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Influence of SiC and Al_2O_3 Particulate Reinforcement on the Mechanical Properties of ZA27 Metal Matrix Composites

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Abstract. Zinc aluminum based matrix composites reinforced with SiC and Al_2O_3 particles have significant applications in the automobile field. Stir casting method followed by squeeze process was used for fabrication. ZA27 composites reinforced with SiC and Al_2O_3 particles (20-50µm) in various weight percentage (wt%) ranges from 0-10 in a step of 5 each was fabricated. OM, SEM and EDS analysis of microstructures obtained for matrix alloy and reinforced composites were performed in order to know the effect of varying wt% on physical and mechanical properties of composites. Squeeze casting technique shows better features such as fine microstructure as a result of low porosity and good bonding between matrix and reinforcement. Addition of reinforcements decreased the densities of matrix alloy. SiC reinforced composites showed better results as compared with Al_2O_3 reinforced ones. Hardness and ultimate tensile strength value of 10 wt% reinforced composites showed improved results.

Introduction

Zinc aluminum-based alloys have been found to hold potential for various engineering applications. At this instant, commercially available ZA27 alloys have become the substitute material mainly for bearing bronzes and aluminum cast alloys due to its good fluidity, excellent castability, low density, superior wear properties and lower energy requirement for machining [1,2]. MMCs are synthesized by dispersing reinforcement usually ceramic or organic compounds in a metal matrix. Strength, stiffness, conductivity and many other properties could be enhanced by the addition of reinforcements [3]. Stir casting is one of the promising route for composite with the particle type of reinforcement for the current trend, additionally have some advantages like simplicity and applicability to bulk productions and large sized components [4]. There are the some of the reinforcing particles used in metal matrix composites in the form of carbides, nitrides, borides and oxides - SiC, B_4C, ZrN, TiN, TaB_2, TiB_2, ZrO_2, Al_2O_3 [5]. Addition of these brittle reinforcements tends to reduce ductility and fracture toughness some exception with oxides. Squeeze casting process is used to achieve high integrity engineering components with high performance. This external pressure applied to the material may cause additional effects like a change in cooling rate and melting point of the material. Improvements in properties were observed due to a reduction in gas and shrinkage porosity in alloys [6]. Latest investigations emphasized the opportunity to synthesize the composites characterized by excellent tribological and mechanical properties, further that can be additionally improved by proper selection of reinforcement material, the relative amount of reinforcement in weight percentage and by optimizing the process of particle dispersion. Abou El-khair et al. [7] studied the performance of cast ZrO_2, SiC, or C reinforced ZA27 composites. Composite exhibited better physical and mechanical properties, such as higher UTS and low coefficient of thermal expansion. Presence of reinforcement in squeezed ZA27 MMCs leads to accelerated age hardening response and increased the peak hardness value. Mishra et al. [8] investigated the erosion wear behavior, processing and characterization of SiC particle reinforced in the ZA27 matrix. Composite results showed improved UTS, impact strength and micro-hardness. However, they exhibit slightly inferior flexural strengths as compared with ZA27 alloy. Hashim et al. [9] explained in his work that processing variables such as a number of blades on the impeller, stirring speed, shape and size of the impeller, holding temperature and impeller position are the significant factors to be considered while stir cast these parameters of casting has a major influence on various properties. The objective of this work is to find the effect of SiC and Al_2O_3 particulate reinforcement on mechanical properties of ZA27 metal matrix composites with low porosity level by fabricating the composites with stir casting process followed by squeezing and to investigate the effect of varying weight percentage of these reinforcements on properties.

Experimental Details

The matrix material used is ZA27 alloy having the chemical composition of 27 Al, 2.2 Cu, 0.012 Mg, 0.4 Fe and balance is Zn by weight percentage. The SiC and Al_2O_3 of average particle size 20-50 µm were used as reinforcements. Fabrication of composite was done by the stir casting method. In this method, the reinforcement phase (SiC and Al_2O_3) was added to ZA27 alloy by mechanical stirring in different compositions as shown in table 1. A known quantity of ZA27 matrix material was taken in a crucible and melted in a furnace. Temperature was gradually raised to 550°C at 5 degrees per minute. To degas the melt, hexachloroethylene tablets were used. Vortex was created in a crucible by stirring the molten metal at 650 rpm to achieve uniform distribution of particles.

