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Fabrication Characteristics and Mechanical Behavior of Fly Ash-Alumina Reinforced Zn-27Al Alloy Matrix Hybrid Composite Using Stir-Casting Technique

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***Abstract*—**This paper reports the viability of developing Zn-27Al alloy matrix hybrid composites reinforced with alumina, graphite and fly ash (solid waste bye product of coal in thermal power plants). This research work was aimed at developing low cost-high performance Zn-27Al matrix composite with low density. Alumina particulates (Al_2O_3), graphite added with 0, 2, 3, 4 and 5 wt% fly ash were utilized to prepare 10wt% reinforcing phase with Zn-27Al alloy as matrix using two-step stir casting method. Density measurement, estimated percentage porosity, tensile testing, micro hardness measurement and optical microscopy were used to assess the performance of the composites produced. The results show that the hardness, ultimate tensile strength, and percent elongation of the hybrid composites decrease with increase in fly ash content. The maximum decrease in hardness and ultimate tensile strength of 13.72% and 15.25% respectively were observed for composite grade containing 5wt% fly ash. The percentage elongation of composite sample without fly ash is 8.9% which is comparable with that of the sample containing 2wt% fly ash with percentage elongation of 8.8%. The fracture toughness of the fly ash containing composites was however superior to those of composites without fly ash with 5wt% fly ash containing composite exhibiting the highest fracture toughness. The results show that fly ash can be utilized as complementary reinforcement in ZA-27 alloy matrix composite to reduce cost.

***Keywords*—**Fly ash, hybrid composite, mechanical behaviour, stir-cast.

I. Introduction

RECENTLY, the development of low cost and high performance composites material with low weight is one of the major focuses of researchers in material engineering field. One of the areas currently being exploited is the production of metal matrix composites (MMC's). Several authors have reported about different MMC's such as Aluminium matrix composite, Zinc-Aluminium alloy matrix composite and so on [1], [2]. Zn-Al alloy based composites are gaining popularity recently owing to their unique properties such as low melting point, excellent castability, high strength, good machining, tribological properties and low manufacturing cost [3]. Zn-Al alloys are designated ZA-8, ZA-12 and ZA-27 corresponding to their approximate aluminium content in the alloy [4]. These alloys have found applications as engineering material in wide areas such as industrial fittings and hardware, sleeve bearings, and wear plates [5]. Reference [6] reported that ZA-27 alloy has the highest strength and the lowest density of all the ZA alloys, as well as excellent bearing and wear resistance properties.

Despite all these favourable properties of ZA alloys, deterioration in mechanical properties at elevated temperature (above 80^0C) has limited their applications [7]. However, several authors have reported that the use of hard particles such as silicon carbide (SiC) and Alumina (Al_2O_3) to reinforce ZA alloys improve the mechanical properties at elevated temperature but has negative effects on machinability and conductivity of Zn-Al [8]. The use of graphite being a solid lubricant and possessing good conductivity has been reported to offset these effects [8]. Reference [2] reported that the use of SiC, Groundnut shell ash and graphite as complimentary reinforcements in ZA-27 alloy improved the fracture toughness, impact resistance, as well as its corrosion resistance.

In recent times, several authors from developing countries have reported about the high cost of importing synthetic reinforcements such as Al_2O_3 and SiC because they are not produced locally in developing countries. The use of these reinforcements has led to increase in the cost of producing composites material in these countries. One of the low cost options currently being exploited by researchers from these countries is the use of agro-wastes ashes and coal ash as complementary reinforcements [9]. These ashes have been reported to contain refractory materials such as Sio_2, Al_2O_3, Fe_2O_3 and they are also characterized by low densities (1.5-2.3g/cm^3) in comparison with SiC (3.18g/cm^3) and Al_2O_3 (3.9g/cm^3) [10]. However, meager information is available regarding the processing and characterization of this ZA-27 alloy hybrid composite. In the light of this, this present research work is aimed at developing and characterizing low cost-high performance ZA-27 alloy matrix hybrid composite reinforced with fly ash, alumina and graphite using stir-casting techniques. Fly ash is generated as product of combustion of coal especially in thermal power plants. This investigation when completed is expected to give value to abundantly available industrial waste fly ash as complementing reinforcements for production of composites.

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II. Materials and Method

A. Materials

The ZA-27 alloy with chemical compositions as per ASTM B669-82 presented in Table I as selected as the matrix.

TABLE I
ELEMENTAL COMPOSITION OF ZA-27 ALLOY

Elements	Percentage Composition
Al	25-30
Si	0.02
Mg	0.012
Cu	2.06
Fe	0.065
Zn	Balance

Chemically pure alumina having particle size of 50 µm-80µm and fly ash obtained from thermal plant together with graphite particles were used as reinforcements for the ZA-27 alloy based composites. The chemical composition of the fly ash was determined using XRF and the result is as presented in Table II.

