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Design and Property Enhancement of Aluminum Metal Matrix Composites (AMMC's) to Match Specific Areas of Application - A Review

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ABSTRACT

The necessity for the design of efficient load bearing materials together with superior directional properties, high specific strength and stiffness that can be tailored for specific applications where monolithic materials and conventional alloys can't be used has given impetus to the development of modern composites. The development of composite technology spanning several decades has given rise to an exotic class of materials whose characteristics could be tailored for specific applications to enhance mechanical and other properties besides incorporating easy machinability by conventional machining methods using conventional tools. This paper deals with the charting of a strategy for the application of aluminum metal matrix composites citing the specific reasons for selecting the particular material system pertinent to its functionality as a worthy candidate meriting its applications. A brief review of the modern composites is followed by a general discussion and the logical choice of a particular material system that has gained wide acceptance. With this knowledge as the basis, the materials engineer is well placed to create innovative designs that are having vast improvement over its predecessor designs and achieve not only fast effective gains, but also material enhanced properties.

Keywords: Polymer Matrix Composites, Ceramic Matrix Composites, strength, stiffness.

INTRODUCTION

Composites may be broadly classified as Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC) and Ceramic Matrix Composites (CMC), all the matrixes are formed by combining two or more materials to achieve enhanced and superior properties compared to their component parts. There are quite a few properties that are relevant to all the three categories. They are low-density, enhanced strength and stiffness, weight optimized performance and in the case of aerospace structures fuel-efficient design and high temperature resistance. While these properties are more or less the general requirements for all the three type of composites, they may however be imparted additional property enhancement in certain critical areas of applications notably in the aerospace sector. In the applications area, Aluminum Matrix Composites have taken a lead, the thrust being a legion. The selection of a particular system required to be tailored, depends on a host of conflicting requirements, which a system has to satisfy. It is important to note that the production and properties of several AMC's either for continuous fiber, discontinuous fiber or particulate reinforced is profoundly affected by the reinforcement. These property enhancements due to the reinforcement are compared to the matrix composites.

SELECTION OF COMPOSITES

The selection of the materials comprising the composite is by no means a random process. The systematic selection apart from the composition of the components comprising the MMC also takes into account the optimization factor where the so called merit parameters play a significant role in analyzing the competitiveness between the materials that are functionally related to material properties, such as density, resistance to temperature, resistance to corrosion, besides cost and value of weight savings. This approach is conducive to the evaluation of AMC's in the specific realm of application whether aerospace, military, automotive or sport. This analysis will lead to the conclusion that continuous fiber reinforced AMC's have a low density, are stiff and strong, and are known to have a weight optimized performance and are fuel-efficient design. In the aerospace sector cost is not necessarily the governing factor because of the low production volume and the profit realized by weight savings. Perhaps another reason is that in the aerospace sector the defense overtones outweighs cost factors. Be this as it may today's sophisticated defense industries of advanced nations develops aerospace products and systems that are market specific and performance oriented. This has led to a situation in which aerospace technologies have become highly competitive designed for excellence and optimum performance. As for as the automotive sector is concerned cost plays a vital role (since large volumes prevails and as such material cost will significantly effect the competitiveness of the component produced)

Application Potential:

There are three different types of Aluminum Metal matrix Composites depending on the specific field of application. They can be reinforced with

- Particulates.
- Whiskers mono-crystalline or discontinuous fiber that are poly-crystalline.
- Continuous fibers

Common reinforcements are Silicon carbide (SiC), alumina (Al_2O_3) also Titanium carbide (TiC), Barium Carbide (B_4C), Barium (B), Graphite, etc.,

Selection of Matrix:

The matrix is selected on the basis of oxidation, corrosion resistance and other properties (1,2)
Commonly used Matrix materials are Aluminum, Titanium, Magnesium, Nickel, Copper, Lead, Iron, Silver, Zinc, Tin and Silicon.