Table.1 Composition mixture of composites

	1	2	3	4	5
Matrix	ZA27 - 100 %	ZA27 - 95%	ZA27- 90%	ZA27- 95%	ZA27- 90%
Reinforcement	0%	SiC - 5%	SiC - 10%	Al_2O_3 -5%	Al_2O_3 -10%

Wettability of particles was improved by heat treating the reinforcements to a temperature of 400°C, additionally, it also helped in the elimination of moisture content. Reinforcements were added at a rate of 20-25 g/min into the melt with an addition pouring attachment. Further, molten metal was poured into a metallic die which was preheated to 300 °C and 80 MPa of pressure was applied during squeezing. The densities of composites were measured by using a density measurement kit: Contech-CAS-44. Experimental density was calculated by dividing the measured weight of a sample by its measured volume and rule of mixtures was adopted to evaluate the theoretical density [10]. Tensile specimens were prepared by cutting from the middle location of the cast composites. The tensile tests were carried out in agreement with ASTM E8 M standard using a UTM: AG-X plus TM 100 kN at room temperature. Rockwell hardness was measured under a load of 100 kgf and dwell time of 30 seconds. For microstructural analysis samples were etched using Nital 3% etchant. Scanning electron microscope (Model- JEOL JSM 6380LA) is used for examining the microstructure. CARL Zeiss-FESEM (Oxford Instruments-EDS) was used to analyze the composition of matrix alloy and composite.

Results and Discussion

Microstructures of the ZA27 alloy in as-cast conditions are presented in fig. 1. Microstructure of ZA27 alloy consists of a dendritic structure with α aluminum-rich dendrites, zinc rich eutectoid α+η phase in inter-dendritic regions along with metastable ε (Cu-rich) phases [11].

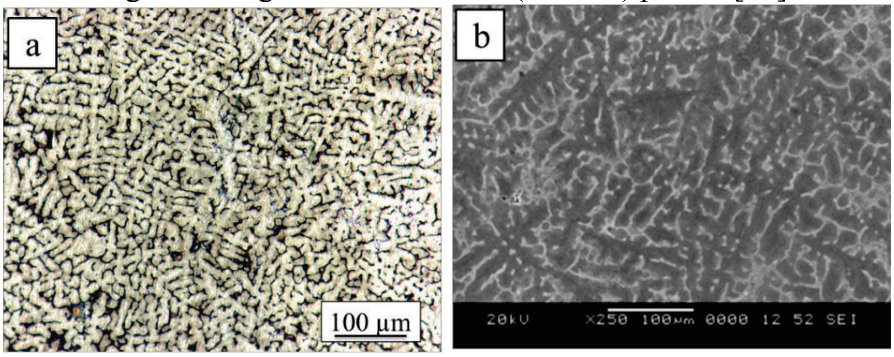
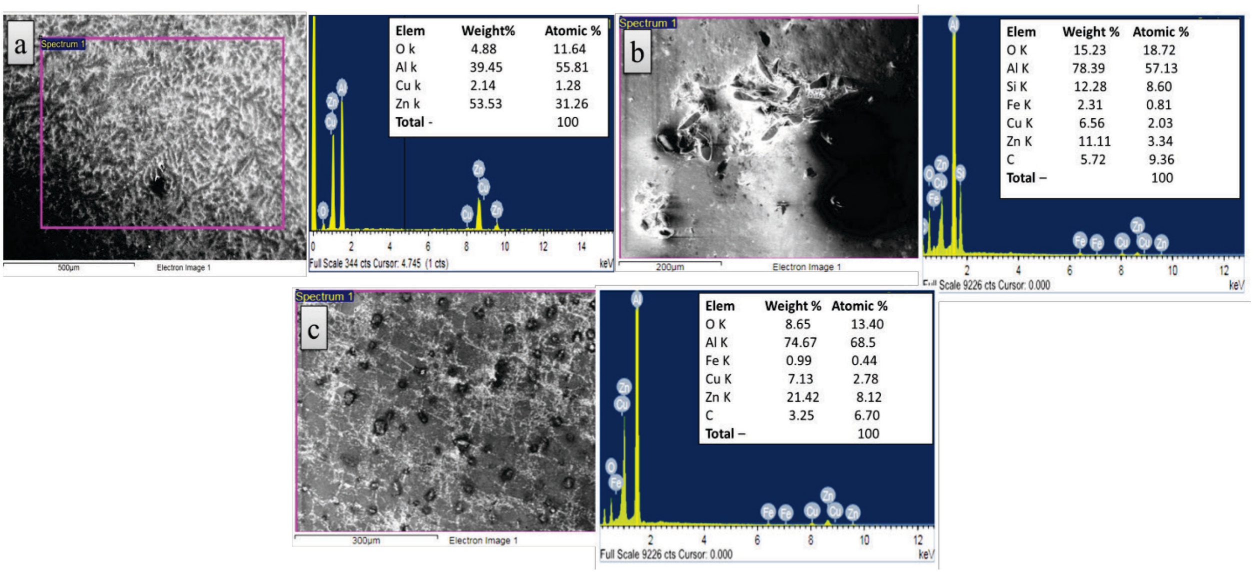


