Metal and ceramic matrices:

new composite materials

Introduction

In the case of materials subjected to mechanical loads, the use of composite materials has improved the properties by using substances that would theoretically not be present in a conventional material at the same time or at least in the required form, according to traditional implementation methods by the laws of equilibrium and chemical kinetics.

This increase in the number of degrees of freedom for the material heralds new possibilities (*e.g.*anisotropy, material gradient,and so on) as well as a new set of challenges, such as questions relating to material compatibility and stability. These issues may restrict the number of choices available, but this obstacle can be overcome in time in light of the development of new fabrication methods (additive manufacturing, friction stir welding, etc.).

In principle, composite materials are not necessarily limited to the aviation and transport industries, where maximising the specific stiffness-to-weight ratio is essential. However, the high cost of such materials reduces their use in applications where material and fabrication costs are mission-critical, such as in civil engineering and, to a lesser extent, mechanical engineering.

A noticeable change is currently sweeping the composites sector. Whereas research from the 1950s to the 1980s focused on the development and use of polymer matrices reinforced with glass, carbon and aramid fibres, efforts are increasingly being made to develop alternatives, such as the choice of materials and fabrication method, which are closely related to the theoretical properties actually obtained and their dispersion.

Non-polymer matrix composites

This section describes the alternatives to resin and thermoplastic matrices. The properties of metal and ceramic matrices are also likely to be improved (resistance to creep and wear, thermal or electrical behaviour modified through the addition of nano-fillers, etc.) by adding a second phase.

The use of metal and ceramic matrices can also be justified in light of the limitations inherent in polymer matrices, even though such limitations are constantly being resolved. It is mostly certain mechanical properties of the resins combined with the use of ceramic reinforcements that may cause doubts to arise. For each limitation, metal or ceramic matrix composites may represent an alternative.

Stiffness

Although polymer matrices achieve satisfactory strength and ductility properties, and it is the reinforcement in the composite material that bears the external load, doubts may arise about the stiffness ratio between the matrix and the reinforcement. It has been proven that shear forces acting on the interfaces depend on this ratio. A very low or very high ratio is undesirable. This means that advanced work must be undertaken to ensure compatibility between the fibres and the matrix to produce a high level of binding energy at the interfaces. However, this improvement lowers the resilience of the materials, since fissures can spread more easily. The material tends towards the properties of the macroscopic ceramic material containing defects and then becomes more fragile.

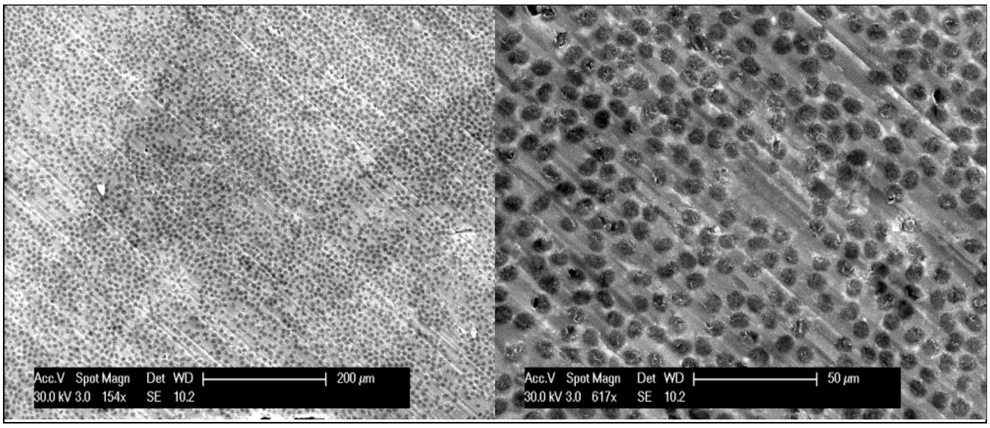


***Figure**: Microstructure of an Mg matrix composite (9% Al, 1% Zn) reinforced with 35% high-resistance UD carbon fibres (view of the wafer) by injection moulding (Winnomat project C-Mg MMC, ULg, UCL, Sirris).*

Using a metal matrix some 10 to 50 times more rigid provides a solution to this particular problem. For example, in the case of structures, lightweight aluminium or magnesium matrices have been combined with carbon fibres. These materials involve complex fabrication methods and feature between 30 and 60% volume of fibres, with mechanical properties superior to equivalent polymer matrix composites, while offering high resilience. If a magnesium matrix is used, the following table shows that the stiffness-to-weight ratio and the strength-to-weight ratio are superior to an equivalent epoxy matrix composite.

