LIGHT METAL MATRIX COMPOSITES – PRESENT STATUS AND FUTURE STRATEGIES

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Abstract

The unique tailorability of the composites to meet the required properties has made them as advanced engineering materials. The continuous fibre reinforced metal matrix composites were developed first. The high cost of the fibre as well as fabrication made them very expensive and hence they are used only in selected critical areas of aerospace and defence. The invention of synthesising discontinuous reinforced metal matrix composites by stir casting initiated in India in the early seventies is a landmark in the history of Metal Matrix Composites (MMC). The initial feasibility studies on making the composites with variety of dispersoids for tailoring new materials possessing special properties with lower cost had kindled interest in many R&D and academic institutions in India in the eighties. Extensive R&D activities were witnessed during this period. The work carried out during this period can broadly be classified into processing methods, structure property correlation, specific property evaluation, prototype component development and evaluation, etc. The expected impact of composite as an exciting engineering material did not take place in the nineties. The industries are still not receptive and their response is lukewarm. At present, only selective academic and R&D Institutions in India are pursuing MMC activity on a low profile. Eventhough similar trends in R&D were observed abroad in the developed countries wherein the industrial applications of composites specially in automotive and engineering industries is steadily increasing Indian industries are yet to think of using MMC components. This calls for a renewed concerted and sustaining effort, pooling up the resources and knowledge as well as consortium type approach among Indian R&D and Academic Institutions. The identified areas include generation of data bank on MMC and their properties, pilot plant production facility for demonstration of prototype developments under simulated industrial conditions, bringing down the cost by redesigning the components, etc.

Introduction

The composites are now well accepted structural materials for wide variety of engineering applications. The most attractive feature of the composite is its tailorable property to suit the needs. In metal matrix composites (MMC) with light matrices, Al, Mg and Ti are the important ones. Most of the R&D and present industrial applications are centered round Al alloy matrix composites, while Mg and Ti alloy matrix composites are slowly now picking up [1]. The continuous fibre reinforced Al alloy matrix composites were the first ones to commercialise in early sixties with boron fibre as reinforcement. The high cost of the fibre as well as the sophisticated method of fabrication technique had made these composite very expensive [2]. The subsequent development of cheaper carbon and silicon carbide fibres for reinforcement brought down the cost of the composite marginally. At present, these composites are used in strategic areas like defence, aerospace, etc. where cost is secondary.

The concept of discontinuous dispersoid reinforced composite by solid state processing is another land mark in the development of MMC [3]. Reinforcing the matrix with whiskers, short fibres or particulates of ceramics could give a composite of special and improved properties compared to monolithic base alloy. Further, the attractive feature is the isotropic nature of the properties. Eventhough the property improvements are not as high as those achievable with continuous fibre ones, they are sufficiently attractive enough for most of the intended engineering applications. The cost of the component production by solid state processing route was still high and hence large scale commercialisation of wide spectrum of engineering component did not take place.

The evolution of solidification technique that too by stir casting [4] is a breakthrough in the processing of light metal matrix composites. At present, a large number of approaches are available (Table I) for synthesising Al alloy matrix composites using basically solidification approach. Among these, a few are commercialised, a few are in pilot plant trials and most of others are in R&D stage. The status of some of these processes are given in Table II. By liquid metal processing technique i.e., by stir casting route, composites are synthesised in tonnes level per batch [5] and are available in the form of ingots for remelting and casting into components as well as semi finished wrought alloy products viz, extruded rods, tubes and other shapes [6]. The commonly used dispersoid is silicon carbide particulates (SiCp) in cast alloy matrix (modified compositions of 356 and 357 Al alloys) and alumina particulates in wrought alloy matrix (6061/2024). Even though the possibilities of using different kinds of dispersoids in Al alloys as reinforcements/fillers have been reported in the literature [4], except SiCp and Al_2O_3 others have not shown any commercial potential. Of late, use of fly ash as filler in aluminium alloy matrix has been discussed, but further development is yet to take place [7]. Further, combinations of two or more different types of reinforcements with similar and different shapes/size/morphologies are also been used to make a new class of composite called hybrid composites [8]. These composites can be tailored to have some special unique combination of the properties.

