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Evaluation of Mechanical Properties of Aluminium Alloy2024 Reinforced with Silicon Carbide and Fly Ash Hybrid Metal Matrix Composites

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ABSTRACT

Materials are frequently chosen for structural applications because they have desirable combinations of mechanical characteristics. Development of hybrid metal matrix composites has become an important area of research interest in Materials Science. In view of this, the present study focuses on the formation of aluminium-Sic-fly ash hybrid metal matrix composites. The present study was aimed at evaluating the physical properties of Aluminium 2024 in the presence of silicon carbide, fly ash and its combinations. Consequently aluminium metal matrix composite combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The compositions were added up to the ultimate level and stir casting method was used for the fabrication of aluminium metal matrix composites. Structural characterization was carried out on metal matrix composites by x-ray diffraction studies and optical microscopy was used for the micro structural studies. The mechanical behaviors of metal matrix composites like density, tensile strength, yield strength, elongation and hardness tests were ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. In the presence of silicon carbide and fly ash [SiC (5%) + fly ash (10%) and fly ash (10%) + SiC (10%)] with aluminium, it was fairly observed that the density of the composites was decreased and the hardness was increased. Correspondingly, the increase in tensile strength was also observed but elongation of the hybrid metal matrix composites in comparison with unreinforced aluminium was decreased. The aluminium-SiC-fly ash hybrid metal matrix composites significantly differed in all of the properties measured. Aluminium in the presence of SiC (10%)-fly ash (10%) was the hardest instead of aluminium-SiC and cluminium-fly ash composites. The study can be further extended by evaluating the wear and corrosion of the resultant material.

Keywords: Aluminium, Fly Ash, Silicon Carbide, Hybrid Metal Matrix Composites

1. INTRODUCTION

Discontinuously reinforced aluminium matrix composites are fast emerging as engineering materials and competing with common metals and alloys. They are gaining significant acceptance because of higher specific strength, specific modulus and good wear resistance as compared to ordinary unreinforced alloys

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(Sarkar and Singh, 2012). Reinforcing particles used in this study are silicon carbide and fly ash particles which are added externally.

Aluminium alloy 2024 has good machining characteristics, higher strength and fatigue resistance than both 2014 and 2017. It is widely used in aircraft structures, especially wing and fuselage structures under tension. It is also used in high temperature applications such as in automobile engines and in other rotating and reciprocating parts such as piston, drive shafts, brake rotors and in other structural parts which require light weight and high strength materials (Ibrahim *et al*., 1991). Aluminium is also a ubiquitous element and one of the trace elements with moderate toxic effect on living organism (Buraimoh *et al*., 2012). One of the main drawbacks of this material system is that they exhibit poor tribological properties. Hence the desire in the engineering community to develop a new material with greater wear resistance and better tribological properties, without much compromising on the strength to weight ratio led to the development of metal matrix composites (Sinclair and Gregson, 1997; Sannino and Rack, 1995).

Silicon carbide is a compound of silicon and carbon with a chemical formula SiC. Silicon carbide was originally produced by a high temperature electro-chemical reaction of sand and carbon. Any acids or alkalis or molten salts up to 800°C do not attack silicon carbide. In air, SiC forms a protective silicon oxide coating at 1200°C and is able to be used up to 1600°C. The high thermal conductivity coupled with low thermal expansion and high strength gives this material exceptional thermal shock resistant qualities. Silicon carbide ceramics with little or no grain boundary impurities maintain their strength to very high temperatures, approaching 1600°C with no strength loss. Chemical purity, resistance to chemical attack at temperature and strength retention at high temperatures has made this material very popular as wafer tray supports and paddles in semiconductor furnaces. It is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics and numerous high-performance applications (Neudeck, 1992).

