Journal of Chemical Technology and Metallurgy, 56, 2, 2021, 366-374

MECHANICAL AND CORROSION PERFORMANCE OF ZA-27 BASED COMPOSITES REINFORCED WITH AUSTENITIC STAINLESS STEEL MACHINING CHIPS

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Received 21 March 2019
Accepted 20 December 2019

ABSTRACT

The present investigation aimed at evaluating the mechanical and corrosion performance of stir-cast ZA-27 based composites reinforced with stainless steel machining chips (SSMC), which is presumed offer to improve ductility and toughness to the composite but it is unclear how it can affect the strength and the corrosion resistance. The results indicate that the ZA-27 composites produced were technically not defective, judging from the very low porosity levels observed in them. The hardness and ultimate tensile strength of the composites improved with increase in wt. % SSMC, and no significant difference in values noticed when compared to the ZA-27 based composite reinforced with alumina. The ductility and fracture toughness of the SSMC containing ZA-27 based composites increased with the increase in the reinforcement wt. % and were significantly better than the alumina reinforced composition. The corrosion resistance of the composites in H_2SO_4 solution also improved with increase in the wt. % of SSMC, and the resistance to corrosion for all the composites were higher than the unreinforced ZA-27 alloy.

Keywords: corrosion behavior, mechanical properties, metal matrix composites, stainless steel chips, Zn27Al based alloy.

INTRODUCTION

ZA-27 alloys are engineering alloys which have good combination of properties including high strength, low density, good tribological characteristics, excellent bearing and wear resistance [1 - 3]. These properties make ZA-27 alloys suitable for the usage in sensitive engineering applications where very high strength is required, specifically in bearings and bushing applications as a replacement for bronze bearings [4 - 5]. There however exist some metallurgical constrains which have limited the use of ZA-27 alloys in the stated applications. These constrains include dimensional instability at relatively high temperatures (above 120^{o}C), deterioration of mechanical and wear properties at temperatures above 90^{o}C, and large coefficient of thermal expansion [5 - 7].

The limitations encountered with the use of ZA-27 systems in engineering applications motivated researchers to seek means to enhance the properties of ZA-27 alloys. Material scientists and engineers sought the use of reinforcement materials to improve and stabilize the properties of ZA-27 alloys at elevated temperatures. Reinforcements which have been explored for this purpose are ceramic particulates (silicon carbide, alumina), agro based derivatives (rice husk ash, bamboo leaf ash), and industrial by products (fly ash, quarry dust, red mud) [8 - 10]. The results obtained from these studies established the suitability of these reinforcements in the improvement of strength, hardness, and wear properties of ZA-27 based composites at the expense of ductility, and fracture toughness. In addition, there are also issues like poor wettability/interfacial decohesion, and high mismatch of thermal coefficient of expansion which results in poor thermal fatigue and high dimensional instability in the composites [11 - 13]. This is a huge concern for an alloy (ZA-27 alloy) which is already known to have unstable properties at elevated temperatures [14].

The implication is that the currently explored reinforcements (ceramic based, agro based derivates, and industrial by products) for the production of ZA-27 composites impose some limitations on ZA-27 composite systems, particularly lowered formability and resistance to fracture. In order to address some of the observed concerns with the use of ceramic based reinforcements, there has been interest in the use of metallic based reinforcement for the development of ZA based composites. Some of the attraction of metallic based reinforcements are good wettability and thermal stability in metal-metal systems, inherent ductile and tough nature, and their relative success in Al and Mg matrices. These factors have buoyed the consideration of metallic reinforcements in ZA based composite systems.

Presently, very few studies exist which have explored the use of metallic materials as reinforcement in ZA-27 based composites. Iglesia et al. [15] and Alaneme et al. [10] in their studies explored the use of steel machining chips as reinforcement in ZA-27 based composites and reported improved mechanical and wear properties. Hardly any other metallic material can be found in literature which has been reported to serve as reinforcement for ZA based systems, indicating that scientific knowledge in this area is still quite limited. The present study explores the use of stainless steel machining chips as metallic reinforcement to enhance the mechanical properties of ZA-27 based composites with a view to establish their suitability over currently explored reinforcements in ZA-27 based composite development. Specifically, the mechanical and corrosion behavior of ZA-27 based composites reinforced with varied weight percent of stainless steel machining chips is investigated in this research. For the corrosion studies, 0.3M H_2SO_4 acidic solution was used as a corrosion medium to simulate typical industrial service environment where the matrix material (Zn based alloy) is deployed. The solution is often used as a cleaning agent and could come in contact with the developed composite in some applications.

