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Evaluation of Dry Sliding Wear Characteristics in Al5052/TiB_2/ZrO_2 Composites Against EN-31 Steel Counterbody

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Abstract. The current study inspected the dry sliding wear characteristics of composites with Al5052 matrix. The composites were stir-casted with nano-TiB_2 and nano-ZrO_2 as reinforcements. The test specimens were examined using a pin-on-disc device with an EN-31 steel disc under multiple loads (10 N, 20 N, and 30 N) and speeds (0.94 m/s, 1.57 m/s and 2.20 m/s). To inspect the worn surfaces, scanning electron microscopy is utilized. The wear rate increased with the load, reaching a maximum value at 30 N. The resistance to wear for Al5052-based composite with 1% TiB_2 and 1% ZrO_2 was found to be best. The wear rate was observed to increase initially at 1.57 m/s and then decrease when the speed was increased to 2.20 m/s. SEM micrographs revealed abrasion and delamination of the worn-out surfaces.

Keywords: aluminium matrix composites, titanium diboride, zirconia, stir casting, dry sliding wear.

Introduction

Aluminium matrix composites (AMCs) are evolving as a significant class of materials for advanced technical applications due to improved properties like enhanced specific strength, improved stiffness, and greater resistance to wear when compared to unreinforced Aluminium alloys [1, 2]. The applications include the components for the aerospace, automobile, marine and transportation industries [3–5]. AMCs consist of Aluminium alloy matrices reinforced with ceramic materials like Silicon carbide (SiC), Alumina (Al_2O_3), Silicon Nitride (Si_3N_4), Titanium carbide (TiC), Graphene, Titanium diboride (TiB_2), Carbon Nanotube (CNT) and Zirconia (ZrO_2) [6].

The wear characteristics of AMCs are critical for many load-bearing applications. Enhancing the wear resistance can extend the service life of components exposed to repetitive sliding conditions [7]. Factors like reinforcement content, size and distribution of particles affect the hardness and wear characteristics of AMCs [8]. The lowest wear rate was found in Al7075-AMC reinforced with 2 weight% Al_2O_3 by Baradeswaran and Perumal [9]. Shanmugaselvam et al. [10] conducted the wear test on AMCs reinforced with SiC, B_4C and graphite. Composite with 13 wt% SiC, 13 wt% B_4C and 10 wt% graphite had the lowest wear rate.

Studies have shown that factors like load, sliding speed, and distance influence the rate of wear in Aluminium-based composites [11–13]. However, there is limited understanding of the combined effects of these factors, along with the reinforcement amount, on the wear characteristics of nanoparticle-reinforced AMCs using Al5052 as matrix material. Al5052, an aluminium-magnesium alloy, provides a stable and ductile matrix for the reinforcement materials. Its combination of moderate strength, good corrosion resistance, and excellent formability makes it an ideal choice for marine, fuel tanks, automotive and aerospace applications [14–16].

The current research examines the wear attributes of Al5052-based AMCs with varying compositions of nanosized TiB_2 and ZrO_2 reinforcements, taking into account wear between cylinder liners and piston rings in automobiles and also between brake pads and discs for automobile and marine vessels. The wear characteristics will be evaluated under different loads and speeds at room temperature. The assessment of stir-cast TiB_2 and ZrO_2 nanoparticles in Al5052 alloy AMCs—a combination that is rarely studied—is what makes this research study novel.

1. Materials and Methods

1.1 Materials

A commercially available Al5052 alloy served as the matrix for this study. Table 1 shows the chemical content of Al5052 as determined by spectro analysis of the sample. TiB_2 nanoparticles of average particle size (APS) of a maximum of 80 nm size and 99.9% purity were procured from Intelligent Materials Pvt. Ltd., Punjab; whereas, ZrO_2 nanoparticles of 30-50 nm APS and 99.9% purity were obtained from Nano Research Lab, Jamshedpur.