The most widely used Matrix Materials are Aluminum, Titanium and Magnesium. Our main focus as a matrix is on Aluminum (3), because it has good corrosion resistance, low electrical resistance and excellent mechanical properties. This is one reason for the use of Aluminum Metal Matrix as an aerospace material. Titanium Matrix Materials are mainly used in aero engines (4), compressor blades and disks because they offer very high resistance at elevated temperature. Magnesium Matrix Materials are used in reciprocating parts, pistons, gudgeon pins and springs caps in automotive engines (5). Also in aerospace sector to a limited extent where low C.T.E, hi-stiffness and low density are required. Reinforcement characteristics will depend on the chemistry, morphology, micro-Structure, mechanical and Physical properties subject to cost consideration. The matrix characteristic factors are density, strength potential and strength retention at high temperature, ductility, toughness are also important.

e.g. 7xxx Aluminum alloy has the best combination of strength & toughness in aerospace applications rather than 2xxx alloy. But this doesn't preclude the selection of 2xxx for aerospace application since one has to select depending on what final properties to bestow on the composites. The reason for the above is that if 7xxx aluminum alloy composites are used, an interface is developed between 7xxx aluminum alloy and reinforcement which degrades the strength of the composites (6)

2xxx, 6xxx, 7xxx aluminum alloys are widely used as matrix materials for making composites. Aluminum lithium alloy 8xxx engaged the attention of researchers because of its good wettability characteristics. For good bonding and high strength in the composites, metal alloy are used as the matrix element instead of monolithic metals (pure metals).

All alloys containing reactive elements such as Mg, Li, etc. normally aid interfacial bonding with dispersoids are they will be ideal matrix materials. Generally Al-Cu-Mg (2xxx) matrix systems have excellent combination of strength and damage tolerance. However Al-Zn-Mg-Cu (7xxx) matrix system offer higher potential.

Al-Mg-Si—Cu (6xxx) systems provide improved resistance to corrosion in severe environment and give improved product fabricability.

Al-Fe-Li (8xxx) systems provide the opportunity for higher temperature performance (7)

Reinforcement:

Reinforcement increases strength, stiffness, temperature resistance capability but generally lowers density of MMC's

ROLE OF FIBERS:

The prime role of fiber reinforcement is to carry the load and that of the matrix to transfer the load to fibers with maximum efficiency.

Reinforcements are of two types:

1) Continuous reinforcements
2) Discontinuous reinforcements

Continuous reinforcements are associated with MMC's which are produced by using continuous fibers and discontinuous reinforcements are associated with MMC's produced with discontinuous fiber. These two types of reinforcements can be further divided into 5 major categories.

i) Continuous fibers

ii) Short fibers (chopped fibers, not necessarily of the same lengths)

iii) Whiskers

iv) Particulate or platelets, generally ceramics which are oxides, carbides, nitrides and carbonates. They are used because of high strength, stiffness at room and elevated temperature. The common reinforcing elements are SiC, Al_2O_3, TiB_2, Boron and Graphite.

Continuous fiber reinforcement:

The main continuous fibers usually called filaments include Boron, Graphite, aluminum and SiC fibers which are unique for unidirectional load when oriented in the same direction as the load, but the strength perpendicular to the fiber orientation is low.

Characteristics of the fibers:

Multi filament family of C-C, SiC, and Aluminum fibers are available in the form of single yarns or three-dimensional weaves. The mono filaments family is based on Boron only.

Boron Fiber:

Boron fiber shows the greatest strength in comparison with other fibers and MMC's are relatively easy to make with these fibers. However high cost of these fibers prevents widespread use. It is made by chemical vapor deposition (CVD) on a tungsten core. To retard reaction between Boron and metal at high temperatures, fibers coatings of SiC or Boron carbide are used.

Carbon Fiber:

It is unsuitable to form Al based MMC's because of fiber degradation during processing but T300 is used successfully to form the cheapest Mg composites (8). Some times CVD coatings of carbon fiber using Ni and Si has been used to improve the wettability of Carbon fiber MMC's to improve tensile properties.

Silicon carbide monofilament is made by the CVD process utilizes tungsten or a carbon core. There are SiC fibers sold under the brand name Nicalan and Tyranno containing additives of Titanium which possess enhanced strength and stiffness characteristics. MMC materials reinforced with Tyranno possess high transverse strength and are used in the aerospace industry.

Short Fibers:

Short fibers exceeds the critical length $lc = d(S_f / S_m)$ where d = fiber diameter, S_f is the reinforcement strength and S_m is the matrix strength and hence show a high strength in composites considering aligned fibers. Mis-oriented (randomized) short fibers (used with AMC) have been used with some success as AMC. Certain oxide fibers mainly Saffile and Kaowool find applications as reinforcements in the manufacture of automobile engine components.

Zirconia fibers are not compatible with AMC's but short fibers of Zirconia are widely used for refractory insulation purposes. Their main stay is in the refractory industry is due to their low cost.