Fig. 1 OM and SEM images of ZA27 matrix alloy



a

Elem	Weight%	Atomic %
O k	4.88	11.64
Al k	39.45	55.81
Cu k	2.14	1.28
Zn k	53.53	31.26
Total -		100

b

Elem	Weight %	Atomic %
O K	15.23	18.72
Al K	78.39	57.13
Si K	12.28	8.60
Fe K	2.31	0.81
Cu K	6.56	2.03
Zn K	11.11	3.34
C	5.72	9.36
Total –		100

c

Elem	Weight %	Atomic %
O K	8.65	13.40
Al K	74.67	68.5
Fe K	0.99	0.44
Cu K	7.13	2.78
Zn K	21.42	8.12
C	3.25	6.70
Total –		100

Fig. 2 Energy dispersive spectroscopy images for alloy composition confirmation

Composition of ZA27 alloy and the presence of reinforcing particles (SiC and Al_2O_3) in the metal matrix was confirmed by the EDS analysis, which is shown in fig. 2. Four different types of material were fabricated with different compositions. Particles are fairly distributed in the ZA27 alloy matrix as it is clearly observed in optical and SEM micrographs. Dendritic structure of the composite was refined with the addition of reinforcement, furthermore porosity level decreased because of applied squeeze pressure of 80 MPa during casting which directly influences the density of ZA-based alloy and its composites [12]. Fig. 3 (a-d) shows the optical microscopic and scanning electron microscopic images of SiC particles of 5 and 10 wt% reinforced in the ZA27 matrix. Some SiC particle clusters were observed as depicted in fig. 3 (b, d). SiC and Al_2O_3 reinforcements present in the ZA27 matrix affect the microstructure of composites. From the optical microscopic images, it is observed that a black region around the SiC particle is due to the lower thermal conductivity of ceramic particles, the cooling rate of the matrix is faster than that of particles. Solidification of the particulate surrounding alloy was delayed because the temperature of the liquid alloy is slightly lower than reinforcing particles and it may heat up the liquid in their surroundings.