Table 1. Chemical content (weight %) of Al5052

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Composition	0.122	0.230	0.024	0.071	2.233	0.154	0.072	Remainder

The EDX mapping of TiB_2 and ZrO_2 powders are shown in Figs. 1a) and 1b) respectively.

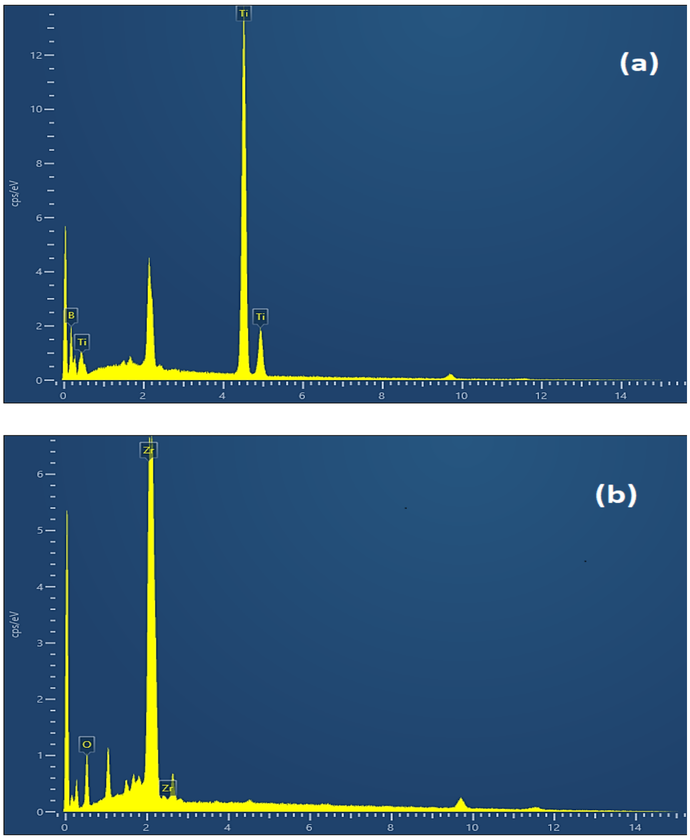


Fig. 1 - a) EDX mapping of TiB_2 and b) EDX mapping of ZrO_2

1.2 Composite fabrication

Al5052-based composite test specimens were fabricated by stir casting. In a muffle furnace, the TiB_2 and ZrO_2 nanoparticles were first preheated to 350°C for 1 hour. This preheating step assisted in removing any moisture or gases that had been adsorbed on the nanoparticles [17].

Meanwhile, approximately 800 grams of Al5052 alloy were added to a furnace preheated to 700°C. At this temperature, the Al5052 alloy melted into a liquid state. Once the metal was fully molten, the preheated TiB_2 and ZrO_2 nanoparticles were introduced slowly into the melt. Potassium Hexafluorotitanate Powder and Mg were added to improve the wettability. The ceramic nanoparticles were distributed evenly throughout the molten aluminum alloy by agitating the composite slurry for 10 minutes with a mechanical stirrer containing high-strength steel impellers rotating within the furnace [18, 19].

Following that, the heated steel mould was filled with the composite melt and was allowed to harden into the required shape. Table 2 shows the composition of the test specimens prepared for this study.

Table 2. Specimen composition for the Al5052 composites

Specimen	Weight %		
	Al5052	TiB_2	ZrO_2
S1	99	1	0
S2	99	0	1
S3	98	1	1

2. Wear Experiment

The DUCOM pin-on-disc machine served as the primary instrument for evaluating the dry wear characteristics of Al5052-based composite samples, adhering to the ASTM G99 standard for specimen preparation. The samples, shaped as square pins, measured 25 mm in height and 10 mm in width. To evaluate the wear specimens, an EN-31 steel disc with a 200 mm diameter and a hardness of 62 HRC is employed on a pin-on-disc device. Emery sheets of grit sizes 220, 400, 600, 1000, 1500, and 2000 were employed to polish the surfaces of test specimens. The evaluations took place at 60 mm track diameter for time period of 15 minutes [20, 21]. The specimen weights were recorded using an electronic weighing machine with a resolution of 0.001 g. A scanning electron microscope analysis concluded the study, examining the worn-out surfaces of the samples. Before and after the experiment, the rotating disc and pin samples were wiped with tissue and acetone.

