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RESEARCH

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Properties of Metal Matrix Composites for Automotive Applications

This article is concerned with overall or macroscopic properties of a composite material in which no distinction is made between the reinforcements and the matrix in which they are embedded, and all properties are regarded as averaged over a volume of material whose dimensions are large compared with the filament's diameter and spacing. The systems of particular interest here are in the reinforcement embedded in Metal matrix that may be extensively used in automotive applications.

Keywords: *composite, metal matrix, automotive applications.*

1. INTRODUCTION

In recent years there has been considerable activity in the study of the behaviour of composite materials and possibilities of their applications in automotive industry. For example, aluminium alloys are used in advanced applications because their combination of high strength, low density, durability, machinability and cost are very attractive. However, using aluminium matrix composite materials may considerably extend the scope of these properties.

Generally composite material must be man-made as a combination of at least two chemically distinct materials with a distinct interface separating constituents. It should create properties, which could not be obtained by any of the constituents on its own. Here we are concerned with metal matrix composite materials. One should distinguish metal matrix composites from metal alloys, which are achieved via control of naturally occurring phase transformations during solidification or thermo mechanical processing. The metal matrix composites may offer specific advantages compared to unreinforced metal alloys.

According the geometry of reinforcement, metal matrix composites may be classified into two main groups as

- continuous fibre reinforced composites, and
- discontinuously reinforced composites with short fibres, whiskers or particulates.

The continuous fibre reinforced composites have as main feature improvement of stiffness and strength, reduction of wear and creep, anisotropic properties, improved strength in fibre direction, high price and complex manufacturing techniques.

The discontinuously reinforced composites are developed, when strength is not the main objective, but when a better wear resistance, a controlled thermal expansion, and a higher service temperature are expected.

2. PRINCIPAL PROPERTIES OF METAL MATRIX COMPOSITES

Composite material technologies offer an opportunity to tailor the properties of metal to increase strength, decrease weight, to gain higher service temperature, higher elastic modulus, improved wear resistance, controlled coefficient of thermal expansion etc. Composites derive their basic load carrying and chemical properties from three sources, which are matrix, reinforcement, and the matrix-fibre interface. The matrix imparts the resistence to environmental degradation while the reinforcement provides the strength characteristics and resistence to deformation. The interface between the matrix and reinforcement is probably the most important but least understood of the sources of properties. It is generally thouth that this interface together with fibre orientation dictates the overall stress-strain characteristics of the composite.

Metal matrix composites (MMC), because of the basic metallic construction, do not suffer the problems of high temperature, vacuum and radiation damage and moisture that is present in polymer matrix composites.

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For lower temperature service a variety of aluminium and magnesium alloys are being considered as matrix materials. In these alloys, the gratest concerns are for adequate protection from corrosive attack either in marine atmospheres or from the fact that significant galvanic couples may be already set up inside if matrix and reinforcement have potencial diference between materials.

2.1 Contnous fibres reinforced composites

The mechanical behaviour of unidirectionally reinforced metals is relatively well understood. The tensile behaviour of the composite can be predicted from the behaviour of the individual constituents by simple rules of mixture and simple structural mechanics to describe off-axis behaviour.

For unidirectional, long fibre composites with fibre volume fraction greater than certain prescribed minimum (V_{min}) and with fibres that are stiffer and stronger than the matrix, the tensile failure, when loading in the fibre direction, is determined by the fibre failure. The component fracture strength is then given by:

$$\sigma_{cf} = \sigma_{ff} V_f + \sigma^*_m V_m \,, \qquad (V_f > V_{\min}), \qquad (1)$$

where V_f and V_m are the fibre and matrix volume fraction, σ_{ff} is the fracture stress of the fibre and σ^*_m is the matrix stress corresponding to a matrix strain equal to the fibre fraction strain. For fibre fraction below V_{min} there is no strength reinforcement and

$$\sigma_{cf} = \sigma_{mf} V_f \,, \qquad (V_f < V_{\min}), \qquad (2)$$

where σ_{mf} is the matrix fracture stress. Volume V_{min} may be calculated as follows

$$V_{\min} = \frac{(\sigma_{mf} - \sigma^*_m)}{(\sigma_{ff} + \sigma_{mf} - \sigma^*_m)} \,. \qquad (3)$$

For the majority of metal matrix composites reinforced with continuous fibres, the fibres are much stronger than the matrix and V_{min} generally lies below 10 vol per cent.

For only small deviations of loading from the fibre direction, failure occurs by the shear in the matrix or the fibre matrix interface, and strength falls sharply with the angle of deviation.