Whiskers:

They are fibrous, single crystal structure with no crystalline defects. A whisker has a single dislocation, which runs along its central axis. This factor renders it immune from dislocation which is the reason for its high yield strength close to the theoretical strength of the materials (18). The method of vapour deposition is widely used in whisker preparation. It has been established that its response to elevated temperature is better when compared to any other fiber (18). So outstanding have been the specific mechanical properties of whiskers that they have become the focus of many researchers, in this area of fabricating MMC's using whiskers (19-25). Another attractive feature is the small diameter of the whiskers (d = 0.1 to 2μm) and hence the small length (i/d = 50 to 100) facilitates the efficient transfer of the load (9).

SiC whisker reinforcements are produced from rice husk (a low cost material). SiC whisker reinforced Al has been widely used in aerospace vehicles. It must be remembered that the physical characteristics of whiskers play a role for different chemical activity with the matrix alloy (9). For e.g. high strength C fibers exhibit a much higher chemical reactivity towards liquid Al than to high modulus Carbon fiber because of their different states of Crystallization.

Particulate:

They are the cheapest and widely used reinforcement material used in MMC's as reinforcement. They produce isotropic properties and hence are popular in structural application. Some research has been reported in producing reinforced Al alloy with graphite powder (13,14) with low volume reinforcement (<10%). Currently success with higher volume fractions of reinforcements for various kinds of ceramics particles (Oxide, Carbide, and Nitride) has been reported (9). The emphasis is now shifted to the use of SiC short fiber, whiskers and particulate in Al alloy matrix. The reason for the shift is due to the fact that SiC imparts adequate thermal stability with Al alloys during synthesis and application in the aerospace sector. Another features is that SiC has good wettability with Al alloys. The density of SiC and Al alloy are pretty close (2.8 to 3.3 gm cm^{-3}) and reinforcements imparts substantial increases in the modulus and UTS. If soft particulates (Graphite, Mica, etc) are dispersed in Al alloys they do not contribute to the strength. Indeed they lower the mechanical properties, but other special properties such as adhesion wear resistance are enhanced. In an identical situation the dispersion of Zircon particulates in Al alloys improves abrasion resistance properties to the composites, provided the amount of dispersion is 5 weight %. Higher amounts deteriorate mechanical properties (15).

The USA leads in the field of particulate research followed closely by Japan. Current research has reached such an advanced stage that 20% SiC in particulate form has shown improvement in yield strength and tensile strength of an equal percentage. While there is no change in density, stiffness it seems has improved by 50% (4), which contradicts the "rule", that, the specific thickness of all engineering metals, regardless of the density is roughly the same (16). Research in this field on SiC_p – Al and SiC_w – Al composite materials has shown that the SiC particulate reinforced Al matrix composites are not strong as the SiC whisker reinforced composites. Be this as it may, SiC particulate reinforced Al matrix composites are good candidates in wear-resistant materials. Their potential is further enhanced by the fact that the particulates have a favorable effect on other mechanical properties such as hardness, wear resistance and compressive strength.

Wire:

Essentially they are metallic filaments having high elastic modulii, some of them are molybdenum and tungsten. Current research has also shown some promise in using a steel wire. Their obvious disadvantage is the high density they possess when compared to ceramic whisker. However they have good ductility and are therefore used to fabricate composites where high tensile loads are to be hauled with toughness (17). Honda of Japan is credited for using 45% by volume of stainless steel fiber in Al alloy for the fabrication of connecting rods using the squeeze-casting method. These rods seem to have demonstrated 40% reduction in weight than the equivalent forged design while simultaneously contributing to substantial improvement in engine power and fuel economy. This is just one indication of the fact how versatile and fascinating composites are where in unfavorable situations can be reversed by ingenuity to yield the most favourable solution in the frontier areas of this technology. There is another disadvantage associated in that at high temperature there is a high possibility of metal to metal reaction thus creating fabrication problem (18).

We have thus far made a rapid survey of the part played by the reinforcement in AMC's citing in general the area of application. We continue to proceed along with the road map keeping in focus the application potential of AMC's and how profoundly the fabrication route affects them.

The application potential of Aluminium Matrix Materials will also depend on;

1. The production process involved in tailoring of specific properties.
2. It will depend on the type of the reinforcement.
    a. Particulate
    b. Whiskers that are mono crystalline or discontinuous fiber that are poly-crystalline.
    c. Continues fibres.