A total of 27 experiments were performed, with each sample subjected to nine sets of investigations. The experiments were repeated 3 times and the average wear rate was calculated. Table 3 contains the test parameters.

Table 3. Test parameters along with their respective levels

Parameters	Level 1	Level 2	Level 3
Load (N)	10	20	30
Sliding speed (m/s)	0.94	1.57	2.20
Sample	S1	S2	S3

3. Result and Discussion

3.1 Wear result

The wear attribute of the AMCs was determined using the pin-on-disc examination by finding the mass loss and calculating the specific wear rate (SWR) [22] from the Eq. 1 and Eq. 2:

$$SWR=\frac{Mass\ loss}{Density\times Sliding\ Distance\times Load}\ mm^3/N\text{-}m \tag{1}$$

$$Sliding\ Distance\ (m) = Sliding\ speed\ \times time \tag{2}$$

Wear testing is conducted on composites to evaluate their resistance to wear and understand the underlying wear mechanisms. These tests help in comparing the different material compositions, predict component lifespans, and optimize material design. By simulating real-world conditions, wear tests provide crucial data for selecting appropriate materials for specific applications and ensuring manufacturing consistency.

The changes in the wear rate with respect to different loads (10N, 20N and 30N) and sliding speeds (0.94m/s, 1.57 m/s and 2.2 m/s) are shown in Figs. 2 – 5. The effect of load and sliding speed on SWR is discussed below.

3.1.1 Effect of load on wear rate of Al5052 composite

A general trend was observed from these figures that there was increase in SWR with increasing load up to 30 N which implies that wear resistance decrease with the load [23]. Minimum SWR at 0.94 m/s and 1.57 m/s was shown by S3 samples at a load of 10 N (refer to Fig. 2 and Fig.3). Low amount of SWR in any specimen means that its resistance to wear is high. The wear rate for S3 specimen spiked to $1.482 \times 10^{-4}\ \mathrm{mm^3/Nm}$ when the load was increased to 30 N at 0.94 m/s (refer to Fig. 2). It was also observed that the wear rate for S3 ($1.316 \times 10^{-4}\ \mathrm{mm^3/Nm}$) was higher than that of S2 ($1.007 \times 10^{-4}\ \mathrm{mm^3/Nm}$) when tested at 2.2 m/s under a 10 N load (refer to Fig. 4). This happened as a result of presence of void and pores (or agglomeration) within the specimens tested under those conditions.

3.1.2 Effect of sliding speed on wear rate of Al5052 composite

From the Fig. 5 it is evident that the SWR increases initially with the sliding speed at 30 N applied load but as the speed increased from 1.57 m/s to 2.2 m/s the SWR was reduced [24]. Similar trend was observed by Alidokht et. al [25], where the wear resistance of hybrid metal matrix composites was improved at higher sliding speed and sliding distance. At lower sliding speeds, adhesive wear dominates, resulting in an initial rise in wear rate. The wear mechanism changed to abrasive wear as the speed increased, resulting in a drop-in wear rate. The SWR was found minimum for sliding speed of 0.94 m/s.

The minimum SWR of 0.303 mm^3/N-m was observed when Al6061 alloy was reinforced with 3% graphene nanoplatelets (GNPs) and 3% CeO_2 [20]. Mahmut et al. [22] tested Al/GNP composite for wear attribute at 10 N to 40 N load. The lowest SWR noted at 10 N and 40 N were 1.2×10^{-4} mm^3/N-m and 1.8×10^{-4} mm^3/N-m respectively. Sharma et al. [23] performed dry sliding wear test on Al6101/graphite composite and found the minimum SWR of 2×10^{-4} mm^3/N-m at 4% graphite.

