Journal of Materials and Environmental Sciences
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2018, Volume 9, Issue 7, Page 1979-1986

http://www.jmaterenvironsci.com

Processing and Characterization of Hybrid Metal Matrix Composites

Chinish Kalra[1], Shivam Tiwari[1], Akshay Sapra[1], Sidhant Mahajan[1], Pallav Gupta[1]*

[1]Department of Mechanical Engineering, A.S.E.T., Amity University, Uttar Pradesh, Noida-201313, INDIA

Received 17 Feb 2017,
Revised 08 Apr 2017,
Accepted 14 Apr 2017

Keywords

- ✓ Reinforcement;
- ✓ Stir Casting;
- ✓ Squeeze Casting;
- ✓ Vapour Deposition;
- ✓ In-Situ Fabrication;
- ✓ Powder Metallurgy;
- ✓ Aluminium Matrix Composites

Pallav Gupta
pgupta7@amity.edu
+918860490258

Abstract

A Metal Matrix Composite (MMC) is a composite material which is formed of at least two individual parts, one necessarily being a metal and the other constituent may be a ceramic material. A metal matrix composite is fabricated by using metals like aluminium, magnesium etc. (which are generally of low density) with ceramic reinforcements like silicon carbide (SiC), aluminium oxide (Al_2O_3) or minerals like mica, graphite etc. MMC produced have improved tensile strength, higher wear resistance, higher operating temperature, greater stiffness etc. as compared to the individual metallic element. MMC offer a great change in the mechanical, electrical, structural and even magnetic properties which can be studied and can be further used in various industries and fields like aerospace, marines, jet engines, satellites, automobiles etc. Modern world has introduced various methods of reinforcement addition into metal like stir casting, squeeze casting, physical vapour deposition (PVD), chemical vapour deposition (CVD), in-situ fabrication, powder metallurgy etc. The present paper reports a review on the structural and mechanical behaviour of aluminium hybrid metal matrix composite. Aluminium matrix composites (AMC) are modern and advanced metal matrix composites (MMC) that can meet the recent increasing demands of various industries. The physical, structural and mechanical properties of aluminium matrix composites have made them useful in fields of aerospace, marines etc. It is necessary to select the right combination of compounds or minerals to reinforce with the metal as it will directly affect the properties of metal matrix composite thus formed. Selection of different constituents will affect the properties of MMC differently and the composition of constituents can also be varied to observe the changing properties of MMCs. This paper describes the various processing techniques and the various research and development activities taking place in the field of hybrid metal matrix composites.

1. Introduction

A composite material can be defined as a combination of a matrix and a reinforcement, which when combined gives properties superior as compared to that of individual components. The development of a composite is done so that the combination of the reinforcement and the matrix can be changed to meet the required final properties of a component. Different types of Composite Materials are: Carbon fibre-reinforced polymers (CFRP), Glass fibre-reinforced polymers (GFRP), Aramid products and Biocomposites. Advanced composite materials (ACMs) are generally characterized by unusually high strength fibres with unusually high stiffness when compared to other materials. Advanced composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness, strength and relatively easy processing. Advanced composites are replacing metal components in many uses, particularly in the aerospace industry. ACMs are classified according to their matrix phase. These classifications are Polymer Matrix Composites (PMCs), Ceramic Matrix Composites (CMCs), Metal Matrix Composites (MMCs), Carbon-Carbon Composites and Hybrid Metal Matrix Composites.

Metal Matrix Nanocomposites (MMNCs) are made by dispersion of hard ceramic reinforcement into ductile metallic matrix. In MMNCs among the two phases either of the phase should be in nano size. Many applications found in our daily lives are based on metal matrix composite materials. Metal Matrix Nanocomposites (MMNCs) usually incorporates micron/nano scale ceramic reinforced with bulk material, which offers various opportunities to material such as tensile strength, ductility, strength, density, electrical and wear resistance [1].

