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Effect of Zinc Addition on the Mechanical and Corrosion Characteristics of Aluminium Matrix Composites

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Abstract:

Aluminium and its alloys are materials of interest because of their availability, unique properties and affordability, which have promoted their application in many areas. This study aims to investigate the effect of zinc particulate reinforcement or addition on aluminium matrix. Aluminium cans were reinforced with zinc particulates in varied proportions (0 – 2 wt. %) by mould casting. Morphology (microstructure), mechanical and corrosion characteristics of the composites were examined. The results showed that there was dispersion and dissolution of zinc particulates in the aluminium matrix as indicated by replacement of dark phases with bright ones in the micrographs. The mechanical characteristics indicated a reduction in the hardness of the specimen at 1 wt. % zinc reinforcement. Further increase in zinc concentration improved the hardness of the specimens. The ultimate tensile strength increased with zinc addition but reduced to about 97.2 MPa at 0.75 wt. % zinc addition. The ductility, impact energy and corrosion resistance of the specimens increased with increasing zinc concentration.

Keywords: Aluminium Cans; Corrosion Resistance; Mechanical Characteristics; Microstructure; Zinc Addition.

DOI:

1. INTRODUCTION

Aluminium is the third most widely used metal in the world. It is an important metal for construction, automotive, airplane, and packaging industries. The construction of doors, windows, and facades, followed by walls and roofs is the main uses of aluminium in building. In automotive, aluminium is used as engine blocks, wheels, cylinder heads, gearboxes and many other automotive and engineering components. It is used in packaging of food and beverages due to its unique barrier and physical properties. It effectively protects foods and drinks against quality-reducing effects of oxygen, light, moisture, microorganisms and unwanted aromas even in its thinnest form [1].

It has been established that every year, about 1.5 million tons of aluminium cans are trashed worldwide. Less than half of over 100 billion aluminium cans sold in USA every year are recycled. The volume of trashed cans is replenished with new cans made from raw materials. However, apart from the hazards caused by the dumping of aluminium cans indiscriminately, manufacturing new cans damages the environment through emission of toxic gases [2]. The biggest environmental problem in various towns and cities around the world is that of solid wastes. In many societies especially in underdeveloped and developing countries, solid wastes generated are indiscriminately dumped and littered landscape of towns causing pollution. Pollution is a global threat to the world and environmental pollution occurs due to the introduction of any material into the environment in quantities greater than its natural concentration, which has a damaging effect on the

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environment. Much of its escalation arises from the increased production and consumption of materials that eventually become wastes. Its effect is increased by the fact that the quantity of material that is recycled is of low percentage (aluminium inclusive). Pollution results from the large numbers of used aluminium cans that are disposed of indiscriminately. Hence, failure to recycle aluminium is a prelude to environmental pollution [3]. Therefore, it has become imperative to convert the aluminium wastes into useful engineering materials thereby mitigating the problem of environmental pollution. Recycling of aluminium wastes to produce aluminium products is encouraged because it promotes wealth creation for those involved in recycling and scavengers who search for the wastes (Figure 1). It also and saves energy, cost and stress due to the high-energy consumption and rigorous processes involved in the extraction of aluminium from its ores like bauxite.

Figure 1. Aluminium cans stacked by scavengers [3].

The contribution of recycled metal to the global output of aluminium products has increased from 17 % in 1960 to 34 % today, and it is expected to rise to almost 40 % by 2020 [3]. Global recycling rates are high, with approximately 90 % of the metal used for transport and construction applications recovered, and over 60 % of used beverage cans are gathered [4]. Aluminium scraps can be reprocessed for use in products after the initial production. Used beverage containers (UBC) are one of the main components of aluminium scraps with most of the scrap metal recycled back into cans. UBC recycling is the most readily recognized of the recycling programmes. Aluminium is also recycled at the end of life from products such as cars and building parts. Window frames, wire, tubing and electronics are additional examples of aluminium that is recycled at the end of life.

Globally, close to 70 % of aluminium beverage cans are recycled, making it the world's most recycled packaging product. Because aluminium is infinitely recyclable, it can be reused in applications different from its previous use, and it can be recast into its initial form [3]. This impact is put to good use in the production of cast alloys, which generally need these elements to attain the desired alloy properties [4].

In engineering applications, pure aluminium has problems such as relatively low strength and unstable mechanical properties. However, its microstructure can be modified and mechanical properties can be improved by alloying, cold working and heat treatment. Aluminium alloys with a wide range of properties are used in engineering structures and choosing the appropriate alloy for a given application requires considering its tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance [5].