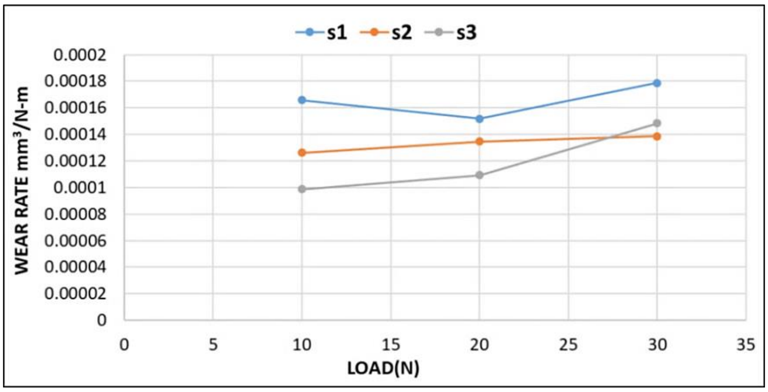


Fig. 2 - Change in SWR with load at 0.94 m/s

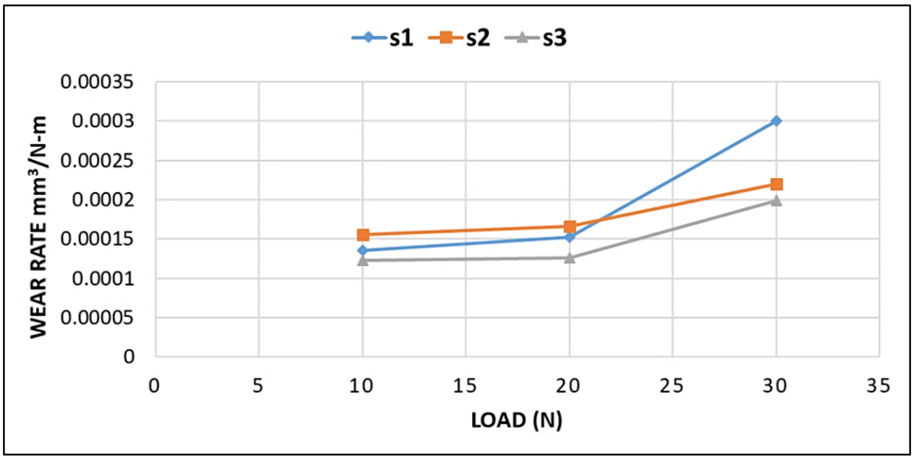


Fig. 3. - Change in SWR with load at 1.57 m/s