The relative cost of nano-scale reinforcement is a great task in the development of metal matrix nanocomposites because of complex process and synthesis. The methods used to synthesize the metal matrix nanocomposites (MMNC) includes in-situ fabrication technique, chemical vapor deposition, stir casting, squeeze casting and any others discussed further in this paper. A main reason for selection of aluminium is that it is available in ample amount on earth' crust, making its availability more than 8 percent of earth's mass. Aluminum binds very easily with the other elements. It offers many valuable properties. It is the lightest metal and it is almost 3 times lighter than Iron (Fe). It is also very flexible, strong and corrosion resistant because the surface of aluminum is covered with extremely thin and strong layer of oxide film. It is a good conductor of electricity as well [2]. Lot of researchers throughout the globe have carried out various investigations on aluminium based metal matrix composites. However, no systematic attempt has been made to study the structural as well as mechanical behaviour of hybrid Metal Matrix Composites. Therefore, the present paper reports the processing and characterization of aluminium based hybrid Metal Matrix Composites. The present class of material is useful for aerospace applications.

Aluminium matrix composite is very competitive in industrial world. Aluminium matrix strengthens when it is reinforced with hard ceramic materials such as Al_2O_3, SiC, B_4C etc. The present paper reports overview of hybrid metal matrix composites. Figure 1 shows the development curve of market for modern materials.

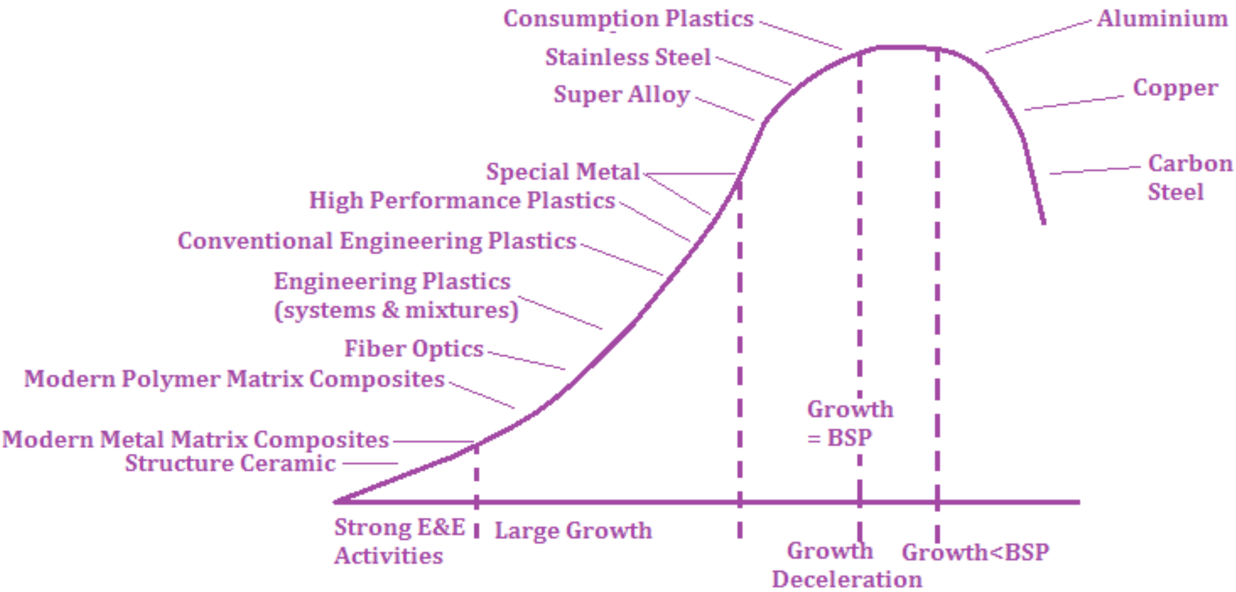

Figure 1: Development Curve of Market for Modern Materials [3]

2. MMNC Manufacturing Techniques

The improved properties of MMC are not only the result of various reinforced components, but the technique used for the manufacturing of the MMC plays a vital role not only in the physical appearance of the composite but also plays major role in the development of different mechanical properties. Techniques used for the manufacturing of the composites are classified according to the nature and behaviour, form of raw material and required grain structure of the final MMC. These techniques are carried out in both molten and powder form of metal with the effect of change in mechanical properties during the fabrication process itself.