It has been established that MMC components of improved performance can be made using conventional fabrication techniques like gravity/pressure die casting, etc. They can also be fabricated using the advanced processing techniques like squeeze casting, semisolid processing [9], etc. In fact all fabrication processes which are used with monolithic metals and alloys can be extended to composite materials shaping sometimes with little modifications in the processing parameters. Moreover, the improved performance of the MMC components have been established for automotive applications while some of the other engineering applications are under prototype evaluations [10].

Inspite of all the advantages and merits of MMC, its commercialisation for large scale applications has not taken place still. The potential users have not made up their minds for MMC components in large scale. A few giants in automotive sector with their own R&D are developing and evaluating the performance of the MMC components with very little informations available to others. Hence, due to the non-availability of the performance details, the other potential users are sceptical about the MMC.

The paper overviews the present status of light metal matrix composites in the world and Indian scenario and identifies some of the key points that need to be looked into.

Present Status

International Process Developments :

Different synthesising techniques presently available and their status are listed in Table I and II. Among the processes, powder metallurgy (PM) route for synthesising particle reinforced composites is considered to be the best for tailoring the properties. Use of wide size range particles, nano to a few hundred micron, as well as high vol% (~60) reinforcements are possible with this method with uniform dispersion of the dispersoids. The high cost of the infrastructural requirements limit the commercialisation of this technique. Sintered bearings and smaller size automotive composite components are now produced commercially by this method. High performance composites are made by a few companies at USA, UK and France by PM route.

M/s DURALCAN, USA and M/s Hydro Aluminium Corporation, Norway are the two commercial companies synthesising SiCp and Al_2O_3p dispersed Al alloy matrix composites by liquid metal processing route (stir casting) by a high energy mixing system. The composites are made in a few tons/batch level [5]. They are using high Si (> 7%) matrix alloy for overcoming the reactions of SiCp with molten Al during synthesis. These composites can be remelted and cast into components. In the wrought alloy matrix (6061/2024), Al_2O_3 in particulate or in short fibre form are used. The standard composites contain 15 and 20 vol% of reinforcements and in special cases higher volume percentages reinforcements are also used.

Smaller size composite components with higher vol% (~30) reinforcements are prepared by infiltration technique. Liquid matrix alloy is infiltrated through a porous bed of particulates or short fibres or preform of fibres of specific shape to make the reinforced components. Vacuum or pressure or both are used simultaneously for better infiltration. Squeeze casting technique is also used to make selective area preform reinforced composites. By this, automotive pistons are made for which process equipments are now commercially available. By addition of reactive metals like Mg, pressureless infiltration techniques have also been developed. PRIMEX™ pressureless infiltration process developed by Lanxide Corporation, USA [11] consists of infiltration of molten Mg containing Al alloy through a bed of particles or fibre preforms in a nitrogen atmosphere. Mg improved wetting. By this process 40-80 vol% reinforcements are possible. Components for automotive, robotic, metrology, sports goods, high performance components for aerospace and other engineering applications are prepared by PRIMEX™ process [11].

Mg base alloy matrix composites with SiCp reinforcements are now commercially being made by Magnesium Elekron, UK. Presence of Li (0.2-0.7 wt%) in Mg aids wetting. SiCp particles of wide size range are dispersed in Mg alloy matrix [12]. M/s International Nickel company (UK), (INCO) has Ni coated carbon fibres. They have developed a hybrid composite using these coated fibres in combination with silicon carbide particulates [13]. During the composite synthesis, Ni combined with matrix Al to form $NiAl_3$ intermetallic which along with SiCp gives an excellent adhesive and abrasive wear resistant composite. The excellent thermal conductivity of this composite viz., three times higher than that of the cast iron along with low density (one third of cast iron) have made this composite an excellent material for automotive cylinder liner applications. This composite can be cast into components using any of the conventional casting techniques, viz., sand, gravity or pressure die casting. The presence of fibres hinders the settling of the particles thus avoids segregation [13-14].

M/s COMALCO Australia has developed Al alloy matrix composites with microspheres of alumina as reinforcement by stir casting technique [15]. They have not initiated large scale manufacture of these composites since its demand was not felt.