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 plants. Coal Combustion Products (CCP) is produced in coal-fired power stations, which burn either hard or brown coal. Due to the mineral component of coal and combustion technique, Fly Ash (FA) is produced (Gatima *et al*., 2005). In the US alone each year over 118 million tons of coal combustion products are produced. In India the stature was about 90 million ton during 1995 and is likely to exceed 140 million tons in 2020. Percentage utilization of fly ash differs between countries between 95% in Belgium and the Netherlands and 3% in India in the 1990s (Ulrichs *et al*., 2009). The utilization of fly ash instead of dumping it as a waste material can be both on economic and environmental grounds (Mohan *et al*., 2012). There is already a vast body of information on utilization of Fly Ash (FA) in building/construction, production of aggregates and more recently for agriculture (Brian *et al*., 2003).

Composites are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties that remain separate and distinct within the finished structure. The bulk material forms the continuous phase that is the matrix (e.g., metals, polymers) and the other acts as the discontinuous phase that is the reinforcements (e.g., ceramics, fibers, whiskers, particulates). While the reinforcing material usually carries the major amount of load, the matrix enables the load transfer by holding them together (Pai *et al*., 2004).

The challenges and opportunities of aluminium matrix composites have been reported much better to that of its unreinforced counterpart (Surappa, 2003). The addition of reinforcing phase significantly improves the tribological properties of aluminium and its alloy system. The thinking behind the development of hybrid metal matrix composites is to combine the desirable properties of aluminium, silicon carbide and fly ash. Aluminium have useful properties such as high strength, ductility, high thermal and electrical conductivity but have low stiffness whereas silicon carbide and fly ash are stiffer and stronger and have excellent high temperature resistance but they are brittle in nature (Prabu *et al*., 2006).

In this study, an attempt has been made to fabricate a hybrid metal matrix composites from commercial silicon carbide and fly ash. Aluminium 2024 is used as matrix material for the fabrication of Al-SiC-fly ash hybrid composite material. Methods available for the production of hybrid metal matrix composites are powder metallurgy, spray deposition, liquid metal infiltration, squeeze casting, stir casting (Nai and Gupta, 2002; Hashim *et al*., 1999). Though various processing techniques available for particulate or discontinuous reinforced metal matrix composites, stir casting is the technique, which is in use for large quantity commercial production. This technique is most suitable due to its simplicity, flexibility and ease of production for large sized components. Hence stir casting method is used in this study.

The objective of the present work is to form the reinforcing phase within the metallic matrix by reaction of silicon carbide, fly ash and its proportions with aluminium in the metallic melt. To increase the wettability, commercially pure magnesium (1.5%) was added. The composites were characterized with the help of x-ray diffraction methods and optical microscopy. Its density, tensile behavior and hardness were also evaluated.

2. MATERIALS AND METHODS

2.1. Materials

The matrix material used in the present investigation was pure aluminium. Aluminium was purchased from Perfect Metal Works, Bangaluru, Karnataka, India. Silicon carbide, fly ash and magnesium were commercially available.

2.2. Experimental Work

The Stir casting method (also called liquid state method) is used for the hybrid composite materials fabrication, in which a dispersed phase is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional metal forming technologies.

In this study, the aluminium-SiC, aluminum- fly ash, aluminium-SiC-fly ash and aluminium-fly ash-SiC metal matrix hybrid composite was prepared by stir casting route (**Fig. 1**). For this we have chosen 100gm of commercially pure aluminum and desired amount of SiC, fly ash, SiC-fly ash mixtures in powder form. The fly ash and SiC and their mixture were preheated to 300°C for three hours to remove moisture. Pure aluminum was melted in a resistance furnace. The melt temperature was raised up to 720°C and then the melt was stirred with the help of a mild steel turbine stirrer. The stirring was maintained between 5 to 7 min at an impeller speed of 200 rpm. To increase the wettability, 1.5% of pure Mg was added with all composites. The melt temperature was maintained 700°C during addition of Mg, SiC, fly ash, SiC-fly ash mixture particles. The dispersion of fly ash and other particles were achieved by the vortex method. The melt with reinforced particulates were poured into the preheated permanent metallic mold. The pouring temperature was maintained at 680ºC. The melt was then allowed to solidify in the mould (**Fig. 2**). The metal matrix hybrid composites that we obtained are shown in the **Fig. 3**.

