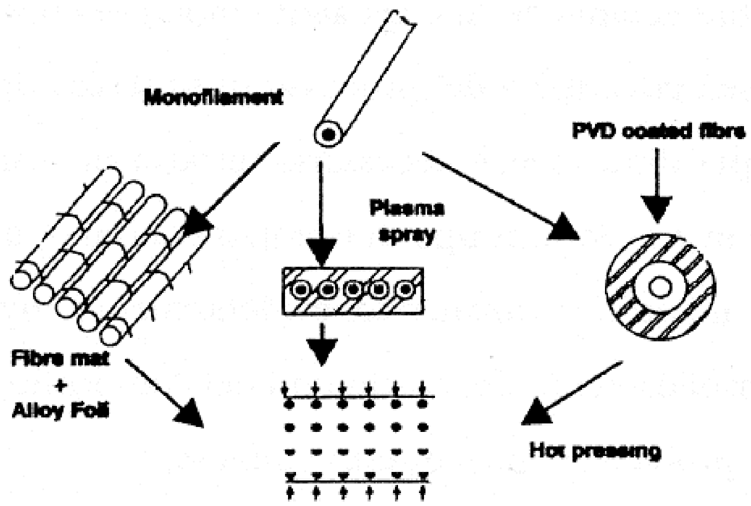


Fig.5 Main processes of fibers arrangement

Diffusion forming is really a very good method to produce composite with high mechanical properties. The problem is that these processes require high intensity of energy (high pressures and high temperatures). It appears one of the most technological processes used about MMCs, due to the possibility to produce composite for high-strength applications in the medium/high temperatures.

Powder metallurgy

The powder metallurgy is one of the methods used in the production of metal matrix composites. An explanation for its remarkable expansion is due to the fact that this technique was designed, developed and applied about traditional metallurgy and than adapted to the case of metal-matrix composites. In particular Fig.6 is illustrated in the fundamental steps for MMCs for this production technique.

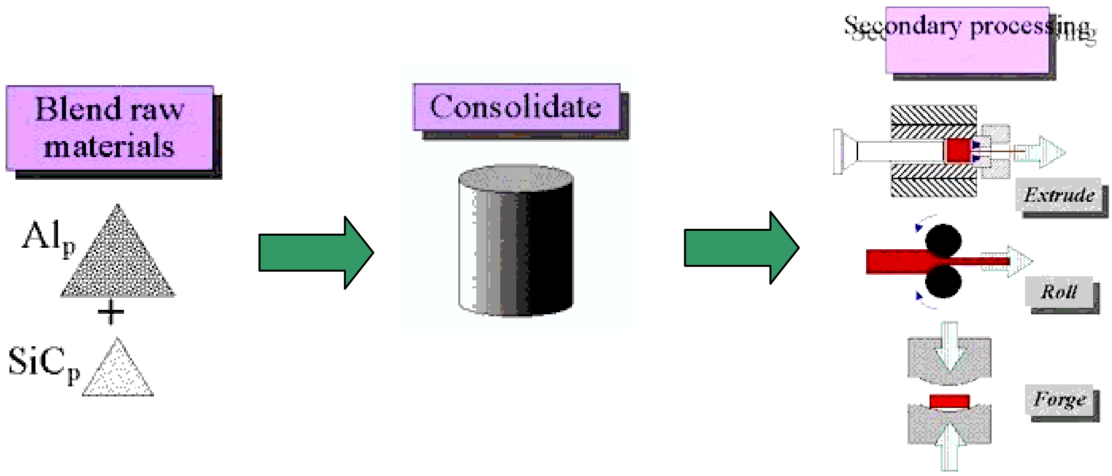


Fig.6 Illustration of key steps in a process of production through MMC powder metallurgy

The primary processes of a “powder metallurgy” process generally consist of three phases, which, starting from the raw materials, leading up to the final product. The first phase regards the preparation of the powder that will be constituents of the mixture to be processed in the successive stages. In particular, the powdered metal that will be responsible for the formation of metal matrix is derived directly by the elements which form the alloy matrix and then measured according to the composition of this. One of the most popular methods for the implementation of this phase is the “gas atomization”, in which a metal liquid vein is directly hit by a gas jet at high pressure that splintered it in small spherical drops not bigger than 300 μm. Thus the powders formed are spherical morphology, that gives good slider and packaging.

In the second phase prepared powders are mixed together with reinforcements ceramic particles and then compacted in the required forms (phase blending/milling). About the “blending” part, this is a pure and simple operation of mixing between the dry powder of atomised alloy matrix and the powder of the ceramic phase (both types of particle reinforcements that whiskers ca be used), allowing effective control in reinforcing the content of the whole mixture. However in this case obtaining an uniform mixture during the mixing is difficult, especially with the whiskers, which tend to get entangled in clusters hardly refillable by the matrix particles. For the formation of these agglomerations, another important factor is also the relative size of the particles. In particular, in some applications, to cope with this problem, “sponge fines” is developed the technique, which leads to obtain particles of about 100 μm with spongy structure, allowing to reinforcing fillers to wedge oneself into the matri. By contrast, the spongy particles have both a low flow capacity and a low-density compaction, due to their morphology.

The “milling” are however the processes by which powders are amalgamated order to obtain a homogeneous distribution of constituents. The most common is the “mechanical milling” in which a crushing machine by high energy impact generates a high heating by friction, causing in the particle interfaces local micro-fusions that may facilitate the next phase sintering. Despite the process effectiveness it is important to put some attention about the possibility of contamination of equipment for grinding, hammers and containers, as well as the presence of reactive gas, that however also eliminated by the use of an inert atmosphere.

