Microstructural and wear characterisation of as-cast AS21A magnesium alloy

Sumit Joshi¹, Ramesh Chandra Singh¹, Rajiv Chaudhary¹

¹Department of Mechanical Engineering, Delhi Technological University, Bawana Road, New Delhi-110042, India

*Email: sumitrke1989@gmail.com

Abstract. The present study consists of wear investigations performed on AS21A magnesium alloy. AS21A alloy falls in the category of Mg-Al-Si alloy system which is recommended for high-temperature applications. The condition of the studied alloy was as-cast and annealed. Microstructural features of AS21 alloy comprised of a soft α-Mg matrix reinforced with hard and brittle coarse Mg₂Si intermetallic. Wear behaviour of the alloy experimented through pin-on-disk apparatus and at varying loads from 10-40 N. It was observed that the wear resistance and Coefficient of Friction (COF) decrease with an increase in applied load. Further, the presence of Mg₂Si intermetallic in the magnesium matrix had a significant effect on the wear properties of the AS21A alloy.

Keywords: AS21A; Mg-Al-Si; Mg₂Si; intermetallic; wear

1. Introduction

In the last few decades, the strict government norms on emission encouraged the demand for lightweight materials in the aerospace and automotive sectors. Magnesium alloys which are lightest among structural materials have become a suitable choice in commercial industries. Magnesium alloys have earned a reputation because of the attributes such as high specific strength, excellent castability, low density, high thermal and electrical conductivity and shock absorption capability [1-3].

Despite remarkable bulk properties, magnesium alloys are inferior in surface properties like wear and corrosion resistance. The literature concerning wear behaviour of magnesium alloys is quite a few and limited to Al-Zn (AZ) [4], Al-Mn (AM) [5] and Rare Earth [6] series. Chen and Alpas [4] reported the dry sliding wear behaviour of AZ91 alloy subjected to a load range of 1–350 N and sliding velocity range of 0.1–2.0 m/s. They observed a mild wear regime consisting of an oxidational and delamination regime while the severe regime comprising of severe plastic deformation and a melt regime. Similarly, Taltavull et al. [5] and Lopez et al. [6] reported a similar wear mechanism corresponding to different load and sliding velocity during the wear study of AM60B and ZE41A alloy respectively.

The Mg-Al-Si (AS series) is another potential alloy for structural applications because of in-situ synthesised hard and brittle thermally stable Mg₂Si phase [7]. Mg₆Si exhibit attributes such as high melting point (1085 °C), low density (1.99×10³ kg/m³), high elastic modulus (120 GPa), high hardness (460 HV) and low coefficient of thermal expansion (7.5×10⁻⁶ /K) [8,9]. The study on Mg-Al-Si alloys is limited to microstructure modification and synthesis. There is limited literature [10,11] available
regarding the wear characterisation of Mg-Al-Si based alloys. Akyuz et al. [10] studied the behaviour of AS series magnesium alloys and reported that the Mg$_2$Si presence in the alloy had a strong influence on the wear and machining properties.

Ajith Kumar et al. [11] reported the reduction in wear rate of Mg–Si based alloys with an increase of Si reinforcement and with the load. The primary aim of the past studies was to study the effect of the varying composition of Aluminium [10] and silicon [11] on the wear characterisation of magnesium alloys. However, there is no literature available specifically dedicated to AS21 alloy. In the present experiment, the microstructural and wear characterisation were performed on as-cast AS21 alloy. The aim was to know the effect of intermetallic on the mechanical and wear properties of AS21A alloy.

2. Material and methods
The material selected for the present study was as-cast AS21A magnesium alloy fabricated through gravity die casting in the form of a plate having 15 mm thickness. The as-received casting plate was machined in conventional machines along with the plate softening for further investigations. The casting plate was softened to mitigate the effect of casting defects. It was achieved through heating followed by atmospheric cooling. Figure 1 depicts the as-cast and machined surface of the studied alloy. The spectroscopy analysis of AS21A carried out as per ASTM B94-2013 for chemical composition of the alloying elements is presented in table 1. The chemical analysis was performed using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy) spectrometer, Model: Spectro Max, Made in Germany.