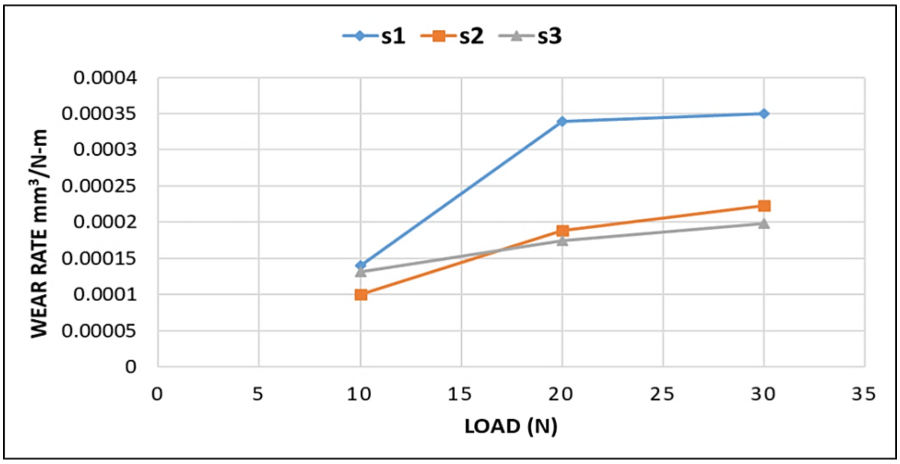


Fig. 4. - Change in SWR with load at 2.2 m/s

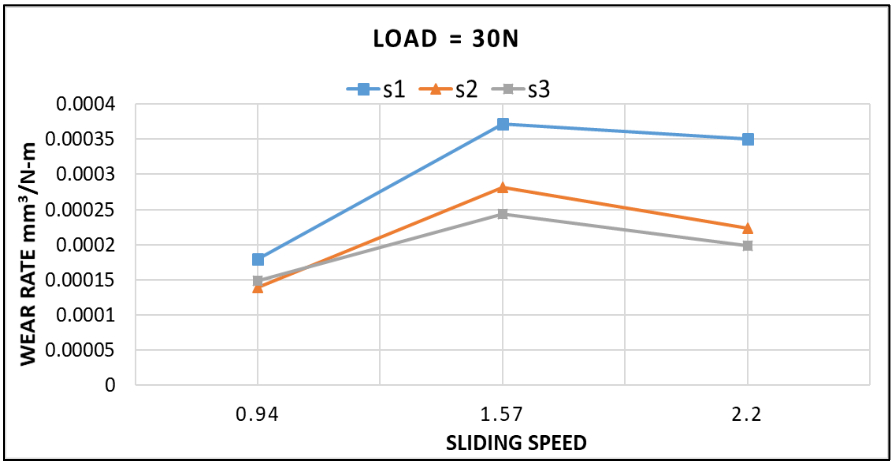
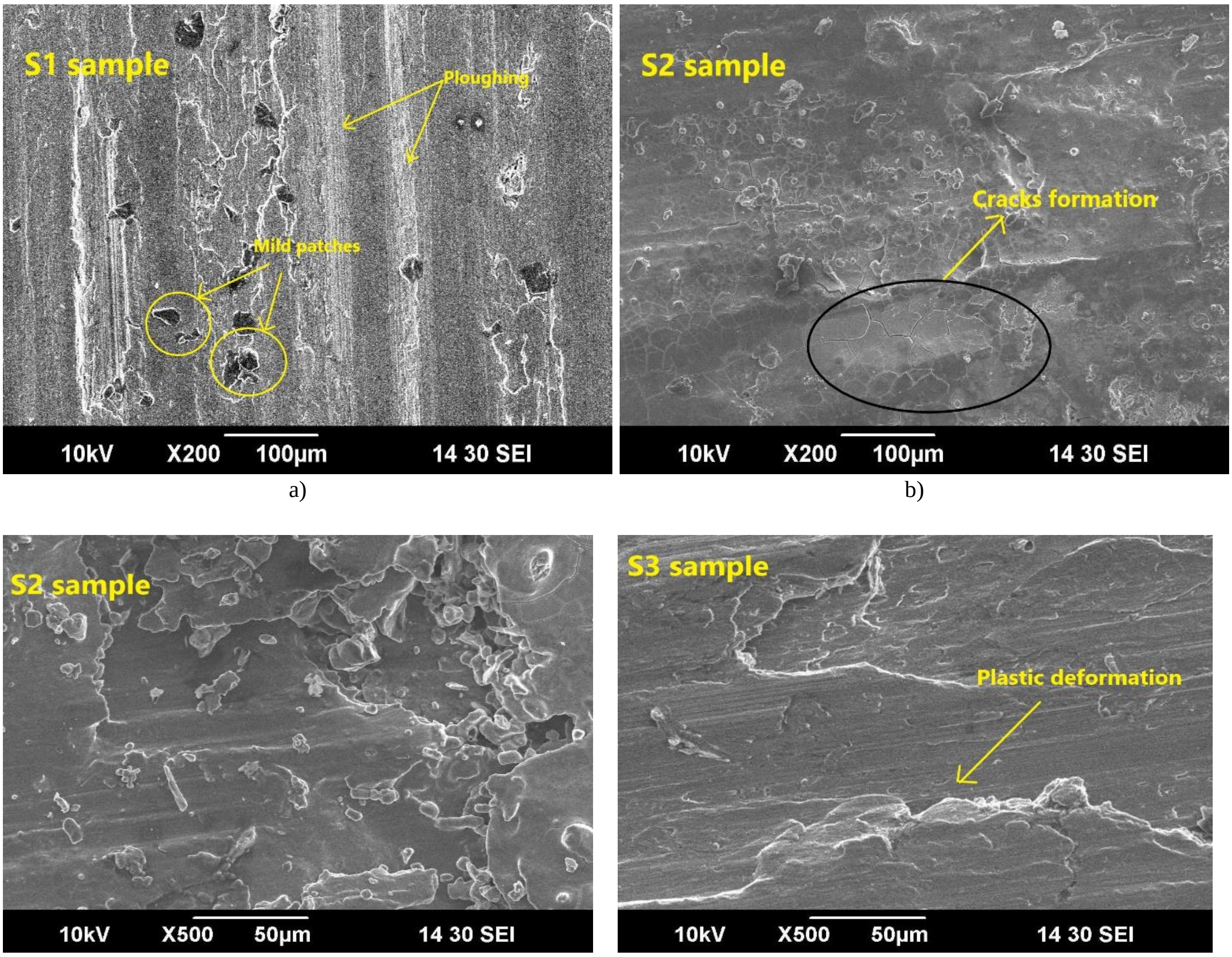


