Microstructure and Mechanical Properties of Fly Ash Particulate Reinforced in LM6 for Energy Enhancement in Automotive Applications

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Abstract. Fly ash has gathered widespread attention as a potential reinforcement for aluminium matrix composites (AMCs) to enhance the properties and reduce the cost of production. Aluminium alloy LM6 reinforced with three different amounts (0, 4, 5 and 6 wt. %) of fly ash particle that were prepared by compo-casting method. The fly ash particles were incorporated into semi-solid state of LM6 melt. In this study, the microstructure of prepared AMCs with the homogenous distribution of fly ash was analysed using optical microscope. The microstructure having refinement of structure with the decreasing of Si-needle structure and increasing the area of eutectic α-Al matrix as shown in figure. Besides, as the increasing amount of fly ash incorporated, there are more petal-like dark structure existed in the microstructure. The density of the AMCs decreased as the incorporation of fly ash increased. While the hardness and ultimate tensile strength of the AMCs increased with the incorporation of fly ash. The addition of fly ash particles improved the physical and mechanical properties of the AMCs. Thus lead to improve the energy consumption in automotive parts.

1. Introduction
Metal matrix composites (MMCs) are an advanced materials resulting from a combination of two or more materials in that the tailored properties (Kumar et.al, 2013). MMCs possess significantly improved properties including high specific strength, better properties at elevated temperatures, lower coefficients of thermal expansion and good wear resistance compared to unreinforced alloys (Akio et.al, 1999; Kulkarni et.al, 2014). Meanwhile, aluminium based MMCs (AMCs) have gained significant attention in recent decades as engineering materials with most of them possessing the advantages of high strength, hardness and wear resistance (Anilkumar et.al, 2011). Good physical and mechanical properties of AMCs have made attractive materials for automotive and aerospace applications (Kretschmer, 1988; Ibrahim et al., 1991; Surappa, 1997).
Cost is the key factor for the AMCs wider application in modern industry, while the potential benefits in weight reduction, increased composites life and improved recyclability should be taken into account (Klimowicz., 1994; Hashim et al., 2001). According to Shorowordi et al., cost reductions can be achieved only by simpler fabrication methods, higher production volumes and cheaper reinforcements (Shorowordi et al., 2003). These composite materials represent a new product opportunity for automotive manufacturers to improve performance and thus reduce the cost. Currently, the particulate reinforced aluminium composites are gaining importance because of their low cost with better performance (Deepak and Mediratta, 2013; Rohatgi, 1994).

There are variety of methods for fabrication of AMCs including diffusion bonding, powder metallurgy, liquid casting and pressure infiltration have recently become available (Ebisawa, 1991; Rohatgi, 1990; Hunt et al., 1991). Even though there are various method in producing AMCs, the greatest attention has been on the liquid casting route, especially stir casting that appears to be most attractive (Rohatgi, 1994). The conventional foundry process of making AMCs components readily lend themselves to the manufacture of high-volume, complex components at high production rates and low costs required by industry. In view of low cost requirements is imperative to industry, it appears that discontinuous composite incorporating inexpensive particles will find the widest applications in industry. Currently, many researchers works on the waste materials as the inexpensive reinforcement particles in AMCs such as rice husk ash, red mud, fly ash and coconut ash (Ervina et al., 2016).

Among various discontinues disperoids used, fly ash is one of the most inexpensive and low density reinforcement available in large quantities as solid waste by product during combustion of coal in thermal power plant (Lokesh et al., 2013). Fly ash as a filler has been proved to increase the mechanical, physical and tribological properties including hardness, stiffness, wear and abrasion resistance and decrease density. It also improves the maintainability, damping capacity, and coefficient of friction which are which are desirable in automotive and industrial applications (Sukanya et al., 2014).

