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Materials Today: Proceedings 22 (2020) 2597–2605

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ICMMM 2019

A Comprehensive Review on Manufacturing Methods and Characterization of Al6061 Composites

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Abstract

Now a days the world moves from monolithic materials to composite materials due to its good properties and low cost. In particular, these composites are used in aerospace, automobile and transportation application because of high strength to weight ratio, good wear and corrosion resistance and better damping properties etc. Among various metal matrix composites, aluminium based composites (Al6061) are used for such applications. These composites are manufactured by using various manufacturing techniques such as sand casting, stir casting, squeeze casting and friction stir welding. Moreover, these composites are prepared by reinforcing it with ceramic particles, hard metals and natural particles to enhance its properties and also to suit for various engineering applications. Hence, a complete understanding of the above is very much essential for selecting appropriate composites for various applications and also to prepare new composites with enhanced behavior. This paper reports the various manufacturing techniques used for the preparation of Al6061 composites, reinforcements used and its various characterization studies.

Peer-review under responsibility of the scientific committee of the 2nd International Conference on Materials Manufacturing and Modelling, ICMMM – 2019.

Key words: Al6061; metal matrix composites; reinforcements; manufacturing process;

1. Introduction

The good mechanical and physical properties can be obtained by metal matrix composites (MMC) such as thermal stability, high specific modulus and strength. MMC is nothing but the metallic properties is mixed with ceramic properties which leads to high strength in compression and shear and it also has high service temperature

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2214-7853
Peer-review under responsibility of the scientific committee of the 2nd International Conference on Materials Manufacturing and Modelling, ICMMM – 2019.

Nomenclature

MMC Metal matrix composites
AMC Aluminium matrix composites

capabilities [1, 2]. MMC with Al is having high strength to weight ratio and it is used in automobile application. These MMC have low coefficient of thermal expansion, high thermal resistance, high specific strength, high specific stiffness, good damping capacities, good wear and corrosion resistance. MMC is a conventional metallic alloy it has applications in aerospace, automobile in defence, marine, sport and recreation industries[3].The Aluminium matrix composites can be manufactured by methods such as stir casting, squeeze casting, spray deposition and powder metrology. Metal carbides, metal borides, metal nitrides and metal oxides can be reinforced with Al using casting process. Among different manufacturing methods stir casting method is the best method for manufacturing AMC because of its inexpensive and provides wide range of selection of materials and processing conditions[4]. This paper focuses on the following.

- Selection of matrix material
- Selection of reinforcements
- Selection of manufacturing methods and
- Characterization of composites

2. Selection of Matrix

Many matrix materials such as aluminium, magnesium, titanium and cobalt etc. are available to fabricate the MMC. Among these matrix materials aluminium is mostly preferred because of its lightweight and low-cost. In particular, Al6061 series is used as matrix materials in various engineering applications. The Table 1 shows the properties of Al6061[5].

Table 1. Properties of Al6061 [5]

Density (g/cc)	2.7
Modulus (GPa)	75
Strength (MPa)	180
Fracture toughness (MPa $m^{1/2}$)	30
Coefficient of thermal expansion	23.8 (10-6C-1)

Al 6061 series MMC is used in manufacturing of cylinder blocks and pistons [6]. Also transportation, construction and engineering industries also used Al6061 Metal matrix composite. It also found application in naval vessels manufacturing because of its good mechanical properties and its corrosion resistance [7]. It is found that Al6061 reinforced with Sic has increased its hardness. Table 2 shows the increase in hardness of Al6061 with increase in % of SiC [8]. Addition of 2wt% of B_4C and 5, 10, 15, 20 wt% of fly ash increase the tensile and yield properties with increase in wt% of flyash which is increased upto 15% [9, 10]. The chemical compound of SiC is silicon and carbide. By electrochemical reaction of sand and carbon it is produced. It is a good abrasive. By obtaining combination of (Al80%+SiC10%+Neem leaf ash10%) the tensile stress of Al is increased. Table 3 shows the tensile strength of Al6061 based MMC [7].

Table 2. Hardness properties of Al6061 reinforced with SiC [8]

Material	Rockwell hardness test (HRB)
Al6061+10%SiC	60
Al6061+15%SiC	70
Al6061+20%SiC	80

Table 3. Tensile strength of Al6061 based MMC [7]

Matrix or Material	Tensile stress (MPa)	Tensile strain (%)
Al6061 T6	81	14.5
Al80%+SiC20%	88	16.9
Al80%+SiC10%+flyash10%	83	18.3
Al80%+SiC10%+neem leafash10%	93	19.7

Al alloy 6061 with sic and neem leafash produced by stir casting method has high hardness when compared with Al6061 [7]. The properties of Al6061 are improved with increase in % of Al_2O_3. Table 4 shows the mechanical properties of Al6061 reinforced with Al_2O_3 [7], addition of 1-20% of Al_2O_3 with Al6061 showed higher ultimate tensile strength (UTS) of 379 MPa. Few literatures mentioned that, adding 10wt% of B_4C with Al6061 gives good fracture toughness. It can be mixed by using a powder metallurgy and hot extrusion method [9, 11].