2.3. Microstructural Characterization

The composites produced were examined by optical microscope to analyze the microstructure. A section was cut from the castings, which is first belt grinded followed by polishing with different grade of emery papers. After that they were washed and again cloth polishing of the sample was done. After etching they were examined for microstructure under optical microscope at different magnifications.

2.4. X-Ray Diffraction Analysis

The composites prepared were analyzed with the help of x-ray diffraction technique to check the presence of different compounds in the composites.

2.5. Mechanical Properties Observation

2.5.1. Density

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

2.6. Tensile Behavior

The tensile testing was done using a computerized UTM testing machine as per the ASTM E-8 standards. The sample rate was 9.103 pts/sec and crosshead speed 5.0 mm/min. Standard specimens (**Fig. 4**) with 36 mm gauge length were used to evaluate ultimate tensile strength, yield strength and percent elongation. Samples used for the tensile behavior tests are shown in **Fig. 5**.

2.7. Hardness

Bulk hardness measurements were carried out on the base metal and composite samples by using standard Brinell hardness test machine. Brinell hardness measurements were carried out in order to investigate the influence of particulate weight fraction on the matrix hardness. Load applied was 10 kg and indenter used was square based diamond pyramid. Samples used for the hardness tests are shown in **Fig. 6**.

Fig. 1. Stir casting unit

Fig. 2. Saples in the mould

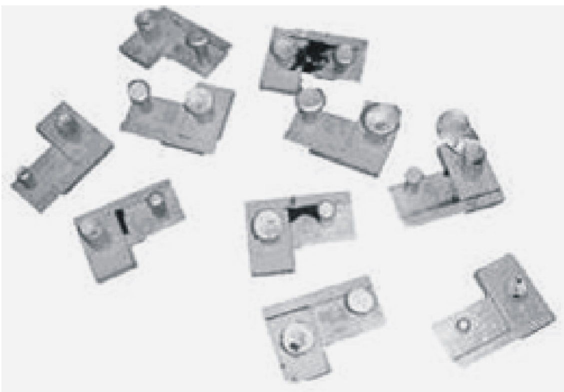


Fig. 3. Samples

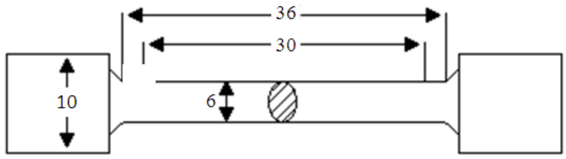


Fig. 4. Standard tensile specimen

Fig. 5. Samples for the tensile tests

Fig. 6. Samples for the hardness tests

3. RESULTS AND DISCUSSION

3.1. Optical Micrographs of MMCs

The morphology, density, type of reinforcing particles and its distribution have a major influence on the properties of particulate composites. The variables that govern the distribution of particles are solidification rate, fluidity, type of reinforcement and the method of incorporation. It is necessary to distribute particles uniformly throughout the casting during production of particulate composites. The first task is to get a uniform distribution of particles in the liquid melt and then to prevent segregation/agglomeration of particles during pouring and progress of solidification. One of the major requirements for uniform distribution of particles in the melt is its wettability. Addition of magnesium improves the wettability.

The microstructures of the samples, cut from the plate casting at different locations, were observed to study the particle distribution. The optical micrographs of hybrid metal matrix composites are shown in **Fig. 7-15**. As shown in the **Fig. 7-15**, well-formed nodules were observed before etching and grain boundaries were observed after etching process.