Zinc content in some alloys has promoted or induced value addition. For instance, zinc bearing aluminium alloys are at the top in ranking in terms of strength among commercial series. The addition of zinc to structural aluminum improves the homogeneity of the matrix and ultimately its hardness and elongation [6].

In attempts to further enhance the properties of aluminium alloys, some studies have been carried out on addition of zinc to pure aluminium. For instance, Khaleed and Bash [7] studied the effect of zinc addition to pure aluminium to resist dry sliding wear. The results showed that the wear rate of the cast alloys decreased with increasing zinc concentration. The results of X-ray diffraction of the alloys also revealed the presence of the main phase ($Al_{0.71}Zn_{0.29}$) which had a great effect on reducing the wear rate. Khan et al. [8] investigated the effect of zinc addition on the characteristics of aluminium alloy sacrificial anode for marine application using anodic efficiency, protection efficiency and polarised potential. Overall findings indicated that addition of zinc increased the rate of corrosion of the

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sacrificial anode. The microstructure showed the intermetallic structures of β-phase which broke down the alumina passive film, thus enhancing the anode efficiency. In an attempt to effect value addition, this study therefore seeks to investigate the influence or effect of zinc particulate addition on the mechanical and corrosion characteristics of aluminium matrix composites.

2. MATERIALS AND METHODS

2.1. Production and Preparation of Specimens

Aluminium cans were melted in batches at 680 °C in a pit furnace and alloyed by zinc addition ranging from 0.25 to 2 wt. %. The molten mixture was stirred mechanically to homogenise the melt after which it was promptly poured into already prepared sand mould of 300 × 150 × 20 mm dimension and allowed to cool and solidify. The cast specimens were machined to standard dimensions and were then characterised. Chemical composition (Table 1) of the specimens determined using an optical emission spectrometer is presented.

Table 1. Chemical composition of the alloyed specimens.

Specimen	**Element**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Cr**	**Ni**	**Zr**	**Pb**	**Sn**	**Al**
	Zn Addition (wt. %)												
A	0 (Control)	0.770	0.810	0.298	0.842	0.307	0.196	0.151	0.152	0.131	-	-	96.50
B	0.25	0.738	0.725	0.318	0.731	0.211	0.310	0.007	0.012	0.003	0.027	0.012	96.91
C	0.50	0.756	0.750	0.379	0.827	0.268	0.455	0.016	0.011	0.003	0.025	0.011	96.48
D	0.75	0.768	0.753	0.327	0.767	0.210	0.644	0.011	0.011	0.001	0.023	0.006	96.48
E	1.00	0.720	0.742	0.315	0.740	0.220	0.786	0.010	0.011	0.005	0.023	0.007	96.42
F	1.25	0.713	0.759	0.340	0.711	0.254	0.894	0.012	0.012	0.005	0.026	-	96.27
H	1.50	0.722	0.742	0.253	0.725	0.241	1.354	-	0.010	0.005	0.026	-	95.92
G	1.75	0.744	0.725	0.255	0.664	0.215	2.761	-	0.021	0.007	0.101	-	94.51
I	2.00	0.694	0.642	0.258	0.626	0.220	3.322	-	0.007	0.002	0.026	0.006	94.12

2.2. Characterisation of the Specimens

Tensile strength test was carried out in line with ASTM B557M standard using an Instron tester (model 313). The hardness test of specimens was conducted in accordance with ASTM E92 standard using Wolpert Testor 930 universal hardness tester. Impact energy test was done in line with ASTM E23 standard. An Avery Charpy impact-testing machine with a capacity of 298.28 Nm and striking velocity of 5.03 m/s was used.

Surfaces of the specimens for microstructural examination were successively smoothened using emery paper of grit size 120 to 1200 microns. Their surfaces were further polished and etched. Fractured surfaces (etched and unetched) were examined using a digital metallurgical microscope at x100 magnification.

Corrosion behaviour of the specimens was monitored via potentiodynamic polarisation employing a three-electrode configuration, consisting of saturated calomel reference (SCE), graphite rod counter, and the composites produced as working electrodes. Prior to commencement of the potentiodynamic polarisation, open circuit potential (OCP) was monitored until the system attained a steady state. Potentiodynamic polarisation was thereafter conducted using a Gamry interface 1000E potentiostat from -0.25V vs OCP to 1.5V vs SCE using scan rate of 1 mV/s. Some of the test

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specimens and experimental set up are illustrated (Figure 2).