![Figure 1](image-url)

**Figure 1.** The surface of AS21A alloy casting plate (a) as received; (b) machined.

| Alloy | Al  | Si  | Mn  | Zn  | Cu  | Fe  | Ni  | Mg  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| Percentage | 2.12 | 1.04 | 0.221 | 0.058 | 0.002 | 0.003 | <0.001 | Rest |

The samples for characterisation were taken from AS21A casting plate through CNC wire cut. The AS21A microstructural features revealed through dry and wet polishing followed by etching. The etchant solution employed was acetic-picral comprised of ethanol (100 ml), picric acid (6 g), acetic acid (5 ml) and water (10 ml) for 5-10 seconds. The Optical Microscope (Olympus, model GX 41) was utilised to capture the Optical Microscopic (OM) images of the microstructure. Further, Scanning Electron Microscope (SEM) equipped with EDS facility was utilised for micrographs and elemental analysis. The microhardness analysis was carried out using a microhardness tester attached with...
Vickers diamond pyramidal indenter (136°) at a load of 100 g and a dwell time of 10 seconds. The tensile test was performed on Universal Testing Machine (UTM) set up (Tinius Olsen H50KS) at a constant crosshead speed of 1 mm/min and room temperature. Figure 2 shows tensile specimens prepared as per ASTM B557M-06. SEM micrographs of the fractured samples were also taken for failure characteristics. Wear investigation was done on the samples shown in figure 2 as per ASTM G99 standard. Pin of 8 mm diameter was used as top specimen while EN-24 steel counter disc (hardened to 55-60 HRC) as a bottom specimen. The top and bottom specimen surface roughness ($R_a$) measured through was nearly 100 µm and 0.2 µm respectively. The surfaces of pin samples were polished with 1200 grit emery before performing wear test. The Pin-on-Disk apparatus (TR-20, Ducom) depicted in figure 3 was used for the study of wear behaviour. The parameters considered during wear test were: Load ranging from 10 N-40 N in steps of 10 N, the constant sliding velocity of 1 m/s and sliding distance of 2500 m. Wear rate (mg/m) was calculated as the ratio of weight loss (mg) and sliding distance (m) for all three samples. Further, weight loss was measured through precision weighing balance (0.001g) as the difference in the weight of the sample before and after wear. Wear analysis was done by utilising SEM micrographs to understand the wear mechanism involved.

![Figure 2](image1.png)

**Figure 2.** Characterisation specimens for: (a) tensile test before fracture; (b) tensile test after fracture; (b) wear test.

![Figure 3](image2.png)

**Figure 3.** Schematic of Pin-on-Disk equipment.
3. Result and discussions

3.1. Microstructure characterisation
The as-cast AS21A alloy microstructure depicted in figure 4 typically comprised of soft α–Mg matrix surrounded by hard and brittle eutectic Mg$_2$Si intermetallic compound. The morphology of Mg$_2$Si particles was found to be coarse and Chinese script. Further, the FESEM of AS21A alloy shown in figure 5a also depicted the presence of intermetallics in the soft magnesium matrix. The Mg$_2$Si nature of intermetallic was confirmed by the EDS spectrum as shown in figure 5b. The Mg$_2$Si behaved as the in-situ reinforcement in the soft α-magnesium matrix thus enhancing the overall mechanical and wear properties of as-cast AS21A alloy. The in-situ reaction during solidification of casting was found responsible for the formation of the Mg$_2$Si phase. The microstructural findings of AS21A alloy were consistent with the available literature [12-14].

![Figure 4](image1.png)

**Figure 4.** Optical Microscopy image of as-cast AS21A alloy

![Figure 5](image2.png)

**Figure 5.** Microstructure characterisation of as-cast AS21A alloy: (a) SEM micrograph; (b) EDS spectrum.

3.2. Mechanical and wear characterisation
Table 2 represents the mechanical and wear characteristics obtained. The AS21A alloy exhibited enhanced ductility that can be attributed to the softening treatment. The tensile morphologies are
shown in figure 6 exhibited cracks, elongated dimples and cleavage facets on fractured surfaces which confirmed the blend of ductile-brittle nature.

Table 2. Mechanical and wear properties of the AS21A alloy

| UTS (MPa) | YS (MPa) | Elongation (%) | Hardness (HV) | Load during wear test (N) | Wear rate ($\times 10^{-3}$ mg/m) | COF |
|-----------|----------|----------------|--------------|--------------------------|----------------------------------|-----|
| 117       | 74       | 15.5           | 55           | 10                       | 11.64                            | 0.32|
|           |          |                |              | 20                       | 17.96                            | 0.26|
|           |          |                |              | 30                       | 26.40                            | 0.22|
|           |          |                |              | 40                       | 39.76                            | 0.12|

Figure 6. SEM micrographs of fractured tensile specimens.

