MECHANICAL, CORROSION AND WEAR BEHAVIOUR OF STEEL CHIPS AND GRAPHITE REINFORCED Zn-27Al ALLOY BASED COMPOSITES

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Abstract

The prospect of enhancing mechanical, corrosion and wear properties of Zn27Al alloy based composites reinforced with steel machining chips by graphite addition was the focus of this investigation. Double stir casting was used to produce Zn27Al alloy based composites with 7 wt.% reinforcement but with varied compositions containing 1, 2, and 3 wt.% graphite, steel chips making up the balance. Microstructural analysis, mechanical, corrosion and wear tests were used to characterise the composites. The results show that the hardness of the composites decreases slightly with an increase in graphite content in the reinforced composites. The tensile strength and fracture toughness of the composite only showed improvement with the addition of 3 wt.% graphite in the hybrid mix (steel chips and graphite) compared with the use of lower graphite content in the mix and steel chips only. The percent elongation did not show dependency on the composition of the reinforcement phase and was basically within the range 6.0 - 6.8 %. The fracture surfaces of all the composites were essentially rough, a preponderant feature of ductile fracture mode. The wear index of the composites was generally low indicating good wear resistance. However, despite the seeming self-lubricating advantage of graphite, the wear resistance of the composite reinforced with only steel chips was relatively better than that of the hybrid graphite, and steel chips reinforced composite compositions. Finally, the steel chips and graphite reinforced Zn-27Al alloy based composites were generally more corrosion resistant in 3.5% NaCl solution compared with the unreinforced Zn-27Al alloy.

1 Introduction

Zn–Al-based composites have continued to find relevance in several technological applications [1-2]. The Zn–Al alloys, which serve as the matrix for this class of MMCs, are known for their good combination of physical, mechanical and technological properties [3-4]. High strength, excellent castability, good machinability, low melting point and good tribological properties, as well as low manufacturing cost, are among its notable characteristics [5]. They are also reported to show satisfactory service performance when used for the design of components such as bearings, dies, punches and seals which require high mechanical and wear resistance [6]. Budding technologies for the use of these components require the ability to operate in harsh

environments with extreme mechanical, corrosion and wear resistance as core requirements. These requirements are untenable with the use of base Zn-Al alloys and have given impetus to research efforts aimed at enhancing the said property requirements. The incorporation of reinforcements such as silicon carbide (SiC) and alumina (Al_2O_3) in Zn-Al alloys has been explored in this regards, and this has resulted in marked improvement in hardness, strength, specific strength, wear and creep resistance of Zn–Al-based composites [7-8]. The problem of machinability of Zn-Al based composites which appeared to be a concern has been improved on (without any deleterious effect on mechanical and tribological properties) by the use of graphite as complementing reinforcement to SiC and Al_2O_3 [9-10].

Currently, there is a drive for the production of low-cost Zn-Al alloy based composites using waste/by-products derived from industrial processes (red mud, fly ash, quarry dust) and agro-based materials (rice husk ash, bamboo leaf ash, groundnut shell ash among others) [11]. These waste/by-products have shown some promise as reinforcements, but engineering performance particularly where combinations of properties are needed has produced mixed outcomes. This has resulted in the exploration of more low-cost reinforcement options for development of MMCs in general and Zn-27Al based composites in this specific instance. Recently, the use of steel machining chips as reinforcement has been reported [12-13]. Its choice as reinforcement is predicated on economics, waste management and metallurgical considerations. Based on economics, there is little or no cost incurred in its use apart from sieving to the required particle size. Meanwhile, there is at present little secondary use of the steel chips, thus deploying it for use as reinforcement is an environmentally apt strategy of recycling steel chips and waste management. Mechanical behaviour and machining mechanics, explains that steel chips due to the large shear strains associated with the chip formation process possess ultra-fine/nano-structures which impart exceptional mechanical properties compared to the bulk metal [14].

The use of steel chips as reinforcement has been explored in Zn, and Cu-based MMCs and the indications are that it could be utilised to solve the often low fracture toughness and ductility challenges associated with the use of ceramic-based reinforcement [13] [14]. In Zn-27Al based composites, its bearing properties are very crucial in most of the applications it is utilised. Graphite is well known to have self-lubricating properties which ideally is helpful in enhancing bearing properties in Zn-27Al based composites. This research explores the use of steel chips and graphite as mixed reinforcement in the development of Zn-27Al based composites. This is from the viewpoint of harnessing the advantages of each, that is steel chips (good strength, toughness and ductility) and graphite (self-lubricating characteristic which aids wear resistance). Breakthrough in this research as conceptualised has the potential of offering reduced composite production cost, an additional channel for industrial waste recycling while enhancing the technical efficiency and performance levels of Zn–Al-based composites.

