A Review on Mechanical and Tribological Properties of Particulate Reinforced Aluminium Matrix Composites

S. Venkat Prasat[1], Malthumkar Mahesh[2]

[1,2]*Department of Mechanical Engineering, Nalla Malla Reddy Engineering College, Hyderabad, Telangana, India*

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Abstract - *Particulate reinforced Aluminium Matrix Composites (PAMCs) are potential materials for various automotive and aerospace applications due to their good physical and mechanical properties. The addition of particulate reinforcements to the aluminium alloy matrix improves properties like stiffness, specific strength, wear resistance and fatigue resistance of the resulting PAMCs. This paper presents an overview of the effect of addition of different particulate reinforcement to aluminium alloy, highlighting their merits and demerits. Major issues like particle agglomerating phenomenon, fiber-matrix bonding and the distribution of particles are discussed in this paper. Effect of different particulate reinforcements on the tensile strength, strain, hardness, wear and fatigue resistance of PAMCs are also discussed in detail.*

***Key Words*: Aluminium Matrix Composites, Particulate reinforcements, Tensile strength, Hardness, Wear, Agglomerating phenomenon.**

1. INTRODUCTION

Finding ways to develop new structural materials with higher strength to weight ratio is one of the biggest challenges in the transportation and aerospace industry in recent times. There is an increasing attention towards Metal Matrix Composites (MMCs) due to their properties like high specific strength, high stiffness, better wear resistance and improved thermal resistance compared to the conventional monolithic metals and alloys. MMCs are combinations of two or more different materials with at least one being a metal and another being a ceramic or organic compound. When at least three materials are present in MMCs, they are known as hybrid composites. Three decades of intensive materials research have provided a wealth of new scientific innovation to synthesize special materials with enhanced efficiency and low manufacturing cost to fulfill the long pending demands of the engineering sector. A new system of materials containing hard particulates embedded in a metal matrix have exhibited superior operating performance and improved tribological behaviors.

Among MMCs, aluminium alloy based composites have shown the significant improvement in the mechanical, thermal, electrical and wear properties in order to cater to the demand of the industries. Aluminium alloys are termed as versatile materials to be used for numerous engineering applications because of their better machining, joining and processing properties. In addition to this, low cost, increased strength to weight ratio and other environmentally friendly characteristics of aluminium alloys make them as preferable materials in engineering applications. In addition, aluminum alloys have high corrosion resistance, high thermal conductivity, recyclability, ductility, durability and especially low density. Therefore, it can be widely used in aerospace industry, architectural construction, marine industries and the automotive applications. Aluminium Matrix Composites (AMCs) are the materials in which aluminium metal is used as matrix material and it is reinforced with other materials, i.e. mostly ceramics like SiC, Al_2O_3, B_4C, Ti_2B, etc. Reinforcement can be in the form of continuous and discontinuous form like the whiskers, particulates and fibers.

Particulate reinforced Aluminium Matrix Composites (PAMCs) are those composites in which aluminium matrix material is reinforced with particulate reinforcements. These composites contain ceramic reinforcement with aspect ratio less than five. PAMCs have a number of applications in ground transportation like pistons, transmission components, cylinder liners, bearings, brakes, etc. These composites are also isotropic in nature. They can be fabricated by solid state (Powder Metallurgy) and liquid state processes (Stir casting, Compo-casting, Squeeze Casting, in situ casting routes). Mainly particulate-reinforced composites are considered best due to their price advantage. Further, they are ingrained with wear and heat resistant properties. For MMCs, SiC, Al_2O_3, Gr, B_4C are predominantly utilized as particulate reinforcements.

PAMCs are used for fabrication of automotive parts (pistons, cylinders, head and block, chassis, connecting rods, brake components, clutches), brake rotors for high speed trains, bicycles, golf clubs, electronic substrates, cores for high voltage electrical cables, defense weapons and safety instruments. This review paper will identify the necessary properties of PAMCs that are of utmost importance to the automotive and aerospace industry. This review would also explore and analyze the different factors that could exert an influence on the fabrication and the final properties of the various PAMCs.