The third phase is the process of consolidation, during which the powders of the worked mixture are welded together by sintering to form the final product. During this process compression is conducted at a temperature as high as possible in order to bring the matrix in its most malleable state, through establishing the conditions of movement of dislocations, but without causing the presence of liquid phase, which would adversely affect the mechanical properties of the product, cause to segregation on grain and the formation of harmful intermetallic compounds. Nevertheless a small amount of liquid metal allows a pressure reduction required to complete the consolidation, i.e. without the porosity of the powder mixture. Moreover the presence of not deformable ceramics inclusions helps to decrease the needed time for the initial consolidation, because with their jagged and sharp edges, cause at first time an increase of local tensions in the matrix. However, clusters of ceramic particles can oppose a significant resistance during the completation of the process.

More effective methods of compaction may be rolling, where high pressures are given in the mill, both hot (with temperatures above the recrystallization of the matrix) and cold (with temperatures below the same). With the same temperature limit other both hot and cold compaction processes can be taken, regarding extrusion and forging.

Completed the consolidation phase, usually discontinuously reinforced composites, additional deformation processes are added to improve microstructure and thus the mechanical properties. Then some modelling and secondary processing are applied as stamping, rolling an extrusion . For example, the extrusion is commonly used to generate a sufficient amount of shear deformation inside material and to create new grain boards and stronger interfaces. To improve the process cheapness the possibility of combining the extrusion process with the consolidation is assessed ("co-extrusion") In practice this has happened hot consolidating the cylinder filled with powder mixture using a press extrusion similar to that for the compression at high temperature and then replacing it with a die for the extrusion, to make it. Finally the porosities, if they exist, are subject to a complete removal thanks to shear flowing and hydrostatic compression present during the extrusion process.

All these techniques help to align the reinforcing phase and therefore a logical loss of the component disorder.

1.2.2 Liquid metal processing

Many times it is better to have the matrix in liquid form so as to facilitate the flow of filling the interstices and to cover completely the fibers, whatever form they may be. That's the reason because the foundry is one of the techniques more used and less expensive to produce metal matrix composites. In such a situation, using a molten bath, production can be increased considerably: it is not coincidence that it is widely used by industry to produce semi-finished products and for this there are several solutions.

Generally in this case technologies are divided between those that provide for the incorporation of ceramic reinforcement into the liquid metal, and that where the cast is infiltrated into a pre-forms of the same reinforcement. The most common are shown below.

Hot forming

This is a production technique based on the diffusion forming a low pressure, used in manufacturing processes long fiber MMC, which the alloy of the matrix is partially in molten form (i.e. at a temperature between the solidus and liquidus of the considered particular alloy). This approach is adopted when the reaction between the fiber and the matrix is not a problem. Otherwise the fiber must be covered with a layer of material should be able to act as a barrier for the diffusion phenomena (such as silicon carbide or boron).

Hot forming has the great advantage of being able to manufacture large components at low pressure, ensuring the high property typical of the forming process but high pressure.

Liquid infiltration

Used especially for long-fiber composites, this production technique provides ceramic filaments arranged in the files and mats form in a pre-forms, in which infiltration of liquid metal occurs, using either gravity, vacuum or pressure. (Fig.7).

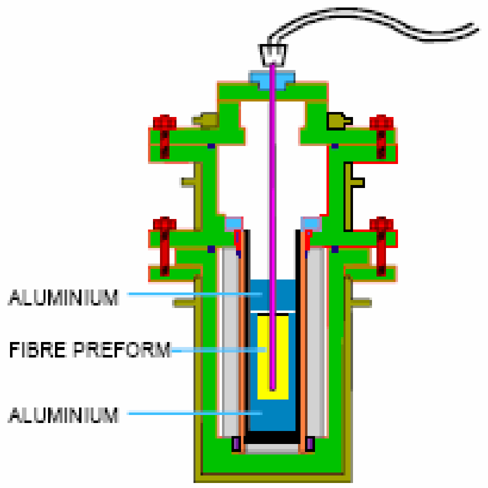


Fig.7 Infiltration of Preforms of Continuous Fibres

A similar technique combines the liquid infiltration to the hot forming. In particular, the infiltration is aided by the coating of fiber (usually obtained by means of vapour deposition) that promotes the wettability of the same.

At this point, the covered reinforcement passes in the molten metal bath from by that comes out a composite wire that does not usually reach 0.5 cm. These wires are arranged to form sheets or rods to be formed by diffusion with non-reinforced matrix coatings.

LPF (Liquid Pressure Forming)

This is a implementation process of composites in which a semi-workpiece of fibers is placed inside the shell in which also the molten metal matrix will be placed. Once realized the vacuum and a rapid cooling, you get pieces in particle and whiskers with homogeneous distribution.

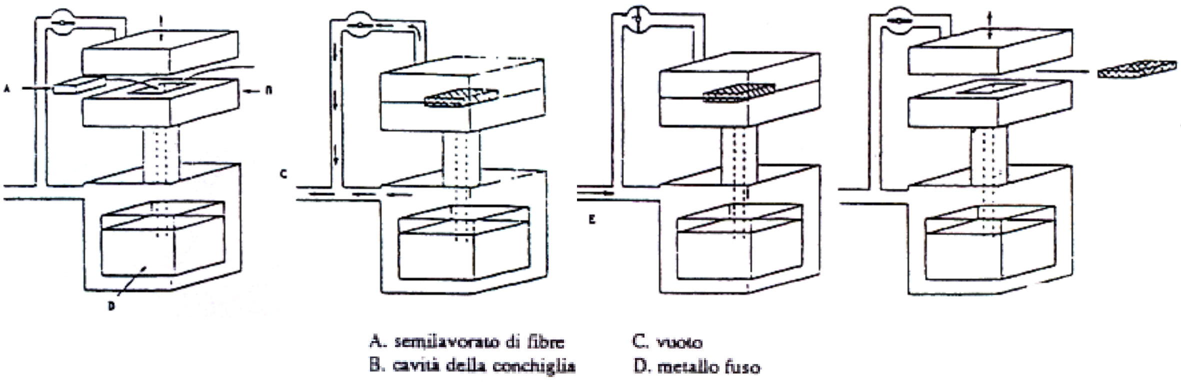


Fig.8 LPF (Liquid Pressure Forming) process

Squeez casting

Squeeze casting is a popular technique especially for the fabrication of aluminium based composites. It is a unidirectional pressure infiltration (pressure is typically between 70 and 150 MPa).