Previously, there were several researches on the characteristic of reinforcement materials that affected the properties of AMCs have been done. According to Rohatgi, mechanical properties of composites can be affected by the size, shape and volume fraction of the reinforcement, matrix material and reaction at the interface. These aspects have been discussed by many researchers (Rohatgi, 1994). The same author reported that with the increase in volume percentages of fly ash, hardness value also increases in the Al–fly ash (precipitator type) composites. Besides, the tensile elastic modulus of the ash alloy increases with increase in volume percent (3–10) of fly ash. On the other hand, Aghajanian concluded that the interface between the matrix and reinforcement plays a critical role in determining the properties of MMCs.

Whereas, Anilkumar et al. investigated Al6061 with fly ash processed by stir casting and concluded that the tensile strength increased with an increase in the weight percentage of fly ash. This is due to the fly ash particles acted as barriers to the dislocations when taking up the load applied. The hard fly ash particles obstruct the advancing dislocation front, thus strengthening the matrix. However, as the size of the fly ash particles increased, there was a decrease in tensile strength (Saravindan, 2015). Good bonding of smaller size fly ash particles with the matrix is the reason for this behaviour. Despite this, the decrease in the tensile strength of the samples with fly ash weight fraction beyond 15 % is due to the poor wettability of the reinforcement with the matrix (Anilkumar et al., 2011). In the present work, an attempt was made to fabricate aluminium hybrid composites with fly ash as reinforcements by using compo-casting method. Properties such as density, metallurgical, and mechanical behaviour were investigated and the related mechanisms have been discussed and presented.

2. Experimental Method
Aluminium alloy (LM6) is used as the matrix material while fly ash is used as the reinforce material. The aluminium alloy (LM6) was supplied from Foundary Equipment Supply with the elemental details as shown in Table 1. Fly ash powders (precipitator fly ash) were received from Jimah Power Plant, Port Dickson, Negeri Sembilan. The fly ash is sieved to 45µm to get smaller particle size. According to Saravindan, the smaller particle size of reinforcement the better properties of composite can be obtained (Saravindan, 2015). The fly ash is then undergoing characterizations that are particle size analysis and chemical composition (XRF). Before incorporated into the aluminium slurry, the fly ash is pre-heated at 600°C for 3 hours to remove impurities and water content. The amount of fly ash used are 4, 5 and 6wt.%. The chemical composition of fly ash particle is shown Table 2.

Table 1. Chemical composition of LM6

| Elements | Cu  | Fe  | Mg  | Mn  | Ni  | Pb  | Si  | Al (%)  | Reference          |
|----------|-----|-----|-----|-----|-----|-----|-----|---------|---------------------|
| Percentage (%) | 0.10 | 0.60 | 0.10 | 0.50 | 0.10 | 0.10 | 10.00-1300 | Remainder Material Data Sheet FES Sdn.Bhd. |

Table 2. Chemical composition of fly ash

| Compound | Na2O | MgO | Al2O3 | SiO2 | P2O5 | K2O | CaO | TiO2 | Fe2O3 | LOI   |
|----------|------|-----|-------|------|------|-----|-----|------|-------|-------|
| Weight Percent(%) | 0.481 | 1.102 | 15.939 | 65.61 | 0.28 | 0.684 | 2.098 | 0.813 | 4.517 | 1.87  |

The LM6/fly ash composite (AMCs) was fabricated by using the compo-casting method where the reinforcement is added into aluminium slurry in semi-solid state. The LM6 matrix is melted in a graphite crucible in melting furnace at 800°C. Measured quantity of fly ash particles was added to the semi solid aluminium slurry. Simultaneous stirring of the semi solid aluminium slurry was carried out using a stainless steel mechanical stirrer driven by an electric motor with speed of 300rpm for 5 to 10 minutes. The stirring process was continued until all the fly ash particles were added to the semi solid aluminium alloy and then poured into the mould. The composite is then undergoing CNC machining process for tensile specimen preparation following the standard code of ASTM E8 which is suitable for automotive application.

The AMCs also being prepared for other testing and characterizations including density analysis, microstructural analysis, and hardness test. The sample for metallurgical analysis is prepared according to standard metallographic process that is ground using SiC paper and then undergo polishing process by using diamond paste before the etching process. The hardness was measured using a Rockwell hardness tester at 15kg load applied for 5s.