EXPERIMENTAL

Materials

Commercial pure grade zinc and aluminium were used for the production of ZA-27 alloy, which served as matrix for the composite. The chemical compositions of the pure grade metals are presented in Tables 1 and 2. Stainless steel machining chips (SSMC) derived from milling operation was used as the reinforcements. The chips were milled and particles of size 100 µm passing were used for the composites development. Alumina was also used as reinforcement for the ZA composite composition which served as control composition.

Composites Production

Double stir casting process was used in the production of the composites in accordance with the procedures documented by Alaneme and Aluko [16]. The quantity of the reinforcement materials required to produce composites containing 2, 4, and 6 wt. % stainless steel machining chips was determined using charge calculations. A composite composition containing 6 wt. % of alumina was also produced to serve as control composition for comparison of the mechanical and corrosion results. The Al was charged first into a crucible and heated using a temperature probe fitted crucible furnace. The Al was heated to a temperature of 700^{o}C ± 20^{o}C to ensure complete melting of the

Table 1. Chemical Composition of Zinc Ingot.

Element	Zn	Fe	Si	Pb	others
% Composition (wt. %)	99.96	0.02	0.006	0.004	0.1

Table 2. Chemical Composition of the Aluminium (6063) alloy.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
% Composition (wt. %)	0.45	0.22	0.02	0.03	0.05	0.02	0.02	0.03	balance

Table 3. Sample designation for the ZA-27 composites produced.

Composition	**ZA-27 (wt.%)**	**SSMC (wt.%)**	**Alumina (wt.%)**
ZA27	100	-	-
ZA27SSC2	98	2	-
ZA27SSC4	96	4	-
ZA27SSC6	94	6	-
ZA27AM6	94	-	6

Al. The furnace temperature was then lowered to 500°C before Zn was charged. The molten melt was subsequently furnace cooled to a temperature of about 450°C (now in semi-solid state), and then stirred at 200 rpm for 5 min to achieve melt homogeneity. The reinforcements were then charged into the melt and stirred manually for 5 - 10 min. The semi-solid slurry developed in the process, was superheated to a temperature of 530°C ± 10°C, and stirred for 10 min with a mechanical stirrer operated at 400 rpm. Thereafter casting of the composites was done using metal moulds. The compositions and sample designations of the composites are presented in Table 3.

Evaluation of the Composite Densities and Percent Porosity

The effect of the alumina and SSMC wt.% on the densities of the ZA-27 composites was studied using Density measurements. The actual (experimental) density for each composite composition was evaluated dividing the weighed mass of the test sample (obtained using a high precision electronic weighing balance) with the sample volume. The porosity levels in the composites were also evaluated by comparing the experimental and the theoretical densities of each wt. % of alumina and SSMC reinforced composite produced [17]. The theoretical density was evaluated using the rule of mixture relation expressed in equation 1:

$$\rho_{ZA-27/SSMC-Al_2O_3} = Wt._{ZA-27} \times \rho_{ZA-27} + Wt._{SSMC} \times \rho_{SSMC} + Wt._{Al_2O_3} \times \rho_{Al_2O_3} \quad (1)$$

where:

$\rho ZA-27/SSMC-Al_2O_3$ is the composite density,

$Wt._{ZA-27}$ is the ZA-27 alloy weight fraction, ρ_{ZA-27} is the ZA-27 alloy density,

$Wt._{SSMC}$ is the SSMC weight fraction,

ρ_{SSMC} is the SSMC density,

$Wt._{Al_2O_3}$ is the Al_2O_3 weight fraction,

$\rho_{Al_2O_3}$ is the Al_2O_3 density.