2   Materials and method
2.1 Materials
The materials selected for the production of the Zn-Al hybrid composites are commercial pure zinc and aluminium, medium carbon steel machining chips (100 µm passing), and graphite (75 µm passing). The chemical composition of the zinc and aluminium used in the research are presented in **Tab. 1**.

Table 1 (a): Chemical composition of commercial pure Zinc

Elements	Zn	Fe	Si	Pb	Others
Composition (wt. %)	99.96	0.02	0.006	0.004	0.01

Table 1 (b): Chemical composition of commercial pure Aluminium

Elements	Si	Fe	Mn	Others	Al
Composition (wt. %)	0.033	0.003	0.021	0.023	99.92

2.2 Composites production

The production of the Zn-27Al alloy matrix composites with steel machining chips and graphite as reinforcements was performed using double stir casting in agreement with [15]. The amount of reinforcements (steel machining chips and graphite) required to prepare five composite compositions presented in **Tab. 2** were determined using charge calculation. The melting was done using a gas-fired crucible furnace fitted with a temperature controller. The aluminium was charged in first and heated to about $680^{o}C \pm 20$ ^{o}C until the aluminium melted completely. The temperature of the furnace was then reduced to about 500 ^{o}C before zinc was introduced into the aluminium melt. After the zinc had melted completely, the melt was cooled in the furnace to a semi-solid state and therein stirred for about 5minutes to obtain homogenised molten Zn-Al alloy. The steel machining chips and the graphite were then added into the semi-solid melt and stirred manually for 7-10 minutes. The slurry was returned into the furnace and superheated to a temperature of 530 $^{o}C \pm 10$ ^{o}C. The second stirring was performed on the superheated liquid composite for about 6 minutes using a mechanical stirrer, after which it was poured into prepared sand moulds to solidify.

Table 2 Samples Designation and Composition

Sample Designation	Composition
A	Zn-27Al
B	Zn-27Al + 7 wt.% steel chips
C	Zn-27Al + 6 wt.% steel chips +1wt.% graphite
D	Zn-27Al + 5 wt.% steel chips +2wt.% graphite
E	Zn-27Al + 4 wt.% steel chips +3wt.% graphite

2.3 Mechanical testing

Hardness testing, tensile properties and fracture toughness evaluation were used to determine the mechanical properties of the composites produced. The hardness values of the samples were determined in accordance with the provisions in ASTM E18-16 [16] using a Rockwell Hardness Tester. An indentation load of 60 kgf (588.4 N) was applied on flat smoothly polished specimens of the composites for 10 seconds, and the hardness readings were assessed following standard procedures. Six repeat tests were carried out on each sample per composition, and the average value was taken as a measure of the hardness of the specimen.

The tensile properties of the composites were evaluated at room temperature using a universal testing machine (UTM) operated at a nominal strain rate of 10^{-3}/s (quasi-static strain rate). The tensile test samples machined with a gauge length of 30 mm and diameter of 5 mm were pulled in tension to fracture. The testing procedure and data analysis were done in accordance with ASTM E8M-15a [17] standard.

Fracture toughness of the Zn-27Al composites was determined using circumferential notch tensile (CNT) testing approach in accordance with [15]. The specimens for the test were machined to have a specimen diameter of 5 mm (D), a gauge length of 30 mm, notch diameter of 4.4 mm (d), and notch angle of 60°. The specimens were subjected to tensile loading to fracture

using a Universal tensile testing machine. The fracture load (pf) obtained from the CNT specimens load-extension plots were used to evaluate the fracture toughness using the empirical relations in accordance with Dieter [18]:

$$k_{Ic} = \frac{P_f}{(D)^{\frac{3}{2}}[1.72(\frac{D}{d})-1.27]}$$

(1.)

Also, the basis for the evaluation for plain strain conditions was determined using Alaneme [19]:

$$D \geq \left(\frac{K_{Ic}}{\sigma_y}\right)^2$$

(2.)