3. Result and Discussion

Aluminium alloy LM6 reinforced fly ash particulate composites were successfully fabricated using compo-casting process. The metallurgical and mechanical characterizations of the fabricated aluminium composite are discussed below.

The particles size of cenosphere fly ash is below than 45µm as shown in Figure 1. The fly ash is sieved to 45µm following the standard method ASTM C311-77. Fly ash particles are typically spherical, ranging in diameter from <1 µm to 150 µm. The type of dust collection equipment used largely determines the range of particle sizes in any given fly ash. The fly ash from boilers at some older plants using mechanical collectors alone is coarser than from plants using electrostatic
precipitators (Malhotra et al, 1993). In this research, the used fly ash was taken from the plants using the electrostatic precipitators where the average particle size from <1µm to <100µm. According to Sudarshan and Surappa, the smaller particle size (<45µm) of fly ash will able to give superior properties of AMCs. It is the same way to the particle size of fly ash used in this research. The average particle size of fly ash after sieving process is 10µm which falls into the range of small size (<45µm) as shown in Figure 1. Thus the sieved fly ash was successfully incorporated into the aluminium slurry as the reinforcement.

*Characterization of Fly ash*

![Graph showing particle size distribution of fly ash](image)

**Figure 1.** Average particle size of fly ash

Meanwhile, the shape of the powder particles was evaluated using scanning electron microscopy (SEM) micrograph as shown in Figure 2. The SEM micrograph shows the homogeneous size distribution of fly ash particles (grey region) with only three particles in bigger size (100 and 75 µm). However, the average size distribution in the SEM micrograph is below than 50µm. Cenosphere particles were hollow spheres with an apparent density ranging from 0.4 - 0.6 g cm$^{-3}$ (Rohatgi, 1997). On the contrary, the shape of fly ash used in this research was spheres with no hollow structure. The micrograph in Figure 2 revealed the shape of fly ash is spherical with an average size below than 50µm.
The microstructure plays an important role in the overall performance of a composite. The physical properties depend on the microstructure, reinforcement particle size, shape and distribution in the alloy. The fabricated aluminium composites were examined using optical microscope to study the distribution pattern of fly ash in the LM6 matrix. Optical micrograph of cast aluminium alloy LM6 and the prepared aluminium fly ash composite (AMCs) with 4, 5 and 6wt% of fly ash compositions at 25x magnification are shown in Figure 3a, 3b and 3c respectively.

Before the addition of fly ash reinforcement, the microstructure of unreinforced LM6 alloy is dominated by Si-rich (dark region) and Al-rich (bright region) phases, as illustrated in Figure 3a. The Si-rich phase reveals itself in three different types of morphologies, the cuboid, the needle, and the irregular polygon. In some instances, the Si cuboids are surrounded by the primary $\alpha$-Al phase. These Si-rich cuboids might be the primary Si phase. This result was confirmed by Pena and Lozano (Pena and Lozano, 2006). According to them, the primary Si phase resembles cuboid-type of morphology. They serve as the nucleating sites of primary $\alpha$-Al phase occasionally. Regarding the irregular polygons, they exhibit a similar morphology to the primary Si phase. The microstructure also reveals the formation of $\alpha$-aluminium dendritic network structure which is formed due to the supercooling of composite during solidification.
Figure 3. a) Microstructure of unreinforced LM6 alloy, b) microstructure of 4wt% of LM6/fly ash composites, c) microstructure of 5wt% of LM6/fly ash composite, d) microstructure of 6wt% of LM6/fly ash composites.