The spray casting technique developed by M/s Osprey Industries, UK for monolithic metals and alloys now has been extended for the production of composites. This technique is capable of producing high deposition rates (10 kg/min) of composites with about 30 vol% reinforcements. The dispersoid size is limited to 2-10μm. However, the spray deposited composites require further consolidation which adds up to the cost [16].

Electromagnetic stirring and mixing [17] in liquid or semisolid phase of Al alloys for synthesising composites followed by continuous casting into cylindrical shaped billets or plates is now the state of art technology for composite making. A large scale production of composites is now being attempted. In addition, extensive work is being carried out on processing of composite components using special fabrication techniques like squeeze casting, thixoforging, centrifugal casting, pressure die casting, etc.

International Supporting Developments :

The various processing methods available to synthesise the light metal matrix composites have been well established. Efforts will continue in modifying the processing condition for improving the properties and reducing their cost. The first and the foremost in this direction is the quality control of composite during production and subsequent processing. The conventional methods available for on-line testing and quality control of the monolithic alloy have been extended for composites also. The important ones are electrical resistivity, ultrasonic and eddy current techniques. However, these techniques are still not standardised for MMC.

Machining is another area where some detailed studies have been initiated. With reinforcements like SiCp, Al_2O_3p, the composites are extremely difficult to machine with conventional tools like HSS, etc. The use of polycrystalline diamond (PCD) tools are necessary for these composites [18]. The use of PCD tools makes the machining process expensive adding to the high cost to the composite component. To keep the machining cost down the composite components have to be made by resorting to net shaped composite component processing technology. In this context, semisolid processing takes the lead role for MMC component development.

Recycling and reclamation of monolithic metals and alloys have been very well established. The scrap value is an important feature for high volume market components. A proper selection and grading of the MMC components are essential for this necessitating development of right methods. Duralcan has established the effective recyling and reclamation techniques for their composites [19].

Current International Trends For Application

The relatively high cost of composite component compared to the monolithic alloys has limited MMC applications to a few sectors in spite of their very attractive features. The application areas of MMC include improved stiffness, elevated temperature, better damping property, superior wear resistance, lower thermal expansion, etc. The volume percentage of reinforcements is limited to about 20-30 vol% and under special requirements has gone even upto 50-60. The commercially sold composites are with 10, 15 and 20 vol% reinforcements [6].

In the transportation section, the use of MMC has shown about 5% fuel economy by reducing the automotive component weight by about 10%. Further, MMC is also helping in keeping lower emission standards. Thus, MMC application contemplates new concept of corporate average fuel economy (CAFE). The fleet tests conducted by Ford Motor Co. on Duralcan F3S20S (359 Al alloy with 20% SiCp) cast composites brake rotors showed improved life of both rotors and pads. The higher thermal conductivity of the composite over conventionally used cast iron has mainly contributed to this. Japanese automotive industries are using fibre reinforced MMCs with both petrol and diesel engine vehicles for the last several years. Honda is using hybrid Al composite engine blocks with alumina and carbon fibre preforms. The components are made by modified die casting. However, due to the high cost of the components, only limited volume is used. Honda is also making brake rotors using evaporative, squeeze and permanent mould casting techniques. Al_2O_3 reinforced cylinder liners are made by squeeze, pressure and/ or pressure die casting methods. Toyota is making saffil fibre reinforced Al alloy pistons [20,21]. Some of the cast MMC components developed and reported from Japan are given in Table III, while potentials of AMC in automotive application [7] is given in Table IV and demonstrated AMC Automotive components [22] are given in Table V.

In USA, Woupaca Foundry has commissioned a plant to produce 15,000 brake rotors and drums with SiCp-Al alloy composites. The capacity is expected to go up to 60,000 components per year shortly. The technology of this was originally developed by Lanxide Corporation. The first American automobile to incorporate MMC brake rotor is "The Lotus Elise" [23]. In U.K [24], a consortium of companies has ventured in using Al matrix MMCs with SiCp and Al_2O_3 reinforcements in machines and prototypes such as connecting rods, textile machinery, high speed machining parts. British Railways have also gone in a big way for using of Al-SiCp composites. Mg alloy matrix composites with SiCp are now being used recently for pulleys, sheaver, chain enclosures, bearing surface, connecting rods for pistons etc.