If we assume linear elastic behaviour, and both materials to be isotropic then by further assumption that both constituents undergo an axial extension e under the mean axial stress σ, then from the simple model illustrated in the Fig. 1a. one obtains

$$\sigma = (E_f V_f + E_m V_m)\, e \,, \qquad (4)$$

so that, in this rough approximation, the axial extensional modulus of the composite is

$$E_L = E_f V_f + E_m V_m \,. \qquad (5)$$

When the composite undergoes an extension in the direction transverse to the fibre, as illustrated in the Fig. 1.b., then the stress σ is the same in each constituent, and the total strain in the transverse direction is

$$e = \left(\frac{V_f}{E_f} + \frac{V_m}{E_m}\right) \sigma \,, \qquad (6)$$

and thus, approximately, the transverse extensional modulus is given by

$$E_T = \left(\frac{E_f E_m}{V_f E_m + V_m E_f}\right). \qquad (7)$$

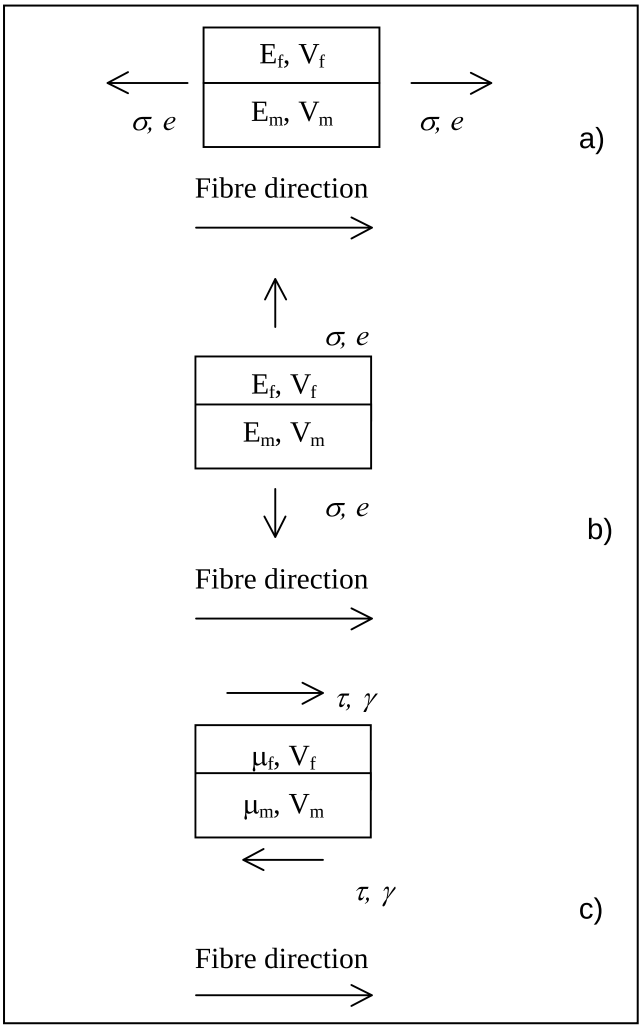

Figure 1. Deformations of a simple model of a composite material; a) axial extension, b) transverse extension, c) axial shear

Finally, in axial shear (Fig 1.c), the shear stress τ is approximately related to the mean shear strain γ by

$$\gamma = (\frac{V_f}{\mu_f} + \frac{V_m}{\mu_m})\,\tau . \qquad (8)$$

The same result is obtained in the case of transversal shear.

It must be emphasized that these simple law of mixtures reaults are only approximations. This model, however, correctly predicts that the composite formed from an elastic fibre and an elastic matrix will behave as an elastic solid. Furthermore, for both and fibres and matrix isotropic, behaviour of resulting composite is transversaly isotropic solid characterized by five elastic constants. A considerably effort has been devoted to expressing these five constants, but exact relations can be obtained only for certain constants, and for remainder it is only possible to set upper and lower bonds.

2.2 Discontinuously reinforced composites with short fibres, whiskers or particulates

Behaviour of discontinous fibre composites depends upon type, aspect ratio, volume fraction and distribution of the reinforcement, matrix material and its heat-treated conditions. Low strength matrix, for example pure aluminium, are greatly strengthened by ceramic phased as SiC. Aluminium based composites are also very attractive for applications at intermediate temperature (200^0C – 400^0C). The effect of particulate reinforcement depend on particle size and volume fraction. Also the presence of inhomogeneities and particle clusters have negative influence on fatigue strength, although fatigue properties of aluminium composites are usually better than in unreinforced equivalent alloys.

Therefore particulate composites find application in cases when strength is not main objective, i. e. when it is necessary controlled thermal expansion, reduced wear, increased service temperature and improverd friction properties. The wear resistance of MMC depends on particular wear conditions, but there are many circumstances where they achieve exellent wear resistance. The interfaces between matrix material and reinforcements play fundamental role in MMC. The success of MMC is higly dominated by the control of the interface. The interfacial reactions between matrix and reinforcement should be very limited, in order to avoid the degradation of the reinforcement and the formation of new brittle phases. When using liquid state technique with low pressure for fabrication it is necessary to have good wetting. It is also required correct bonding to deliver intended property.