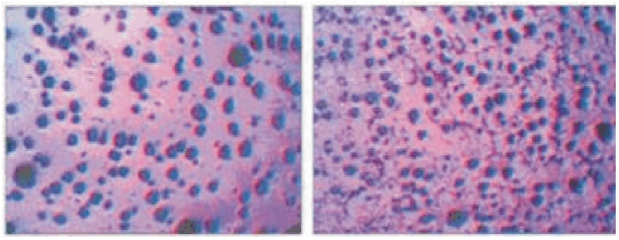
It is observed that particles were not uniformly distributed in the case of Al/(5% SiC), Al/(10% SiC), Al/(5% fly ash) and Al/(10% fly ash). Here, the particles were segregated at the selected places of the plates. The outer of the casting contained few particles. This is due to the gravity-regulated segregation of the particles. But uniform distributions of particles were observed in the micrographs of aluminium in the presence of SiC-fly ash mixture at various concentrations.

Here, particles were present more throughout the casting. The particle distribution strongly influences the physical and mechanical properties of the composites. The result shows that volume percentage of reinforcement increases with the addition of magnesium, SiC and fly ash to the melt.

3.2. X-Ray Diffraction Analysis

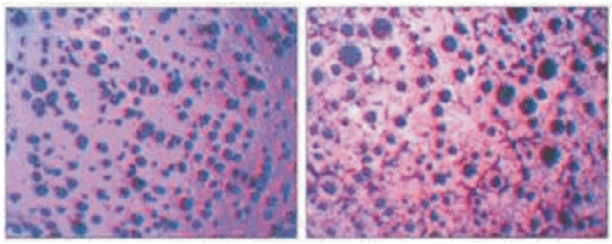
The addition of SiC, fly ash and SiC-fly ash mixture are expected to react with liquid metal and to produce reaction products of various types. The strengthening of the composites is influenced by the nature of the reinforcing phase. Hence there is necessity of identification of the compound produced by the chemical reaction; X-Ray diffraction studies have been used for this purpose. Ou of all, the XRD analysis of the Al/(10% SiC +10% fly ash) composite is shown in **Fig. 16**.

XRD spectrum shows the presence of reacted SiC, fly ash and SiC-fly ash mixture. The presence of aluminium, magnesium, SiC and fly ash indicates the possible reaction, which has taken place between the mixture (SiC and fly ash) and the aluminium-magnesium alloy.



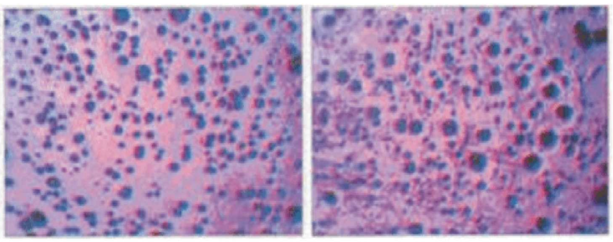
(a) (b)

Fig. 7. Optical micrograph (100X) of pure Al 2024. (a) before etching and (b) after etching



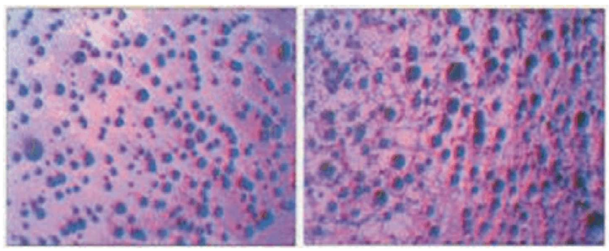
(a) (b)

Fig. 8. Optical micrograph (100X) of Al 2024/(5%SiC). (a) before etching and (b) after etching



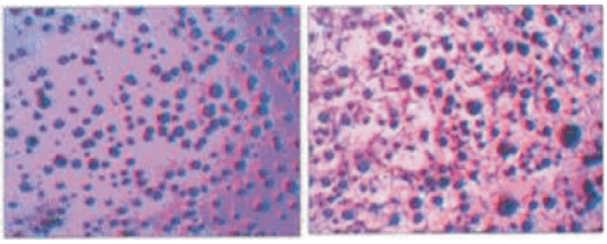
(a) (b)

Fig. 9. Optical micrograph (100X) of Al 2024/(10%SiC). (a) before etching and (b) after etching