2. LITERATURE REVIEW

2.1 Silicon Carbide Reinforced AMCs

Sedat Ozdenet et al. investigated the impact behavior of Al and SiC particle reinforced with AMC under different temperature conditions. The impact behaviour of composites was affected by clustering of particles, particle cracking and weak matrix-reinforcement bonding. The effects of the test temperature on the impact behaviour of all materials were not very significant. Srivatsan et al. conducted a study of the high cycle fatigue and investigated the fracture behaviour of 7034/SiC/15p-UA and 7034/SiC/15p-PA metal matrix composites. The modulus, strength and the ductility of the two composites decreased with an increase in temperature. The degradation in cyclic fatigue life was more pronounced for the under-aged microstructure than the peak-aged microstructure. Also, for a given ageing condition, increasing the load ratio resulted in higher fatigue strength.

D. Sujan, et al. investigated physio-mechanical properties of AMCs reinforced with Al_2O_3 and SiC. The composite materials exhibited significant improvement in hardness and tensile strength compared to Al 356 alloy. It was found experimentally that the wear rate decreases significantly with the addition of reinforcement particles. Al-SiC composites exhibited lower wear rate compared to Al-Al_2O_3 composites. Tzamtzis et al. suggested processing Al/SiC PAMCs under intensive shearing by novel Rheo-process. The current processing methods such as conventional stir casting technique often produce agglomerated particles in the ductile matrix and as a result these composites exhibit extremely low ductility. The Rheo-process significantly improved the distribution of the reinforcement in the matrix. Yanming and Zhou Zehua investigated about the tool wear and its mechanism for cutting SiC mints and they showed that the major damage mechanism was abrasive wear on tool flank edge for conventional tools and brittle failure for high hardness tools.

Palani Kumar and Karthikeyan assessed the factors influencing surface roughness on the machining of Al/SiC particulate composites. The parameters like feed rate, cutting speed, % volume fraction of SiC were optimized to attain minimum surface roughness using response graph, response table, normal probability plot, interaction graphs and analysis of variance (ANOVA) techniques. Feed rate was the factor that exhibited the greatest influence on surface roughness, followed by cutting speed and % volume fraction of SiC. The recommended machining conditions were low cutting speed with high feed rate and depth of cut for rough and medium turning process. Using coated carbide cutting tool, high cutting speed and low feed rate produced better surface finish.

2.2 Aluminium Oxide Reinforced AMCs

B. Vijaya Ramnath and C.Subramanian investigated the behavior of PAMCs. It has been found that the increase in volume fraction of Al_2O_3 decreases the fracture toughness of the MMC. The optimum conditions for fabricating Al_2O_3 reinforced AMC were pouring temperature-700ºC, pre-heated mould temperature-550ºC, stirring speed-900 rev/min, particle addition rate-5g/min, stirring time - 5 min and the applied pressure - 6 MPa. Park et al. investigated the effect of addition of Al2O3 to Aluminium alloy for volume fractions varying from 5-30% and found that the increase in volume fraction of Al2O3 decreased the fracture toughness of the MMC. This was due to decrease in inter-particle spacing between nucleated micro voids.

Park et al. 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. Kok fabricated the Al2O3 particle reinforced 2024 Al alloy composites by vortex method and studied their mechanical properties and found that the optimum conditions of the production process were pouring temperature of 700ºC, preheated mould temperature of 550ºC, stirring speed of 900 rev/min, particle addition rate of 5 g/ min and an applied pressure of 6 MPa.

Abhishek Kumar et al. experimentally investigated the characterization of A359/Al2O3 MMC using electromagnetic stir casting method. They found that the hardness and tensile strength of MMC increased and electromagnetic stirring action produced MMC with smaller grain size and good particulate matrix interface bonding. Abouelmagd studied the hot deformation and wear resistance ofpowder metallurgy aluminium metal matrix composites. It was found that the addition of Al2O3 and Al4C3 increased the hardness and compressive strength. The addition of Al4C3 improved the wear resistance of the MMC.