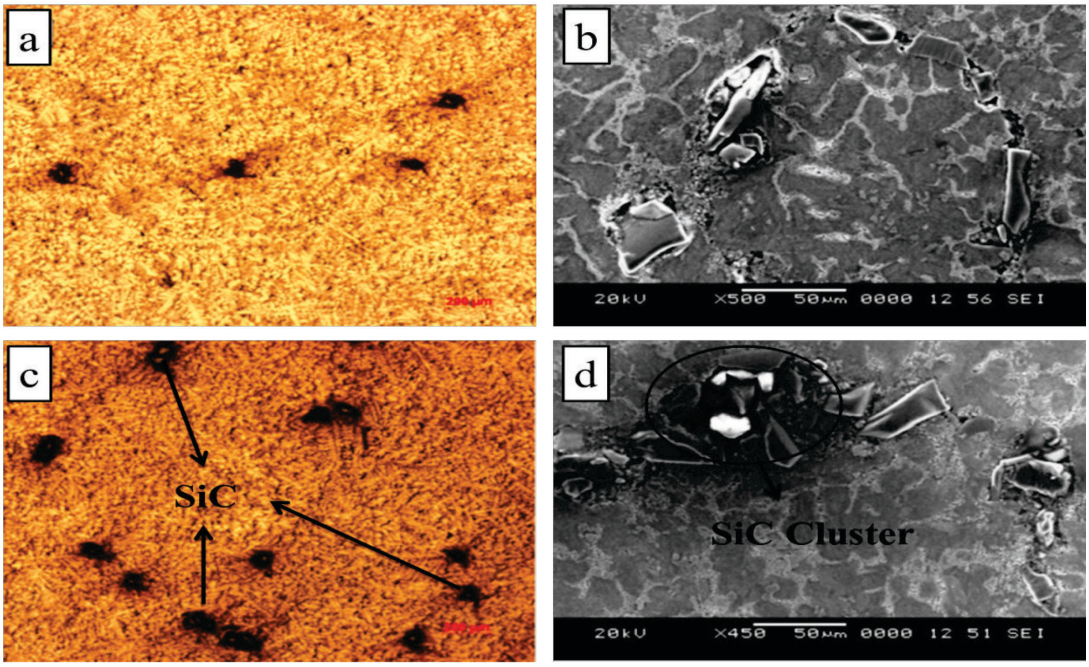


Fig. 3 Optical microscopic and scanning electron microscopic images of ZA27/SiC (a) OM- ZA27 5% SiC (b) SEM- ZA27 5% SiC (c) OM- ZA27 10% SiC (d) SEM- ZA27 10% SiC

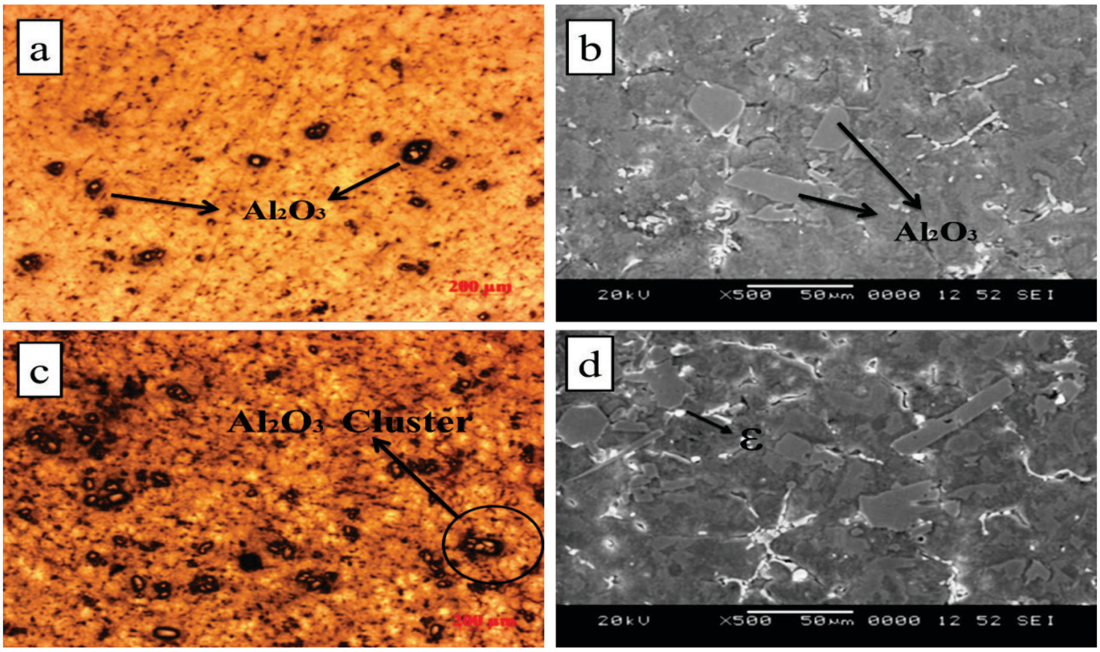


Fig. 4 Optical microscopic and scanning electron microscopic images of ZA27/ Al_2O_3 (a) OM-ZA27 5% Al_2O_3 (b) SEM-ZA27 5% Al_2O_3 (c) OM-ZA27 10% Al_2O_3 (d) SEM- ZA27 10% Al_2O_3

The constraint caused by the reinforcing particle to solute enrichment makes the dendrites grow away from them [13]. Thus, the grains grow outward from the reinforcement and remaining matrix liquid solidifies over the particles. Figure 4 (a-d) indications the optical micrographs and SEM images of ZA27 alloy reinforced with 5 and 10 wt% of Al_2O_3 particles. Intermetallic compound $CuZn_4$ (ε) was formed by the addition of lower Cu content in Zinc aluminum alloy [14] which is shown in fig.4(d). Micrograph of cast ZA27 alloy based composites did not have any macroporosity as shown in fig.3 and 4. Distribution of the Al_2O_3 particles is nearly uniform in the matrix and some cluster were also observed in composite reinforced with 10 wt% of Al_2O_3 shown in fig.4(c). Mechanical properties of composite material depend on size and distribution of particles, therefore the porosity level should be maintained minimum. Porosity cannot be avoided, but it can be controlled during the casting process by following a proper step in casting. Entrapped gases, shrinkage during solidification and hydrogen evolution are the causes of porosity formation. The shortest possible distance has to be maintained from the crucible to mould while poring to achieve sound casting. Theoretical and Experimental density results are shown in table 2 with its corresponding porosity percent of composites with respect to composition. Archimedes's principle was used to measure theoretical density. Composites are somewhat porous with porosity less than 2.5%. Furthermore, the density of SiC and Al_2O_3 reinforced composite is less when compared to the base alloy matrix.