TABLE II
CHEMICAL COMPOSITION OF FLY ASH

SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	K_2O	Na_2O
55.20	23.87	0.93	4.71	1.25	4.37	1.07

B. Composite Production

Charge calculation was used to determine the weight of fly ash, alumina and graphite required to prepare 10wt% of fly ash-alumina reinforcements in the ZA-27 alloy matrix. The weight ratios of 0: 9.5: 0.5, 2: 7.5: 0.5, 3: 6.5: 0.5, 4: 5.5: 0.5 and 5: 4.5: 0.5 consisting of fly ash, alumina and graphite respectively was utilized. Two steps stir casting technique was utilized for the production of the composites as in [11]. The reinforcements to be used (fly ash, alumina and graphite) were preheated to temperature of 250^0C to remove moisture contents and improve wettability with the ZA-27 alloy. The Za-27 alloy ingot was charged into a gas fired crucible furnace (fitted with a temperature probe), and heated to the temperature of 550^0C until the alloy melted completely. The melted alloy was then allowed to cool to semi-solid state and initially preheated fly ash, alumina particles and graphite particles were dispersed into the alloy at semi-solid state and stirring of the slurry was performed for 5minutes using mechanical stirrer operating at speed of 450rpm. The composite slurry was superheated to 580^0C and stirring was also performed using mechanical stirrer operating at the same speed for 5minutes. The melt was degassed using C_2Cl_6 as it has been reported to reduce porosity and remove entrapped air [12]. After stirring, the composite was poured into sand moulds inserted with chills.

C. Density and Estimated Percentage Porosity

There is always a difference between the measured and the theoretical density values of a composite due to the presence of voids and pores. These voids significantly affect some of the mechanical properties and even the performance of composites. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering. The knowledge of void content is desirable for estimation of the quality of the composites.

The density of the composite produced was determined in order to study the effect of the fly ash-alumina wt% proportions on the densities of the composites produced. The experimental density was also used to determine the porosity levels in the composites produced. This was carried out by comparing the measured and theoretical densities of each weight ratio of fly ash-alumina reinforced composite produced using established procedure as in [13]. The density for each composite sample was determined by accurately weighing the sample using a high precision electronic weighing balance. The measured weight of each was divided by their respective volume. The theoretical density was determined by using the rule of mixtures given by:

$$d_c = d_m * V_m + d_f * V_f \qquad (1)$$

where dc, dm, df are densities of the composite, matrix and dispersed phase, respectively; Vm, Vf are volume fraction of the matrix and dispersed phase respectively.

The percent porosity of the composites was evaluated in accordance with [14] using:

$$\%\,\text{porosity} = \{(\rho T - \rho EX) \div \rho T\} \times 100\% \qquad (2)$$

where ρT = Theoretical Density (g/cm^3), ρEX = Experimental Density (g/cm^3).

D. Microstructural Examination

A Zeiss Metallurgical Microscope with accessories for image analysis was used for optical microscopic analysis of the composites produced. Prior to the microscopic examination, the specimens for the test were metallographically polished and etched. The specimens for the test were machine-cut from rods and then ground and polished. Grinding was performed with 80, 120, 360, 600 and 800 grits emery papers, while polishing was done using polishing cloth and polishing paste with Al_2O_3 particles. The Polished samples were etched in dilute aqua regal before they were viewed under microscope.

E. Hardness Test

Hardness test was performed on the composites samples using an Emco TEST DURASCAN Microhardness Tester equipped with ecos workflow ultra modern software. The specimens used for the test were cut out from each composite and polished to obtain smooth surface finish. A load of 100 g was applied on the specimens and the hardness profile was determined by using standard procedures. Multiple hardness tests were performed on each sample and the average value taken as a measure of the hardness of the specimen.

F. Tensile Test

Tensile tests were performed on the composites produced in accordance with the specifications of ASTM 8M-91 standards.

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The samples for the test were machined to round specimen configuration with 6 mm diameter and 30 mm gauge length. The test was carried out at room temperature using an Instron universal testing machine operated at a strain rate of 10^{-3}/s, the machine generated data and graphs during the test. The tensile properties evaluated from the stress-strain curves developed from the tension test are the ultimate tensile strength (σu), the 0.2% offset yield strength (σy), and the strain to fracture (εf).