Table 4. Comparison of Composite Densities and Percent Porosity of the ZA-27 based alloy and Composites.

Samples	Theoretical density(g/cm^3)	Experimental density(g/cm^3)	% porosity
ZA27	5.94	5.87	1.35
ZA27SSC2	6.09	6.00	1.48
ZA27SSC4	6.07	5.97	1.64
ZA27SSC6	6.05	5.94	1.82
ZA27AM6	5.82	5.70	2.06

Table 5. Electrochemical data for the unreinforced zinc matrix composite and the reinforced zinc matrix composite produced in 0.3M H_2SO_4.

Samples	Ecor (mV)	Icorr (mA/cm^2)
ZA27	852.893	44.901
ZA27SSC4	695.411	15.245
ZA27SSC6	692.54	9.319
ZA27AM6	738.127	8.932

The percent porosity of the composites was determined using the relation in equation 2 [17]:

$$\%\ \text{porosity} = \frac{\rho_T - \rho_{EX}}{\rho_T} \times 100\% \qquad (2)$$

where:
ρ_T and ρ_{EX} are the theoretical and experimental densities in g/cm^3.

Evaluation of the Mechanical Properties

Hardness Test

The hardness of the ZA-27 based composites produced were evaluated using Brinell hardness tester in accordance with ASTM E10-17 [18] standard. Specimens for hardness test were cut, ground and polished prior the testing to obtain smooth surfaces for the test. A load of 120 kgf for a dwell time of 10 seconds was applied on the samples, and the hardness values determined following standard procedures. Five hardness indentations were made on samples for each composite composition and the average value determined, taken as the composite hardness.

Tensile Test

A universal testing machine was utilized for tensile testing of the ZA-27 based composites, adopting test procedures prescribed in ASTM E8/E8M-16a [19]. The specimens for the tensile test were machined to 30 mm gauge length and ϕ 5 mm, and testing was performed at 10^{-3}/s strain rate. Three replication tests per composite composition were performed to ensure that the results generated are reliable. The ultimate tensile strength and the percent elongation (strain to fracture) were determined from the test results.

Fracture Toughness (K_{1c}) Evaluation

Circumferential notch tensile (CNT) testing based fracture toughness evaluation was used in this study. CNT samples preparation and the testing procedure were performed in accordance with Alaneme, [20]. The samples machining to gauge diameter, notch diameter, gauge length and notch angle of 6 mm, 30 mm, 4.5 mm, and 60°, respectively, was performed using a laboratory lathe machine. After machining, uniaxial tensile loading to fracture using a universal testing machine, operated at 10^{-3}/s strain rate, was performed on the composite samples. The fracture toughness (K_{1C}) was evaluated from the load-extension plots, using equation 3 [21]:

$$K_{1C} = \frac{P_f}{D^{3/2}}\left[1.72\left(\frac{D}{d}\right) - 1.27\right] \qquad (3)$$

where P_f, D, and d are the fracture load from the load – extension plot, specimen diameter and notch diameter, respectively.

Attainment of plane strain condition for the test sample configuration was used to establish the validity of results obtained, by using the relations according to Nath and Das [22] in equation 4:

$$D \geq \left(\frac{K_{1c}}{\sigma_y}\right)^2 \qquad (4)$$

Three replication tests per composite composition were conducted to assure consistency of the fracture toughness results.

Evaluation of Corrosion Behavior of the Composites

Electrochemical measurements, conducted using potentiodynamic polarization methods in accordance with ASTM G5-14e1 [23] standard were used to evaluate the corrosion behavior of the composites. The corrosion studies was conducted in 0.3 M H_2SO_4 solution at room temperature (25°C), using an AutoLab potentiostat (VersaSTAT 400) with versaSTUDIO electrochemical software. A three electrode corrosion cell was used for the experiment with the ZA-27 composites sample substrates, saturated silver/silver chloride, and platinum serving as the working electrode, reference electrode, and counter electrode, respectively. A scan rate of 1.0 mV/s at a potential initiated at -200 mV to +250 mV, was utilized for the potentiodynamic polarization measurements. Three replication tests per composite composition were performed to assure that results are consistent and thus reliable.