After the addition of 4wt.% fly ash reinforcement, the most distinguishable feature will be the increasing Si-rich (dark region) phase as demonstrates in Figure 3b. Si-needles and Si-cuboids have been gather in certain part in the fabricated AMCs, while a wide area of eutectic $\alpha$-Al matrix has formed. The Si-needle become closely packed each other. However, upon the addition of 5w.% fly ash reinforcement, the microstructure of the composites still dominates by the Si-rich (dark region) and Al-rich (bright-region). There are also some petal-like dark structures and Si-cuboids existed as demonstrated in Figure 3c. The Si-needles were well distributed and dominated most of the structure whereas the eutectic $\alpha$-Al matrix dominated minor region of the structure. Meanwhile, Figure 3d showed the microstructure of LM6 with 6wt.% of fly ash reinforcement. The microstructure shows the increasing region of petal-like dark structures and Si-polygon existed while the Si-needle structures are decreased. Conversely, the eutectic $\alpha$-Al matrix (bright region) has increased. This is due to the homogenous distribution of fly ash particles in the fabricated AMCs. As for the needle-like structure, it is frequently referred as sharp eutectic Si embedded in the eutectic $\alpha$-Al matrix that deteriotes the mechanical performances of Al-Si alloys(Pena and Lozano,2006; Sebaie et.al,2008; Ervina et.al,2013).
Thus, the decreasing amount of Si-needles in the structures as the increasing wt.% of fly ash incorporation is good as its can improves the properties of fabricated AMCs. It was shown that the addition of fly ash particle as the reinforcement can modify the microstructure of fabricated AMCs in better form. This is because, the increasing of Si in the composites is expected to improve the properties of the composite (Ervina et.al, 2014).

![Figure 4](image.png)

**Figure 4.** Density analysis of unreinforced LM6 and LM6/fly ash composites

The variation of density of LM6 and fabricated AMCs are shown in Figure 4. The density of the fabricated AMCs were decreased gradually as the wt.% of fly ash reinforcement added increased. Before the addition of fly ash particles as the reinforcement, the density of LM6 alloy is 2.71 g/cm$^3$ which is nearly same to the theoretical density of Al 6xxx in the range of 2.69-2.72 g/cm$^3$ (Zhong et.al, 2014) where is the current used aluminium materials in automotive parts. Although the density of Al 6xxx is relatively 50-60% lower than the conventional cast iron used, the automotive manufacturer still looking forward for the lower weight materials that can be used in the automotive parts. It is apparent that the lower weight parts of automotive potentially increasing the efficiency of the vehicles (Hadley et.al, 1999). Efficiency gains can be used to lower the amount of energy needed for transportation, reducing the emissions while improving the energy security of the country. So that, in order to achieve the required density of materials for automotive part, the LM6 alloy is reinforced with a low density reinforcement materials that is fly ash.

The density of fly ash cenospheres particles is in the range of 0.4-0.6 g/cm$^3$ where is far lower than the density of LM6. After the addition of 4wt.% fly ash particles as the reinforcement, the density of the fabricated AMCs was decreased to 2.66 g/cm$^3$. While the density of fabricated AMCs with 5wt.% of fly ash particles has decreased to 2.62 g/cm$^3$. Lastly, the density of fabricated AMCs with 6wt.% of reinforcement is decreased again to 2.58 g/cm$^3$. This is due to the homogenous distribution of fly ash in the composites as shown in the microstructure in Figure 3. The atomic structure of unreinforced LM6 is closed pack with some small space among the atom that leads to introduce the porosity which will deteriotes the properties of the materials. Upon the addition of fly ash particles, the particles distributed homogenously and filled up the space among the atom, thus replaced some of them. As the density of fly ash particles is lower than the LM6, it is able to reduce the density of the fabricated AMCs. According to the Figure 4, the addiction of fly ash particle is able to reduce the density of fabricated AMCs up to 13% reduction. There are some comparisons of density value of fabricated AMCs with others finding have been summarized in Table 3.
Table 3. Comparisons of density value of fabricated AMCs with other finding

| Composition (wt.%) | 4%  | 5%  | 6%  | References                                      |
|-------------------|-----|-----|-----|------------------------------------------------|
| Density (g/cm³)   | 2.66| 2.58| 2.64| (Kulkarni et.al, 2014; Rohatgi, 1997; Lokesh et.al, 2013) |
|                   | 2.66| 2.62| 2.58| Current Study                                   |