Table 4. Mechanical properties of Al6061 based MMC [1]

Matrix	Modulus (GPa)	Elongation (%)	UTS (MPa)	Yield strength (MPa)
Al6061 1-10% Al_2O_3	81	7.6	338	297
Al6061 1-0% Al_2O_3	69	20	310	276
Al6061 1-20% Al_2O_3	99	2.1	379	359
Al6061 1-18% Al_2O_3	88	5.4	359	386

3. Selection of Reinforcements

Metal matrix composites are ductile metals. It can be for high temperature application than their base metal. Addition of metals may improve specific stiffness, specific strength, creep resistance, abrasion resistance and additional stability [9]. Increasing the toughness is the main objective of ceramic reinforced composites. At high temperatures ceramics are resistant to oxidation and deterioration. Table 5 shows the properties of some ceramics [1, 12, 13]. It is used mainly in components of automobile and aircraft turbine engines [9].Ceramic components are selected based on [1]

- Tensile strength
- Melting temperature
- Elastic modulus
- Coefficient of thermal expansion
- Size and shape
- Thermal stability
- Cost

Table 5. Properties of some ceramics [1, 12, 13]

Ceramic	Density($\times 10^{-3}$ Kg/ m^3)	Expansity(10^{-6} °C)	Strength(MPa)	Elastic modulus(GPa)
Al_2O_3	3.98	7.92	221(1090°C)	379(1090°C)
sic	3.21	5.40	-	324(1090°C)
B_4C	2.52	6.08	2759(24°C)	448(24°C)
Mgo	3.58	11.61	41(1090°C)	317(1090°C)
Tib_2	4.50	8.28	-	414(1090°C)

3.1 SiC

Chemical compounds of silicon carbide are silicon and carbide. By the electrochemical reaction of sand and carbon sic is produced. It is a good abrasive and is used in many grinding wheels. It found its application in flame igniters, electronic components and resistance heating [7]. It has low density and high strength [14]. SiC has low thermal expansion and high thermal conductivity [15]. It provides good hardness and high elastic modulus [16]. It has excellent thermal shock resistance and superior chemical inertness [17].

3.1. Flyash

Fly ash is similar to volcanic ash. It is a waste product of coal based power plants. It causes water pollution, ill effects to agricultural land, soil and air pollution and diseases to mankind. It can be reused one of the common reuse of flyash is with concrete. Its particles are spherical in shape. It increases the durability of concrete [7]. It has low bulk density and water holding capacity [18]. It is a non-shrink material [19].

3.2. Boron carbide

Boron carbide is a stable compound. It does not reacts with cold chemical reagents. Oxidizing acids such as HNO_3, H_2SO_4 can oxidize B_4C. The density of B_4C is 2.52 g/cm^3. Shear modulus of B_4C decreases with decrease in carbon content. The young's modulus of boron carbide is in the range of 360-460 GPa. It has high hardness and strength [20]. It has low thermal conductivity and high stiffness [21].Table 6 shows the properties of boron carbide with respect to carbon percentage [20]. It is difficult to sinter to high relative densities without the use of sintering aid [22]. It also has good nuclear properties [23].

Table 6. Properties of boron carbide with respect to carbon percentage [20].

Carbon(%)	Young's Modulus (GPa)	Shear Modulus (GPa)	Poisson ratio
20	471	200	0.18
18.2	465	197	0.18
11.5	351	150	0.17
10	348	150	0.16

3.3. Zirconium oxide

It has the highest strength and toughness at room temperature [24] and it provides extremely smooth surfaces [25].

4. Selection of manufacturing methods

Al6061 reinforcement was manufacturing by various methods there are

- Spray Casting & Extrusion method
- Squeeze casting
- Stir casting
- Powder metallurgy, vaccum plasma spraying
- Plaster mold casting

Among the following methods some methods are explained they are

4.1. Plaster Mold casting

Plaster mold casting is similar to sand casting manufacturing process. For casting instead of using casting sand mold is formed by using plaster of paris. Parts such as valve, gears, tooling and lock components are produced by this method. First plaster of paris mixed with water to form the formation of plaster part. To improve the strength of plaster and control the setting time water and plaster of paris mixed with talc and silica flour additives. After that in casting pattern the mixture is poured. Metal or plastic pattern is used for this method. Wood pattern will wrap because it experienced long exposure to water from the mixture. To remove moisture and to become hard the mold is baked for several hours. Then Molds are assembled and it is ready for casting. This method mainly used for casting zinc, cu, aluminium and magnesium based alloys [7].