Based on the different aspects of the fabrication equipments and nature of the materials, the manufacturing techniques are classified as:

A. Stir Casting
B. Squeeze Casting
C. Chemical Vapour Deposition
D. Physical Vapour Deposition
E In-situ Fabrication Technique
F. Powder Metallurgy (P/M)

A: Stir Casting

Stir Casting involves continuous stirring of molten metal along with ceramic material and immediately pouring it into the mold, where it is allowed to cool and solidify. In this process of stir casting, particles come together to form a collected mass which can only be dissolved by continuous and vigorous stirring of molten mixture at high temperature. This method is one of the low cost process out of available manufacturing techniques for AMCs, with advantage of low cost; it also offers a wide range of material and processing conditions. It can also manufacture composites with up to 30% volume fraction of reinforcement with better bonding of metal matrix. The addition of ceramic particles is done with continuous stirring. Figure 2 shows the stir casting process. Required components to fabricate a composite with the method of stir casting involve the following stepwise process:

1. Frame of stirring system- Its frame is generally made of iron rods. Its frame is generally of square structure.
2. Fabrication of Stirrer- The material of stirrer is generally of mild carbon steel. .
3. Motor- The motor is generally fitted on top or on center of the frame for the stirring process.
4. Furnace Specification- Generally an underground coal fired furnace is used for the matrix preparation.
5. Raw Materials- For the preparation of metal matrix composite, the base metal is melted and ceramic material is added to it [4].

B: Squeeze Casting

Squeeze Casting is another liquid metallurgy technique which is a combination of both casting and forging. Metal matrix composite produced by the process of squeeze casting generally has improved mechanical properties. Since this process combines the advantages of both casting and forging, hence, it can be used to produce high quality products. The liquid form of metal is poured into the bottom half of the preheated lubricated die and it is forged until it solidifies

Further, as the metal begins to cool, pressure is applied as the upper die closes and it is maintained until the solidification of entire casting. Coring can be done to form holes. Generally, warm dies are sprayed with a good graphite lubricant spray prior to casting. Mostly the non-ferrous alloys like alloys of aluminium, magnesium are compatible with this process [5]. Squeeze casting offers a wide range of shapes and components than offered by any other manufacturing techniques and also there is no wastage of any material. This process also offers low level of porosity and good texture. Figure 3 shows the Squeeze Casting process.

C: Chemical Vapour Deposition (CVD)

Chemical vapor deposition (CVD) is a technique which helps to produce high performance and quality in solid materials and also helps to attain pure, uniform coating of metals or polymers, on contoured surfaces. CVD is mostly used for material processing technology. The major application of CVD involves coating of solid thin films on contoured surface which helps to produce refine materials and powder. Major group of elements in periodic table have been tested or performed by CVD technique which is then combined to form composites [6]. CVD involves flowing of a precursor gas into a chamber which contains one or more heated object which is further coated inside the chamber. Further, chemical reaction takes place on and near the hot surfaces, which results in deposition of thin film on the surface. This is followed by production of chemical by-products and unreacted by-products which are exhausted out of the chamber. The material which is deposited inside the chamber has a wide range of applications. This is done in hot wall reactors and cold wall reactors, with and without carrier gases and temperature ranging from 200-1600°C. Chemical vapor deposition has very high purity because of which we can produce a wide variety of materials. It results in removing of impurities from gaseous precursors using distillation techniques [7].One of the major disadvantages lies in the properties of precursor. Precursor should be volatile near room temperature, but it is significant for number of elements in the periodic table. In some conditions precursor can be highly toxic, explosive, or corrosive. Figure 4 shows chemical vapour deposition technique.

D: Physical Vapour Deposition (PVD)

Physical Vapor Deposition (PVD) is a collective set of processes used to deposit thin layers of material, typically in the range of few nanometers to several micrometers. It is carried out in between the temperature range of 150°C to 500°C under high vacuum. Thermal evaporation and sputtering are the two most common PVD processes. Thermal evaporation relies on vaporization of source material by heating the material using appropriate methods in vacuum whereas sputtering is a plasma-assisted technique that creates a vapour from the source target through bombardment with accelerated gaseous ions [9]. Figure 5 shows the physical vapour deposition process.

PVD technique is carried out in three following steps:

- Vaporization of material from a solid source assisted by high temperature in vacuum or gaseous plasma.
- Transportation of the vapor in vacuum or partial vacuum to the substrate surface.
- Condensation onto the substrate to generate thin films [10].