National Process Developments :

The particle reinforced Al alloy matrix composites through stir casting technique were prepared in India nearly three decade back. In seventies extensive work had been carried out on the feasibility of making composites incorporating different types of dispersoids exclusively in Al alloy matrices and correlation of structure and properties. In all studies, the stirring was carried out using a mechanical impeller. Composites were made by both semisolid and fully liquid processes. The composite casting facility is at present limited to about 25 kg/batch at RRL-T and RRL, Bhopal and about 40 kg/batch at HAL, Bangalore. The composite making capacity at all other institutions is maximum of 5 kg/batch. Graphite particles and SiCp are the dispersoid used.

By powder metallurgy technique, composites (Al-SiCp system) are made at DMRL Hyderabad, HAL Bangalore and a few other academic institutions. Based on the DMRL knowhow, NFTDC, Hyderabad is producing composites up to around 15-20 kg/batch. Composites are made by spray casting techniques like pressureless infiltration, reaction synthesis etc., at IISc, Bangalore and DMRL, Hyderabad.

Even though, in India, extensive work on synthesis and structure property correlation of particle and short fibre reinforced composites was carried out, no technology has been developed or commercialised. Hence, the process development is still at infancy.

On secondary processing of the composites mainly on extrusion, NPL, New Delhi has carried out detailed work on powder metallurgy and casting based composites. In recent years, NML, Jamshedpur and a few other academic institutions have initiated some work.

National Supporting Developments :

Unlike, UK, USA and Japan, the supporting developments on processing to components have not taken place in India. Very limited studies that too more of academic in nature have been carried out on nondestructive evaluation, machining, corrosion studies and even on advance techniques like squeeze casting, pressure die casting etc.

On component development front, limited work has been carried out by RRL-T, RRL-Bhopal and DMRL, Hyderabad. However, none of the components are commercialised so far. There is no specific trend for industrial application of MMC in India since most of the industries are either ignorant or have no interest. Table VI gives the list of organisations helping RRL-T in various aspects of MMC developments, characterisation and evaluation.

Future Strategies

The acceptance of a new engineering material for commercialisation is an exceedingly slow process. Replacement of a proven conventional material by a new material is possible only on cost and performance grounds. MMCs having proven engineering advantages and tremendous potential for the future, their cost needs to be brought down. The long term performance and reliability of MMC components in automotive sector have proven since they have entered these sector seriously less than a decade back. The engineering performance evaluation takes nearly two decade. According to BDM Federal Inc, USA [12] four goals need to be addressed. They are (i) reduction in production cost (ii) improving communications among government industries, R&D institutions and academia (iii) increasing the commercial demand and (iv) overcoming the technical problems. Towards achieving this, it is suggested that industry should develop a low cost MMC insertion programme for automotive application, military retrofit applications, more efficient secondary processing techniques, lower cost reinforcing materials and improved integrated design, analysis and test methods.

The nine major American Companies which are involved in R&D, process and component developments and use of MMC components have come up with some action points [1,6]. Some of them are (i) Tailoring composites to the requirements by specific reinforcements and matrix alloy even with new matrix alloy, (ii) Reducing the reinforcement cost by choosing the byproduct of some other technology, (iii) Developing cheaper fabrication techniques, (iv) Enhancing the ductility and fracture toughness of the composites by giving treatments to disperoids and improving its toughness, (v) Developing methods for faster quantification in measuring the degree of non uniformity of dispersion, (vi) Understanding the flow behaviour of the composite slurry and segregation behaviour of the dispersoids during casting and mould filling, (vii) Structure property correlation, variations and tolerances, (viii) Better understanding of surface and interface in composites, (ix) Role of environments and other parameters such as pressure, vacuum, etc. on structure and properties of composites, (x) Use of conventional grain refiners, vibration etc. on structure properties of composites, (xi) Development of hybrid composites (xii) Development of suitable master composites, (xiii) Recycling and use of composite scrap and (xiv) Creation of a data bank on properties of the composites, etc.

Since the composite development in India has not reached to a stage of industrial application all the above mentioned strategies may not be applicable completely to India. As a first instance, there is a need to identifying few sectors where MMC can increasingly be used. In these areas, identifying the key users, product development and evaluation have to be carried out involving the users. There should be a nodal agency which makes the composite in large scale (150-200 kg/batch) and supply to the needed customers. A strong database on the composites should also be available. For this, a consortium approach will be more appropriate. The like minded R&D and academic institutions should come together in sharing the facility, knowledge and resource.