Microstructural Examination

A Zeiss optical microscope was used for microstructural examination of the composites with metallographic sample preparation carried out following standard procedures. Etching of the samples was performed in $1HNO_3$:1HCl solution before the microstructural examination was carried out.

RESULTS AND DISCUSSION

Percent Porosity

The densities and percentage porosities determined for the ZA-27 alloy and composites are presented in Table 4. It is apparent that the composite densities increased with

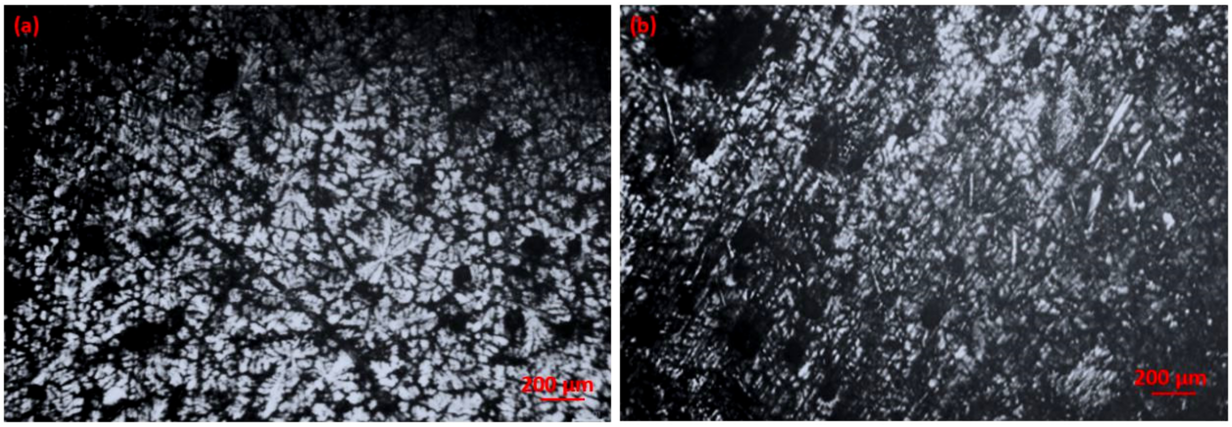

Fig. 1. Representative micrographs of ZA-27 based composites reinforced with (a) 4 wt. % SSMC, and (b) 6 wt. % SSMC.

the addition of SSMC as a reinforcement, however, the densities of the composites slightly decreased as the weight percent of the SSMC in the composite increased. The alumina reinforced ZA-27 composite composition had the least density. The increase in the composite density of the SSMC reinforced ZA-based composite is expected as SSMC has a density 7.7 g/cm^3 which is higher than that of alumina which is 3.95 1.9 g/cm^3. The percent porosities are generally lower than 2.5 % which is below the maximum permissible of 4 % in cast MMCs, and thus of satisfactory quality for further investigation to be carried out.

Microstructure

Fig. 1 shows representative optical micrograph of the unreinforced ZA-27 alloy and selected ZA-27 reinforced composites. It is observed that the reinforcements are visible (dark phases) and fairly well distributed in the ZA-27 matrix and very sparse pockets of particle agglomerates. This supports the low porosities observed in Table 4, as porosities are usually enhanced when there are large amounts of particle agglomerates because their vicinities experience non-uniform solidification patterns/rates which facilitates pores/voids formation [24].

Mechanical Properties

Hardness

The hardness values of the ZA-27 alloy and composites are presented in Fig. 2. It is discernable that the composites generally had higher hardness values compared to the ZA-27 alloy. Additionally, the hardness of the composites are observed to increase with increase in wt. % of the SSMC. Thus, sample ZA27SSC6, which contains 6 wt. % stainless steel machining chips has the highest hardness value (BHN 65.6). The increase in hardness with increase in SSMC can be linked to the comparatively higher hardness of steel to that of ZA alloys [15]. The alumina reinforced composition had