G. Fracture Toughness Evaluation

The fracture toughness of the composites was determined using circumferential notch tensile (CNT) specimens as described by [15]. The composites were machined for the CNT testing and the corresponding gauge length, specimen diameter (D), notch diameter (d), and notch angle were noted. The specimens were then subjected to tensile loading to fracture using an instron universal testing machine. The fracture load (*P*f) obtained from the CNT specimens' load – extension plots were used to evaluate the fracture toughness using the empirical relations in accordance with [16]:

$$K1C = Pf/(D)3/2[1.72(D/d) - 1.27] \quad (3)$$

where, D and d are respectively the specimen diameter and the diameter of the notched section. The validity of the fracture toughness values was evaluated using the relations in accordance with [17]:

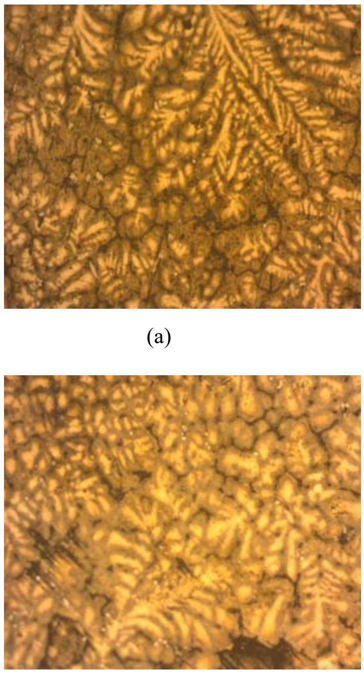
$$D \geq (K1C/\sigma y)2 \quad (4)$$

Using the above relation, the value of fracture toughness for each samples were determined.

III. Results and Discussion

A. Microstructure

Representative optical photomicrographs of ZA-27/Al_2O_3-C_g and ZA-27/Fly ash- Al_2O_3-C_g composite grade are presented in Fig. 1. It is observed from Fig. 1 (a) that a somewhat feathery feature which is actually the dendritic pattern of the Zn-27Al alloy indicating the solidification pattern and grain morphology. From Fig. 1 (b), the distribution of reinforcements are clearly evident and a partially concealed dendritic grain structure arising from the presence of the fairly homogeneously distributed reinforcement particles in the Zn-27Al alloy. A few pockets of particle clusters were also observed which are very common features of MMCs produced by stir casting technique [2].



(a)

(b)

Fig. 1 Representative micrograph showing (a) ZA-27 matrix composite reinforced with Al_2O_3 –Cg in weight percent 95% Al_2O_3: 5% Cg and (b) the microstructure of ZA-27 matrix composite reinforced with Al_2O_3-FA-Cg in weight percent 45% Al_2O_3 : 50% FA: 5% Cg etched in dilute aqua regal

B. Density and Void Fraction

The results of the density and percentage porosity of the composites is as presented in Table III.

Result of the percentage porosity of the composites is as presented in Table III. From Table III, it is observed that slight porosities exist in the composites produced. However, the maximum percentage porosity of 1.49 was observed in the composite sample containing 5wt% fly ash. This shows that the use of fly ash and Al_2O_3 as complementing reinforcements in the ZA-27 alloy matrix did not arise in any significant rise in porosity level of the hybrid composites when compared with the single reinforced ZA-27/ Al_2O_3. Reference [14] has reported that percentage porosity of less than 4% is acceptable in cast metal matrix composite.

TABLE III
Composite Density and Estimated Percentage Porosity

Sample	Weight Ratio of Reinforcements	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Porosity (%)
A	Fly ash 0: Al_2O_3: 9.5 : C_g 0.5	4.79	4.74	1.04
B	Fly ash 2: Al_2O_3: 7.5 : C_g 0.5	4.76	4.73	0.63
C	Fly ash 3: Al_2O_3: 6.5 : C_g 0.5	4.74	4.69	1.05
D	Fly ash 4: Al_2O_3: 5.5 : C_g 0.5	4.73	4.67	1.27
E	Fly ash 5: Al_2O_3: 4.5 : C_g 0.5	4.71	4.64	1.49

C. Mechanical Characterization of Composites

The Mechanical properties of the composites are presented in Figs. 1-4. The hardness (Fig. 1), Ultimate tensile strength (Fig. 2), and Percentage elongation (Fig. 3) of the composites are observed to decrease with increase in the fly ash content of the composites. 2.39%, 6.64%, 12.60% and 13.72% reduction in hardness and 2.96%, 6.61%, 10.22% and 15.25% reduction in ultimate tensile strength were observed for composites containing 2, 3, 4 and 5wt% fly ash respectively in comparison with sample without fly ash. This trend can be attributed to the composition of fly ash which is predominantly silica. References [18] and [19] have reported that silica has lower hardness and strength level in comparison to Al_2O_3 particles, SiO_2 has elastic modulus of 60-70GPa in comparison with Al_2O_3 with modulus of elasticity value of 300-375GPa.