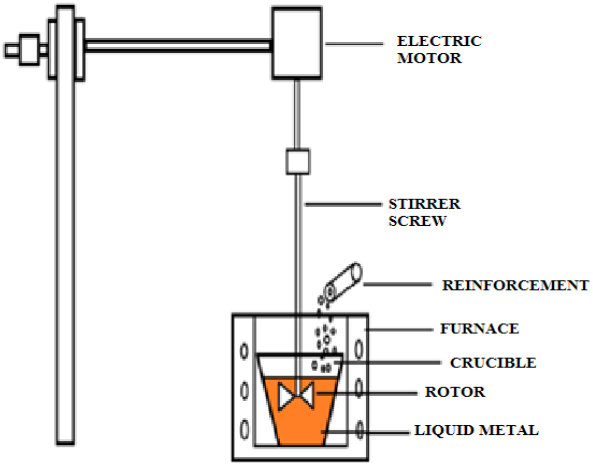

Figure 2: Stir Casting Process.

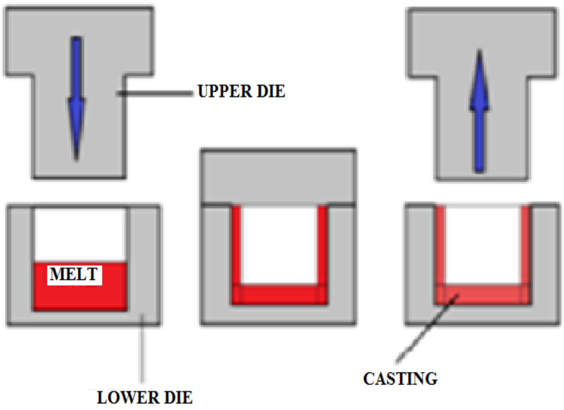

Figure 3: Squeeze Casting Process.

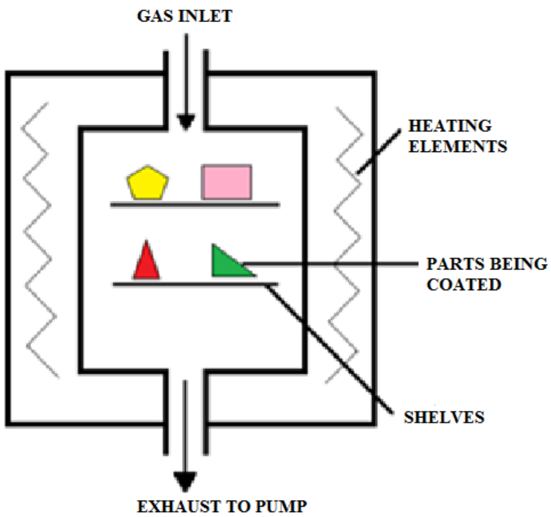

Figure 4: Chemical Vapour Deposition.

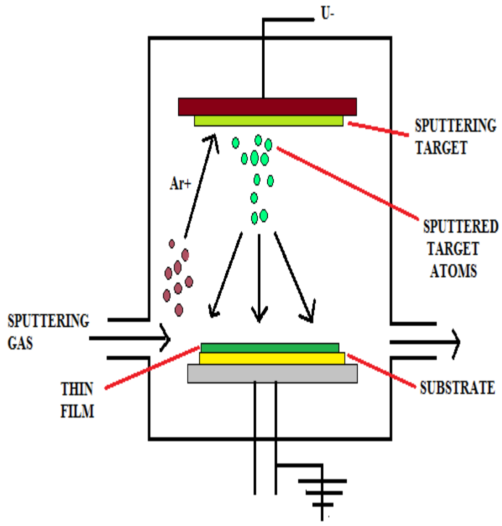

Figure 5: Physical Vapour Deposition.

E: In-Situ Fabrication Technique

In-situ fabrication technique involves chemical reactions which results in formation of a very fine and thermodynamically stable metal state which is reinforced with ceramic phase within a metal matrix. This technique provides thermodynamic compatibility at the matrix reinforcement interface. As a result, reinforcement surfaces obtained are free of contamination and hence, a stronger matrix dispersion bond interface is obtained. In-situ fabrication technique analyzes the intrinsic properties of individual nanostructures and it accomplishes best design of the nano-devices from nanostructures [8]. This technique also provides exploration of intriguing phenomena at very small scale which is further followed by small integration of the nanostructures into functional devices. In situ technique is also discussed in biological imaging and energy generation. It has also been developed for macro porous scattering film. This method of scattering film is very helpful because it helps to decrease the transmittance of electrode (e^-) film from 58 percent% to below 1 percent% which increases the efficiency by 22%. Figure 6 shows the in-situ fabrication technique.