Kannan and Kishawy conducted orthogonal cutting tests to study the effect of cutting parameters and particulate properties on the micro-hardness variations on the machined Al2O3 particulate reinforced AMC. They found that the micro-hardness is higher near the machined surface layer. Micro-hardness variations were higher for low volume fraction and coarseparticles.

2.3 Boron Carbide Reinforced AMCs

Vogt et al. studied the cryomilled aluminium alloy and boron carbide nano-composite plates made in three methods, (1) hot isostatic pressing (HIP) followed by high strain rate forging (HSRF), (2) HIP followed by two-step quasi-isostatic forging (QIF), and (3) three-step QIF. The test results showed that the HIP/HSRF plate exhibited higher strength with less ductility than the QIF plates, which had similar mechanical properties. Mahesh Babu et al. investigated the characteristics of surface quality on machining hybrid aluminium-B4C-SiC metal matrix composites using taguchi method. It was found that feed rate was the most important parameter followed by the cutting speed. Moreover it was concluded that the feed rate does not have a significant effect on surface quality.

Barbara Previtali et al. investigated the effect of application of traditional investment casting process in aluminium metal matrix composites. Aluminium alloy reinforced with SiC and B4C were compared and the experiments showed the wear resistance of SiC reinforced MMC was higher than that of B4C reinforced MMC. Sun

Huanhuan et al. studied the corrosion behaviour of A356 composite films in NaCl solution by electrochemical impedance spectroscopy. He identified that the outer layer of the composite films had good protection effect.

2.4 Zircon Reinforced AMCs

Jenix Rina et al. compared the properties of Al6063 MMC reinforced with Zircon Sand and Alumina with four different volume fractions of Zircon sand and Alumina with varying volume fractions of (0+8)%, (2+6)%, (4+4)%, (6+2)% and (8+0)%. The hardness and the tensile strength of the composites are higher for (4+4)%. In this combination, the particle dispersion was uniform and the pores were less. Sanjeev Das et al. comparatively studied the abrasive wear of Al-Cu alloy with alumina and Zircon sand particles and found that wear resistance of the alloy increases significantly after the addition of alumina and zircon particles. However, zircon reinforced composites showed better wear resistance than that of alumina reinforced composite due to its superior particle matrix bonding.

Scudino et al. investigated the mechanical properties of Al-based metal matrix composites reinforced with Zircon-based glassy particles produced by powder metallurgy. The test results showed that the compressive strength of pure Al increases by 30% with 40% volume of glass reinforcement. The compressive strength of the PAMCs was increased by 25%, when the volume fraction of the glassy phase was increased by 60%.

2.5 Fly Ash Reinforced AMCs

Fly ash particles are potential discontinuous dispersoids used in metal matrix composites due to their low cost and low-density. These reinforcements are available in large quantities as a waste by product in thermal power plants. The major constituents of fly ash are SiO2, Al2O3, Fe2O3 and CaO. Rajan et al. compared the effect of the three different stir casting methods on the properties of fly ash particles reinforced Al-7Si-0.35Mg alloy. The three stir casting methods were liquid metal stir casting, compo-casting, modified compo-casting followed by squeeze casting. The compression strength of the composite processed by modified compo-casting cum squeeze casting was improved compared to the matrix alloy. However, the tensile strength was found to be reduced.

Zuoyong Dou et al. studied the electromagnetic interference shielding effectiveness properties of the 2024 Al alloy-fly ash composites. The composite has effective shielding property in the frequency range of 30.0 KHz – 1.5 GHz. But the addition of fly ash particulate decreases the tensile strength of the composites. Ramachandra and Radhakrishna experimentally found that the wear resistance of PAMC increases with the increase in fly ash content, but decreases with increase in normal load and sliding velocity, and also observed that the corrosion resistance decreases with the increase in fly ash content.