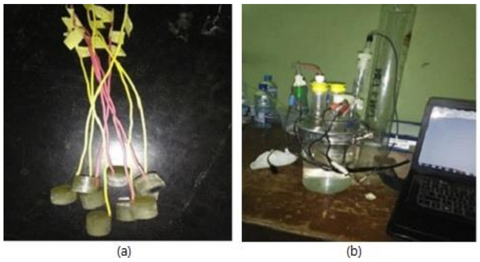

Figure 2. (a) Specimens for corrosion test (b) Potentiodynamic polarisation technique setup.

3. RESULTS AND DISCUSSION

3.1. Hardness of the Specimens

The hardness of the specimens is presented in Figure 3. The increase in the percentage of zinc addition was accompanied with a corresponding decrease in the hardness values and it reached a lowest value of 76.1 HV at 1 wt. % after which the hardness value appreciated to 106.4 HV at 1.75 wt. %. The reduction in hardness could be due to clustering/agglomeration of the zinc particles in the molten aluminium matrix. This might have occurred during casting which resulted in porosity of the specimens. The enhancement of the hardness values is due to the dispersion of Zinc particles in the molten aluminium matrix.

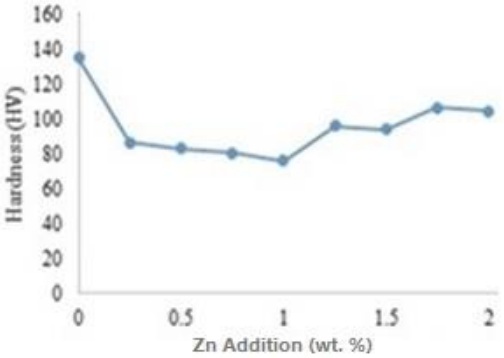

Figure 3. Effect of zinc addition on hardness of specimens.

3.2. Specimens' Ultimate Tensile Strength

The ultimate tensile strength (UTS) of the rolled samples increased with increase in zinc addition from 112.51 MPa to 144.94 MPa at 1.75 wt. % zinc addition as shown in Figure 4. However, a significant fall in UTS is observed at 0.75 wt. % zinc addition. The abnormal UTS could be attributed to morphological features where there is agglomeration of the particles in the matrix (Figure 7). The mechanisms for the increase in UTS with thickness reduction at the beginning of deformation are of two folds; one due to increasing dislocations generated [9, 10] and second to the nature of hard intermetallic precipitates evolved from solid solution consequent on increase degree of deformation and severity of imposed stress on the material [11].

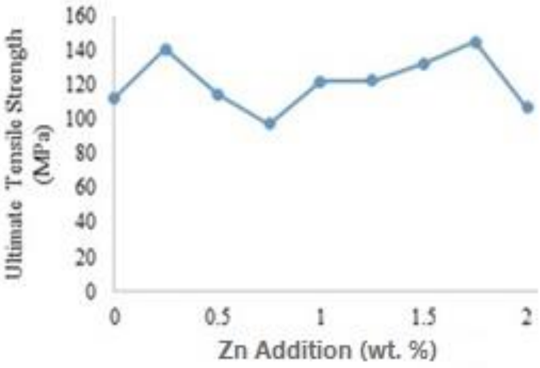

Figure 4. Effect of zinc addition on tensile strength of specimens.

3.3. Ductility of the Specimens

As illustrated in Figure 5, the ductility of the alloyed samples appreciated with increase in zinc addition from 4 % percent at 6.2 %. Increase in the movement of dislocation after deformation [12] may be responsible for this. Dislocations, that were produced during the deformation process, were pinned down and could not move across grain boundaries as would be less expected for a highly ductile material. However, the barriers to this dislocation motion increased with severity of deformation due to strain hardening [9]. The

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ductility of the alloyed samples increased with increase in zinc addition. The values peaked at 6.2 % elongation at 1.0 wt. % zinc. The nature of intermetallic barriers, distribution and volume fraction all contributed to affect the propensity for dislocation motion and hence impacted on the stretching/elongation degree (ductility) [9].

