Effect of Stainless Steel Powder as Reinforcement on Mechanical and Tribological Properties of Stir Cast Zn-Al Alloy

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Abstract. In this study, Zn-40Al alloy is reinforced with 310 stainless steel particle of size 45 µm and its effect on tensile strength, hardness and wear rate were investigated. The Zn-40Al-SS composites were fabricated with 310 tainless steel particle of 3, 6, and 9 wt. % of volume fractions using stir casting technique. Tensile strength and vickers microhardness were tested for the base alloy and for the various combinations of Zn-40Al-SS composite. Dry sliding wear test using Pin-on-Disc machine were carried out for the base alloy and for all the combinations of the composites. Characterization techniques like optical microscopy, scanning electron microscope (SEM) and elemental distribution by energy-dispersive X-ray spectrometry (EDS) were carried out to analyse the composite. The tensile strength and hardness were high for the reinforcement of 9 wt. %. Also the wear resistance was maximum for the reinforcement of 9 wt. %. The microstructure shows the fine uniform dispersion of the reinforcing particles over the entire matrix. Overall the composite shows a significant improvement in the wear resistance and mechanical properties.

Keywords: Metal matrix Composite, Zinc Aluminum, Mechanical properties, Wear, Friction, Stir casting

1. Introduction
Zinc Aluminum (Zn-Al) combinations are being used in numerous modern applications because of their better castability and good mechanical properties [1-4]. These alloys are functionally limited above the temperature of 100 °C. Usage of these alloys are limited in high temperature applications. These alloys experience lower mechanical properties at elevated temperature [5, 6]. A feasible methodology of enhancing the properties is the incorporation of thermally stable second phase particles [7,8]. The impact of size and introduction of the reinforcement phase on mechanical and wear properties have been explored over the past. Ceramic dispersoids and glass fibers are particularly reinforced in the zinc based composites [9, 10]. Sliding mechanical components like bearings, piston rings are subject to wear. Reinforced second phase particles in Zn-Al alloy have been suggested to sliding wear applications as compared to Metal Matrix composites (MMC) [11-13]. MMC increases the wear resistance in most of the cases. Moreover, these composites exhibit excellent mechanical
properties. Preheating the reinforcement helps enhance the interface strength and facilitates the dispersion of the particles throughout the alloy. In view of above, an attempt to fabricate improved materials with enhanced properties in comparison to those of the matrix. The present work investigates the effect of 310 stainless steel (SS) powder additions on the mechanical and Tribological behavior of Zn–40Al alloy system. The wear surfaces were examined using SEM.

2. Experimental Procedure

2.1 Material Preparation
In the present study, commercial pure zinc (Zn - 99.96 %) and LM0 Aluminium were used to fabricate the Zn-Al alloy. The composites were prepared by dispersing 3 - 9 % in steps of 3 wt. % of the 310 SS powder of size 45 µm in the melt of the base alloy. In a previous study, the similar 3 to 9 wt. % alumina is added in AlSi10Mg aluminium alloy along with 3 wt. % of graphite and the effect of these reinforcements on the mechanical and wear properties were studied [14]. In general, when the wt. % of reinforcement is increased up to some level, it will improve the mechanical and wear properties and after that properties will gradually decrease. Samples fabricated through stir casting techniques with more wt. % of reinforcement particles are difficult to machine. During machining of such more wt. % of reinforced samples, the particles will detach itself from the composites due to abrasive nature [15]. Table 1 shows the detail formulation of four different types of Zn-Al-310 SS powder. The liquid metallurgy process was used to manufacture the composites.

| Description | Chemical Composition (wt. %) |
|-------------|-----------------------------|
|             | Zn  | Al  | Stainless steel powder |
| Zn-40Al     | 60  | 40  | -                    |
| Zn-40Al-3SS | 57  | 40  | 3                    |
| Zn-40Al-6SS | 54  | 40  | 6                    |
| Zn-40Al-9SS | 51  | 40  | 9                    |