Table: Comparison of the average specific mechanical properties of equivalent composite materials (60% volume of high-resistance carbon fibres) with an epoxy or metal matrix (Mg + 1wt.% Al), baseline year 2009

	CFRP (Epoxy 60% vol. UD f C HS)	CFRMg1%Al (60% vol. UD f C HS)
Ratio $\frac{E}{\rho}$	$\frac{111}{1.6} = 69.37$	$\frac{140}{1.8} = 77.77$
Ratio $\frac{\sigma_r}{\rho}$	$\frac{1225}{1.6} = 765.6$	$\frac{1450}{1.8} = 805.5$
Price (€/kg)	~ 30	~ 120

However, two difficulties remain when using such materials - the limited cohesion between the fibres and the matrix significantly reduces the tensile limit compared to the theoretical values. For example, if producing an aluminium – carbon fibre composite by liquid pressure forming, the problem can be overcome by using additives, which removes the oxides and thereby allows for direct reactive contact with the carbon fibres during infiltration. Interface cohesion is strengthened, while the resilience of the metal is retained for the matrix.Nevertheless, interfacial reactions must be controlled to avoid excessive damage and fibre use by the reactions during infiltration.

Hardness

Typically, the use of particulate ceramic reinforcements increases the material's macroscopic hardness and therefore its wear resistance. However, in case of matrices with low relative hardness, the combined application of a normal load and sliding degrades the interfaces and deforms the matrix. Without any cold working or hardening capacities, the polymer matrix composite often represents the weak link in the tribological system, accelerating the degradation of the material as a whole.

This is the reason why composite wear applications are mainly performed on metal or ceramic matrix composites.

At the industrial level, nickel-diamond or nickel-tungsten carbide deposits may also be used for matrix composites. The hardness of the nickel matrix composite is between 30 and 65 HRC inclusive, which limits fatigue on the interface between the hard ceramic particle and the matrix. The material is most often performed by means of cold electrolytic deposition or hot wire laser cladding.

Resilience

As mentioned earlier, improving the interfaces in polymer matrix composites results in a fall in resilience, which represents a major limitation. Furthermore, the impact strength of polymer matrix composites comes from the increased length of the crack path, since neither the reinforcement (except for the aramid fibres) nor the matrix alone has any resilience or high tenacity.

On a practical level, to maximise the service life of cutting tools, special composite materials called cermets are used. Since a high level of hardness is required to ensure wear resistance, the quantity of tungsten carbide reinforcements is greater than 90 vol.%. Although only representing 10 vol.%, the cobalt or nickel-based matrix binds the particles together and is beneficial in terms of heat dissipation and impact resistance.