Where: K_{IC} is fracture toughness,
P_f is the fracture load,
D and d are respectively the specimen diameter and the diameter of the notched section,
σ_y is the yield strength.

2.4 Microstructural examination

A Zeiss Optical Microscope with accessories for image analysis was used for optical microscopic investigation of the composites. The samples for the test were prepared using standard metallography procedures and etched using dilute aqua regal solution ($3HCl + 1HNO_3$) before the microscopic examination was performed. The fracture surface morphologies were also examined using field emission scanning electron microscope (FE-SEM).

2.5 Wear Testing

Wear test of the composites was performed using a Taber abrasion tester in accordance with ASTM G 99-05 [20] standard. The wear samples in the form of discs were machined to 100 mm diameter and 5 mm thickness. The samples were placed on the turntable platform of the wear machine and gripped at a constant pressure by two abrasive wheels lowered onto the sample surface. In operation, the turntable rotates at 150 rpm with the samples driving the abrasive wheels in contact with its surface. Rotation of the turntable causes the wheels to drive in reversed direction about a horizontal axis which is tangentially displaced from its axis. The rubbing action between the sample and the abrasive wheel during the rotating motion of the machine lead to the generation of loose composite debris from the sample surface. The test was conducted for 15 min, and the sample weight before and after the tests are recorded.
The Taber wear index method was used to evaluate the rate of wear using the relation [14]:

$$I = \frac{[(A-B)\times1000]}{C}$$

(3.)

where: I is wear index,
A and B are weight of specimen before and after abrasion test respectively,
C is a number of test cycles (150 rpm).

2.6 Corrosion behaviour evaluation

Corrosion testing was conducted using potentiodynamic polarisation electrochemical methods in accordance with ASTM G48-11 [21] standard. Corrosion behaviour of the samples was investigated in 3.5 wt. % NaCl solution at room temperature (25 ˚C) using an AutoLAb

potentiostat. Potentiodynamic polarisation measurement was carried out at a scan rate of 1.0 mV/s at a potential initiated at 200 mV to +250 mV using a three-electrode corrosion cell set-up comprising the sample as the working electrode, saturated silver/silver chloride as a reference electrode, and platinum as the counter electrode. The working electrodes were prepared by attaching an insulated copper wire to one face of the sample using an aluminium conducting tape, and cold mounting it in resin. The surfaces of the samples were wet ground with silicon carbide papers from 220 down to 600 grade in accordance with Alaneme and Bodunrin [22], washed with distilled water, degreased with acetone and dried in air. Three repeat tests were carried out for all compositions of the composites to guarantee the reproducibility of results from triplicates. The surface morphology of the composites after immersion in the corrosion solutions was assessed using a Field Emission Scanning Electron Microscope (FE-SEM).

3 Results and discussions
3.1 Microstructural Examination
Fig. 1 shows the optical micrographs of selected compositions of the Zn–27Al alloy matrix composites produced. The microstructures show evidence of reinforcing phases dispersed in the Zn-27Al alloy matrix with pockets of particle agglomerates which is common in cast metal matrix composites. The dispersion of the reinforcements in the matrix was fair although the reinforcement type - that is steel chips and graphite were not distinguishable.
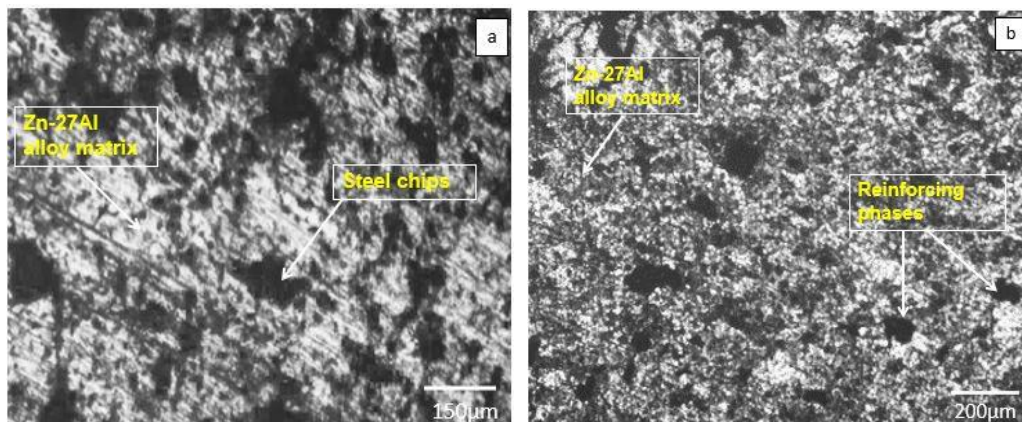