F: Powder Metallurgy (P/M)

It is the manufacturing science of producing solid parts of desired material and geometry from powders. It can also be named as powder processing technique considering that non-metal powder can also be involved. The processing generally compromises a family of production technologies, these technologies process a feedstock in powder form to manufacture components of various types. P/M can be carried out for both ferrous and non ferrous components, ferrous components for P/M structural part production are manufactured using either metal sponge process or spray atomization and the non ferrous components are processed by the introduction of alloying addition in the elemental powder form or the incorporation of a pressing lubricant. This involves pressing the powder component in a rigid toolset, comprising a die, punches and possibly mandrels or core rods.

Sintering is essential in achieving the desired compactness, enhance integrity and strength, the process involves heating of the material usually in an inert atmosphere to a temperature that is below the melting point of the major constituent. In some cases the minor constituent can form a liquid phase at sintering temperature such cases are described as liquid phase sintering. The need of size reduction after crushing of the macro constituents has significant effect on the uniformity of the finished product and reduction in size of the constituent is achieved with ball milling process where with the help of impact and attrition the macro constituents are converted into nano size constituents. In P/M, there are a lot of considerations, but the powder used in the metallurgy is considered first and it can be in pure elemental form or an alloy powder or both elemental and alloy powders together. The ratio of powders depends on the properties of the material to be derived from P/M. It may be noted that powders itself are considered to be potential hazard and may be flammable, thus causing health risks to the individuals [11]. P/M has potential advantages over the conventional manufacturing technologies, in comparison to sintering it gives a varied flexibility to produce metal-metal as well as metal-non metal combination with huge potential saving in production which is geared towards mass production. P/M is near net shape forming process, resulting in no requirement of finishing operation in many cases and possibility of achieving high dimensional accuracy is also very high compared to other conventional fabrication techniques.

Figure 7 shows the steps involved in P/M process.

Apart from open pores, vacancies like closed pores may occur during processing and these are not open to the environment but are generally produced during the pressing and sintering process when open pore region is being closed off.

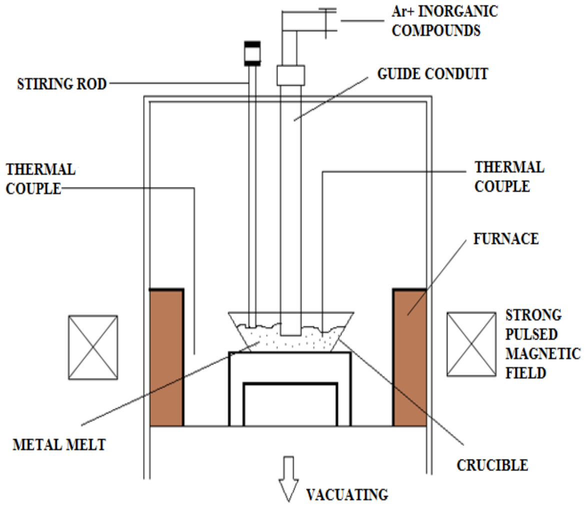

Figure 6: In-situ Fabrication Technique.

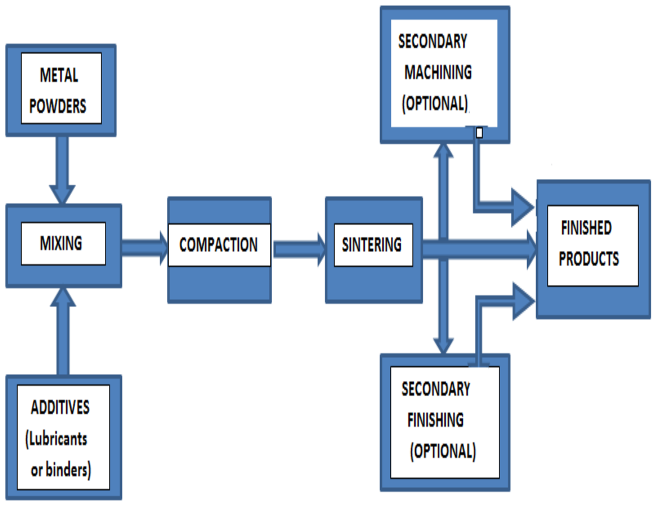

Figure 7: Steps Involved in P/M.