Fig. 5. - Change in SWR with speed at 30 N load with change in sliding speed (m/s)

3.2 SEM analysis of wear surfaces

The worn surfaces of Al5052-based AMCs after wear experiments were examined through SEM. The wear debris that is being formed between pin and disc were wiped off using clean cloth [26]. Fig. 6 (a-d) depict the microscopic study of the worn-out surfaces.

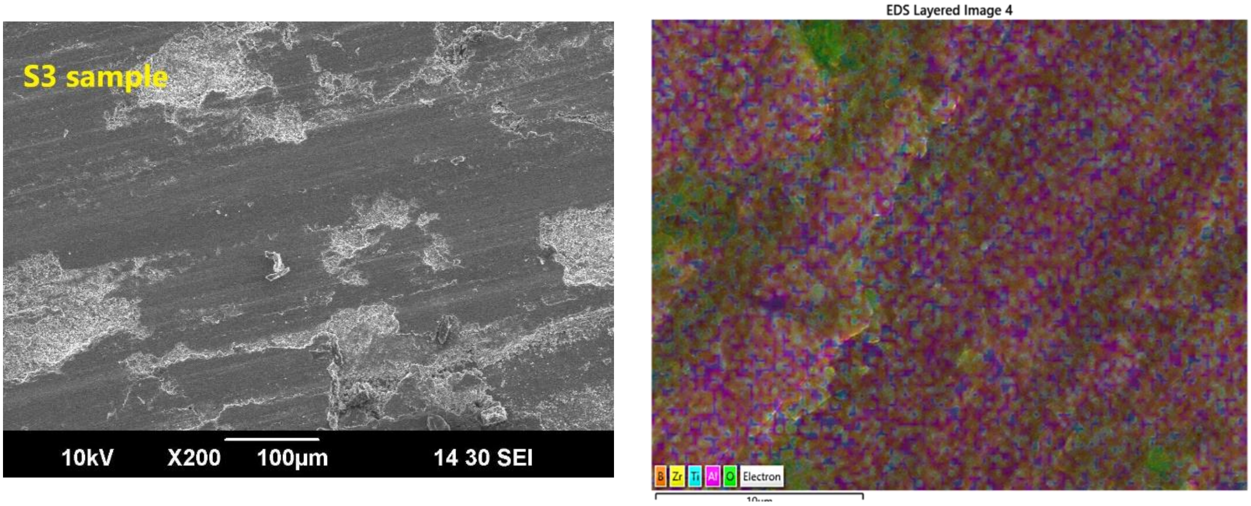


a) b)

c) d)

Fig. 6. - SEM images of worn surfaces at 30N load: a) S1 sample at 0.94 m/s, b) and c) S2 sample at 1.57 m/s, d) S3 sample at 1.57 m/s