Table 1. Chemical Composition

The chemical compositions of these alloys were weighed according to ratios and melted in a graphite crucible. The SS powder was weighed as per the ratio and preheated separately at the initial stage to a temperature of 450 °C. This helped to remove the moisture and improves the wettability of the Zn-Al alloy. Aluminium is heated to 670 °C in a crucible furnace until it melts completely. Then before the Zinc was added, the furnace temperature was lowered to 500 °C. After Zinc had melted completely, it was cooled to a semi solid state (to about 450 °C) and stirred at 200 rpm for 5 min to achieve homogenization. The preheated SS powder is then charged into the melt which is stirred for 5 min. The semi-solid composite slurry formed was superheated to a temperature of 530 °C and stirred again at 400 rpm for 10 min. The melt was released through an orifice at the base of the crucible. Mould made of cast iron is used to shape the melt in the form of 30 mm diameter and 300 mm long cylindrical casting. Figure 1 shows the base substrate and the composites.

![Fig. 1. Pure alloy and reinforced composites.](image-url)
Hydraulic press runs for 30 s time with 6 MPa pressure applied on the composite to reduce porosity and to improve the bonding force between the Zn-Al alloy and SS particles. Finally, the mould was opened after 5 min and the fabricated composites were air-cooled to room temperature.

2.2 Mechanical and Physical Characterization

2.2.1 Density and Void

The effect of SS powder wt. % on composite density was analyzed by resolving the density of composite fabricated. The experimental density is calculated using Archimedean water displacement method. The theoretical density was calculated according to rule of mixture [16]. Porosity was determined by comparing the experimental density and theoretical density of individual weight proportion of SS reinforced composite fabricated. An accurate electronic weighing balance with an accuracy of 1 mg was used to analyze the density of the specimen. The void fraction of the composites was evaluated using the relation Eq. (1) where $\rho_{cal}$ is the theoretical density and $\rho_{exp}$ is the experimental density.

$$\text{void fraction} = \frac{(\rho_{cal} - \rho_{exp})}{\rho_{cal}}$$  (1)

2.2.2. Tensile test

Tensile test specimens as shown in Figure 2 are prepared according to ASTM standard E8 – 04. Tests were conducted on Tinius Olsen testing machine with the capacity of maximum 25 kN and at the extension rate of 2 mm/s. Tests were repeated three times to guarantee reliability of the data. Dimensions for tensile test specimen were tabulated in Table 2.

![Figure 2. Tensile test specimens](image)

Table 2. Dimensions for Tensile Test Specimen

| Specimen Dimension (mm) |
|-------------------------|
| G – Gauge length 30     |
| D – Diameter 6          |
| R – Radius of fillet 6  |

2.2.3. Hardness

The Mitutoyo MVH-H11 equipment was used to measure the microhardness. The specimens were prepared as per ASTM E384 standards. Before the measurement of hardness the surface of the specimen is polished by using emery paper ranging from 300 µm – 1200 µm. A load of 100 gf is then applied to the sample for a period of 15 sec.

2.2.4. Dry Sliding wear test

Pin-On-Disc machine was used to conduct the dry sliding wear test of the base material and the stainless steel powder reinforced composite. (Make: Ducom; Model:TR-20 with Wear and Friction Monitor). The contact load was varied by 10, 20, 30 and 40 N. Sliding velocity was varied by 1, 2, 3 and 4 m/s. Sliding distance was varied by 500, 1000, 1500 and 2000 m. Track diameter was kept constant at 60 mm. ASTM 99-95a standard was followed. The sample (Ø8 mm × 25 mm) is held stationary against the rotating disc made of En-31 steel having hardness of 60 HRC. Load was applied to the sample by a
cantilever mechanism. The disc is cleaned to remove debris after every test. The weights of specimens were measured by an electronic weighing balance before and after the wear test. Wear rate were calculated by weight loss method.

2.2.5. Microstructure
An inverted metallurgical microscope (Zeiss Axiovert 25 CA) was used to investigate the microstructure of the composite. Specimens were initially polished using emery paper followed by a disc polishing to get a fine finish and finally etched using mixture of Ethanol – HCl solution. Microscopic examinations were done using Scanning Electron Microscope (SEM) to characterize the wear surface and wear debris by using JEOL JSM - 6490LA. The distribution of elements was carried out by EDS at 15 kV.