4.2. Plasma spraying of composites

By injecting mixtures of Al 6061 and Ceramic (TiB_2 or $Al_2O_3.2SiO_2$) powders by DC plasma jet composites are formed [26, 27]. 10-45 micro meters are the average size range of powders. On copper substrates these composites were deposited and removed mechanically to yield free standing plate. This forming technique has extremely rapid solidification rate. After that heat treatment and rolling tests are performed. At 450°C Al based composites are annealed for 1hour. Standard T6 treatment is given for Al6061 alloys [26].

4.3. Stir casting

In this stir casting process by mechanical stirring reinforcing phases are distributed into molten matrix. Manufacturing composites consists upto 30% volume fraction of reinforcement are suitable for stir casting method. Placement of the mechanical stirrer in the melt, stirring parameter, mechanical stirrer geometry, melting temperature and characteristics of particle controls the distribution of particles in molten matrix [28, 29]. Table 7 shows the specifications of stir casting for some samples [7].

Table 7. Stir casting specifications for different samples [7]

Work pieces	Furnace temperature (°C)	Metal melting temperature (°C)	Stirrer speed (RPM)	Stirrer timing (Min)	Reinforcement preheating temp (°C)
Al80%+SiC20%	800-820	780-790	750	5	562-570
Al80%+SiC10%+flyash10%	800-820	775-790	750	5	616-627
Al80%+SiC10%+neem flyash10%	800-820	778-794	750	5	623-640

4.4. Squeeze casting Method

Al6061 and sicp metal matrix composites are fabricated in this process. Table 8 shows the chemical composition of Al6061.Table 9 shows the chemical composition of Sic. Scip reinforcements are added in the volume fractions of 10%, 15% and 20% [8].Mostly preheating temperature of reinforcement range is 200°C to 800°C [8, 30, 31, 32].

Table 8. Chemical composition of Al6061 [8]

Elements	Mn	Cr	Fe	Cu	Si	Mg	Zn	Ti	Al
Wt%	0.01	0.05	0.17	0.33	0.71	1.12	0.1	0.01	balance

Table 9. Chemical composition Sic [8]

Elements	Sic	Al_2O_3	SiO_2	Fe_2O_3	Free C	Others
Wt%	98.54	0.20	0.68	0.24	0.26	0.08

In this method it was preheated by putting it in mould to solidus temperature of Al6061, which is 580°C. This molten alloy is poured into the mould after heating at 700°C and thus is followed by pushing action of preheated ram, which works under the control of hydraulic press. A pressure of 100 Mpa was applied in this process so that the ram cannot move further which then penetration of liquid metal into the perform was completed. The composites are cooled after casting [8].Table 10 shows the different manufacturing methods and its specifications [28, 33].

Table 10. Different manufacturing methods and its specifications [28, 33]

Methods	shape and size ranges	vol fraction range	Reinforcement damage	Cost of process
Stir casting process	large range of size and shape, large size range upto 500kg	0- 0.3	No damage	Least expensive
Squeeze casting process	preform shape limited upto 2 cm height	0- 0.5	Damage is severe	Moderate
Powder metallurgy process	Restricted size and wide range	-	Fracture in reinforcement occurs	Expensive process
Spray casting process	Large shape and limited shape	0.3-0.7	-	Expensive process

5. Characterization of composites

By using spray casting method Al 6061 reinforced with a SiC material which has greater stiffness when compared to unreinforced alloy .Both of the reinforcement material SiC and B_4C having identical properties. B_4C having good wetting characteristics compared with SiC. B_4C having absence of interfacial bonding .Sic having poor wetting characteristics compared with B_4C.Sic thermal expansion is closer to the unreinforced Al6061 alloy.Al6061 with Sic reinforcement does not having any significant changes in thermal expansion [5].In case of squeeze casting there will be lots of changes in properties of Al6061 density of 2.7g/cm3 reinforced with SiC 10 micrometre particle size because of this it gives high tensile strength and good ductility. Homogenous SiC distribution obtained by squeeze casting method. There will be a strong bonding between Aluminium and SiC particles led to increase in density. Hardness increased linearly therefore load bearing capacity is increased. Also increased in impact energy linearly [8]. Higher ductility and toughness of the material can obtain by stir casting. Non uniform distribution of SiC particles influences the material properties. Requires a preheating (600-640°C) to remove the surface oxides. It is observed that the transfer of load from matrix to reinforcement is better and higher hardness value was obtained. Addition of Neem ash helpful to reduce the component material [7]. In a powder metallurgy process producing Al matrix with good strength and lower thermal coefficient is possible. Material Si_3N_4, TiB_2, B_4C, $3Al_2O_3$ are comes under strength phase. It is observed that there is negligible amount of porosity after a heat treatment process that can also be eliminated. Smaller value of hoop stress and uniform distribution of particles [26]. Reinforced with the SiC and zirconium oxide and the stir speed maintained at the 900 rpm higher softness occurred in the outer surface material. Shape of the alloy depends upon the cooling time and flow rate. Moreover, increase in strength and weight is noted [6].

