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Charting of a Strategy for the Application of Aluminium Metal Matrix Composites for Different Engineering Service Requirements

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ABSTRACT

The necessity for the design of efficient load bearing materials together with superior functional properties, high strength and stiffness that can be tailored for specific applications where monolithic materials and conventional alloys that cannot 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 aluminium metal matrix composites citing the specific reasons for selecting the particular material system to its functionality as a worthy candidate meriting its applications. A brief review of the modern composites is followed by a general discussion and 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: **Fabrication Route, Field of Applications, Matrix, MMC, Selection Strategy Reinforcement.**

1. INTRODUCTION

Composites may be broadly classified as Metal Matrix Composites (MMC), Polymer Matrix Composites (PMC) and Ceramic Matrix Composites (CMC), all the matrices 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 general requirements for all the three types of composites, they may however be imparted additional properties enhancement in certain critical areas of applications, notably in the aerospace sector. In the applications area, Aluminium Matrix Composites have taken a lead, the thrust being a legion. The selection of a particular system require tailored depends on the host of conflicting requirements, which a system has to satisfy. It is important to know that the production and properties of several AMC's either for continuous fiber, discontinuous fiber or particulate reinforced is profoundly affected by the reinforcements. These property enhancements due to the reinforcement are compared to the matrix composites.he introduction of the paper should explain the nature of the problem, previous work, purpose, and the contribution of the paper. The contents of each section may be provided to understand easily about the paper.

1.1 The Road Map for the Selection of Composites

The selection of the materials comprising the composites 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 materials properties, such as density, resistance to temperature, resistance to corrosion besides, cost and value of weight savings. This approach is conducive is to the evaluation of AMC's in specific realm of application, whether aerospace, military, automotive or sport. This analysis will lead to the conclusion that continuous fiber reinforced AMC's have low density, are stiff and strong, 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 aerospace sector defense overtone outweighs cost factors. Be this as it may today's sophisticated defence 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 design for excellence and optimum performance. As far as the automotive sector is concerned, cost plays a vital role (since large volumes prevails and as such material cost will significantly affect the competitiveness of the component produced).

1.2 Application Potential

There are three different types of Aluminium 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.

1.3 Selection of Matrix

Matrix is selected on the basis of oxidation, corrosion resistance and other properties [1, 2]. Commonly used matrix materials are Aluminium, Titanium, Magnesium, Nickel, Copper, Lead, Iron, Silver, Zinc Tin and Silicon.
The most widely used matrix materials are Aluminium, Titanium and Magnesium. Our main focus as a matrix is on Aluminium [3], because it has good corrosion resistance, low electrical resistance and excellent mechanical properties. This is one reason for the use of Aluminium Metal Matrix as an aerospace material. Titanium Metal matrixes are mainly used in aero-engines [4], Compressor blades and discs, because they offer very high resistance at elevated temperatures. Magnesium Matrix materials are used in reciprocating parts, piston, gudgeon pins and springs cap in automotive engines [5]. Also in aerospace sector to limited extent where low coefficient of expansion, high stiffness and low density are required. Reinforcement characteristics will depend on chemistry, morphology, and microstructure, mechanical and physical properties subject to cost consideration. The matrix characteristics factors are density, strength potential and strength retention at high temperature, ductility, toughness are also important.

For example, 7xxx Aluminium alloy has the best combination of strength and toughness in aerospace applications rather than 2xxx alloy. But this does not preclude the selection of 2xxx for aerospace applications since one has to select depending on what final properties to bestow on the composites. The reason for the above is that if 7xxx Al alloy composites are used, an interface is developed between 7xxx Al alloy and reinforcement which degrades the strength of composites [6].

2xxx, 6xxx, 7xxx Al alloys are widely used as matrix materials for making composites. Aluminium Lithium Alloy 8xxx engaged the attention of researchers, because of its good wettability characteristics. For good bonding and high strength in the composites, metal alloys 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 as 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 systems 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 high temperature applications [7].

1.4 Reinforcements

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

1.4.1 Role of fibers

The prime role of reinforcement is to carry the load that of the matrix to transfer the load to the fibers with maximum efficiency. Reinforcements are of two types.

1. Continuous reinforcements
2. Discontinuous reinforcements
3. 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 fibers. These two types of reinforcements can be divided into five major categories.

a. Continuous fibers
b. Short fibers (chopped fibers, not necessarily of the same length)
c. Whiskers.
d. Particulate or Platelets, generally ceramics which are oxides, carbides, nitrides and carbonates. They are used because of high strength, stiffness at room at elevated temperatures. The common reinforcing elements are SiC, Al_2O_3, TiB_2, B and Graphite.

1.4.1.1 Continuous fiber reinforcement

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

1.4.1.2 Characteristics of the fibers

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

1.4.1.3. 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

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Boron and metal at high temperatures, fibers coatings of SiC or Boron carbide are used.

1.4.1.4. 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]. Sometimes 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.

Boron fiber possesses the greatest strength in compression with other fibers with additional advantage that it is easy to make MMC's with this fiber. However, their high cost restricted used in aerospace structure. SiC and Al_2O_3 are very popular in high temperature applications and consequently they figure prominently in the aerospace industry. MMC's with Al, Ti, Ni alloys as one of the matrix materials with Al_2O_3, B, C, SiC and SiO_2 as reinforcements are attractive propositions for the use in the aerospace industry Al alloys with Al_2O_3, SiC etc. are effectively used in areas where turbine entry temperature of 600^0 K are encountered.