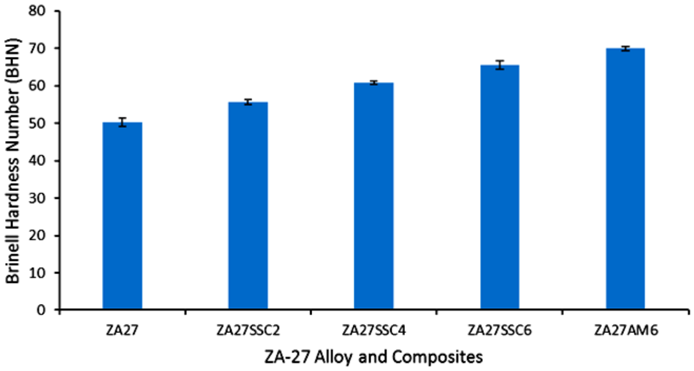

Fig. 2. Hardness Results of the ZA-27 alloy and ZA-27 composites.

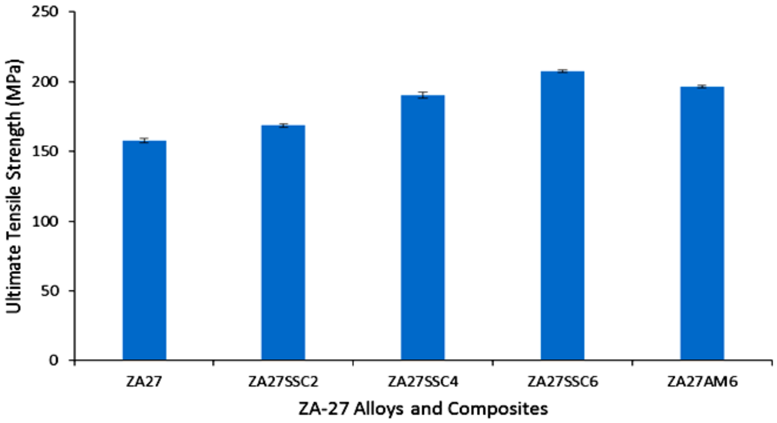

Fig. 3. Ultimate Tensile Strength Values of ZA-27 alloy and ZA-27 based composites.

the highest overall hardness value in the composites produced which is expected since alumina is known to have a high hardness value [25]. It is however important to note that SSMC reinforced ZA-27 alloy with 6 wt.% of reinforcement (ZA27SSC6) compares favourably with the composite reinforced with alumina of same weight percent. Since there is only a 6.7% difference in hardness between both composite grades.

Ultimate Tensile Strength

The ultimate tensile strength (UTS) of the ZA-27 alloy and composites are presented in Fig. 3. The result show that the UTS values of the composites are higher than the unreinforced ZA-27 alloy. It is also observed that the UTS values of the SSMC reinforced composite grades increased as the weight percent of reinforcement in the matrix increased. The percent increments in UTS of the SSMC reinforce ZA-27 based composites are 6.7, 20.3, and 31.3 %. The composition containing 6 wt. % SSMC (sample ZA27SSC6) is observed to have slightly higher UTS (5.6 %) compared to that containing 6 wt. % alumina (sample ZA27AM6). The higher UTS observed for the ZA-27 based composite containing 6 wt.% SSMC reinforcement is likely due to good metallic chips/matrix wetting which results in strong interface bonding. The strong bonding aids effective load transfer from matrix to reinforcement improving the strength of the composites [26]. Similar results reflecting improved strength with the addition of steel based reinforcements was also reported by Alaneme et al. [10]. The improved strength was attributed to the ultrafine microstructures normally imparted by the chip formation process due to the high shear strains sustained by the steel which boosts its strength levels 50 % - 100 % above that of the bulk steel material [10, 15].