There are two types of fabrication methods

1. The solid phase fabrication method: This method includes diffusion bonding, hot rolling, extrusion, drawing, explosive welding, PM route, pneumatic impaction etc.
2. Liquid Fabrication methods: These methods involve liquid metal infiltration, squeeze casting, compo-casting, pressure casting, spray co-deposition which come under liquid metallurgy. Generally liquid phase fabrication is regarded as more efficient because the solid phase processing is a time consuming process (16). The form in which the matrix material is used varies with different fabrication methods. As an example powder is used in the Powder matrix impaction and powder metallurgy techniques and obviously liquid matrix material is used in liquid metal infiltration, plasma spray, squeeze casting, pressure casting, gravity casting, compo-casting and investment casting etc. But in todays industry diffusion bonding, powder metallurgy route, liquid metal infiltration, squeeze

casting, spray co-deposition and compo-casting (19) are sufficiently advanced to merit their industrial status. There is a keen competition between these methods the focus being on producing the lowest cost material with the best mechanical properties. Without going in to the specifics of each of these methods we will just indicate briefly the comparison of different techniques referred to above as given below. A detail appraisal is given in the appendix.

MECHANICAL PROPERTIES

The tensile strength, stiffness and elongation of different AMC's. in respect of Al 6061 – T6, SiC_w / Al6061 – T6 shows significant increase in modulus yield strength and ultimate tensile strength due to the addition of the reinforcement SiC (21). Whisker additions are seen to be more effective in strengthening than are particulate addition. Particulate reinforced composites are the more isotropic material which is a desirable characteristic for use in structural unit, aerospace, automobile etc. (21). Among the casting routes, sand casting results in slightly higher tensile strength, but generally in all casting techniques, the mechanical properties are considerably high if heat treatment is applied to both particulate and whisker reinforced composites, the particulate reinforced composites give higher strength
than that of whisker reinforced composites.

It has been found out that the strength of both matrix and composite drops down remarkably at high temperature. At about 200 – 250^0 C the strength of particulate reinforced composite shows better performance than that of fiber reinforced composite. SiC_p/x8019 composite shows outstanding performance at high temperature (7), so at elevated temperature SiC_p/x8019 composites can be used successfully.
It has been indicated that like the tensile strength and stiffness, the hardness also increases if heat treatment is used as a secondary operation (20).

The fracture toughness of composites fracture toughness of the composites increase if heat treatment is applied (21). The fracture toughness decreases with increase of reinforcement as ductility decreases.

Appendix:

Fabrication route	**Cost effectiveness**	**Field of application**	**Comments**
Diffusion bonding	High to very high	Suited for making sheets, rotor blades, vane, and shaft structural components.	Capable of handling foils or sheets of matrix and filaments of reinforcing elements

Powder metallurgy technique	Medium to high	Suitable for the production of small items that are round in shape, bolts, pistons, valve and generally high strength and high resistance materials	The matrix as well as the reinforcements is used in powder form particularly suitable for using particulate reinforcement. There is no melting involved and as such there is no existence of the so-called reaction zone
Liquid metal infiltration fabrication	Low to medium	Particularly suitable for the production of structural shape such as tubes, beams, rods with excellent properties in the uni-axial direction.	The reinforcement is in the form of filament
Squeeze casting	Medium	Has matured to achieve and in dispute industrial status in the automotive industry for providing automotive components such as pistons, connecting rods, rocker arm, cylinder head of various geometry	It is very versatile and as such applicable to any type of reinforcement. It application can be widened to cater for large scale manufacturing
Spray codeposition	Medium	Particularly suitable to produce friction materials such as brake lining, cutting and grinding tools etc.	Reinforcements is in particulate form. Maximum density materials can be produced
Compo casting	Low	Has wide usage in automotive, aerospace, industrial equipment and sporting goods industry. Also used to manufacture bearing materials.	Suitable for discontinues fiber specially particulate reinforcement.

CONCLUSIONS

The following inferences are made with the charting of strategy for the application of Aluminum Metal Matrix Composites.

1. 8xxx alloys can be used as a matrix material for the use of composite at high temperature.
2. For making the composite with high strength, hardness and fracture toughness x6061 matrix is the best.
3. As a reinforcement material SiC can be used for making AMC. For the manufacturing route.

4. PM with extrusion and heat treatment can be used for making AMC with good mechanical properties.

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