3. Research and Development

Pradeep et al. reported the effect of silicon nitride particles (Si_3N_4) reinforcement on mechanical properties and microstructures of Aluminium alloy composites (AA6082-T6). Stir casting technique was used for fabrication of these composites. Reinforcement content of silicon nitride was varied from 0% to 12% in a step of 3%. Scanning electron microscopy was used to reveal the presence of Si_3N_4 particles in the aluminium matrix by showing the microstructure images. Also, the distribution of Si_3N_4 particles has been recognized with X-ray diffraction technique. It was seen that density of fabricated composites were increased from 2.69 to 2.75 g/cm^3 respectively, with respect to addition of weight percentage of Si_3N_4 particles (i.e. from 0% to 12%). Hardness of composites increased from 49.5 VHN to 93.5 VHN and 31.6 BHN to 58 BHN with respect to addition of weight percentage of Si_3N_4 particles [12].

Table 1 shows the density and porosity of various composites and table 2 shows the chemical composition of base metal AA6082. Figure 8 shows the XRD pattern of AA6082-Si_3N_4 composite and figure 9 shows the micro-hardness variation with weight % of Si_3N_4.

Mohammed Imran utilized waste sugarcane bagasse-ash and graphite as reinforcement in fabricating of an aluminium alloy (Al-7075) based hybrid matrix composites. The matrix composites were fabricated by stir casting process at 750°C. Mechanical properties of aluminium matrix composites were studied at different weight ratios of the reinforced composites and with variation of graphite by keeping the weight of bagasse ash constant at 2%. It was observed that ultimate tensile strength and yield strength increases gradually with increase in graphite. The same is followed with increase in weight% of graphite and keeping bagasse ash constant at weight of 4%. Effect of graphite on hardness of composites shows that as graphite increases, hardness also increased gradually while 2% bagasse ash was kept constant and kept on increasing as the % of graphite is increased by keeping bagasse ash constant at 4 weight % also. The similar trend is observed when the effect of bagasse ash is carried out by keeping graphite at 1 weight % and also at 3 weight % of graphite [13].

Table 1: Density & Porosity of Various. Composites [12]

Wt. % of reinforcement	Density (g/cm^3)	Porosity (%)
0	2.69	0.37
3	2.70	0.55
6	2.72	0.73
9	2.74	1.08
12	2.75	1.43

Table 2: Chemical Composition of Base Metal AA6082 [12]

Constituent	Al	Cu	Mg	Si	Fe	Ni	Mn	Zn
Content (%)	97.14	0.038	0.690	1.16	0.258	0.04	0.580	0.027

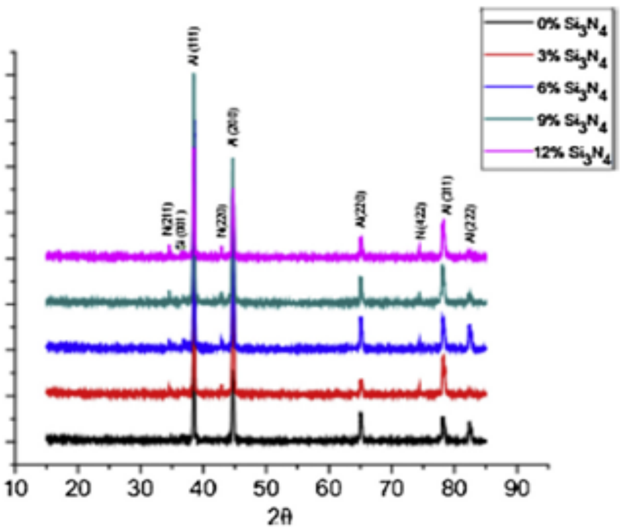

Figure 8. XRD Pattern of AA6082-Si_3N_4. [12]

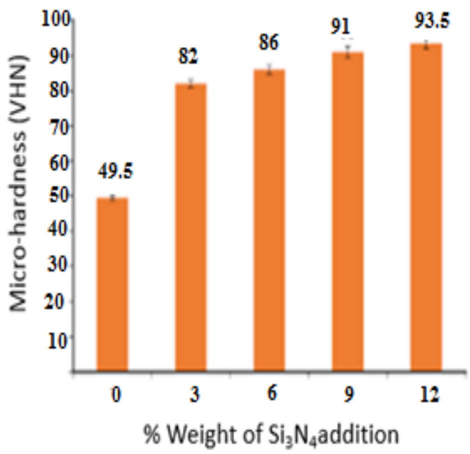

Figure 9. Micro-hardness variation of Si_3N_4wt [12]

Table 3 shows the experimental results of mechanical properties. Table 4 shows the effect of graphite on hardness of the composites. Table 5 shows ultimate tensile strength (UTM) of composites with variation in graphite. Table 6 shows ultimate tensile strength of composites with variation in bagasse-ash.