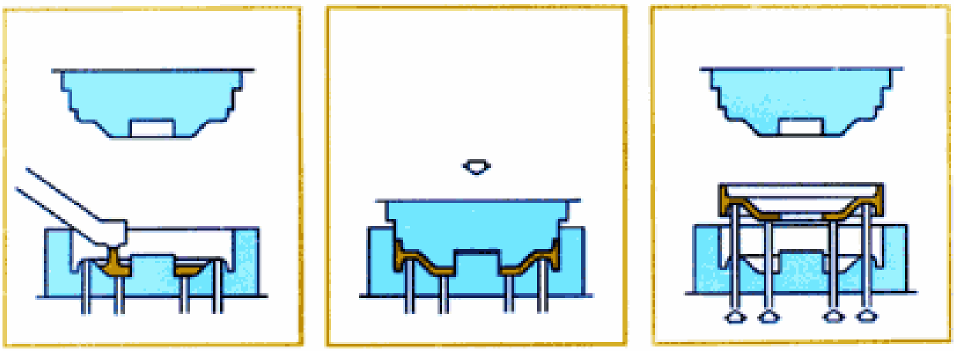


Fig.9 Squeez Casting technology about the MMCs

The process consists of casting the liquid metal into a preheated and oiled die and forged it while it solidifies. The pressure is applied as soon as the metal begins to solidify and is maintained until its complete solidification. The high pressure is applied with immediate contact with the metal surface of the die, causing a rapid transfer of heat that leads to a casting characterized by fine-grained crystalline, no internal porosity and mechanical properties that are similar to those of articles made by plastic deformation. The integrity of the obtained casting, virtually free of porosity, allows the possibility to work on them a heat treatment, which is impossible with the pressure die castings.

It is generally used for discontinuously reinforced composites, which are in the form of pre-forms before being submitted at the processing (in particular the whiskers seems the most used in this case). In this case a porous ceramic material “pre-forms”, properly placed in die, it is infiltrated with liquid metal. The pressure has also meant to help the liquid metal to infiltrate into the ceramic pre-forms. The reinforcement can also be located in order to selectively enforce the component. The process is easily automated, allowing the realization of high quality components and minimize machining, that results particularly advantageous in the case of components made of composite materials.

The basic parameters of such a process are the infiltration speed (which is mainly caused by applied pressure), the capillary, the space between particles of reinforcement, the viscosity of the liquid metal, the permeability of pre-forms, the die temperature, the pre-forms and the cast.

The final components are void free and have a small equiaxed grain size microstructure. It is a fast process with a good surface finish and may be used for selective reinforcement. It is most common to use performs (exceptionally premix or pellets are used). The infiltration rate depends upon the applied pressure, the capillarity, the spacing between the dispersed particles (whiskers), the viscosity of the liquid metal, the pre-form permeability, the temperature of the die, pre-form and melt.

Stir Casting

This is a primary process of composite production whereby the reinforcement ingredient is incorporated into the molten metal by stirring.

A variant very applied of the StirCasting is called "Compocasting" (or "Rheocasting), in which the metal is semi-solid. In particular the reinforcing ingredient are incorporated into vigorously agitated partially solid metal slurries. The discontinuous ceramic phase is mechanically entrapped between the pro-eutectic phase present in the alloy, which is held between its liquidus and solidus temperatures. This semi solid process allows near net shape fabrication since deformation resistance is considerably reduced due to the semi-fused state of the composite slurry.

The technologies just displayed are the most common and widespread, but there are many variations, mostly applied depending on the specific case and based on the particular application which will face the piece in producing. Techniques is adopted such as processes involving infiltration by centrifuge, ultrasound and magnetic electromagnetic even having all the essential purpose of obtaining a composite reinforced by the distribution of more homogeneous as possible.

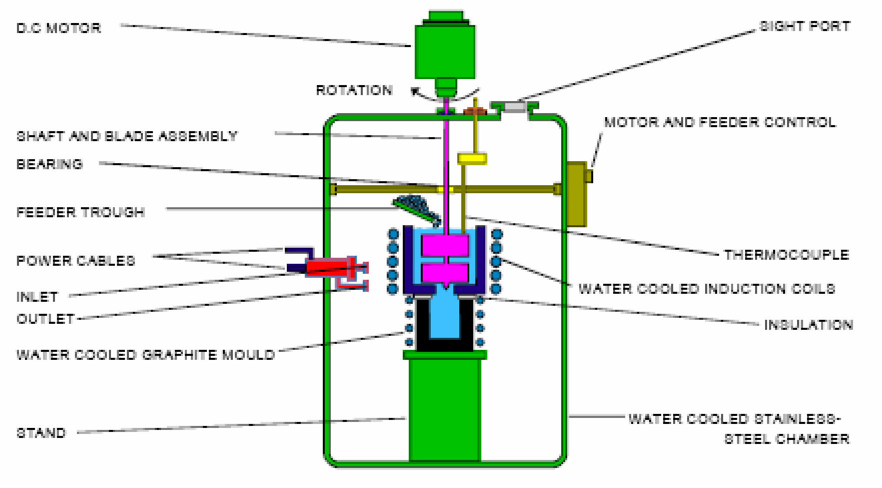


Fig.10 Compo-casting technology

1.2.3 Vapor state processing

This type of process includes the methods by which composites are formed by deposition on the reinforcement of successive layers of matrix.