Fig. 1 Optical Micrographs of (a) Zn-27Al alloy based composite containing 7 wt.% steel chips, and (b) Zn-27Al alloy based composite containing 5 wt.% steel chips + 2 wt% graphite

3.2 Mechanical Behaviour
The results from the mechanical testing performed on the composites are presented in **Figs. 2 - 5**. From **Fig. 2** it is observed that the unreinforced Zn-27Al alloy (sample A) had the least hardness value; and that hardness of the composites decreases marginally with increase in the graphite content in the hybrid reinforced composites. This is expected as graphite is relatively soft compared to steel. The hardness values obtained for the composites are noted to be comparable to values reported by Alaneme et al. [23]. For the tensile strength results (**Fig. 3**), it is observed that the tensile strength reduces with graphite addition, attaining the least value with the use of 2 wt.%. However, the addition of 3 wt.% graphite in the hybrid mix (steel chips and

graphite), resulted in the highest tensile strength value for all the composites produced. No reason could be adduced for this dramatic increase, which will need to be clarified in future studies. The percent elongation did not follow a consistent trend and was essentially by the same margin for both the unreinforced and the reinforced composites, varying between 6.0 - 6.8 % (**Fig**. **4**). However, the highest elongation of 6.8 % was recorded for the composite reinforced with only steel chips. This is evidently due to the steel chips which is more ductile and hence plastically deformable compared with graphite contained in other composite grades which has predominantly ceramic characteristics. The fracture toughness results (**Fig**. **5**) were reported as valid as they met the requirement for plane strain condition [19][24]. It is observed that the addition of 1 and 2 wt.% graphite did not appear to improve the fracture toughness value but the reverse effect was observed with the use of 3 wt. % graphite in the hybrid mix of steel machining chips and graphite. This was closely followed by the composite reinforced with only steel chips (sample B). This trend is typical to what was observed for the tensile strength results of the composites (**Fig.** 3), suggesting that a unique composition of graphite (in this case 3 wt.% graphite) mixed with steel machining chips is required to achieve improved mechanical properties in Zn-27Al based composites.

A fractographic (for Zn-27Al reinforced with 7 wt.% steel chips only) with fracture surface topography characteristic of all the composite compositions is presented in **Fig**. 6. The fracture surface is observed to be essentially rough indicating the predominance of ductile fracture mode which is typical of metallic based material systems.
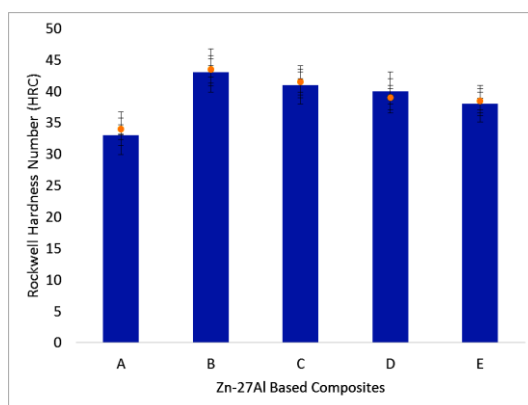

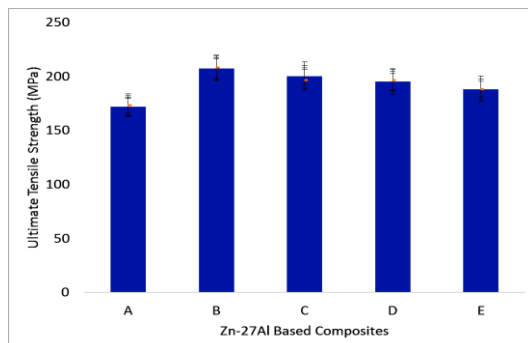**Fig. 2**   Hardness values for the Zn-27Al alloy based composites

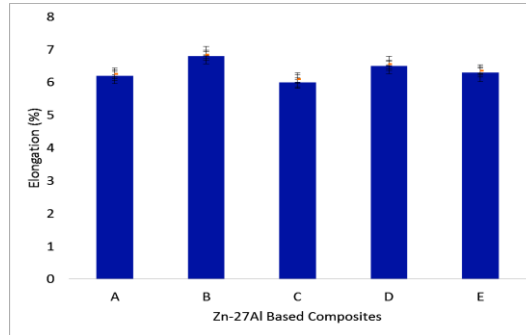**Fig. 3**   Ultimate tensile strength for the Zn–27Al alloy based composites