Elongation

The strains to fracture of the ZA-27 alloy and composites are shown in Fig. 4. The SSMC reinforced composite are observed to possess the highest percent elongations of the composites compositions studied. The

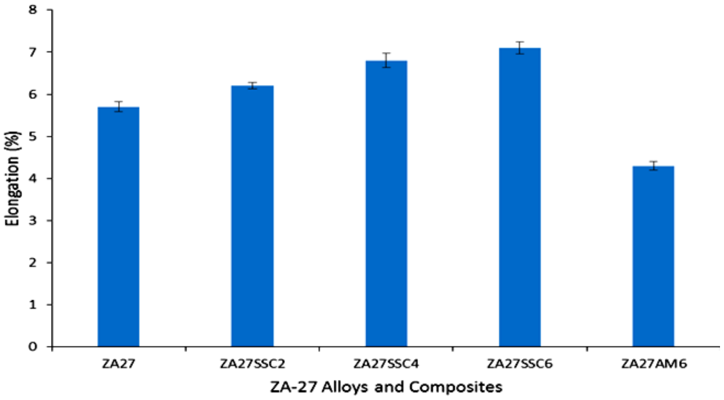

Fig. 4. Percentage Elongation of ZA-27 alloy and ZA-27 Composites.

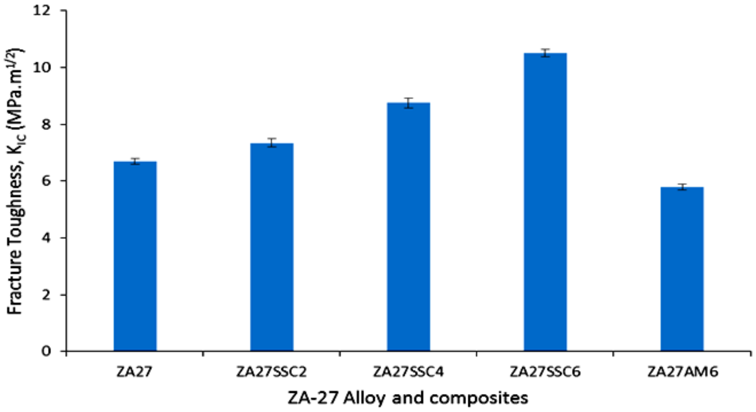

Fig. 5. Fracture Toughness of ZA-27 alloy and ZA-27 Composites.

percent elongation values of the SSMC reinforced ZA-27 composites are between 6.2 and 7.1, and increased with increase in wt.% of SSMC. This is quite unlike the observation for most ceramic reinforced ZA-27 based composites, where ductility scales inversely with increased weight percent of the ceramic reinforcements [3]. The results indicate that the SSMC reinforcement improves the capacity of the ZA-27 composite to sustain more plastic strain before fracture compared to the unreinforced ZA-27 alloy and that reinforced with alumina. This could be attributed to the inherent ductile nature of stainless steel and good ZA-27 matrix/SSMC interface bonding in the composites [27]. Thus, it is resulting in a relatively higher capacity to sustain plastic strains (deformation) before fracture. This is in agreement with other works which recorded improvement in percent elongations when metallic based reinforcements were used to reinforce ZA based MMCs [10].

Fracture Toughness

The Fracture toughness of the ZA-27 based composites presented in Fig. 5 show that the SSMC reinforcement increased the fracture toughness of the ZA-27 alloy matrix. The fracture behavior of the composites is also sensitive to the weight percent of the SSMC present in the composite. Thus it is observed that sample ZA27SSC6, which contains 6 wt.% of SSMC in the ZA-27 based composite, has the highest fracture toughness value, a reflection of its higher resistance to crack propagation among all the composites studied. The improved fracture toughness can be credited to the higher toughness and ductile characteristics of the SSMC particles compared to the ZA-27 matrix and alumina which is a brittle ceramic material [9]. The results show that SSMC are viable reinforcements for the production of ZA-27 composites for the use in structural and reliability critical applications. The trend of fracture toughness of the SSMC reinforced composites with increasing reinforcement weight percent is also an improvement on the results obtained when increased wt.% ceramic reinforcements are used in ZA based composite development, basically resulting in decline in fracture toughness as the wt. % of the ceramic reinforcement increases [28].