Table 2 highlights the enhancement of wear rate with an increase in load. It was observed from the Coefficient of Friction (COF) Vs Sliding Distance (m) plot shown in figure 7 that an increase in normal load decreased the fluctuation in COF value. COF at a lower load of 10 N exhibited large fluctuations as compared to small fluctuations in case of a higher load of 40 N. The coarse Mg$_2$Si characteristics of AS21A alloy (shown in figure 4) was in a capacity to support the normal load acting during wear test thus decreasing the fluctuation at higher loads. A similar observation was evaluated by An et al. [15] during sliding wear behaviour of Mg$_{97}$Zn$_1$Y$_2$ alloy. The worn-out surfaces of wear samples were captured in the form of SEM micrographs, as shown in figure 8, to study the wear mechanism of the AS21A alloy. The major wear mechanisms observed during wear study were adhesion, oxidation, abrasion, and delamination. At 10 N loads, the presence of narrow grooves along with material sticking confirmed the combination of abrasion and adhesion wear mechanism. At 20 N loads, there were signs of grooves and oxide layer which confirmed the combination of abrasion and oxidation wear mechanism. At a higher load of 30 N and 40 N, the wear subsurface undergoes plastic deformation, and material removal takes place in the form of platelets. It confirmed the onset of delamination wear mechanism at higher loads. The wear mechanism observed was consistent with the literature [16, 17]. Selvan et al. [16] and Taltavull et al. [17] reported that the desired wear characteristics are a strong function of the applied load and sliding velocity.
Figure 7. Graph showing COF variation with sliding distance

Figure 8. SEM micrographs of wear samples tested at an applied load of (a) 10 N; (b) 20 N; (c) 30 N and (d) 40 N.
4. Conclusions
The conclusions derived from the microstructural and wear study of as-cast annealed AS21A alloy are as follows:

1. The microstructural features of as-cast annealed AS21A alloy comprised of a primary α-Mg matrix reinforced with in-situ Mg$_2$Si intermetallic compound. The morphology of Mg$_2$Si found to be coarse and Chinese script.
2. The mechanical properties obtained were UTS of 117 MPa, YS of 74 MPa and % elongation of 15.5. Further, the high ductility of the studied alloy was confirmed by the fracture morphologies.
3. Wear resistance and coefficient of friction (COF) were found to be decreased with an increase in applied load. Furthermore, the Mg$_2$Si phase in the Mg matrix was found responsible for the decrease in COF fluctuations.
4. AS21A alloy exhibited a variety of wear mechanism at different loads: adhesion and abrasion at a low load of 10 N, abrasion and oxidation at an intermediate load of 20 N and finally delamination at a higher load of 40 N.

References
[1] Polmear I, St. John D, Nie JF and Qian Ma 2017 Light alloys: metallurgy of light metals 5th ed. (Oxford: Butterworth-Heinemann).
[2] Mordike BL and Ebert T 2001 Mater Sci Eng A 302 37–45.
[3] Avedesian MM and Baker H 1999 Magnesium and magnesium alloys: ASM specialty handbook ISBN 0-87170-657-1.
[4] Chen H and Alpas AT 2006 Wear 246 106–16.
[5] Taltavull C, Torres B, Rodrigo P Lopez AJ and Rams J 2013 Wear 301 615–25.
[6] López AJ, Rodrigo P, Torres B and Rams J 2011 Wear 271 2836–44.
[7] Luo A and Pekguleryuz MO 1994 J Mater Sci 29 5259–71.
[8] Mabuchi M, Kubota K and Higashi K 1996 Mater Sci Technol 12 35–9.
[9] Mabuchi M, Kubota K and Higashi K 1996 J Mater Sci 31 1529–35.
[10] Akyuz B 2014 Proc Inst Mech Eng B J Eng Manuf. 1–9.
[11] AjithKumar KK, Pillai UTS, Pai BC and Chakraborty M 2013 Wear 303 56–64.
[12] Li GH, Gill HS and Varin RA 1993 Metall Mater Trans A 24 2383–91.
[13] Evangelista E, Gariboldi E, Lohne O and Spigarelli S 2004 Mater Sci Eng A 387–389 41–5.
[14] Dargusch MS, Bowles AL, Pettersen K, Bakke P and Dunlop GL 2004 Metall Mater Trans A 35 1905–09.
[15] An J, Li RG, Lu Y, Chen CM, Xu Y, Chen X and Wang LM 2008 Wear 265 97–104.
[16] Anbu selvan S and Ramanathan S 2010 Mater. Des. 31 1930–36.
[17] Taltavull C, Rodrigo P, Torres B, Lopez AJ and Rams J 2014 Mater. Des. 56 549–56.

Acknowledgements
The authors would like to thank National Testing Laboratory, New Delhi for spectroscopy and Institute Instrumentation Centre, IIT Roorkee for the characterisation facility.