K. Radhakrishna and M. Ramachandra conducted research on the effect of reinforcement of fly ash on sliding wear, slurry erosive wear and corrosive behavior of aluminium matrix composites produced by stir casting method and concluded that Al (12 wt.% Si) -15 wt.% of fly ash particulate composite improved the abrasive wear resistance and moreover corrosion resistance decreases as fly ash content increases. Sudarshan and M.K.Surappa have synthesized A356 Al–fly ash particle composites and studied their dry sliding wear behavior. They concluded that the addition of 6% of fly ash particles into A356 Al alloy showed low wear rates at low loads (10 and 20 N), while 12% fly ash reinforced composites showed lower wear rates compared to the unreinforced alloy in the load range of 20–80 N. The corrosion wear of composites is a critical design criterion.

D.M.Aylor and co researchers [stated that pitting corrosion on Al-SiC composites was observed predominantly at the interface between the Al and SiC. Z.Feng and co researchers analyzed the pitting corrosion behaviour of Al-SiC 2024 composites and attributed the corrosion of the composites to pit formation at the Al-SiC interface.

3. EXPERIMENTAL PROCEDURE

Pure aluminium ingot with a purity of 99.5% (weight fraction) was used as matrix material and fly ash particles with average size of (50-100 μm) were used as reinforcement by researchers in their study (Shanmughasundara et al., 2011). The chemical composition of fly ash is shown in the Table 1.

Table 1: Chemical composition of fly ash

Compound	SiO2	Al2O3	Fe2O3	CaO	MgO
Wt.%	54.27	34.73	6.1	2.4	2.1

3.1 Production of PAMCs using Stir Casting Process

In the research work, Al - fly ash composites were produced with a varying amount of fly ash content (i.e. 5, 10, 15, 20, 25 wt. %) by two-step stir casting method. The Stir casting setup is shown in Figure 1. The fly ash particles were preheated to 600ºC for 2 hours in a separate muffle furnace to remove the moisture content. Aluminium was charged in to the graphite crucible, and the furnace temperature was raised up to liquidus temperature of 670ºC in order to melt the Al scraps completely and further the melt temperature was reduced to 620ºC in order to attain the semi solid state. 1.5 wt.% Magnesium and preheated fly-ash particles were added in the crucible. Mg was incorporated into the melt to promote the wetting action between Al matrix and fly ash reinforcement particles. The molten Al composite slurry was stirred with a speed of 300 rpm for 20 minutes. Since high torque was required for mixing the composite slurry in semi solid state, a variable torque- speed controlled mechanical stirrer was employed. The dispersion of fly ash particles with aluminium was achieved by the two-step stirring method. Finally the composite melt was reheated to 670ºC and poured into the steel mould to solidify. Argon gas was blown at the rate of 2CC/min into the furnace during the process to prevent oxidation of aluminium and magnesium. The melting was made in an electrical resistive furnace (Shanmughasundaram et al., 2011).