3. Results and Discussion
3.1. Elemental Composition and Microstructure
Figure 3(a) shows the microstructure of the matrix alloy. From Figure 3(b, c and d), it is evident that the nearly uniform dispersion of the particles in the matrix. Since the SS particles melting temperature (1510 ºC) was higher than the melting point of Zn-Al (490 ºC), the SS particles does not melt during stir casting and also it does not form any other inter-metallic particle. This reveals that the reinforcement is stable and non-reactive in the matrix alloy. The line EDS spectrum shown in the Figure 4 consists of elements like Iron, Chromium and Nickel.

![Figure 3](image_url)

**Figure 3.** Optical micrograph of (a) matrix alloy, (b-d) composite showing stainless steel particles

![Figure 4](image_url)

**Figure 4.** EDS spectrum composite.
3.2. Density

From the Table 3, it can be inferred that when the content of SS powder increases the overall density of the composite also increases linearly. Also it can be noticed that the experimental values of the density are lower than the theoretical one. This shows that these composites contained some porosity. The porosity of the composites was calculated by using the equation (1) and is between 0.6 – 3.33 %. However these values are within the acceptable range of 4 % [17]. The instant pressure applied after casting in this study has reduced the porosity.

Table 3. Density

| Composition (wt. % reinforcement) | Theoretical Density $\rho_{\text{cal}}$ (kg/m$^3$) | Experimental Density $\rho_{\text{exp}}$ (kg/m$^3$) | Void fraction |
|----------------------------------|-------------------------------------|-------------------------------------|---------------|
| 0                                | 4198                                | 4172                                | 0.006         |
| 3                                | 4262                                | 4205                                | 0.013         |
| 6                                | 4336                                | 4242                                | 0.021         |
| 9                                | 4413                                | 4267                                | 0.033         |

3.3. Mechanical Properties

The tensile strength and the hardness of the Zn-Al-SS composite for various wt % were tabulated in the Table 4. From the table it can be inferred that the tensile strength improves from the base by 47 %, 58 % and 64 % with respect to 3 wt. %, 6 wt. % and 9 wt. % of SS powder reinforcement respectively. The maximum improvement in the tensile strength was with the 9 wt. % of SS particle. The tensile strength increases with increase in wt. % of reinforcement, because of the increase in resistance to deformation. Stress generated due to thermal mismatch causes the hard reinforcement in the matrix to bring about an increase in density. Because of this there is an increase in tensile strength of the composites [18, 19]. The increase in tensile strength can be justified by the dispersion of SS particles which hinders the dislocation motion.

Table 4 Mechanical Properties

| Mechanical Properties | Composition (wt. % reinforcement) |
|-----------------------|-----------------------------------|
| Tensile strength (MPa) | 0   3   6   9                      |
| Micro hardness (HV)    | 240 353 9 395                      |
|                       | 83  95 98 106                      |

The hardness values given in Table 4 were the average of five readings. From the table 4 and figure 5 it can be inferred that the hardness increases from the base by 14 %, 18 % and 28 % with respect to wt. % 3, wt. % 6 and wt. % 9 of SS powder reinforcement respectively. Due to the presence of SS particles, an increase is observed in the hardness of the composites from the base substrate as the wt. % of reinforcement increases. The reason behind the increase in the hardness can be inferred that when the hardness measurements were done, the material resists the penetration of indent because of the hard SS powder reinforcement on the soft Zn-Al matrix. Also the increase in the hardness of the Zn-Al-SS composite can be justified because of the higher density than the base material. The enhancement in the hardness properties of the composites can be credited to the factors such as higher hardness of SS particles as well as the active interfacial adhesion between the matrix and SS interfaces.
3.4. Dry Sliding Wear test

Figure 6 shows the effect of applied load on the sliding wear of the Zn-Al-SS composite as a function of reinforcement wt. %. With reference to Figure 6, it can be inferred that when load increases, the wear rate also increases [20-22]. When load applied is low, the wear loss is quite small for the composites. This is due to the load bearing capacity of reinforcement phases. On increase of applied load, the wear mechanisms changes from mild to severe wear and hence wear rate increase [23]. It is clearly noticed that the wear rate of the each composite reduced with the addition of particle content. This demonstrates that the wear behaviour of the composites was found improved significantly with the addition of SS particles as reinforcement. Because of the good interface between the SS particle reinforcement with the base substrate of Zn-Al, the Zn-Al-SS MMC responds with a lower wear rate [24,25].