For aluminium alloys as matrix, for example, wetting may be improved by a chemical reaction with the reinforcement which reduces interfacial energy. Also the disruption of the oxide skin covering the liquid aluminium may improve the wetting behaviour. The parameters that are further influencing the wetting are the temperature, contact time, the pressure of surrounding atmosphere etc.

Discontinuously reinforced composites may be fabricated by either solid state, liquid state or metal spray routes. Particulate and whisker reinforced composites are following similar routes. Special attention should be devoted to handling of fine particles (diameter smaller than 5 μm) and of whiskers, because in that case special health and safety precautions are necessary.

3. TECHNIQUES FOR PRODUCTION OF MMC

There is a number of production techniques of MMC de pending on whether we deal with continuously or discontinuously reinforced composites. These may be further subdivided, according to whether they are based on treating of the metal matrix in a liquid or a solid form. The production factors have influence on the type of the composite, its behaviour, cost, field of application etc.

The production of continuous fibre reinforced MMC depend on both choice of fibre and choice of matrix. One may distinguish two main groups of processes. First group use liquid to infiltrate fibre bundles, and second use, in general, solid state methods. Fibres may surface coated to prevent deterioration of the fibre mechanical properties especially at higher temperatures.

In the group of liquid state techniques we may put hot moulding, braze bonding, liquid infiltration, plasma spray deposition technique etc. In **hot moulding techniques** the reinforcements are put between foils of the matrix material, and then subject to a pressure – temperature treatment. In the case of **braze bonding** a brazing alloy is employed to join and to consolidate MMC. This technique permits lower fabrication temperature and preasure, but it limits maximum service temperature. **Liquid infiltration** consist of infiltration of preforms in liquid metal, using either gravity, vacuum or pressure. In **plasma spray deposition technique** liquid matrix droplets are sprayed with a plasma gun on reinforcement filaments, while they are wound around a core or mandrell.

In the group of solid state techniques we may put diffusion bonding, high energy rate forming, rolling, cold drawing, superplastic forming, hot isostatic pressing etc. **Diffusion bonding** means that continuous fibres or performs are placed between foils of the matrix material and than subjected to a pressure – temperature treatment. The bond between the matrix and the reinforcement is made by the interdiffusion during which the process parameters should be very well controlled. **High energy rate forming** is technique which applies very high pressure pulses for extremely short times which prevent fibre – matrix reaction, but high pressure may cause excessive fibre damage. Other mentioned techniques are well known, because they are widely used in production of conventional materials.

4. ALUMNIUM MATRIX COMPOSITE IN AUTOMOTIVE APPLICATIONS

Applications of aluminium based composites may be devided into three main sectors. These are the automotive industry, the aerospace sector and the leisure market. Interst is also growing in the field of mechanical applications and in the field of electric and electronic applications. Production route of aluminium matrix composites is highly interesting because interfaces between the reinforcement and the matrix is very clean with very good wetting and bonding between them. The exploitation of improved mechanical properties, combined with improved wear resistance, is receiving the greatest attention.

The light weight and high strength make aluminium matrix composite attractive for design ingeneers. The increasing use of low cost ceramic fibres and a metal fabrication method called squeeze casting offer new hope for the feasibility of making automotive components economically from MMC. Extensive testing has been directed toward aluminium diesel piston applications, using ceramic reinforcing fibres. The first commercial application occurred when Toyota used ceramic fibres to reinforce aluminium in 2L-T diesel piston ring produced by squize casting. The ceramic fibre composite replaced the conventional Ni-Resist cast-iron ring, used to reduce wear of the upper piston ring groove. The ceramic fibre reinforced piston offered superior resistance to both wear and seizure. This and lighter weight yielded a great improvement in engine performance and fuel efficiency. The production rate was more tham 10^5 parts per month in 1991.

Squeeze casting of ceramic fibre reinforced aluminium composite can be an economical way to provide improved performance, not omly of pistons but also of other automotive parts such as connecting rods, wrist pins, intake valves, brake parts, hydraulic cylinders, and pumps.

5. CONCLUDING REMARKS

Although the automotive market is a high technology market, costs of the materials should be considered very carefully, and it still may be the reason why application of MMC is not faster. However, there are still a lot of reasons for use of MMC, and specially use of light aluminium composites.Some of them are

- Reduction of the weight of both engine parts and body parts,
- Increase of strength, wear resistance, fatigue life, thermal insulation, and operating temperature of engines,
- Improvement of the tribological properties of moving and connecting components,
- Decrease the product weght,
- matching coefficient of thermal expansion, etc.

For most commercial applications, however, there are trade offs in cost versus performance that designer must take into account. As a compromise, for example, hybrid performs using combination of fibres may be feasible.

When improved wear resistance is wanted, the fibre volume used is generally les than 10%. However for a parameter like high-temperature fatige resistance, fibre volumes as high as 27% may be cost effective.

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