In the wear test, when the composite surface touches the rotating disc, wear occurs through grooving. A lot of scratches and cracks were identified on the worn surfaces indicating abrasive wear mechanism [27]. These grooves happened because the material got pushed around by the ploughing action (refer to Fig. 6a). Delamination wear was also noticed in the composite. On the surface, the cavities and grooves are caused by delaminating and breaking of surface layer [28]. The crater formation was observed in Fig. 6b and 6c. The mild patches formed indicates towards the adhesive wear phenomena. The chipping off of the material can also be seen from the morphology. Fig. 6d shows the formation of grooves by plastic deformation.



a) b)

Fig. 7. - a) Morphology of S3 sample at 2.20 m/s and b) Elemental mapping of S3 sample

Oxidation formation (refer to Fig. 7a) is seen at high loads and high sliding speed [29]. The higher wear strength of S3 sample was observed as the surface was smoother compared to S1 and S2. Fig. 7b shows the element mapping of S3 sample and the existence of Al, Zr, Ti, B and O is observed.

The hybrid composite S3 specimen had the lowest SWR, while the S1 specimen had the highest SWR. The higher wear strength in S3 sample was evident as a result of adding 1% Tib_2 and 1% ZrO_2 to the matrix. The wear resistance also improved due to formation of oxides because of high temperatures during sliding. Fig. 8 displays the EDS (Energy-Dispersive X-ray Spectroscopy) examination of the S3 sample.

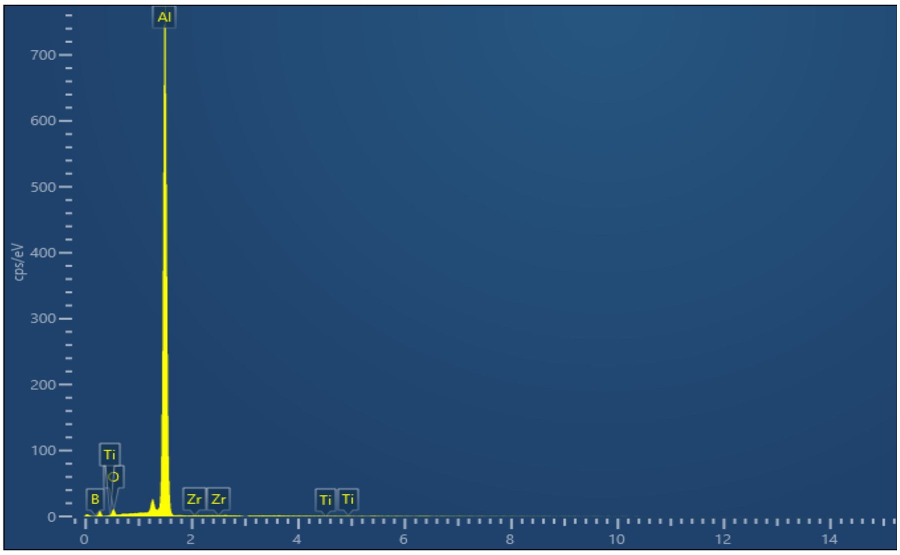


Fig. 8. - EDS analysis of S3 sample

Conclusions

The wear behaviour of Al5052-based AMCs, which were fabricated by stir casting technique, was observed using pin-on-disc device with an EN-31 steel disc at normal room condition. The investigation of experiment outcomes led to the following conclusions:

1. When Al5052-based AMCs were tested for dry sliding behavior at different loads and sliding speed.
2. The wear rate was found to be influenced by load and speed.
3. The lowest wear rate was observed for a load of 10 N and at a sliding speed of 0.94 m/s.
4. The S3 specimen exhibited good wear resistance under varying loads and speeds.
5. SEM micrographs of worn-out surfaces revealed surface faults such as ploughing, wear debris, cracks, and mild patches after dry sliding wear testing.
6. The SEM investigation revealed that some mild patches were identified as a result of material loss, as well as some places with delamination. These defects are formed as a result of the material's abrasion and adhesion during the wear test.
7. Oxidation was observed at high loads and speeds.

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