Figure 5. Tensile strength of unreinforced LM6 and LM6/fly ash composites

The effect of wt.% of fly ash particles on tensile strength of fabricated AMCs is respectively presented in Figure 5. Before the incorporation of fly ash particles, the ultimate tensile strength of the unreinforced LM6 is 136.3 N/mm². While the current used materials for automotive application is cast iron alloy with ultimate tensile strength of 160 N/mm². It is proved from the figures that the incorporation of fly ash particles significantly enhances the ultimate tensile strength of the composites. After the addition of 4 and 5 wt% of fly ash particles, the ultimate tensile strength of the fabricated AMCs increased from 136.3 N/mm² to 142.7 and 154.4 N/mm². Meanwhile, the fabricated AMCs with 6 wt% fly ash particles exhibit 30.4% higher tensile strength that is 166.7 N/mm² compared to unreinforced LM6 alloy. The fracture surface of LM6 alloy exhibits brittle structure surface with small amount of elongation. However, after the incorporation of fly ash, it is able to slightly increase the elongation of the AMCs although still exhibits the brittle fracture surface. Similar results were reported by David et.al and also Ramachandra and Radhakrishna (Ramachandra and Radhakrishna, 2005; David et.al, 2013). The grain refinement and reduction of ductile matrix content when the weight percentage of fly ash particles is increased can reduce the ductility of the AMCs.

During the solidification of the composite, strain fields are created around fly ash particles because of the difference in the thermal expansion coefficients while the strain fields piles up dislocations. The interaction between dislocations and fly ash particles offer resistance to the propagation of cracks during tensile loading. The grain refinement provided by the fly ash particles presents more area to resist the load. The uniform distribution of fly ash particles provides better strengthening (Zhang and Chen, 2008). Therefore, the tensile strength of fabricated AMCs is enhanced by the fly ash particles. However, the tensile strength of the fabricated AMCs does not achieve the requirement of automotive spec since the required tensile strength of aluminium for automotive parts is 245 N/mm². Since the addition of fly ash particle able to increase the ultimate tensile strength of
composite, the higher wt.% of fly ash need to use in order to obtain higher tensile strength, thus achieves the required tensile strength of automotive parts.

**Figure 6.** Rockwell Hardness of unreinforced LM6 and LM6/fly ash composites

Hardness provides a quick, simple and non-destructive means to access the mechanical behaviour of a material. It is defines as the resistance of a material towards plastic deformation. The Rockwell hardness testing is done with 15kg of load and 10s of dwell time. The test is done according to the standard test code ASTM E384 – 09. Hardness is necessary for automotive to ensure good machinability and for assembly of the component. Although the increasing of hardness will decrease the machinability of a material, however, higher hardness stills a vital property of an automotive component. This is because, hardness for automotive is basically the ability of a component to resist permanently deformed when a higher load is applied (Automotive Manual, 2011). So that, higher hardness is important to avoid component failure as higher load is applied.

Figure 6 highlights the hardness of unreinforced LM6 and fabricated AMCs. It is showed the hardness of the fabricated AMCs increased as the increasing of wt.% of fly ash incorporated into LM6. Before the incorporation of fly ash reinforcement, the hardness of LM6 is 20.1 HRC. Upon the incorporation of 4wt.% of fly ash, the hardness of fabricated AMCs is increased to 24.4 HRC. And yet, the hardness of fabricated AMCs increased to 35.7 HRC with addition of 6wt.% fly ash reinforcement, equivalent to 46.31% of hardness increment. This hardness value already achieved the hardness requirement of automotive component as the required hardness is 34.0 HRC (American Foundary, 2004). This significant rise in the hardness of fabricated AMCs is believed to be strongly attributed to the enhancing the microstructural features and hardness LM6.

4. Conclusion
Based on the optical micrograph, the fly ash particles were dispersed homogenously in the AMCs. The incorporation of fly ash particles into semi-solid aluminium alloy improved the wettability.
Meanwhile, the addition of fly ash particles enhance the hardness and tensile strength of fabricated AMCs. The fabricated AMCs with 6wt% of fly ash reinforcement exhibited almost 50% higher hardness and 30.4% higher tensile strength compared to unreinforced LM6 alloy. More the weight percentage of fly ash, more will be the effect of the above discussed factors which further increases the mechanical properties.

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6. References

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