Table.2 Experimental and Theoretical density with porosity percentage

Sl. No	**Material Composition**	**Theoretical Density [g/cm³]**	**Experimental Density [g/cm³]**	**Porosity [%]**
1	ZA27	5.2975	5.2521	0.86
2	5% SiC	5.2458	5.1924	1.01
3	10 % SiC	5.2041	5.1094	1.82
4	5% Al_2O_3	5.2858	5.2189	1.26
5	10 % Al_2O_3	5.2614	5.1548	2.02

Al_2O_3 reinforced composites densities were higher than that of SiC reinforced composites. Porosity percentage increased with an increase in wt % of SiC and Al_2O_3 particles. Void space or porosity will be formed between the clusters of reinforcements trapping air in between them during the incorporation of particles while casting. Acceptable limit of porosity level is a maximum of 4 %

was reported by Alaneme et al. [15] for cast aluminum MMCs. Fig. 5 represents the variation in hardness with different material composition. Hardness of the material increased substantially by the addition of reinforcement. For 10 wt% SiC and Al_2O_3 particle reinforced composite shows the highest hardness value of 74 HRB and 69 HRB respectively when compared with unreinforced ZA27 alloy (51 HRB). The hardness for composites with 5 wt% SiC and Al_2O_3 reinforced samples are 66 HRB and 63 HRB respectively. The variation in the hardness value is attributed to excellent bonding strength between the interface of the matrix and reinforcing particles. Fig. 6 illustrates engineering stress v/s strain curves for a composite material with varying reinforcement percentage. An appreciable amount of improvement in strength was observed for SiC and Al_2O_3 10 wt% particle reinforced composites. The ultimate tensile strength of matrix alloy was 304 MPa and increased to 335 and 329 MPa for 5wt% of SiC and Al_2O_3 reinforced composite respectively. Maximum ultimate tensile strength of 381 MPa was achieved by composite reinforced with 10 wt% of SiC and 369 MPa for 10 wt% Al_2O_3 reinforced composite. Therefore, with the increase in the wt % of reinforcing particles like SiC and Al_2O_3 resulted in an increase in tensile strength of the composites. A fairly good dispersion of the SiC particles was achieved, although some clusters still existed in the ZA27 matrix.