Varying the input parameters pouring rate and material type output parameter also changed. SiC preheated upto 1100c. Brinell tests carried out with the load of 250N. Increasing in SiC hardness and impact strength also increased. Pouring rate influences the homogeneity of material. If pouring rate is increased homogeneity of material increased. If the pouring rate is so high segregation of alloy and SiC will be occurred [34]. Reinforcement of Al80%+SiC10%+neem flyash 10% has better tensile strength than Al80%+SiC20% [3]. Hybrid reinforcement of 88wt% Al 6061 T6 , 5wt% of Si, 5wt% of Al_2O_3 and 2wt% of ZrO_2 is tested under Vickers hardness test and its value of tensile strength is 0.38 kN/mm^2 and percentage of elongation is 9.756[6]. Al 6061+4% Cu reinforced sicp MMC has good hardness and strength than Al 6061+4% Cu. Machining property is improved if 5% sic is reinforced with matrix alloy [34].The wear resistance increased with increase in Wt% of flyash [9].The fracture toughness is good for Al6061 reinforced with 10% of B_4C. Addition of 2, 4 and 6 wt% of flyash with Al increases the wear resistance. Adding B_4C and flyash with Al 6061 increases its tensile and yield strength [9-11]. The mechanical and physical properties of Al 6061 improved with adding Al_2O_3. At the expense of ductility and fracture toughness AMC reinforced with SiC or Al_2O_3 show improved strength and stiffness. Solid lubricating effect is obtained by adding Al_2O_3 and Gr [3]. Mica and sic reinforced hybrid aluminium composites have superior hardness, wear resistance and tensile strength than single reinforced sic aluminium composites [3, 35]. An experiment was conducted to determine the coefficient of friction and wear rate for Al6061 reinforced with 15% SiC. Table 11 shows the tribological properties of Al6061 reinforced with 15% SiC [36].

Table 11. Tribological properties of Al6061 reinforced with 15% SiC [36].

S. No	Load (N)	Sliding velocity(m/s)	Sliding distance (m)	Wear(mm^3/m)	Coefficient of friction	S/N ratio (wear) (db)	S/N ratio (cof) (db)
1	10	2	1000	0.0037	0.356	48.6360	8.9710
2	10	3	1750	0.00317	0.33	49.9788	9.629
3	10	4	2500	0.00593	0.29	44.5389	10.752
4	20	2	1750	0.00402	0.426	47.9155	7.4118
5	20	3	2500	0.00252	0.404	51.9720	7.8724
6	20	4	1000	0.00259	0.455	51.7340	6.8398
7	30	2	2500	0.00207	0.37	53.6806	8.6360
8	30	3	1000	0.002185	0.41	53.1211	7.7443
9	30	4	1750	0.00169	0.39	55.4423	8.1787

With increase in volume of reinforcement fraction normalized wear rate decreases [37-40]. Similarly coefficient of friction also decreases with increase in volume of reinforcement fraction. Wear rate decreases by also reinforcement size [37, 41]. For12% volume fraction of Al_2O_3 lowest wear rate is obtained. Increase in normal stress and contact temperatures increases the wear rate which is higher for matrix material when compared to composites [37]. Wear rate and coefficient of friction can be reduced by graphite which acts as lubricant [37, 42]. For above critical value of normal load the reinforcement breaks and it's separated from the matrix and it acts like abrasive [37].

6. Conclusion

Based on the above literature studies the following points were arrived.

- Stir casting method is cheaper and easier when compared to other methods and good properties also obtained for reinforcement
- Combined reinforcement both metal and ceramics yield good strength and hardness when compared to single metal reinforced Al alloy.
- Hybrid aluminum composites show superior strength, hardness and wear resistance than aluminum composites.
- B_4C and SiC have mostly same properties both used to increase the hardness. But wetting characteristics of B_4C is good compared to SiC.
- Graphite act as good lubricant which can reduce wear rate and coefficient of friction.

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