1.4.1.5. Short Fibers

Short fibers exceeds the critical length lc = d (S_r / S_m), where d= fiber diameter, S_r is the reinforcement strength 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 due to their low cost.

1.4.1.6 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 Vapor deposition is widely used in the 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 smaller 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.

1.4.1.7. Particulate

They are the cheapest and widely used reinforced 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 inadequate thermal stability with Al alloys during synthesis and application in the aerospace sector. Another feature is that SiC has good wettability with Al alloys. The density of SiC and Al alloy are pretty close (2.8 and 3.3 gm cm^{-3}) and reinforcements imparts substantial increase in the modulus and Ultimate tensile strength. If soft particulates (Graphite, Mica, etc) are dispersed in the 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 in 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 density is roughly the same [16]. Research in the field of 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. But 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.

In industrial applications particulates have demonstrated their potential as the most favored candidates in a number of particulates reinforced system, such as cermets in electric industry for the tracks of precision variable resistors and high speed cutting tool tips.

1.4.1.8. 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 Japan is credited for using 45% by volume of stainless steel fiber in Al alloy for the fabrication of connecting rods using 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 wherein unfavorable situations can be reversed by ingenuity to yield the most favorable solution in the frontier areas of this technology. There is another disadvantage associated with this at high temperature there is a high possibility of metal to metal reaction, thus creating fabrication problem [18].

Thus, a rapid survey of the part played made by the reinforcement in AMC's citing in general the area of application, has been made. It is continued to proceed along with the road map keeping in focus the application potential of AMC's and how profoundly the fabrication route affect them.

The application potential of Al matrix materials will also depend on

1. The Production process involved in tailoring of the specific properties.
2. It will depend on the type of the reinforcement, namely, Particulate, Whiskers and Continuous fibers.

2. PRODUCTION PROCESS VIA THE FABRICATION ROUTE

There are different fabrication techniques that are currently being used in the manufacture of MMC materials. However they need not be unique as the designer evolve his own methodology to either modify or even completely replace the existing technique by using his knowledge expertise at his command. This is so, because the choice of the matrix and reinforcing material and of the types of reinforcement and the fabrication techniques vary considerably.

2.1.1. Types of Fabrication Methods

1. The solid phase fabrication method. This method includes diffusion bonding, hot rolling, extrusion, drawing, explosive welding, powder metallurgy route, pneumatic impaction etc.

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 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 into the specifics of each of these methods, a brief comparison of different techniques refers to above are given below. A detailed appraisal is given in the appendix1.

3. MECHANICAL PROPERTIES

The tensile strength, stiffness and elongation of different AMC's in respect of Al6061-T6, SiC_w - Al6061-T6 shows significant increase in modulus yield strength and ultimate tensile strength due to the addition of reinforcements SiC [21]. Whisker additions are seen to be more effective in strengthening than with particulate addition. Particulate reinforcement 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 shows 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 reinforce composites, the particulate reinforce 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 - 250^0C the strength of particulate reinforced composite shows better performance at high temperature [7], so that 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 increase if heat treatment is applied [21]. The fracture toughness decreases with increase of reinforcement as ductility decreases.

Aluminium alloys are widely used in aerospace and most recently in automobile industry and in architectural applications. The demand for improved attention on a

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number of new materials including Aluminium Metal Matrix Composites. Aluminium is susceptible to localized corrosion such as pitting and crevies corrosions.

3.2 Corrosion and Oxidation

Galvanic corrosion is a major concern between the reinforcement constitutes and metal matrix, which governs the corrosion behavior of any MMC. In an Aluminium Metal Matrix Composites, Al which is an active metal is coupled to reinforcement constituents such as graphite and silicon carbide. There is a tendency for galvanic couple to form between Al and the reinforcement constituents. This galvanic corrosion is responsible for the higher corrosion rates observed in Metal Matrix Composites [18].

The corrosion damage in Al/SiC_p composites is generally caused by pitting attack and by the nucleation growth of Al_2O_3 on the metal surface. The corrosion protection of Al alloys and Al based MMC can be effected by chemical passivation like by immersion of Al alloys and Al MMCs in serium chloride solution for a known period of time, which produces a corrosion resistance surface. Besides, a pitting corrosion can also be protected by this treatment [20].

Another method of preventing corrosion is by giving an epoxy coating and a combination of chemical passiveness in metal chlorides with the polymer coating, gives an excellent corrosion resistance.

3.3 High temperature Applications

With regards to the usage of components made of Aluminium Metal Matrix composites at high temperatures like aerospace and automobile applications, a thermal barrier coating of PSZ, Super-Z alloy, Zirconia Toughened Alumina (ZTA) Alumina-Titania (Al_2O_3 + TiO_2) and Alumina could be plasma sprayed to impart maximum thermal resistance and thermal fatigue resistance to the components[22-23].

4. CONCLUSIONS

The following inferences are made with the charting of strategy for the application of Aluminium 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 reinforcement material SiC can be used for making AMC.
4. For the manufacturing route, Powder Metallurgy with extrusion and heat treatment can be used for making AMC with good mechanical properties.
5. The surfaces of Al MMCs can be protected from pitting corrosion and oxidation by a special surface treatment like dipping the components in a solution of serium chloride for a known period of time and also by anodizing of Al alloy components.
6. High temperature resistance quality on the components of Al MMCs can be provided by giving a proper Plasma sprayed ceramic oxide coatings.

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Appendix 1.

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 existence of 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. Its application can be widened to cater for large scale manufacturing.
Spray co-deposition	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 discontinuous fiber especially particulate reinforcement.