Wear and Mechanical Behaviour of Magnesium AZ31 alloy Reinforced with MoS2 through Friction Stir Processing for Aerospace Applications

Tajdeen A, Kamal Basha K, Roshan Shandres C, Sandeeprajkumar S, Saddam Hussain S and Sanjay R
Department of Mechanical Engineering, Bannari Amman Institute of Technology, Sathyamangalam – 638401, Erode(Dt), Tamil Nadu, India.
tajdeena@bitsathy.ac.in

Abstract. Friction Stir Processing (FSP), a solid-state processing technique employed to modify the microstructure, is based on the principles of friction stir welding. FSP is one of the most promising techniques for the production of surface composites. In this investigation, AZ31 magnesium alloy is reinforced with molybdenum disulfide (MoS2) through a friction stir processing method. Before and after the fabrication of the surface composites the wear tests were conducted by varying the condition of sliding load (25 N & 35 N), sliding distance (1 km & 2 km), and sliding velocity (1 m/s & 2 m/s). Hardness values were measured by using the Brinell hardness tester. Both hardness and wear tests were conducted as per the ASTM standards. After reinforcement, composite material enhances hardness values. The wear rate also reduces as MoS2 acts as a solid lubricant material.

1 Introduction
Nowadays, Al and Mg-based Metal Matrix Composites (MMC) are used for the various applications such as aerospace, shipbuilding, defence and automotive applications because of their attractive properties such as good strength and elasticity [1,2]. Surface composites show enhanced characteristics of the material on the surface while retaining several properties of the matrix by using Friction Stir Processing (FSP) [3]. The selection of size and profile of pin is also an important consideration during FSP. For Magnesium AZ31 alloys, Normally Circular pin without and with thread produces the best result in FSP[4].

Friction stir processing and addition of SiC and CNT reinforcement through this route enhance the mechanical and microstructural changes in the material [5]. A single-pass was carried out using a fabricated cylindrical profile FSP tool with operating conditions such as tool rotation speed, travel speed, and downward forces which were 1100 rpm, 60 mm/min, and 6 kN respectively. The hardness of the FSP specimens increased by 40% which contained 50 % SiC + 50 % B4C which is higher than that of the aluminum matrix alloy [6]. Our present work focuses on the wear and the mechanical properties of magnesium AZ31 alloys reinforced with MoS2 through FSP.

2 Materials and Methods
2.1 Friction stir processing
FSP can be used to increases the mechanical, wear, corrosion behaviour of the materials. Friction stir processing is a thermomechanical process for improving material properties. AZ31 Mg alloy was used in this process. The dimensions of the plate were 125 x 75 mm with 6 mm thickness. The 18% volume fraction is fixed. In this present study, the molybdenum disulfide (MoS2) is used as reinforcement. This reinforcement is having excessive reactivity compare to the other bulk materials. The molybdenum disulfide (MoS2) particles are in the black stable form.
During the drilling, the fixed spindle speed at 750 rpm and fixed feed rate of 20 mm/min was chosen. In the same way, 42 holes were drilled and removed the workpiece from the vertical CNC milling machine.

The rotating non-consumable tool comes in contact with the material surface and starts moving along the seam. The two workpieces get fused into a single workpiece by the solid-state welding process, the joint is by the heat produced by the friction of tool with the workpiece. In this process, the workpiece is held on to a rigid table and the FSP tool is made to rotate over the surface of the material at high speed to generate heat and to join with the base material. Schematic illustration of Friction stir processing system is shown in below Figure 1.

![Figure 1. Schematic representation of FSP](image)

The FSP is done mostly by using the groove method, to improve the material distribution, hole method is used instead of the groove method. The drill was done at the center of the AZ31 workpiece with the drill ratio of 18%. The holes are filled with the molybdenum disulphide (MoS₂) and the friction stir processing was done on the surface of the workpiece.

### 2.2 Composition of AZ31 alloy

In this present study, AZ31 Mg alloys selected as base material. Because, AZ31 Mg alloys having good casting properties, high stiffness to weight ratio, high corrosion resistance, wear resistance, etc. The figure 2 shows various elements in AZ31 Mg alloy and its percentage.