Table 3: Experimental Results of Mechanical Properties [13]

Experiments	Composition		MPa) UTS)	BHN	Percentage Elongation (%)	Yield Strength (MPa)
	Graphite(%)	Baggase Ash (%)				
1	1	2	259.3	87.3	6.7	176.84
2	3	2	265.4	92.4	6.4	183.83
3	5	2	272.3	94.3	5.8	197.05
4	1	4	267.3	87.7	6.3	180.68
5	3	4	283.4	94.2	5.9	188.56
6	5	4	290.3	95.4	5.2	199.29
7	1	6	294.2	88.3	5.9	184.93
8	3	6	296.3	95.4	5.4	190.53
9	5	6	299.4	99.6	4.9	200.86

Table 4: Effect of Graphite on Hardness of the Composites [13]

Experiments	Composition		BHN-Hardness			BHN Mean	Standard Deviation	Standard Error	Confidence %95 Interval	
	Graphite (%)	Baggase Ash(%)	1	2	3				Minimum	Maximum
1	1	2	87	89	86	87.3	0.494974	0.234514	86.8403	87.7596
2	3	2	93	91	93	92.4	0.141421	0.081661	92.2399	92.5600
3	5	2	95	94	94	94.3	0.070710	0.040824	94.2199	94.3800
4	1	4	88	89	86	87.7	0.070710	0.040824	87.6199	87.7800
5	3	4	94	95	94	94.2	0.070710	0.040824	94.2199	94.3800
6	5	4	96	95	95	95.4	0.141421	0.081661	95.2399	95.5600
7	1	6	88	88	89	88.3	0.070710	0.040824	88.2199	88.3800
78	3	6	95	95	96	95.4	0.141421	0.081661	95.2399	95.5600
9	5	6	99	1 101	99	99.6	0.141421	0.081661	99.4399	99.7600

Table 5: Ultimate Tensile Strength of Composites with Variation in Graphite [13]

Experiments	Composition		MPa) UTS)
	Graphite(%)	Bagasse hsA (%)	
1	1	2	259.3
2	3	2	265.4
3	5	2	272.3
4	1	4	267.3
5	3	4	283.4
6	5	4	290.3
7	1	6	294.2
8	3	6	296.3
9	5	6	299.4

Table 6: Ultimate Tensile Strength of Composites with Variation in Bagasse-Ash [13]

Experiments	Composition		UTS (MPa)
	(%) Graphite	Bagasse hsA (%)	
1	1	2	259.3
2	1	4	267.3
3	1	6	294.2
4	3	2	265.4
5	3	4	283.4
6	3	6	296.3
7	5	2	272.3
8	5	4	290.3
9	5	6	299.4

Park et al. [14] investigated the effect of Al_2O_3 in aluminium for volume fractions varying from 5-30% and found that the increase in volume fraction of Al_2O_3 decreased the fracture toughness of the MMC. This is due to decrease in inter-particle spacing between nucleated micro voids. Park et al. [15] also investigated the high cycle fatigue behaviour of 6061 Al-Mg-Si alloy reinforced Al_2O_3 microspheres with the varying volume fraction ranging between 5% and 30%. They found that the fatigue strength of the powder metallurgy processed composite was higher than that of the unreinforced alloy and liquid metallurgy processed composite.

Sujan et al. [16] studied the performance of stir casted Al_2O_3 and SiC reinforced metal matrix composite material. The result showed that the composite materials exhibit improved physical and mechanical properties, such as low coefficient of thermal expansion as low as $4.6x10^{-6}$ / °C, high ultimate tensile strength upto 23.68%, high impact strength and hardness. The composite materials can be applied as potential lightweight materials in automobile components. Experimentally it is found that with addition of SiC reinforcement particles, the composite exhibited lower wear rate compared to Al-Al_2O_3 composites [22].