Corrosion Behavior

Fig. 6 shows the potentiodynamic polarization curves for the ZA-27 alloy and selected ZA-27 based composites in 0.3 M H_2SO_4 solution. It is noted that the ZA-27 composites reinforced with SSMC exhibits comparable polarization and passivity features. The observation from the polarization curves is better understood using corrosion parameters presented in Table 5. It is seen that the Icorr values decreased significantly with the addition of SSMC, although the corrosion rate which it reflects is slightly lower for the composite composition containing alumina (ZA27AM6). The Ecorr values basically show that the SSMC reinforced ZA-27 based composites, have a relatively lower thermodynamic stability compared to the unreinforced ZA-27 based composite. However, despite the higher thermodynamic stability as reflected by the higher Ecorr value for the unreinforced ZA-27 alloy, the high Icorr value it recorded shows that as soon as it starts corroding, the rate would be faster compared to that of the SSMC reinforced ZA-27 based composite compositions [29]. The Ecorr values for the ZA-27 based composite containing 6 wt.% alumina (ZA27AM6) is consistent with the relatively lower Icorr

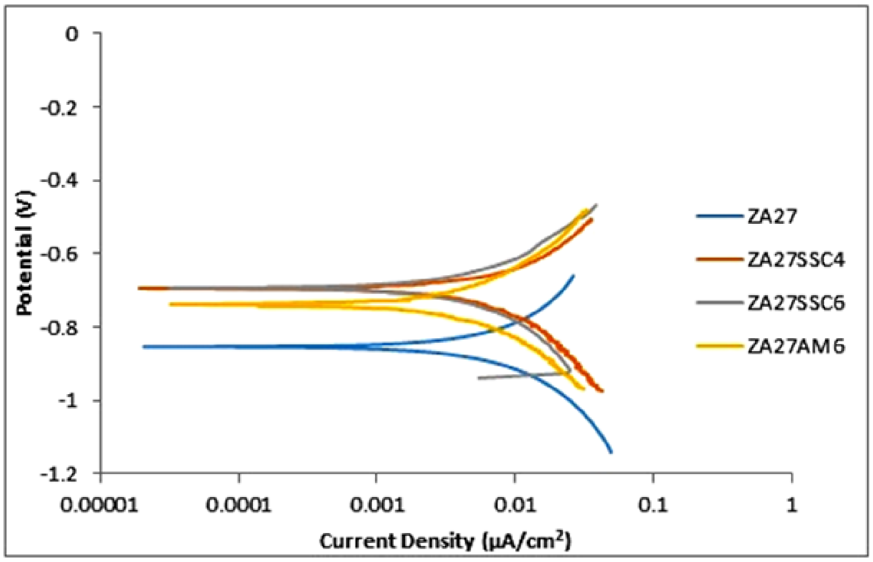

Fig. 6. Polarization curves of ZA-27 alloy and selected ZA-27 Composites.

value observed for that composition, a reflection of its relatively lower corrosion rate.

CONCLUSIONS

This study investigated the mechanical and corrosion performance of ZA-27 based composites reinforced with stainless steel machining chips and compared it with the unreinforced Za-27 alloy and that reinforced with alumina. The manuscript highlighted the benefits of steel machining chips as reinforcement to ZA -27 alloy matrix, which was informed by the enhancement of hardness, strength, and ductility observed from the experimentation. Also, the slower corrosion rates of the composite also corroborate the assertion that the steel machining chips can serve as functionally reliable substitute to ceramic reinforcements in ZA-27 alloy systems.

Specifically, the results show that:

The percent porosity values between 1.35 and 2.06 % observed in the ZA-27 based composites were less than the maximum acceptable limit of 4% for cast metal matrix composites.

The hardness and ultimate tensile strength of the SSMC reinforced composites increased with increase in wt. % of SSMC; and marginal disparity in these properties was recorded between the ZA-27 based composite compositions containing 6 wt. % SSMC and 6 wt. % Al_2O_3.

The percent elongation and fracture toughness of the SSMC reinforced ZA-27 based composites also increased with increase in the wt. % of SSMC, and the values were superior to that of the alumina reinforced ZA-27 based composition of same wt. %.

The corrosion resistance and corrosion tendencies of all the ZA-27 based composites were superior to the ZA-27 alloy, and the corrosion resistance increased with increase in the wt. % of SSMC.

The reinforcement of ZA-27 based matrix with stainless steel machining chips, generally resulted in improved mechanical and corrosion performance of the ZA-27 based composites.

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