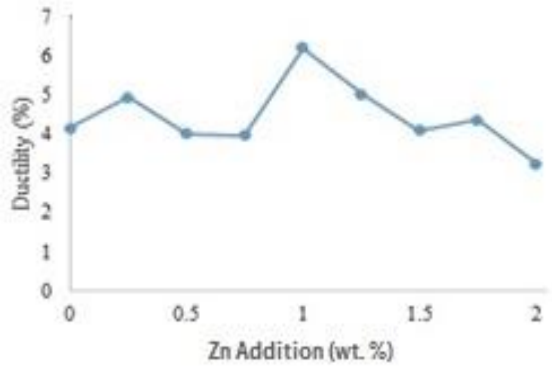

Figure 5. Effect of zinc addition on ductility of specimens.

3.4. Impact Energy of the Specimens

The impact energy of the specimens generally shows increase in values with increase in zinc addition as shown in Figure 6. Increase in impact energy was due to dislocation generated and movement within the microstructure of the specimens because of deformation. This agrees with the report of Oyekeye et al. [9]. The peak (4.73 J) occurred at 1.0 wt. % zinc addition. This was due to the propensity for cracks formation as deformation increased, which agrees with the report of [13].

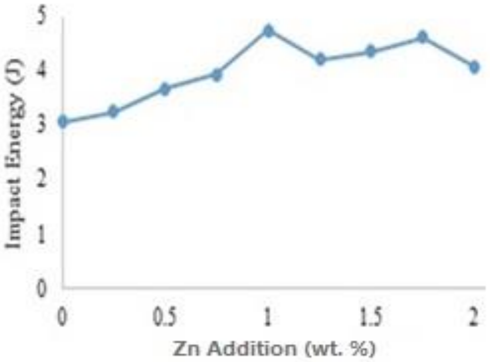

Figure 6. Effect of zinc addition on impact energy of specimens.

3.5. Microstructure of the Specimens

The micrographs (Figure 7) reveal the certainty of dispersion and dissolution of the zinc particulates into the molten aluminium matrix as indicated by the replacement of dark phases with the light phases. Upon solidification of the alloyed specimens, they formed dendritic structures. Recent findings by Friedli et al. [14] have shown that an increase in the zinc composition in Al-Zn alloys always affects the dendrite growth direction. The reason for this dendrite orientation transition is due to the solubility of zinc. Due to the presence of iron (Fe) and silicon (Si) in the alloy composition (Table 1), there was definitely the formation of intermetallic inclusion in the microstructure of the specimens. Zinc addition enhanced the formation of intermetallics due to reactions. This agrees with the report of Springer et al. [15].

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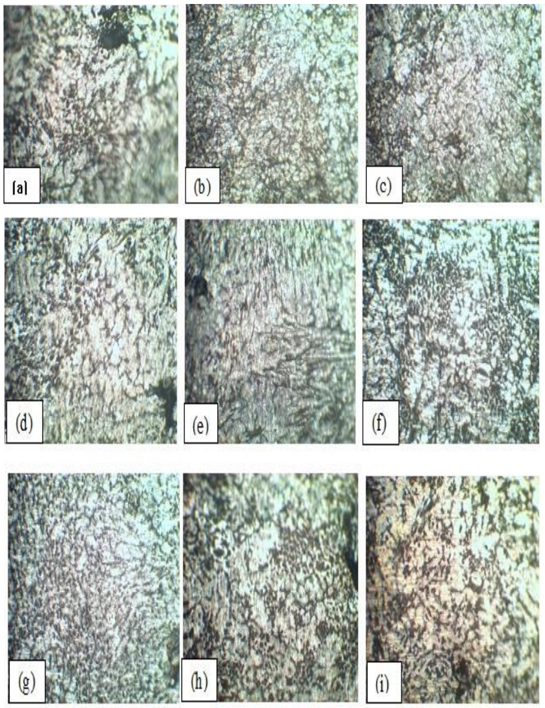

Figure 7. Optical micrographs of specimens at varied weight percent (wt. %) of zinc reinforcement (a) 0 (b) 0.25 (c) 0.5 (d) 0.75 (e) 1 (f) 1.25 (g) 1.5 (h) 1.75 and (i) 2 x100.

3.6. Corrosion Characteristics of the Specimens

Potentiodynamic polarisation curves of the test specimens are shown in Figure 8. Comparison of the corrosion potential (E_{cor}) with corrosion current density (i_{cor}) indicates that E_{cor} increases as i_{cor} reduces. The results shown in Table 2 reveal that zinc addition decreases the i_{cor}, which in turn reduces the corrosion rate, as i_{cor} is directly proportional to corrosion rate of the material. This implies that the corrosion resistance of the specimens is enhanced. Additional alloying of zinc even in trace amounts decreased the driving force of intergranular corrosion (IGC) by reducing the potential difference in a similar way to the anodic Mg-rich grain boundary film as reported by [16].