Conclusion

The unique combinations of tailorable properties of metal matrix composites for a variety of engineering applications have been well established. Development of different types of fabrication techniques further strengthen the product and specific component development. Discontinuous dispersoid reinforced composites are less expensive compared to the continuous ones. Hence, they are considered for application in large volume user sector like automotive and general engineering. Extensive R&D work on MMC product development evaluation has been carried out extensively in Japan, UK, USA and other countries and a large number of components has been identified. Some of the MMC components are now in use in automobiles. The higher costs of the MMC components hinder the use in large scale. A consortium approach has been initiated by the MMC user and some action points have been identified. This will enable the use of MMC in large scale in automotive industries. In India, the work on MMC is limited to a few R&D and academic institutions. Industries have not actively come forward for MMC application even though process knowhow are available. It is advocated to have a composite synthesising facility of about 100-150 kg/batch and to have a data bank on composite properties for effective choice and utilisation of composites.

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Table I
MMC Synthesising Routes

State	Techniques
Solid State	— Powder Metallurgy
	— Diffusion Bonding
Liquid State	— Infiltration
	# Squeeze Casting
	# Low Pressure Casting
	# Vacuum Casting
	# Squeeze Assisted Vacuum Casting
	# Gas Pressure cum Vacuum Casting
	# Pressureless Infiltration
	— Stir Casting
	# Fully Liquid State
	# Semisolid State
	— In-situ Processes
	# Liquid-Liquid
	# Plasma Reactive Synthesis
	# Self Propagating High Temperature synthesis
	— Spray Casting

Table II
Status of light alloy matrix composite systems

Reinforcement	**Matrix Alloy**		
	Aluminium	Magnesium	Titanium
Staple Alumina	C	D	-
Particles Silicon Carbide	C	D (PS)	-
Particles Alumina	C	-	-
Whisker Silicon Carbide	D	-	-
Monofilament Silicon Carbide	D	D	D
Monofilament Boron	C	-	-
Fibre (Tow) Silicon Carbide	D	-	-
Fibre (Tow) Alumina	D	D	-
Fibre (Tow) Graphite	D	D	-

Table III
The Practical Applications of Cast MMCs for commercial products in Japan

Product	MMC System	Method of Manufacture	Characteristics of applied MMC	Year (maker)
Ring Groove reinforced piston	Al_2O_3/Al alloy	Squeeze Casting (SC)	Light weight, wear resistance at high temperature	1983 (Toyota)
Golf goods Face of screwdriver	SiCp/Al alloy	SC	Light weight, abrasion resistance	1984 (Nippon Carbon)
Connection rod of gasoline engine	SUS fibre/Al alloy	SC	Specific strength	1985 (Honda)
M6-8 bolt	SiC_w/6061	SC, extrusion, tread rolling	Neutron absorption, high temperature strength, little degassing	1986 (Toshiba)
Vane, pressure side plate of oil pressure vane pump	$Al_2O_3.SiO_2$/AC4C	SC	Wear resistance, noise damping	1987 (Hiroshima Aluminium)
Joint of aerospace structure	SiC_w/7075	SC, rolling	Specific strength, low thermal expansion	1988 (Mitsubishi Electronics)
Rotary compressor vane	SiC_w/Al-17% Si-4%Cu alloy	SC	Specific strength, wear resistance, low thermal expansion	1989 (Sanyo)
Shock absorber cylinder	SiC_p/Al alloy	Compocasting, SC, extrusion	Light weight, wear resistance, thermal diffusion	1989 (Mitsubishi Aluminium)
Diesel engine piston	SiC_w/Al alloy	SC	Light weight, wear resistance	1989 (Nilgata)
Cylinder liner	Al_2O_3.CF/Al alloy	Low pressure SC	Light weight, wear resistance	1991 (Honda)
Hub of damper pulley[10]	$Al_2O_3.SiO_2$/Al alloy	SC	Light weight, reduction of vibration	1991 (Toyota)

Table IV
Potential AMC Automotive Applications[22]