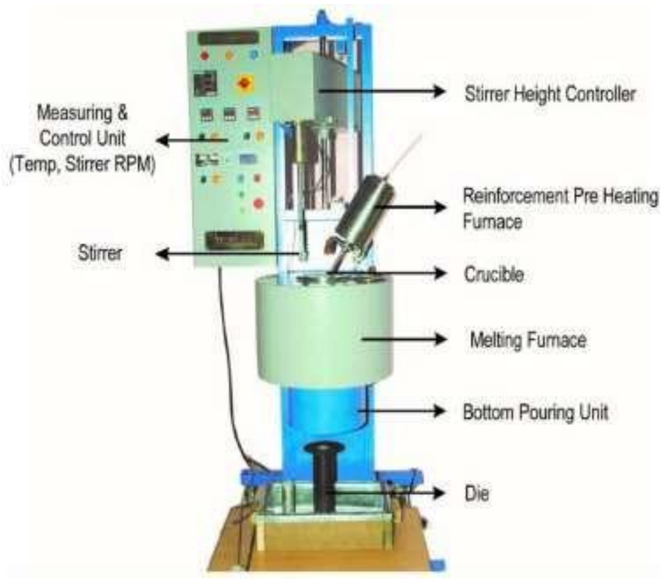

Figure 1: Stir casting setup

3.2 Microstructure Analysis

Optical microscope and Scanning Electronic Microscope (SEM) were employed to analyze the microstructure and also the wear surface profile to investigate the wear mechanism of the material. Samples were mechanically polished using sand metallographic practices and etched with Keller's regent prior to microstructure examination.

3.3 Mechanical Properties

The researchers (Shanmughasundaram et al., 2011) studied the mechanical properties of AMCs like density, hardness, tensile and compressive strength.

3.3.1 Density

Density of composites was obtained experimentally by the Archimedean principle. Theoretical density was calculated applying the rule of mixtures according to the weight fraction of reinforcement.

3.3.2 Hardness

Hardness test was performed on Al and composite specimens. The hardness values of the specimen were measured using Brinell hardness testing system with 10mm diameter at a load of 500 kg. The detention time was 30 seconds. Three tests were taken on each specimen to eliminate possibility of segregation and mean value was considered.

3.3.3 Tensile and Compressive strength

Tensile and compressive strength tests were carried out on Al specimens and composites using a computerized UTM testing machine as per the ASTM E-8 standards. Three samples were tested for each composition and mean value was considered.

4. RESULTS AND DISCUSSION

Al - fly ash composites were successfully synthesised by a two-step stirring method by Shanmughasundaram et al. (2011) and this process ensured homogenous distribution of fly ash particles in the matrix.

4.1 Microstructure Analysis of PAMCs

Optical microscope and Scanning Electronic Microscope (SEM) were employed to analyze the microstructure of the specimens. Figure.2 (a) shows the SEM micrograph of Al-10wt% fly ash composites fabricated by mechanical stirring duration of 20 minutes with the stirring speed of 300 rpm at 670˚C (above liquidus). Figure.2 (b) shows the SEM micrograph of Al-10wt% fly ash composites at 615˚C (in semi solid range).

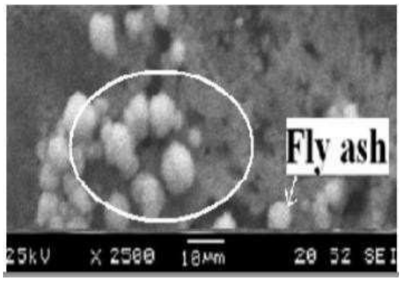

Figure 2 (a): Al - 10wt % fly ash Composites (stirring at liquid state)

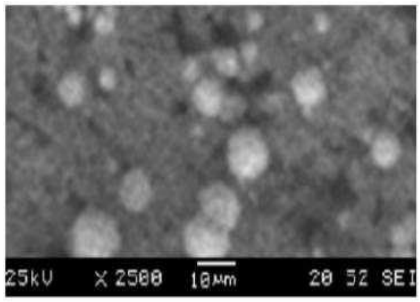

Figure 2 (b): Al-10wt% fly ash Composites (stirring at semi solid state)

It was observed from the Fig.2(b) that the fly ash particles distribute homogeneously in the composites when the stirring was made in semisolid condition. Fly ash particle agglomeration was observed in the SEM micrograph obtained for composites which were stirred at liquid state. The homogeneous distribution of fly ash particles in the Al matrix was achieved due to smashing action of solid dendrites in semi solid state. The interface between matrix and reinforcement was almost perfectly bonded.

4.2 Density of PAMCs

The graphs depicting theoretical and experimental densities of the composites with variations in the fly ash content is shown in Figure 3. Generally the fly ash particles have low density in nature. In the present study, precipitator type fly ash was used and this has a density which is less than 2.2g/cm^3. The density of the composite specimens was determined experimentally using the Archimedes principle. The small pieces cut from the specimens were weighed first in air and thereafter in water and density values were calculated.