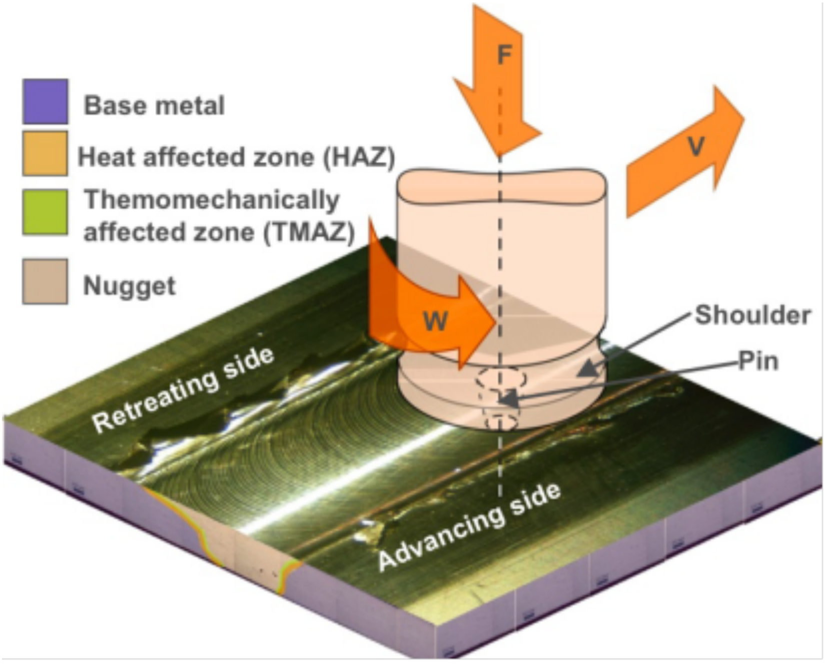
Maximum operating temperature

As with most polymer materials, except for special technical polymers (e.g. PEEK), the maximum operating temperature of polymer materials is at best limited to 250-300°C. Upon approaching the maximum temperature, degradation of the polymer is generally caused by thermal activation. A safety margin therefore needs to be factored into the operating temperature, which restricts the operating range even further.

Ceramic matrix composites (CMCs) offer the highest operating temperature. They also present other advantages, such as thermal shock resistance and improved tenacity. At the present time, the materials used on an industrial scale are carbon-carbon composites (carbon matrix with carbon fibres), SiC-fSiC and C-fSiC. Various fabrication methods are used, including two-step sintering. The first step involves binding the reinforcement in a polymer matrix containing the ceramic elements to be incorporated (*e.g.* C or Si) by sintering at a moderate temperature. The second step is performed by pyrolysis at a higher temperature (1 000-1 200°C). The polymer is then degraded and the density of the sintered material increases.

New fabrication methods

As mentioned earlier, conventional methods for fabricating ceramic / metal matrix composites are fraught with major difficulties. The reinforcement preforms can be effectively wet by the molten metal and the interfacial reactions controlled when developing metal matrix composites by (semi-)liquid-state processes, such as liquid forging and thixomoulding. Effective dispersion of the reinforcement phase within the matrix – or conversely its localised insertion, for example, for the purpose of obtaining a functionally graded material - may also prove problematic, especially in case of nanoparticles, which have a strong tendency to agglomerate. New fabrication methods have therefore been spearheaded in recent years in a bid to overcome such problems.



[Commin, 2008]

Friction stir processing

Friction stir processing, derived from the friction stir welding process, is a method of changing the microstructure of a metal material (especially aluminium or magnesium alloys) and/or fabricating a composite part while remaining in the solid state. The principle behind this technology is as follows: a tool with a pin and shoulder rotates in a stirring motion as it is inserted into the workpiece (rotation

+ lateral movement) (see diagram). Under the effect of the friction generated between the material and the tool, the material heats up and undergoes plastic deformation, which can be used to create a weld or incorporate a reinforcement into a metal matrix. This technology therefore overcomes the problems of wetting and interfacial reactions. It is highly suited to the incorporation of nano-fillers, since the process can be repeated until the fillers are well dispersed within the matrix, and it also supports the insertion of a localised reinforcement or fabrication of parts with functionally graded materials.

Additive techniques

Additive manufacturing techniques can be used for the near net shape manufacturing of dense parts by depositing successive layers of powder, which are then melted / sintered by a laser or electron beam. Since these processes imply a change to the liquid state and high temperatures, they do not fully overcome the problems of wetting and interfacial reactions. However, additive manufacturing offers a high level of flexibility and can be used for the small-scale production of complex geometry parts. Depending on the method used (electron beam melting, laser beam melting, selective laser sintering, laser cladding, and so on), additive manufacturing techniques are also suited to the implementation of metal and ceramic powders, and the fabrication of parts with functionally graded materials.

Article written by the Department of Metal Material Sciences (University of Liege, Faculty of Applied Sciences, www.metaux.ulg.ac.be) with the participation of J. Lecomte-Beckers (Professor), A. Mertens (Postdoctoral Research Fellow) and H.-M. Montrieux (Doctoral Student).

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