Fig. 4   Percentage elongation for the Zn–27Al alloy based composites

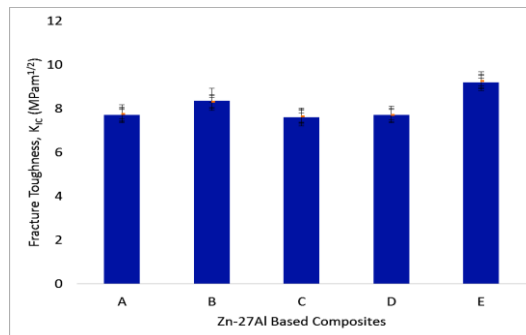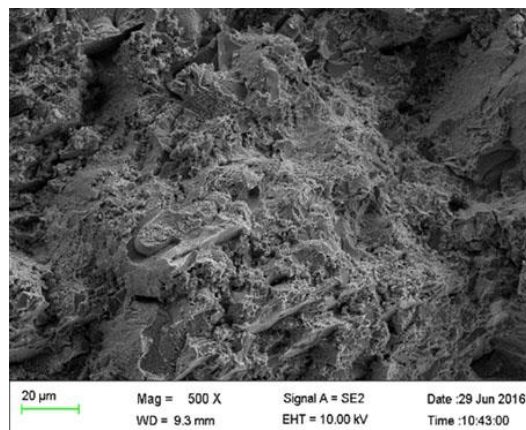**Fig. 5**   Fracture toughness for the Zn–27Al alloy based composites

Fig. 6   SEM fractography of Zn-27Al alloy based composite containing 7 wt.% steel chips only

3.3 Wear Behaviour

The wear index of the composites is presented in **Fig.** 7. It is observed that the wear index was generally low and the composites had wear index values less than that of the unreinforced alloy (sample A) indicating improved wear resistance. However the wear index of the composite reinforced with only steel chips (sample B) was relatively lower than that of the hybrid graphite,

and steel chips reinforced composite compositions (samples C, D and E). This suggests that the use of steel chips alone as reinforcement in Zn-27Al based composites may suffice for wear-related applications notwithstanding the potential self-lubricating quality of graphite.
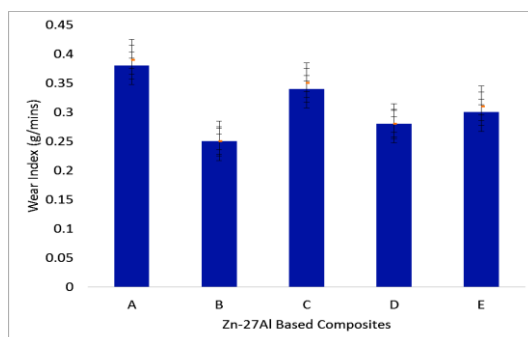

Fig. 7   Wear Index for the unreinforced Zn-27Al alloy and Zn-27Al alloy based composites

3.4 Corrosion Behaviour

Tafel plots extrapolations from the electrochemical studies of the Zn-27Al matrix composites in 3.5 wt.% NaCl solution is presented in **Fig. 8**. It is observed that the composites exhibited similar polarisation and passivity characteristics apart from composition D with polarisation curve displaced to higher potentials. The results of the electrochemical parameters, presented in **Tab. 3**, show that the corrosion current density (I_{corr}) and the corrosion rate (measured in millimeters per year, mmpy) were relatively more intense for the unreinforced Zn-27Al alloy in comparison with the reinforced Zn-27Al alloy based composites. This indicates that the steel chips reinforced and steel chips - graphite hybrid reinforced Zn-27Al alloy matrix composites are more resistant to corrosion in 3.5 wt.% NaCl solution compared with the unreinforced Zn-27Al alloy in the same environment. The E_{corr} values are supportive of the I_{corr} trends as it is observed that the composites have higher corrosion potentials compared with the unreinforced Zn-27Al alloy. This indicates that the reinforced Zn-27Al alloy based composites have a lower thermodynamic tendency to corrode in 3.5 wt.% NaCl solution compared to the unreinforced Zn-27Al alloy. It is noted that the composite compositions in which 2 and 3 wt.% graphite was added to the steel chips as reinforcement had improved corrosion resistance compared with the
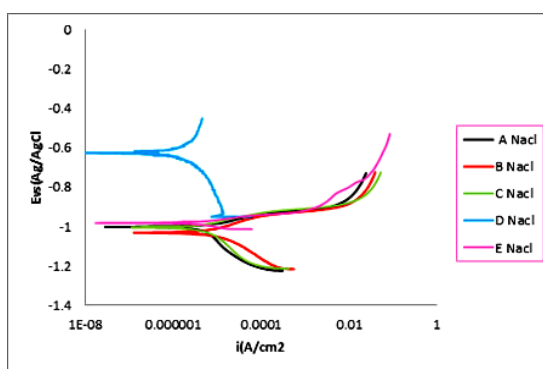