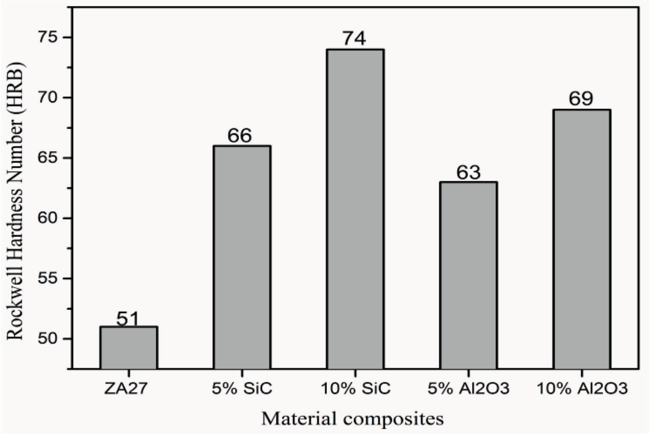


Fig. 5 Hardness number as a function of material composition

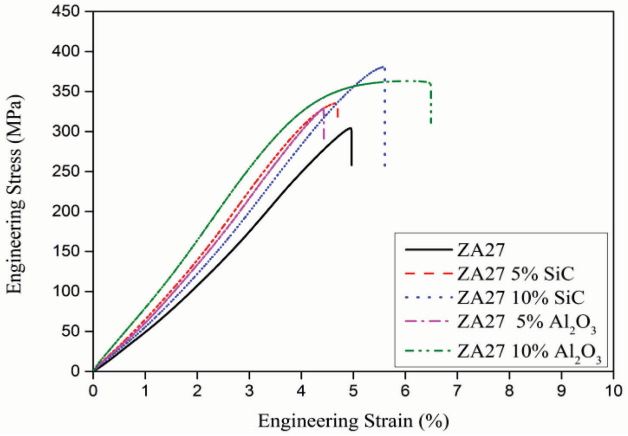


Fig. 6 Engineering stress v/s strain for tensile samples

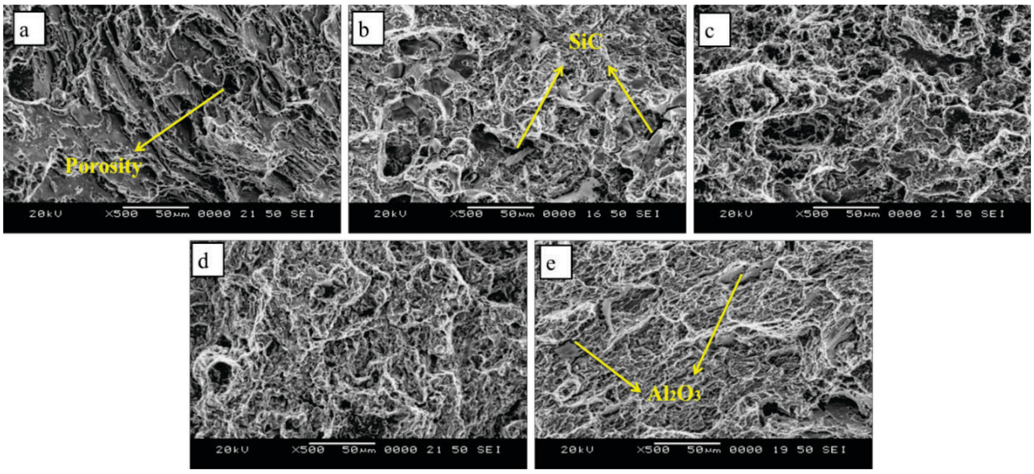


Fig. 7 Scanning electron microscopic images of fractured tensile sample (a) ZA27 as-cast alloy (b) ZA27 5% SiC (c) ZA27 10% SiC (d) ZA27 5% Al_2O_3 (e) ZA27 10% Al_2O_3

Due to the difference in thermal expansion coefficient, during the cooling process dislocations are introduced by the ceramic particles which are the reason for improvement achieved in composite materials [16]. By many investigators, it is reported that the presence of thermal mismatch stress would increase the dislocation density within the matrix. This may lead to local stress, increasing the strength of the matrix alloy [17]. Resistance offered by reinforcing particles, dislocation to dislocation interaction could be the reasons for the strengthening of composite [18]. Fig.7 shows the micrograph of the fracture surfaces for the tensile tested sample. In initial base matrix alloy, the fracture type is mainly brittle mode this is because of incomplete filling of liquid melt in solidification process which forms interdendritic porosity in dendritic type structured ZA27 alloy in as-cast condition. After reinforcement of these alloys with SiC and Al_2O_3 particles, there were no much changes in the mode of fracture, but a small amount of percentage of elongation as decreased with respect to both 5 wt % SiC and Al_2O_3 particle reinforced composites. In the case of composites reinforced with 10 wt% showed a slight increase in the percentage of elongation with a small contribution to ductility as compared with ZA27 base matrix alloy.

Conclusions

Stir casting followed by squeeze technique was successfully adopted for the fabrication of ZA27 based composites with 5 and 10 wt % of both SiC and Al_2O_3 particles. Mechanical properties improved due to the applied pressure in squeeze casting, which leads to a reduction of microporosity in the alloy and composite. SiC and Al_2O_3 were fairly dispersed in ZA27 matrix with some clusters. Porosity percentage increased with an increase in particulate content for both the type of reinforcement (SiC and Al_2O_3). The density of ZA27 alloy decreased by the addition of SiC and Al_2O_3 particles and as the wt% increased the density value decreased. SiC reinforced composites showed better results as compared with Al_2O_3 reinforced composites. Hardness and ultimate tensile strength value of 10 wt% reinforced composites showed improved results in both SiC and Al_2O_3 reinforced composites as compared with base matrix and 5 Wt% reinforced composites. Furthermore, SiC reinforced 10 wt% composites showed better mechanical properties with 1.82 % of porosity level. Percentage of elongation decreased for 5 wt% reinforced composite and increased for 10 wt% reinforced composites in both the SiC and Al_2O_3 type as compared with base matrix alloy. Initial ZA27 matrix alloy showed a brittle type of fracture and there is no much difference in mode of fracture of composites.

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