A major incentive to the use of tihs techniques has been given by the need to achieve large adhesion on the fiber/matrix interface without generating reactions among themselves that they can degrade the final composite properties. In particular, the PVD (Physical Vapor Deposition) technique is used about the formation of the external fiber coatings whose purpose is to consolidate them than the matrix.

Phisycal Vapour Deposition (PVD)

Many PVD processes used to produce MMC, all generally very slow (the typical deposition are of 5-10 mm/min). There is a continuous passage of fibers through a region in which the metal must be deposited at a vapor pressure of relatively high and where the condensation successes in order to produce a thin coating on the fibers. The vapour production occurs directing high-energy electrons flow on the end of a feeding solid bar.

The advantage of this technique is that you can use different alloys, and the change of evaporation rate are controlled by varying of the molten bath composition. Another interesting point is that there is little or not mechanical disturbance, and this is useful when the fibers have a protective film for the diffusion, or when they have a chemical surface that would be ruined, however, by impact of drops in the case of plasma spray.

In general, the composite production continues putting coated fibers into a covering and consolidating by HIP. This will produce uniform distributions of fibers with a 80%, and the volume fraction can be controlled accurately by helping the coating thickness.

PVD processes can be divided into two main categories:

- Vaporization and deposition Techniques using electron beam (EBED)
- “Sputtering” techniques

The first requires the use of a gun which produces the high energy electron beam (EB), which vaporizes the material matrix and produces the metal vapour to condense on the fibers. The evaporation rate depends on the beam power (usually 10 kW), on the reached temperature and on the vapor pressure. In theory, the coating should have the same chemical composition of the material source used for evaporation. An EBED advantages is the high speed coating of the substrate (300 to 600 mm/h), but about the metal use efficiency, for example, the percentage of evaporated metal that is collected on the fiber, is low (~ 10%).

By the “sputtering” techniques instead a piece of coating is bombarded with ions of a processing gas (such as Argon), which breaks off atoms from the workpiece, sketching on the fiber. It is a very slow process, even if virtually it has the peculiarity of being applicable to any material, including those with very low vapour pressures. This technique can produce coating of very little thick and it can be used to introduce during the evaporation EBED processes small quantities of elements with low vapour pressure.

1.2.4 Plasma/spray deposition processing

The methods spraying of manufacturing are based on the generation of a mixture of metal matrix droplets with ceramic particle, which are then sprayed on a removable substrate. The advantages of such process are mainly about the rapid solidification of the matrix, which involves the addition of a reinforcing phase and a reduction in reaction time between reinforcement and matrix. Moreover, the step of mixing and degassing processes typical of powder metallurgy are virtually gone out. The disadvantages may include the formation of residual porosity (at least a small percentage of the composite volume) and high cost of the used inert gas, as well as a substantial waste of material during the deposition.

Spray Forming Process

In the forming process by spraying drops of molten metal is sprayed with particles of reinforcing phase and collected on an underlying support on which the composite is made solidify. Alternatively, directly the reinforcement can placed on a collection chamber and spraying on the molten metal. The spraying technique (especially plasma) is used mainly for the production of composite tapes reinforced with a layer of continuous fibers, which are then usually processed through the HIP process for obtaining a composite of some consistency.

Critical parameters in the spray forming process are the initial temperature, the distribution of droplet size in the spray and their speed, temperature, speed and feed rate of reinforcement (if injected simultaneously) and the location, nature and the temperature of the collection chamber.

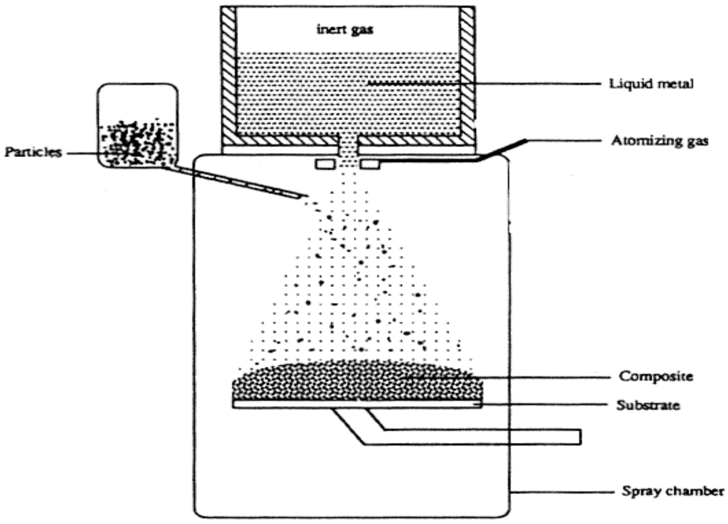


Fig.11 Spray Forming technology for MMCs

Low pressure plasma deposition (LPF)

Alloy powder and reinforcement are fed into a low pressure plasma. In the plasma, the matrix is heated above its melting point and accelerated by fast moving plasma gasses. These droplets are then projected on a substrate, together with the reinforcement particles.

The latter particles remain solid during the whole process if one use lower power settings or may be partially or fully melted when higher power settings are used. By a gradual change of the feeding powder composition, gradient materials can easily be produced.