The percentage elongation of the composite samples ranges between 8.9%-7.7%. The composite without fly ash was also observed to have the highest percentage elongation of 8.9%. But the percentage elongation of 2wt% fly ash containing composite (8.8%) is comparable to that of sample without fly ash. The fracture toughness values obtained were reported as plain strain fracture toughness because it meets the conditions specified by [17]. However, the fracture toughness of the fly ash reinforced composites was superior to that of composite without fly ash. The increase in fracture toughness of 3.67%, 11.01%, 14.68% and 22.94% were observed for 2, 3, 4, and 5wt% fly ash containing composites respectively in comparison with sample without fly ash. Reference [11] has reported that the primary mechanisms of fracture can be attributed to particle cracking and interfacial debonding. Ceramic particulates (SiC and Al_2O_3) are generally hard and brittle; and like most brittle materials, have a poor tendency to resist rapid crack propagation. The improvement in fracture toughness with increase in fly ash content may be attributed to the increased presence of silica which is a softer ceramic in comparison with Al_2O_3. Reference [20] has reported that fracture toughness scales inversely with yield strength for most engineering materials.

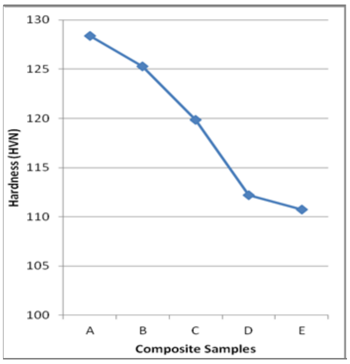


Fig. 2 Variation in Hardness for ZA-27/Al_2O_3–Cg and ZA- 27/Al_2O_3-FA-Cg Reinforced Composite Samples

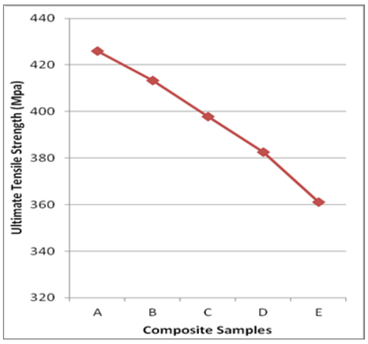


Fig. 3 Variation in ultimate tensile strength for ZA-27/Al_2O_3 –Cg and ZA-27/Al_2O_3-FA-Cg reinforced composite samples

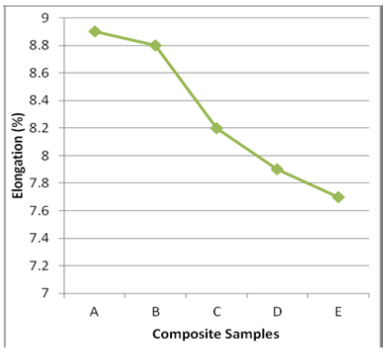


Fig. 4 Variation in percentage elongation for ZA-27/Al2O3 –Cg and ZA-27/Al_2O_3-FA-Cg reinforced composite samples

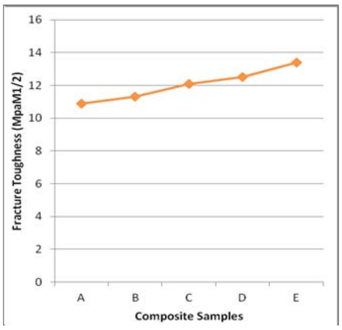


Fig. 5 Variation in fracture toughness for ZA-27/Al_2O_3 –Cg and ZA-27/Al2O3-FA-Cg reinforced composite samples

IV. CONCLUSION

The fabrication characteristics and mechanical behaviour of stir cast ZA-27 matrix hybrid composites reinforced with 0:9.5:0.5, 2; 7.5:0.5, 3:6.5:0.5, 4:5.5:0.5 and 5:4.5:0.5 wt % fly ash, Al2O3 and graphite respectively was investigated. The results show that:

- The hardness, ultimate tensile strength and percentage elongation of the fly ash containing composites slightly decrease with increase in the fly ash content.
- The fracture toughness of fly ash containing composites was superior to composite sample without fly ash.
- The percentage elongation of the 2wt% fly ash containing composite is 8.8% while the percentage elongation for

sample without fly ash is 8.9%. This shows that comparable ductility can still be achieved by using about 2% fly ash instead of expensive Al2O3.

- Fly ash has great potential to serve as a complementing reinforcement for the development of low cost-high performance ZA-27 alloy matrix hybrid composites.

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