It is clearly observed from the Figure 7 as the load increases, the coefficient of friction (COF) increases. An increase in the load increases the deformation of frictional layer. This tends to the increase of frictional force which in turn increases the temperature of material. Hence COF increases. Among the various combination of fabricated MMCs, 9 wt. % composite is having the lowest COF and the highest wear resistance at room temperature.

The lowest wear rate (0.0009 mm$^3$/m) was obtained with the composite with 9 wt. % SS particles which also had the lowest COF (0.48), whereas the base substrate shows the highest wear rate (0.0081 mm$^3$/m) and with the highest COF (0.565). From the above it is clear that the wear resistance of Zn-Al-SS MMC is 88 % higher than that of Zn-Al base alloy. Also it can be inferred that the COF of Zn-Al-SS MMC is 17 % lower than that of Zn-Al base alloy. This indicates the inverse relationship between wear resistance of alloys and COF i.e., as wear resistance increases, there will be considerable decrease in the COF [26-28].
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3.5. Microscopic Examination using SEM on the Wear surface

Figure 8. SEM images on the worn surface of matrix alloy at (a) 10N (b) 20N (c) 30N and (d) 40N.

Figure 8 (a-d) depicts the scanning electron micrograph of worn surface of the base material at different loading conditions. The wear surface of samples, shown in Figure 8 (a), tested at 10 N for the unreinforced alloy consists of ridges and grooves which are the typical characteristics of sliding wear. When the load increased to 20 N, Figure 8 (b), a slight growth in number of grooves were observed. On further increment of load to 30 N, Figure 8 (c), micrographs indicates the formation of continuous wear grooves. At 40 N damaged spots as shown in Figure 8 (d) were observed from the micrographs. These are indication of severe deformation, resulting high wear rate.
Figure 9. SEM images of the wear debris (a) Zn-Al alloy (b) 3 wt. % composition (c) 6 wt. % composition (d) 9 wt. % composition.

Figure 9 (a-d) represents the SEM images of Zn-Al-SS MMC worn surfaces. From the Figure 9 it is clear that some debris formed over the surface. This debris generated mostly from the pin material. The presence of material plastic flow could be noticed from these micrographs. During wear, the particles are pulled off from the surface and smeared onto the worn surface. Figure 9 (a) depicts the morphology of the Zn-Al-alloy worn surface with imprints of ploughing marks. The micrographs of composite with 3, 6 and 9 wt. % stainless steel particles were shown in Figure 9 (b), (c) and (d) respectively. Figures 9 (b, c and d) shows lack of deep marks on the surface compares to Figure 9 (a). Zn-Al-SS MMC worn surfaces shown in the Figure 9 (b), (c) and (d) depicts that less grooves and scratches were found when compare to Figure 9 (a). The size of the debris is reduced with 9 wt. % stainless steel particles as shown in Figure 9 (d) [29].

Figure 10. Morphology of the worn surface of composite at 40N.

But at high loads, protective layer is no longer remaining stable. The worn surface of the composite shown in Figure 10 loses its ability to withstand the load of 40 N. This is due to the development of strain when counter face comes in direct contact with the matrix alloy which causes delamination of wear [30, 31].

4. Conclusions

The following conclusions can be reported from the results of this study of Zn-Al-SS MMC.

• Stir casting was done successfully with fine dispersion of SS particle as reinforcement in the matrix alloy.

• The tensile strength of the Zn-Al-SS MMC increases by 64 % for 9 wt. % of SS particles.
• The hardness of the Zn-Al-SS MMC increases by 28 % for 9 wt. % of SS particles.

• When compared with the Zn-Al base alloy, the wear resistance of Zn-Al-SS MMC improves by 88 % for 9 wt % of SS particle.

• Wear rate of the composite and the base alloy possess direct relation. It increases with increase of load. Wear takes place much faster in the base substrate than in composites.

• From the studies, it can be concluded that Zn-Al alloy reinforced with 310 stainless steel powder exhibits higher hardness and higher wear resistance.

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