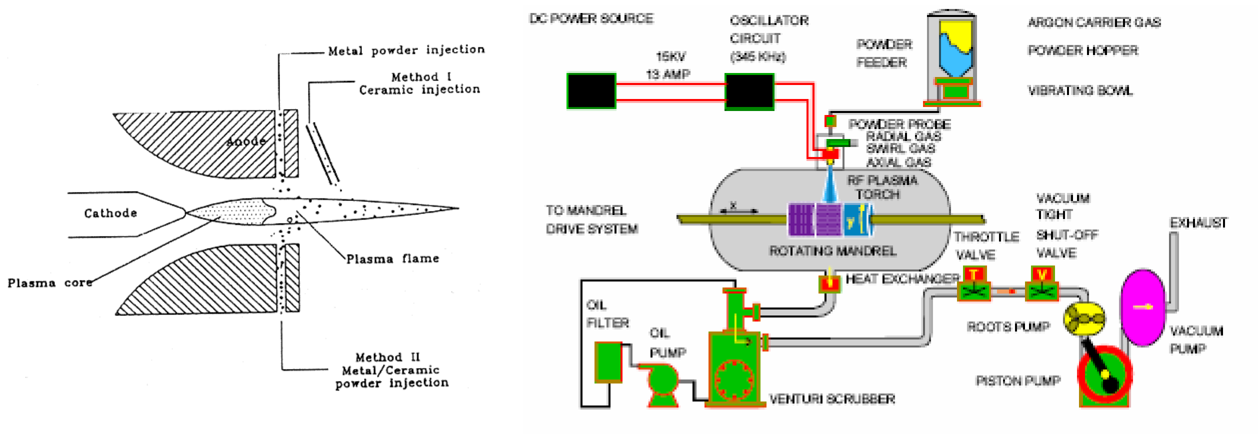


Fig.12 Plasma Spray Facility for the production of particle composites

Eletric Spray Arc Forming

In this case is generated by an electric arc by the use of a potential difference between two filaments consisting of metal matrix composite. Then the tips of the wires melted continuously and are atomized by the one or more inert gas jets, and is then directed to a ceramic fiber pre-forms. Alternatively, for discontinuously reinforced composites, about the metal atomization ceramic particles are released that are deposited with alloy drops of on the collection plate.

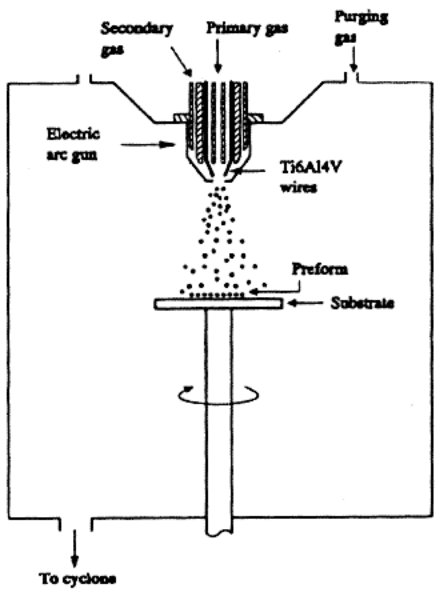


Fig.13 Base functioning about Eletric Arc Spray Forming

Generally argon is used as gas atomization and is also used as a gas purification of the room to protect the composite tapes by oxidation during the process. The chamber forming spray is sterilized beforehand with argon, after being calibrated to the relative positions of metal wire and two gas flows in the direction of the collector.

1.2.5 "In situ" production

The in situ production route of metal matrix composites is highly interesting because it avoids the need for intermediate formation of the reinforcement. Indeed, in this process the reinforcements are formed by reaction in situ in the metal matrix in a single step. A further advantage is that the interfaces between the reinforcement and the matrix are very clean, enabling better wetting and bonding between them and the matrix (no gas adsorption, no oxidation, no other detrimental interface reactions).
Also costs are reduced, as the handling of the fine particle reinforcement phases are eliminated.

Ingot Metallurgy (IM)

This production technique consists of two consequential steps: the first consists of a dispersion process, during which the element that forms the reinforcement ceramic is incorporated, at random and not in default, in the molten metal matrix. Usually the system is mixed to facilitate the dispersion of particles.

The second step consists of a conventional casting process of liquid enriched with reinforcement, derived from the aforesaid first step. The cast produced by this way is then usually subjected to mechanical processing.

This system is now less expensive to produce in situ composites with titanium matrix and generally discontinuously reinforced MMCs, leading, among other things, to produce a wealth of different materials.

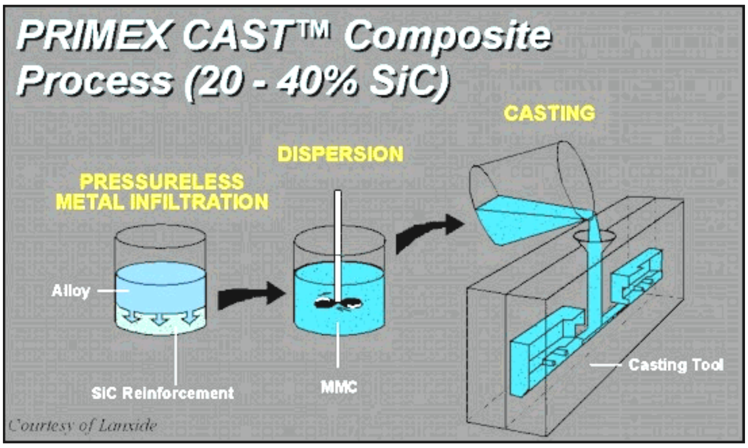


Fig.14 IM (Ingot Metallurgy) Technology

Synthesis by chemical reaction

In the case of composites obtained by in situ reaction between a liquid and other phases, as a gas or solid, the basic mechanisms are the same chemical reaction. To fully understand these mechanisms is necessary to identify the possible chemical reactions that may take place and evaluate them in thermodynamic and kinetic terms. These are a function of temperature and alloy, the compositions and concentrations of gas or solid, as well as the mechanisms of diffusion through the reaction layers. By the production in situ techniques that provide a chemical reaction, are obtained within the matrix metal, ceramic reinforcing phases very fine and stable in thermodynamic terms.