![Figure 2. Chemical composition of AZ31 alloy in %](image)
2.3 Properties of AZ31 alloy

AZ31 alloy concerning its properties it has been used in many application such as automobile industries, aerospace, shipbuilding, railway department, pylons and towers etc. The mechanical properties, physical properties of AZ31 alloy is shown in Table 1 & 2 respectively.

| S.NO | PROPERTY                             | VALUE  |
|------|--------------------------------------|--------|
| 1    | Tensile Strength (N/mm²)             | 260    |
| 2    | Hardness Number - Brinell (500kg load,10mm ball) | 49     |
| 3    | Shear modulus (N/mm²)                | 17000  |
| 4    | Elastic modulus (N/mm²)              | 44800  |
| 5    | Poisson's ratio                      | 0.35   |
| 6    | Yield strength-strain 0.200% (N/mm²) | 200    |

| PROPERTY                             | METRIC   | IMPERIAL   |
|--------------------------------------|----------|------------|
| Density                             | 1.77 g/cm³ | 0.0639 lb/in³ |

3 Experimental Procedure

3.1 Preparation of Reinforcements:

MoS₂ particles were used as reinforcements. The reinforcement powder has undergone a ball milling process for the required size of particles and also for required percentage. The MoS₂ particle was filled in the hole and the FSP non-pinned tool was used to close the hole(capping). Figure 3 shows the EDAX image of MoS₂ with its chemical compositions.

![Figure 3. EDAX image of MoS₂](image)

The chemical composition of MoS₂ is shown below the table 3.

| ELEMENT       | CONTENT(%) |
|---------------|------------|
| Molybdenum    | 59.94      |
| Sulfur        | 40.06      |

3.2 Preparation of FSP tool:

The FSP tool is made up of H-13 tool steel material and the shoulder diameter of the tool is 18 mm. The pin diameter and length of the pin were 6 mm and 3.5 mm respectively [7,8]. A cylindrical pin profile was used for the process which is plunged into the capped surface on the plate. FSP tool and FSP setup was shown in figure 4 and figure 5 respectively.
The FSP tool consists of a shoulder and a pin. The primary purpose of the tool is to create localized heating and the plastic material flow in the stir zone. The tool shoulder also provides confinement for the heated volume of material. The hardness of the workpiece is based on the tool rotational speed [9, 10]. The hole diameter and depth depend upon the amount of powder to be used to make the metal matrix. The FSP tool dimensions are given in Table 4.

### Table 4 FSP tool dimensions

| Pin                        | Values (mm)          |
|----------------------------|----------------------|
| Pin length                 | 5.5 (single pass)    |
|                            | 3.5 (double pass)    |
| Tool shoulder diameter, D  | 18                   |
| Pin diameter, d            | 6                    |
| Holder diameter            | 8                    |
| Holder length              | 36                   |
| Shoulder length            | 10                   |

3.3 Experimental work:

After making the hole in the base plate, the hole was filled with reinforcements in the following order: hole was filled with 100% of MoS$_2$. The experimental setup of AZ31 plate with reinforcements is shown in Figure 6. Based on pilot study analysis, the process parameters used in the process is given in Table 5. The FSP process is conducted on Vertical Machining Centre.
Table 5. FSP process parameters

| Sl. No | Process Parameters   | Values |
|--------|----------------------|--------|
| 1      | Rotational Speed (rpm) | 1200   |
| 2      | Traverse speed (mm/min) | 20     |
| 3      | Axial force (kN)    | 7      |
| 4      | Number of passes    | 1      |

Figure 6. FSP experimental setup of AZ31 plate
As the process commences, the tool tends to touch the workpiece, the rotating pin comes in contact to the surface of the workpiece. Friction is produced due to which the workpiece gets heated and provides the softening of the matrix. This helps to attain a fine-grained, uniform structure. After the process, the material is removed from the setup and it is subjected to polishing for mechanical testing. The FSP processed plate has been shown in figure 7.

Figure 7. Friction Stir Processed plate

3.4 Brinell Hardness Measurement:
Workpiece was cut for the hardness test in the FSP stir zone. Testing was conducted in the Brinell hardness tester at various places of different indentation. Specimen were cut as per ASTM (ASTM E10) standard for Brinell hardness test. If the material is softer, a smaller force is used and the material is harder, a large force is used. Hardened steel ball is used for indentation.