System	Component	Justification
Engine	Piston Crown	High temperature, Fatigue, Creep, Wear
	Piston Ring Groove	Wear resistance, Weight reduction
	Rocker arm	Weight, Stiffness, Wear
	Valve	High temperature, Fatigue, Creep, Wear
	Wrist pin	Specific Stiffness, Wear, Creep
	Cylinder Block (liner)	Wear and Seizure Resistance, Low friction, Weight
	Connecting Rod	Specific Stiffness, Weight
	Bearings	Weight, Reduced Friction
Suspension	Struts	Damping, Stiffness
Drive line	Shift Forks	Wear, Weight
	Drive Shaft	Specific Stiffness, Fatigue
	Gears	Wear, Weight
	Wheels	Weight
Housings	Gearbox Bearing	Wear, Weight
	Differential Bearing	Wear, Weight
	Pumps	
Brakes	Disk Rotors	Wear, Weight
	Calipers	Wear, Weight

Table V
Demonstrator Aluminium MMC Automotive components

Reinforcement	Component	Property	Benefits	Manufacturer
SiCp	Piston	Wear resistance, High strength	Reduced weight	Duralcan, Martin Marietta, Lanxide
Al_2O_3(f).	Piston ring groove	Wear resistance	High running temperarure	Toyota
Al_2O_3 (f).	Piston crown (Combustion bowl)	Fatigue resistance, Creep	Opportunity to use Al, reduced reciprocating mass	T&N, JPL, Mahle and others
SiC(p)	Brake rotor, Caliper, Liner	Wear resistance	Reduced weight	Duralcan, Lanxide
Fiberfax	Piston	Wear resistance, High strength	Reduced weight	Zollner
SiC(p)	Drive shaft	Specific stiffness	Reduction of parts and weight	GKN, Duralcan
SiC(w) .	Connecting rod	Specific stiffness and strength, thermal expansion	Reduced reciprocating mass	Nissan
Al_2O_3(f)+	Connecting rod	Specific stiffness and strength, thermal expansion	Reduced reciprocating mass	DuPont, Chrysler
Al_2O_3-SiO_2-C	Cylinder liner	Wear resistance, Expansion	Increased life, reduced size	Honda
Gr(p)	Cylinder liner, Pistons, Bearings	Gall resistance, Reduced wear and Friction	Increased power output	Assoc.Eng., CSIR, IISc++
TiC(p)	Piston, Connecting rod	Wear, Fatigue	Reduced weight and wear	Martin Marietta
Al_2O_3	Valve spring, Retainer cam, Lifter body	Wear strength	Reduced weight, Increased life	Lanxide
Fly-Ash	Pulleys for power steering systems	Wear resistance	Increased life, Reduced weight, low cost	EPRI & Ford Motor Company
Fly-Ash	Pistons, Cylinder liners & Connecting rods	Wear resistance, Gall resistance	Increased life, Reduced weight, Low cost	Solidification Lab., U/W, Milwaukee

. Short Fibres
+ Long fibres
++ CSIR- Council of Scientific and Industrial Research; IISc - Indian Institute of Science, Bangalore

Table VI
Collaborating Institutions for evaluating Al MMC of RRL-T

Institution	Composite System	Nature of Study
I.I.T., New Delhi	Al-Graphite Al-SiCp	Fracture toughness Machinability & Tribology
NIFFT, Ranchi	Al-SiCp	Forging aspects
I.I.T., Madras	Al-SiCp	Machining Aspects
I.I.T., Kanpur	Al-SiCp	Strip Casting
I.I.Sc., Bangalore	Al-SiCp	Interface studies
I.I.T., Kharagpur	Al-SiCp	Interface studies
NPL, New Delhi	Al-SiCp	Secondary processing
NML, Jamshedpur	Al-SiCp	Secondary processing
NAL, Bangalore	Al-SiCp	Machining aspects
CECRI, Karaikudi	Al-SiCp	Corrosion studies
CGCRI, Calcutta	Al-SiCp	NDT/Interface
BARC, Mumbai	Al-SiCp	Irradiation studies
DMRL, Hyderabad	Al-SiCp	300x300x25mm plates- Evaluation of properties
DRDL, Hyderabad	Al-SiCp	Sand casting properties-components
VSSC, Trivandrum	Al-TiO_2 Al-SiCp	Secondary processing NDT/Secondary processing

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