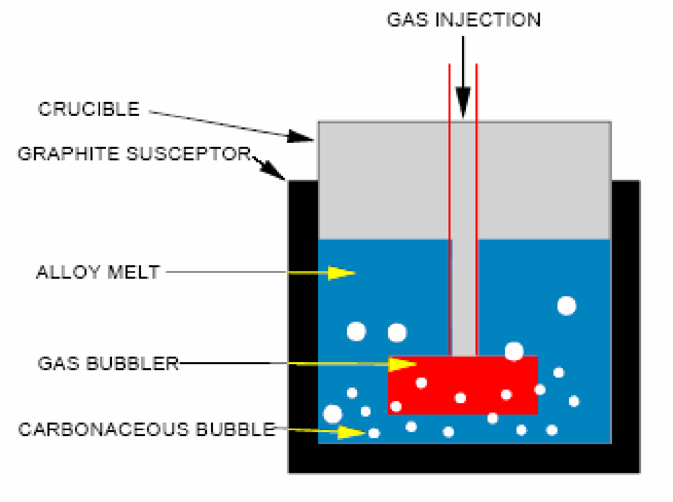


Fig.15 Technology of synthesis by chemical reaction

One of the most important production technologies that are based on the principle of synthesis through chemical reactions regard the process for “exothermic dispersion” (XD).

The process, patented by Martin Marietta Corporation, provides high temperatures heating of various mixtures so as to activate an exothermic reaction, that diffuse by independent and very fast way, allowing to create very fine dispersion of some pottery stable phases. In particular, mixtures of metal and ceramic powders are heated to a temperature of reaction (that is usually above the melting point of the considered metal) so as to generate a new ceramic phase into the matrix metal form.

1.3 Industrial applications

Considered experimental materials, metal matrix composites are a good alternative to traditional materials, due to their hardness, specific strength and creep resistance. Despite this interest, they regards still niche applications, about the industrial world, cause to their cost does not allow a wider use. Major applications are in the aerospace and aeronautical field, where the material costs are not so limited and where it is researched continuous improvement about the specific performance. The fact remains that an ever greater interest are taking MMC applications regarding the automotive areas, with particular attention to the fields of engine and brake systems. The special properties of these materials, particularly their ability to change them depending on the technology adoption process, has enlarged its application field to other interesting areas as sports (where duration and resistance are required during performance of mechanical components) to ultimately get to the electronic applications, where the thermal properties and the right value of C.T.E. are essential.

1.3.1 Aeronautics

Initially (in the early 70's) the attention was focused on increasing the creep resistance of the rotor blades through the reinforcement of aluminium alloys by boron fibers, but the tolerance to the presence of foreign objects was low. Recently, interest has shifted to asymmetric components for aircraft engines, many of which are ideally equipped with unidirectional high-performance, properties that are especially exploited in titanium matrix composites.

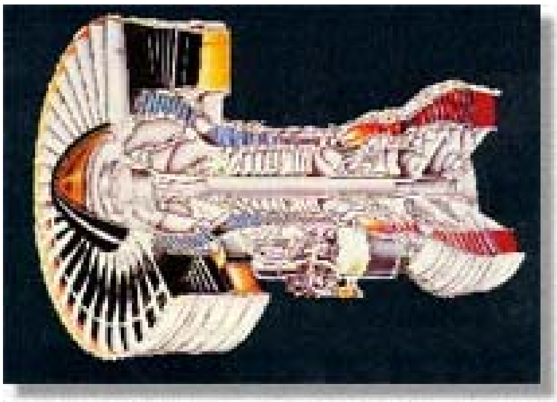


Fig.16 Aircraft engine about that MMC can be used

In fact in a conventional aircraft engine, most of the weight depends on the anchorages and mechanical fasteners, which are supported independently, and are in contact with the flow through the engine.

The main problems are the technical and economic development, the means of production and to determine the properties and microstructural degradation (for example, a procedure is necessary to coverage fibers and to get the right interfacial resistance during the work condition). Nevertheless the fact that an investment of this type is justified by high contribution margins of by product exclusivity.

Interesting applications was also concerned the helicopter sector, particularly in Fig.17 has shown an attack blades- engine in MMC 2009/SiC, in which the composite replaces the Ti6Al4V alloy.

The desire of structures characterized by high precision and high dimensional stability, for elements to be sent to space, has led the MMC development, even if their application has been limited by the difficulty of producing more than their cost, as for space budgets are less restrictive.

Fig.17 Blades-engine connection in MMC 2009/SiC for the EUROCOPTER

During 2003, SP Aerospace (from Geldrop, The Netherlands) accomplished the world's first flight of a primary structural landing gear component in MMC. A Lower Drag Brace for the F16 main landing gear was developed in Titanium Matrix Composite, consisting of monofilament SiC fibres in a Ti matrix. The Royal Netherlands Air Force (RNLAF) provided full support and flight clearance for the test flight on their F16 "Orange" test aircraft.

Fig.18 Particular brace constituted by MMC

The first successful application of MMC reinforced with continuous fibers was a tubular structure made of aluminium/boron used about the support structure in the central part of the Space Shuttle Orbiter (about 1975). Thanks to the implementation of these tubes of aluminium/boron it has been possible to achieved a saving in weight of about 145 kg or a saving of 44% respect to the same aluminium structure.

Another MMC application as Aluminium/Carbon was the “driving” antenna for the Hubble Space Telescope, made with long carbon fiber P100 in Al6061 matrix (Fig.13). This “guide”(3.6 m long), provides high axial stiffness and low thermal deformation in order to maintain the correct position during the working in space.

In addition the structure with square tubular section provides the waveguide function by excellent electrical conductivity and it facilitates the transmission between the antenna and the ship. Thanks to the MMC use has saved around 30% of weight in comparison to a prior draft it in aluminium and carbon/epoxy composite. Moreover, the presence of metal matrix provides a greater resistance to chemical degradation under the radiation effect present in space.