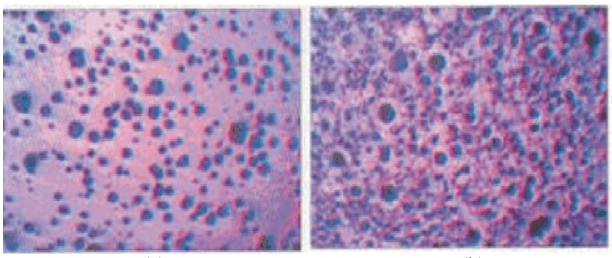
(a) (b)

Fig. 10. Optical micrograph (100X) of Al 2024/(5% fly ash). (a) before etching and (b) after etching



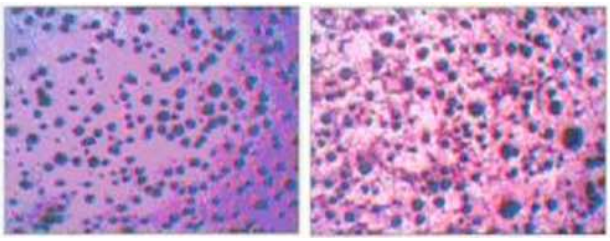
(a) (b)

Fig. 11. Optical micrograph (100X) of Al 2024/(10% fly ash). (a) before etching and (b) after etching



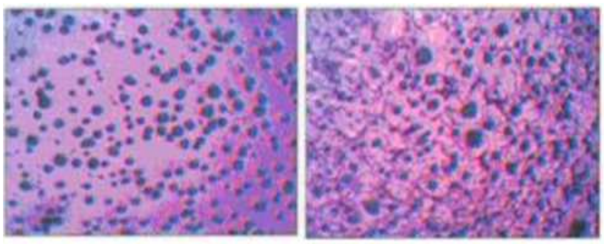
(a) (b)

Fig. 12. Optical micrograph (100X) of Al 2024/ (5%SiC+5% fly ash). (a) before etching and (b) after etching



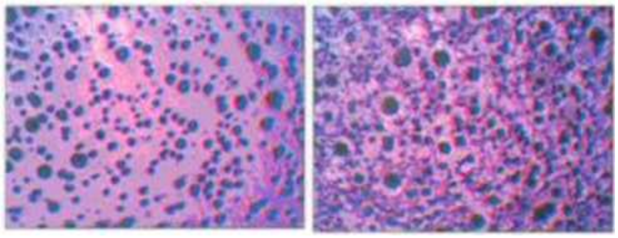
(a) (b)

Fig. 13. Optical micrograph (100X) of Al 2024/ (5%SiC +10% fly ash). (a) before etching and (b) after etching



(a) (b)

Fig. 14. Optical micrograph (100X) of Al 2024/(10%SiC+5% fly ash). (a) before etching and (b) after etching



(a) (b)

Fig. 15. Optical micrograph (100X) of Al 2024/(10%SiC+10% fly ash). (a) before etching and (b) after etching

3.3. Mechanical Properties

Results of the mechanical properties of the hybrid metal matrix composites are shown in the **Table 1**.

3.4. Density

The graph of the experimental densities of the composites according to the SiC, fly ash and their mixtures is shown in **Fig. 17**.

Generally the SiC and fly ash particles are having low density compared with aluminium. In the present study, both SiC and fly ash particles were used with a density less than 2.2 g/cm^3. The density of the composite specimens was determined experimentally by the Archimedes principle. The small pieces cut from the specimens were weighed first in air and then water and density values were calculated using the following expression:

$$\rho = \frac{\text{weight in air}}{\text{weight in air - weight in water}} x\rho_{\text{water}}$$

It was observed (**Table 1**) that the experimental density values of the Al-SiC, Al-fly and Al-SiC-fly ash composites decreased linearly. The decrease in density of composites can be attributed to lower density of SiC, fly ash and SiC-fly ash particles than that of the unreinforced Al. It was also noted that the theoretical values closely matches with the experimental values. This indicates that the interface between matrix and reinforcement was almost perfectly bonded. Similar results were observed by Rao *et al*. (2010) and Gnjidi *et al*. (2001). It is therefore, to improve the density again, apart from Al-SiC and Al-fly ash composites, the mixture of SiC and fly ash particles were added with aluminium. At higher concentration [(Al/(10%SiC+10%fly ash)], the density was decreased 2.06 g/cm^3. It is about 54% improvement when compared pure aluminium.