Fig. 8   Polarisation curves of the unreinforced Zn-27Al alloy and Zn-27Al matrix composites produced in 3.5 wt.% NaCl solution

use of only steel chips or addition of 1 wt.% graphite to steel chips as reinforcement in the Zn-27Al based composite.

Fig. 9 shows the SEM image of the surface morphology of representative sample of the Zn-27Al alloy based composite containing 4 wt.% steel chips + 3 wt.% graphite (Composition E) after electrochemical test in 3.5 wt.% NaCl solution. From the micrograph, it can be discerned that on a large scale corrosion proceeds uniformly over the surface of the samples, exposing the particulates. This suggests that uniform corrosion is the primary corrosion mechanism for the hybrid reinforced Zn-27Al alloy based composites.

Table 3 Electrochemical data for the unreinforced Zn-27Al alloy and Zn-27Al matrix composites produced in 3.5 wt.% NaCl solution

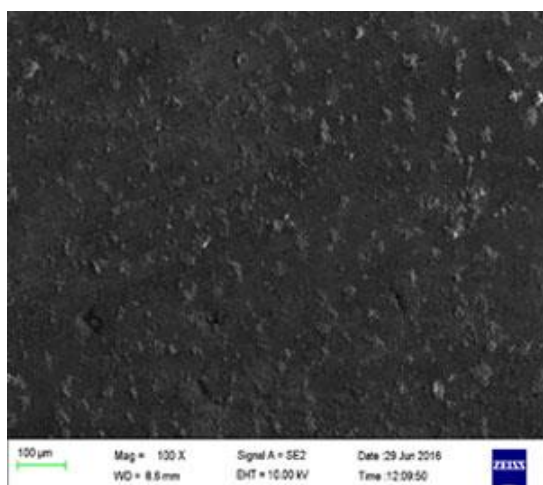| Sample Compositions	E_{corr} (V)	I_{corr} (µA)	Corrosion Rate (mmpy)
A	-1.002	6.542	0.098032
B	-1.031	4.111	0.061599
C	-1.003	5.498	0.082387
D	-0.624993	0.872	0.013062
E	-0.980965	3.415	0.051168

Fig. 9   Representative SEM micrographs are showing surface morphology of Zn-27Al alloy based composite containing 4 wt.% steel chips and 3 wt.% graphite (Composition E) after exposure in 3.5 wt. % NaCl solution

4   Conclusion

The mechanical properties, wear and corrosion behaviour of Zn-Al alloy matrix composites reinforced with graphite and steel machining chips was investigated. The results show that:

- The hardness of the composites decreases slightly with an increase in graphite content in the reinforced composites.
- The tensile strength and fracture toughness of the composite only showed improvement with the addition of 3 wt.% graphite in the hybrid mix (steel chips and graphite) compared with the use of lower graphite content in the mix and steel chips only.

- The percent elongation did not show dependency on the composition of the reinforcement phase and was basically within the range 6.0 - 6.8 %.
- The fracture surfaces of all the composites were essentially rough, a preponderant feature of ductile fracture mode.
- The wear index of the composites was generally low indicating good wear resistance. However, despite the seeming self-lubricating advantage of graphite, the wear resistance of the composite reinforced with only steel chips was relatively better than that of the hybrid graphite, and steel chips reinforced composite compositions.
- The steel chips and graphite reinforced Zn-27Al alloy based composites were generally more corrosion resistant in 3.5% NaCl solution compared with the unreinforced Zn-27Al alloy.

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