Fig.19 Hubble telescope: guide antenna in P100/Al6061

1.3.2 Automotive

By lower production costs and by the attraction about savings in weight the MMC application has increased more and more about the car field and not only about the competition. This is due to the major properties at high working temperature, that have made the material composite an interesting alternative to traditional materials. In fact there is an increasingly important MMC presence about engines (engine block and pistons), drive shaft and disc brakes (including rail type). For example for the brake systems, the MMC application concerns especially the discs that are produced by aluminium matrix reinforced by SiC particle.

For this reason, in October 1991, Ford and Toyota decided to adopt disks made by Al-80%, SiC-20%. The choice of a 20% SiC was made to combine a good surface resistance (increased by SiC) with a thermal and mechanical stability during the work. The matrix is also aged to prevent the property degradations during use. After that use other manufacturers have adopted these material types, companies as: Volkswaghen, Toyota with the RAV4EV, the Plymouth Prowler, GM EV-1, Precept, Impact, Ford Prodigy, Lotus with Elise.

Fig.20 Piston, pads and disk brakes realized by MMC

In Fig.21 is showed also a component of the brake plane of the Copenhagen Metro, constituted by the MMC A359/SiC, by that a gain in weight by 38% has been achieved in comparison to the previous cast iron.

About the motor applications, interesting results have been achieved about the drive shafts, especially as regards the increase in stiffness, with a consequent increase about the maximum attainable rotation (typical material: Al6661/Al_2O_3).

Fig.21 Components of a brake plant about the rail field

The MMC application about pistons is one of the biggest successes in the industrial field of these materials, too. The production of these pistons began in Japan a few years ago from a few units to become a production of a million pieces at one year. In 1983, Toyota Motor Co. introduced a 5% of Al_2O_3 short fibers into the area of the piston-ring, reducing the weight of a 5-10%. With this system the coating thickness has successfully reduced of four times and to get an increase about the creep resistance, compared to not reinforced aluminium.

Another factor is the thermal fatigue life, which is limited by the rupture between the ring and the same piston itself, and by its dimensional instability. Moreover piston made by Al/SiC_p are developing, too

1.3.3 Electronics

New generation advanced integrated circuits are generating more heat then previous types. Therefore, the dissipation of heat becomes a major concern. Indeed, thermal fatigue may occur due to a small mismatch of the coefficient of thermal expansion between the silicon substrate and the heat sink (normally molybdenum). This problem can be solved by using MMCs with exactly matching coefficients (e.g. Al with boron or graphite fibres and Al with SiC particles).

Besides a low coefficient of thermal expansion and a high thermal conductivity, these Al-based MMCs also have a low density and a high elastic modulus. Hermetic package materials are developed to protect electronic circuits from moisture and other environmental hazards. These packages have often glass-to-metal seals. Therefore, materials with an "adjustable" coefficient of thermal expansion are required. Al-based

MMCs are fulfilling this condition, as the coefficient of thermal expansion is depending upon the volume fraction of the fibres or particles.

These components are not only significantly lighter than those produced from previous metal alloys, but they provide significant cost savings through net-shape manufacturing.

MMC is also used for thermal management of spacecraft power semiconductor modules in geosynchronous earth-orbit communication satellites, displacing Cu/W alloys with a much higher density and lower thermal conductivity, while generating a weight savings of more than 80%. These modules are also used in a number of land-based systems, which accounts for an annual production near one million piece-parts. With these demonstrated benefits, application of MMCs for electronic packages will continue to flourish for space applications.

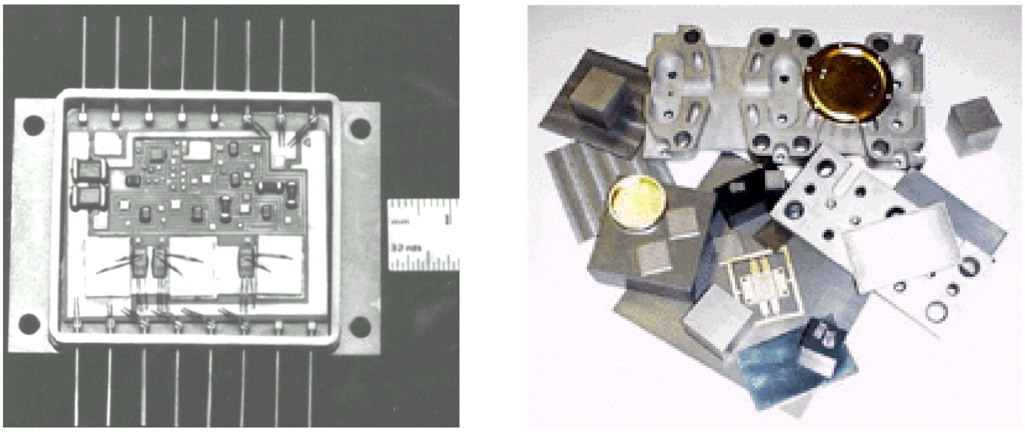


Fig.22 Discontinuously reinforced aluminum MMCs for electronic packaging applications: electronic package for a remote power controller

1.4 Manufacturing

The manufacturing operations of the third level performed on an MMC (for instance, those relating to the cutting and welding operation) are a very refined and important, cause to the particular material shape, making it highly abrasive to the tool during chip machining, and difficult to weld, cause to the not homogeneity in the welded area.

The cutting operations (conventional cutting, turning, milling and grinding) are commonly applied to MMC, but often the problem regards the tool coating.

In general, many problems become significant with the increase in the reinforcement percentage and its greatness, as tool goes to meet the harder material, producing more stress on the same tool.