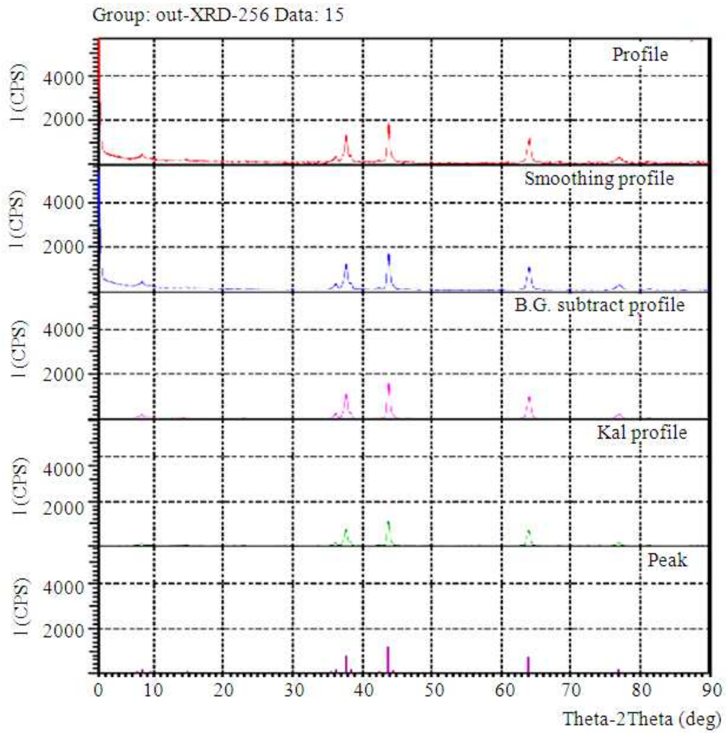


Fig. 16. XRD spectra of the hybrid metal matrix [Al/(10%SiC+10%fly ash)] composites

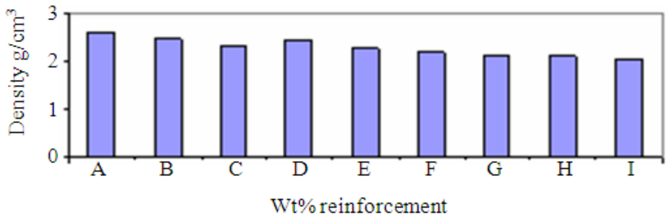


Fig. 17. Graph showing variation in density with different composition (A = Al, B = Al +5% SiC, C = Al +10% SiC, D = Al +5% fly ash, E = Al +10% fly ash, F = Al +5% SiC +5% fly ash, G = Al +5% SiC +10% fly ash, H = Al +10% SiC +5% fly ash, I = Al +10% SiC +10% fly ash) of hybrid MMCs

Table 1. Mechanical properties of the hybrid metal matrix composites

	Composition				Results				
		Wt in %							
Sample No.	Al(%) grams	Mg	SiC	Fly ash	Density g/cm^3	Tensile strength N/mm^2	Yield strength N/mm^2	Elongation in %	Hardness (BHN)
1	100	1.5	0	0	2.6000	236	220	19.4	79.9
2	100	1.5	5	0	2.4660	248	236	19.0	85.3
3	100	1.5	10	0	2.3125	265	257	18.2	87.2
4	100	1.5	0	5	2.4400	245	233	16.3	80.6
5	100	1.5	0	10	2.2700	263	252	15.8	83.8
6	100	1.5	5	5	2.2000	276	262	14.4	88.2
7	100	1.5	5	10	2.1250	278	269	13.8	89.7
8	100	1.5	10	5	2.1170	285	275	12.8	93.9
9	100	1.5	10	10	2.0600	293	287	11.9	95.7