Theoretical density values were determined using the rule of mixtures relation. The experimental density values of the Al-fly ash composites decreased linearly with addition of fly ash particles. The decrease in density of composites can be attributed to lower density of fly ash particles than that of the unreinforced Al. It was also noted that the theoretical values closely match with the experimental values when the fly ash content is less than 20 wt.%. It indicates that the interface between matrix and reinforcement was almost perfectly bonded and that the prepared castings are dense and sound. However when the fly ash content increases beyond 20 wt%, there is a mismatch between the theoretical and measured density values due to increased porosity and particle clustering (Shanmughasundaram et al., 2011).

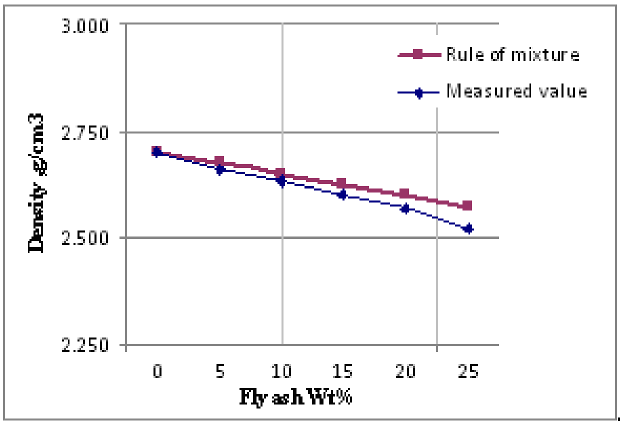

Figure 3: Density of the Composites for various Wt.% of fly ash particles

4.3 Mechanical Behavior of PAMCs

It can observed from the Figure 4 that there was an increase in the hardness of composites when the fly ash content was increased from 5 wt.% to 20 wt.% and maximum hardness of 51BHN was achieved when the fly ash content was 20wt.%. However, there was a decrease in the hardness of the composites when the fly ash content was further increased to 25 wt.%. Similarly, it can be observed from Figures 5 and 6 that there was an increase in the tensile strength and compressive strength of composites when the fly ash content was initially increased from 5 wt.%. The composites exhibited a maximum tensile strength of 118 MPa when the fly ash content was increased to 15 wt.%.

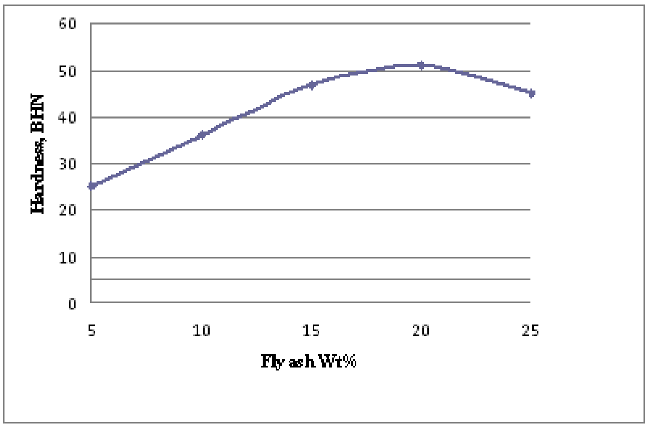

Figure 4: Hardness of the Composites at various Wt.% of fly ash particles

However, there was a decrease in the tensile strength the composites when the fly ash content was further increased from 15 wt.% to 25 wt.%. due to the decrease in solid solution strengthening and particle clustering. The composites exhibited a maximum compressive strength of 622 MPa when the fly ash content was increased to 20 wt.%. However, there was a decrease in the compressive strength of the composites when the fly ash content was further increased from 20 wt.% to 25 wt.% (Shanmughasundaram et al., 2011). The observed values of density, hardness, tensile strength and compressive strength of composites at various wt.% of fly ash content are listed in Table 2.