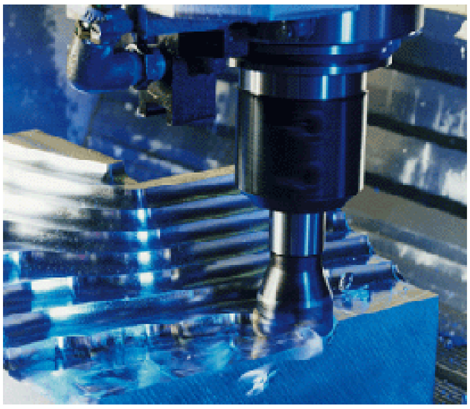
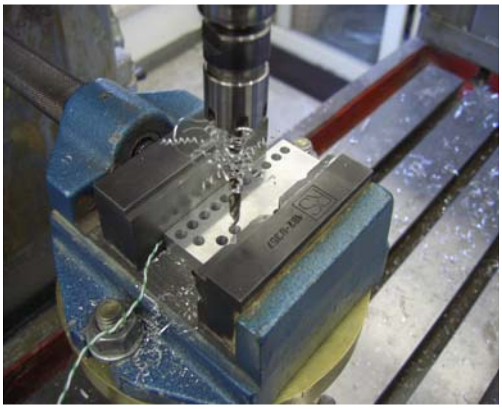



Fig.23 Classical cutting operations (milling and drilling) for MMC

To work MMC reinforced with long fibers diamond coating tool are required. while to work a short-fiber or particle composites tungsten carbide or super-rapid steel protections are exploited. For most of the MMC the best results were obtained with sharp tools, by appropriate and high cutting speed, high presence of liquid refrigerant.

Especially the cutting speed is a key parameter, so much so that many studies are focused to that direction. In particular that of HSM (High Speed Machining) is an approach designed to minimize the tool wear.

The high-speed machining is a machining technology in which the cutting runs at very high speed, generating very high cutting speed (peripheral speed of the cutting tool). The speed makes a lot of energy to focus on a very small area and to soft the material in that point, causing a small fracture in front of the edge. By this way, the cutting edge does not come into contact with the particles, as happens in the traditional working type. The phenomenon can be explained analyzing the forces acting on the cutting tool. In Fig.17 the power cut is plotted as a function of cutting speed and it decreases, as is evident, when a certain cutting speed is reached, that speed necessary to produce enough power to start adiabatic softening.

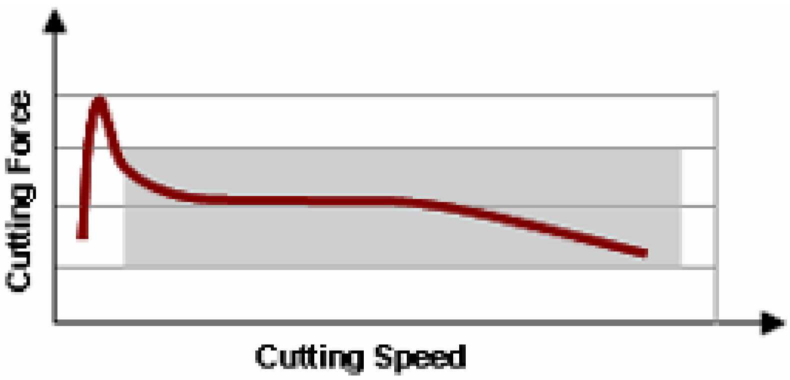


Fig.17 Cutting force vs. cutting speed

For the need to resolve the aforesaid high abrasive problems, new cutting methodologies have been developed more and more technologically advanced.

Some processes that provide an electric field between tool and workpiece can be very useful about the MMC manufacturing. Electrochemical processing leads to the removal of material for anodic dissolution by using a cathode with the appropriate form to define the cut type. An electrolyte ion is passed in the space between workpiece an tool to remove debris. Some difficulty can be in the cutting and removing of long fibers, but this can be done by combining the electrochemical cut with that mechanical using an abrasive moving cathode. Normally, the process doesn’t lead to the contact between the electrode and the workpiece, so that in the material are made few remaining damage.

The electric discharge machining using a wire (which acts as an electrode) wet by a stream of liquid dielectric. The removal of material is the high temperature and the pressure pulse generated by the cut, which is not in contact with the wire. This type of process is slow and can lead to serious damage.

The MMC can be cut successfully using various high-energy rays. To cut along the axis of the long fiber or that by short reinforcement, the fibers should not be fractured and then the cut, the merger or volatilization of the matrix is all that it is required. This can be achieved using laser beams of electrons with non-reinforced materials since the presence of the reinforcement on the thermal conductivity can influence the response of the material. At a energy sufficiently high fibers can be merged or vaporized or, more probably, routes by several mechanical and thermal stress made by the energy beam. Therefore during the cutting process there is tendency to have crack formation, interface bonding breaking and damaged microstructures by heating.

Minor damage can reach high-speed cutting using a concentrated jet of a high-speed fluid, usually water, containing abrasive particles in suspension. This technique is applicable to composite reinforced both in continuous and in discontinuous. There is no need to control the temperature and damage mechanics are usually located only on the worked surface. This technology is considered as one that combines the higher cleaning and cutting speeds.

A process related to the previous one is the abrasive flow, which is used to obtain good surface finishes. In fact, a gel containing abrasive particles is flowing on the surface under pressure. This is also very useful if the request workpiece is a very bright, especially in the components with the very complicated sharp.

As mentioned above, welding is the most critical point about MMC studies and applications. Many data have been analyzed about MMC joining systems. Conventional welding result generally unsatisfactory, particularly about MMC reinforced continuously, since the reinforcement distribution tends to be disturbed by the cast zone. Even in reinforced discontinuous composites it is possible to note not homogeneous zone on the welded area. Moreover these problems of variation about the welding homogeneity can not be resolved by post-welding treatment in order to avoid it.

These unhomogeneities can lead to stress concentration in the joint zone and then to the breaking. To consider the processes in that the joint is very small is preferable, as brazing, diffusion bonding, friction welding, laser welding or electron flow.