4. Industrial Applications

MMCs are considered very useful for industrial applications and they have also shown certain properties which are highly appreciable and recommendable than pure metal [17-18]. Some of them are:

1. They are highly used in automobile industries in manufacturing of various auto parts such as disc brakes, fasteners, engine components etc.
2. MMCs are highly used in the manufacturing of tanks armors, i.e. steel reinforced with boron nitride, which is a great replacement for steel because it is very stiff and it does not dissolve in molten steel.
3. Helicopters and other aircrafts have great necessity of lighter weight components; therefore, it is highly recommendable to use reinforced MMC.
4. F-16 fighting falcon uses monofilament silicon carbide fibers in a titanium matrix for a structural component of the jet's landing gear.
5. In space applications, it is highly advisable to use MMCs, since, in the near-earth orbit, typical spacecraft encounter naturally occurring phenomenon such as vacuum, thermal radiation and other radiation factors which are highly influenced with the use of MMC.

Conclusions

Selection of different techniques has a significant effect on the structural and mechanical properties of Metal Matrix Composites. Processing variables like weight ratio of raw materials, melting point, holding temperature etc. contribute to overall development of the composite as they have considerable effect on its mechanical properties. Some of these methods are very cost effective, but widespread acceptance depends on the satisfactory resolution of the technical difficulties. The following are the outcomes of the present studies:

1. The difficulty of achieving a uniformly distributed mixture can be overcome by selecting the correct MMNC technique for fabrication, according to the properties of chosen raw materials.
2. Stir casting is one of the most convenient and economical technique for producing MMC with enhanced structural and mechanical properties.
3. Introduction of oxides like alumina exhibits excellent corrosion resistance properties, thus making the metal matrix composite corrosion resistive.
4. Introduction of compounds like graphite and mica show some enhancement in the base material properties, which leads to the formation of MMC with improved mechanical properties such as higher tensile strength, improved hardness, higher heat dimensional stability and reduced warpage.

References

1. Bodunrin M.O., Alaneme K.K. and Chown L.H., *J Mater Res Tech* 4 (2015) 434
2. Kaczmar J. W., Pietrzak K. and WøosinÂski W., J Mater Proc Tech 106 (2000) 5867
3. Kainer K.U., Metal Matrix Composites: Custom-made materials for Automotive and Aerospace Engg., ISBN: 978-3-527-31360-0, 2006: Wiley
4. Sable A.D., Deshmukh S.D., *Int J Mech Engg Tech* 3 (2012) 404
5. Ghomashchi M.R., Vikhrov A., *J Mat Proc Tech* 101 (2000) 1
6. Hitchman M., *Chem Vap Dep*1 (2006) 5
7. Luo X., Wu S., Yang Y., Jin N., Liu S. and Huang B., *Mater Chem Phy* 184 (2016) 186
8. Zhang Q., LiH.,Gan L., Ma Y., Golberg D. and Zhai T.,*Chem. Soc. Rev.* 45 (2016) 2694
9. Herklotz G., Eligehausen H., *Microelec rel* 24 (1984) 591
10. Mubarak A., Hamzah E. and Toff M. R. M., *Jurnal Mekanikal* 20 (2005) 4251
11. Wang Z., LiC.,Wang H., Zhu X., Wu M., Li J. and Jiang Q., *J Mater Sci &Tech* 32 (2016) 1008
12. Sharma P., Sharma S. and Khanduja D., *J Asi Cer Soc* 3 (2015) 352
13. Imran M., Khan A.R.A., Megeri S. and Sadik S., *Res Eff Tech* 2 (2016) 81
14. B.G. Park, A.G.Crosky and A.K.Hellier , Composites: Part B 39 (2008) 1270
15. B.G. Park, A.G. Crosky and A.K. Hellier , Composites: Part B 39 (2008)1257
16. Sujan, Z. Oo, M.E. Rahman, M.A. Maleque and C.K. Tan , Engineering and Applied Sciences 6 (2012) 288
17. Garg P., Gupta P., Kumar D. and Parkash O., *J Mater Env Sci* 7(5) (2016) 1461
18. Gupta P., Kumar D., Quraishi M.A. and Parkash O., *J Mater Env Sci* 7(7) (2016) 2505

(2018) ; http://www.jmaterenvironsci.com