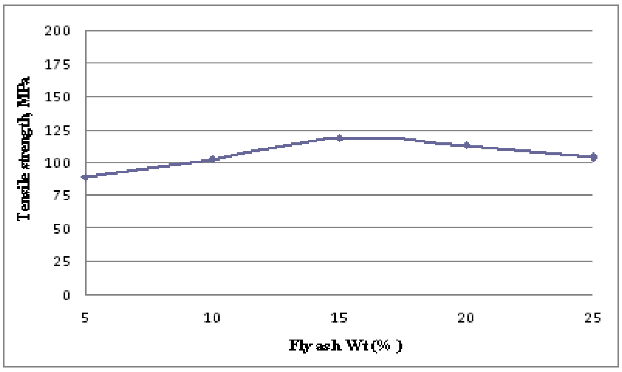

Figure 5: Tensile strength of the Composites at various wt.% of fly ash particles

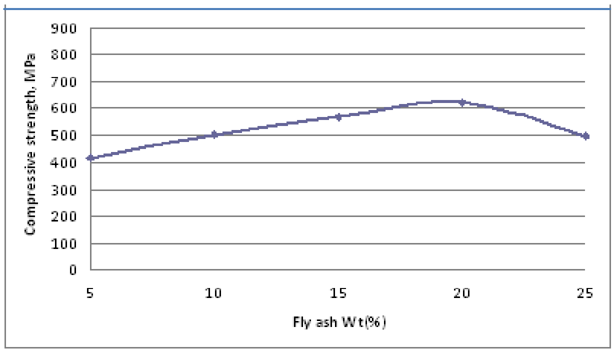

Figure 6: Compressive strength of the Composites at various Wt.% of fly ash particles

Table 2: Mechanical properties of Al and Al-fly ash Composites

Fly ash (wt.%)	Density (g/cm³)	Hardness (BHN)	Tensile Strength (MPa)	Compressive Strength (MPa)
0	2.700	19	77	337
5	2.661	25	89	418
10	2.633	36	102	501
15	2.600	47	118	568
20	2.569	51	113	622
25	2.523	45	104	497

5. CONCLUSIONS

1. The Al –fly ash composite was successfully fabricated by two step stir casting process in order to attain homogenous distribution of fly ash particles in the Al matrix. The density of the composites decreased with increasing fly ash reinforcement content. Hence Al-fly ash composites can be used in applications where weight reductions are desirable.
2. Hardness, tensile strength and compressive strength of composites were determined by varying fly ash content from 5 wt.% to 25 wt.%. Maximum hardness and compressive strength was achieved when the fly ash content was increased up to 20 wt.%. However, the tensile strength begins to drop when the fly ash content exceeds 15wt% due to the decrease in solid solution strengthening and particle clustering. The results indicate that the Al-fly ash composites could be considered as an excellent choice of material in automobile sector where light weight, enhanced mechanical properties and wear resistance are prime considerations.
3. SiC reinforced PAMCs have higher wear resistance than Al_2O_3 reinforced MMCs. SiC reinforced PAMCs are suitable materials for brake drums as they have high wear resistance but cannot be used in brake linings as it lead to the damage of the brake drum.
4. It has been found that the increase in volume fraction of Al_2O_3 decreases the fracture toughness of the PAMCs. The optimum conditions for fabricating Al_2O_3 reinforced PAMCs were pouring temperature-700ºC, pre-heated mould temperature-550ºC, stirring speed-900rev/min, particle addition rate-5g/min, stirring time - 5 min and the applied pressure of 6 MPa.
5. The wear resistance of SiC reinforced PAMC is higher than B_4C reinforced PAMC.
6. The wear resistance and compressive strength of PAMCs increase with the addition of Zircon sand reinforcement. The addition of fly ash reinforcement in Al increases the wear resistance but decreases the corrosion resistance.

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