3.5. Tensile Strength

The reinforcing phase in the metal matrix composites bears a significant fraction of stress, as it is generally much stiffer than the matrix. Microplasticity in MMCs that takes place at fairly low stress has been attributed to stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles (Corbin and Wilkinson, 1994). The increase in volume fraction of reinforcing particles initially decreases the microyielding stress due to increase in number of stress concentration points (Chawla, 2006). Mechanical behavior of Al-SiC and Al-fly ash particles were already reported (Hashim *et al*., 1999; Quin *et al*., 1999; Kok, 2005; Doel *et al*., 1993; Pathak *et al*., 2006; Sudarshan and Surappa, 2008).

The graph of the experimental tensile strength of the composites according to the SiC, fly ash and their mixtures is shown in **Fig. 18**. Results show that the tensile strength of composites is higher than that obtained for the unreinforced Al. Tensile strength of unreinforced Al is 236 N/mm^2 and this value increases to 265 N/mm^2 for Al/(10%SiC), 263 N/mm^2 for Al/(10%fly ash) and 293 N/mm^2 for Al/(10%SiC+10%fly ash) composite, which is about 57% improvement over that of the unreinforced Al matrix.

3.6. Yield Strength

The graph of the experimental yield strength of the hybrid metal matrix composites according to the SiC, fly ash and their mixtures is shown in **Fig. 19**.

Results show that the yield strength of composites is higher than that obtained for the unreinforced Al. Yield strength of unreinforced Al is 220 N/mm^2 and this value increases to 257 N/mm^2 for Al/(10%SiC), 252 N/mm^2 for Al/(10%fly ash) and finally 287 N/mm^2 for Al/(10%SiC+10%fly ash) composite which is about 67% improvement over that of the unreinforced aluminium.

3.7. Elongation

Figure 20 shows the graph of the experimental elongation of the composites according to the SiC, fly ash and their mixtures. It is experimentally observed that the elongation of composites is gradually decreased than that obtained for the unreinforced aluminium. Elongation of unreinforced Al is observed as 19.4%, this value is decreased to 18.2% for Al/(10%SiC), 15.8% for Al/(10%fly ash) and 11.9% for Al/(10%SiC+10%fly ash) composite which is about 75% with a reduction of the unreinforced Al matrix.

3.8. Hardness

The graph of the experimental hardness of the composites according to the SiC, fly ash and their mixtures is shown in **Fig. 21**. As seen from the **Fig. 21**, an increasing trend of hardness was observed with increase in weight fraction of SiC, fly ash and their mixtures. It is observed that the maximum hardness is observed at Al/(10%SiC+10%fly ash), which might leads to the deformation when subjected to strain. Incorporation of fly ash particles with this significantly improves the hardness and also the deformation of the Al matrix. It is observed that the fact that the combination of SiC with fly ash particles possess higher hardness than the aluminium.

Thus, it can be concluded that the mechanical properties such as density, tensile strength, yield strength and hardness of the composites increases by increasing SiC, fly ash and their mixtures. Contradictory, elongation of the hybrid metal matrix composite is very much decreased as that of the unreinforced aluminium. Addition of magnesium improves the wettability between the reinforcement particles and enhances the mechanical properties of the composites by solid solution strengthening. In addition, mechanical stirring in the semi solid state enhances the uniform distribution between them.

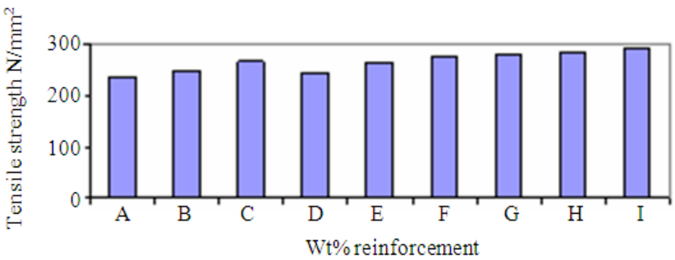


Fig. 18. Graph showing variation in tensile strength with different composition (A = Al, B = Al + 5% SiC, C = Al + 10% SiC, D = Al + 5% fly ash, E = Al + 10% fly ash, F = Al + 5% SiC + 5% fly ash, G = Al + 5% SiC + 10% fly ash, H = Al + 10% SiC + 5% fly ash, I = Al + 10% SiC + 10% fly ash) of hybrid MMCs.