3.4.1 Procedure for Brinell Hardness Measurement
The following are the procedure for hardness measurement. The specimen is placed on the testing area. To turning the loading lever in a backward direction and to apply the minor load on the specimen surface. The load is maintained at 10 to 15 seconds for a dwell time. After the dwell time is completed, the indenter is removed from the specimen. To repeat the above procedure for different loads and materials.

3.5 Wear Measurement:
When, two solid surfaces are sliding, rolling or impact conditions the wear will occur. wear is one kind of material removal process. The dry sliding wear test was conducted by using the pin on disc wear testing machine. Workpiece was cut for the wear test in the FSP stir zone. Testing was conducted in the pin on disc wear test rig. Specimen were cut as per ASTM G99 standard for the wear test.
3.5.1 Procedure for Pin on Disc Wear Measurement

The following are the procedure to wear measurement. The specimen is placed on the testing holder. The track diameter is selected based on our requirement. The load is added in the loading hanger. The input parameters such as load, time, speed, track diameter are entered. The LVDT sensors are used to measure the displacement. The computerized pin on disc system shows results in the display. To repeat the above procedure for different parameters such as load, speed, track diameter, time. The Pin on disc wear test rig apparatus is shown in below figure 8.

![Pin on disc wear test rig](image)

**Figure 8.** Pin on disc wear test rig

4 Results and Discussion

4.1 Effect of reinforcement on the hardness

It was observed that base material AZ31 alloy, friction stir processed with and without reinforcement (MoS₂) shows the increasing trend in hardness because of the grain refinement during FSP and uniform distribution of reinforcements. Figure 9 shows the hardness value variation for base material and FSPed Material.

![Hardness Values](image)

**Figure 9.** Hardness values

4.2 Effect of Reinforcement on Wear:

It was observed that magnesium AZ31 alloy material (base material) and AZ31+MoS₂ composite material (with reinforcement material) were tested at the same wear condition, results show that the wear rate has decreased due to MoS₂ acting as a dry lubricant and uniform distribution reinforcements reduces direct contact on counter surfaces. Figure 10 shows the wear rate variation for base material and FSPed Material.
Figure 10. Wear rates

The observed wear values without reinforcement have shown in Table 7.

Table 6. Wear test values without reinforcement

| ROTATIONAL SPEED (rpm) | TRAVEL SPEED (m/min) | SLIDING SPEED (m/s) | LOAD (N) | WEAR (mm³/min) |
|------------------------|----------------------|---------------------|----------|---------------|
| 900                    | 10                   | 1                   | 25       | 0.04          |
| 1100                   | 20                   | 1                   | 35       | 0.0046        |

From Table 6, it was observed that both normal AZ31 material (without reinforcement material) and AZ31+MoS₂ composite material (with reinforcement material) are tested at the same condition. But, the normal AZ31 material (without reinforcement material) gives wear rate of 0.0051 mm³/min at 1100 rpm rotational speed. The AZ31+MoS₂ composite material (with reinforcement material) gives wear rate of 0.0037 mm³/min at 1100 rpm rotational speed. Based on the above results observed that the combination of AZ31 and MoS₂ (Molybdenum disulfide) shows higher wear resistance than they act as individuals.

5 Conclusions
The FSP on magnesium AZ31 alloy with reinforcement of MoS₂ particles was successfully carried out and the following results were obtained:

- The Magnesium AZ31 alloy showed the hardness value of 114 BHN. After FSP with a single pass without reinforcement, it showed a hardness value of 124 BHN and after reinforcement, with a single pass, the FSP composite material showed the 147 BHN. Hence the hardness value increased due to the grain refinement and reinforcement.
- The Magnesium AZ31 alloy showed a wear rate of 0.0051 mm³/min, after FSP with a single pass without reinforcement showed a wear rate of 0.0037 mm³/min and after reinforcement with a single pass, the FSP composite material showed the value of 0.0031 mm³/min. So the wear rate decreased due to the grain refinement.

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