Table 2. Corrosion potential (E_{cor}) and corrosion current density (i_{cor}).

Zinc Addition (wt. %)	**E_{cor} (V)**	**i_{cor} (A/m^2)**
0 (Control)	-0.581	0.00395
0.25	-0.495	0.00387
0.50	-0.331	0.00341
0.75	-0.302	0.00319
1.00	-0.287	0.00277
1.25	-0.279	0.00232
1.50	-0.262	0.00201
1.75	-0.256	0.00167
2.00	-0.251	0.00122

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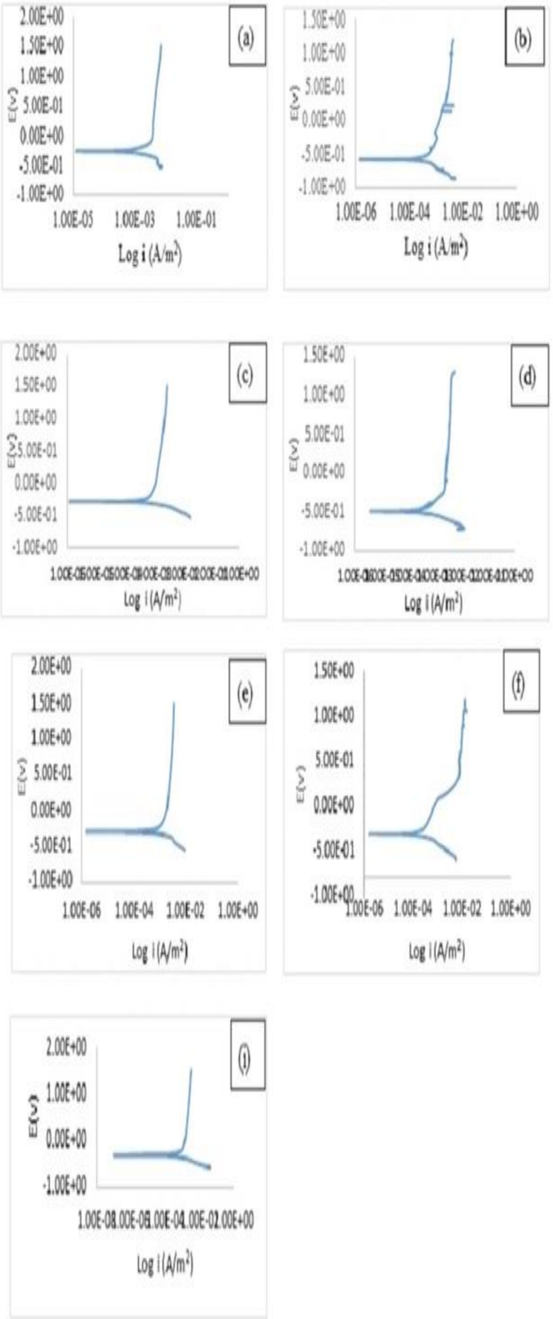

Figure 8. Potentiodynamic graphs of specimens at varied weight percent (wt. %) of zinc reinforcement (a) 0 (b) 0.25 (c) 0.5 (d) 0.75 (e) 1 (f) 1.25 (g) 1.5 (h) 1.75 (i) 2.

4. CONCLUSIONS

Zinc particulate reinforced aluminium matrix composites have been developed and the morphology, mechanical and corrosion characteristics of the composites have been examined. The results showed that there was dispersion and dissolution of particulate in the aluminium matrix as indicated by replacement of dark phases with bright ones in the micrographs.

Mechanical characteristics indicated a reduction in the hardness of the specimen at 1 wt. % zinc reinforcement. Further increase in zinc concentration enhanced the hardness of the specimens. Ultimate tensile strength increased with increasing zinc concentration but reduced to about 97.2 MPa at 0.75 wt. % zinc concentration. The ductility and impact energy of the specimens increased with increasing zinc concentration. and likewise the corrosion resistance.

The addition of zinc decreased the corrosion current density, which in turn reduced the corrosion rate as corrosion current density is directly proportional to the corrosion rate of the material. This ultimately implies an enhancement of the corrosion resistance of the specimens.

Conflict of Interests

The authors declare no conflict of interest.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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