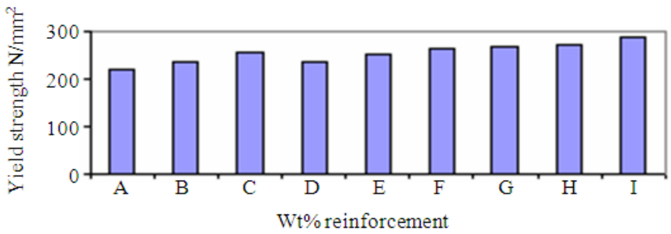


Fig. 19. Graph showing variation in yield strength with different composition (A = Al, B = Al +5% SiC, C = Al +10% SiC, D = Al +5% fly ash, E = Al +10% fly ash, F = Al +5% SiC +5% fly ash, G = Al +5% SiC +10% fly ash, H = Al +10% SiC +5% fly ash, I = Al +10% SiC +10% fly ash) of hybrid MMCs

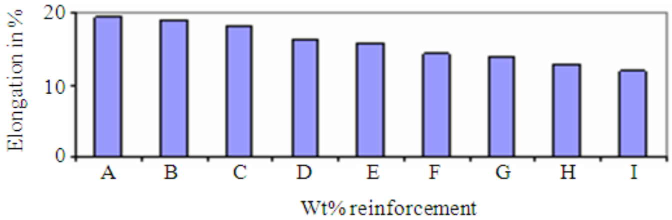


Fig. 20. Graph showing variation in elongation with different composition (A = Al, B = Al +5% SiC, C = Al +10% SiC, D = Al +5% fly ash, E = Al +10% fly ash, F = Al +5% SiC +5% fly ash, G = Al +5% SiC + 10% fly ash, H = Al +10% SiC +5% fly ash, I = Al +10% SiC + 0% fly ash) of hybrid MMCs

Fig. 21. Graph showing variation in hardness with different composition (A = Al, B = Al +5% SiC, C = Al +10% SiC, D = Al +5% fly ash, E = Al +10% fly ash, F = Al +5% SiC +5% fly ash, G = Al +5% SiC +10% fly ash, H = Al +10% SiC +5% fly ash, I = Al +10% SiC +10% fly ash) of hybrid MMCs

4. CONCLUSION

Al-SiC, Al-fly ash, Al-SiC-fly ash (various concentrations) composites were successfully fabricated by two-step stir casting process. Wetting of reinforcements with the aluminium matrix was further improved by the addition of magnesium.

Based on the experimental observations the following conclusions have been drawn:

- Density of the composites decreased by increasing the content of the reinforcement. Hence, it was found that, instead of Al-SiC and Al-fly ash composites, Al-SiC-fly ash composites show better performance. So these composites can be used in applications where to a great extent weight reductions are desirable
- Tensile strength, yield strength and hardness were determined for the test materials. Increase in area fraction of reinforcement in matrix result in improved tensile strength, yield strength and hardness
- With the addition of SiC and fly ash with higher percentage the rate of elongation of the hybrid MMCs is decreased significantly
- Optical micrographs revealed that both the SiC and flay ash particles are well distributed in aluminium matrix
- XRD results showed negligible changes in contents of constituents

From the above results we can conclude that instead of Al-SiC or Al-fly ash composites, the Al-SiC-fly ash composites could be considered as an exceptional material in sectors where lightweight and enhanced mechanical properties are essential.

4.1. Scope of the Future Work

The study can be extended by the addition of other materials with aluminium 2024. Wear and corrosion studies can also be carried out.

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