Investigation on Microstructure and Wear Study on Al-Zn-Mg Alloy Hybrid Composites Fabricated Through Die Casting Process

L Bharath[1], J Kumaraswamy[2,*], T V Manjunatha[3], Suchendra K R[4]

[1,3]Dept. of Mechanical Engineering, Cambridge Institute of Technology, Affiliated to Visvesvaraya Technological University (V.T.U), Belagavi, Karnataka, India.

[*2,4]Dept. of Mechanical Engineering, R. L. Jalappa Institute of Technology, Affiliated to Visvesvaraya Technological University (V.T.U), Belagavi, Karnataka, India.

*Author to whom correspondence should be addressed:
E-mail: kumaraswamyj@rljit.in

(Received April 30, 2024; Revised September 17, 2024; Accepted October 28, 2024).

Abstract: The Al-Zn-Mg hybrid composite play a vibrant role in meeting the definite application in aerospace due to its greater mechanical and tribological properties. In this paper, a die casting technique is adopted to prepare the Al-Zn-Mg hybrid metal matrix composites by changing graphite (Gr.) at 1%, 3%, 5% and 7 weight percentage at constant 2% of silicon carbide (SiC). The test specimens are prepared as per ASTM standard and undergo surface study and wear study. Wear rate for Al-Zn-Mg hybrid metal matrix composite is performed on pin on disc wear equipment by varying sliding distance (250, 500, 750, 1000, 1250 and 1500 m) and applied load (5, 10, 15, 20, 25 and 30 N) at constant sliding velocity (1.5 m/sec). Optical microstructure images reveal sufficient bonding between matrix and reinforcement material. As graphite particle increases wear rate observed to be decreased however, rising in speed and load wear rate was increased. For Al-Zn-Mg/2% SiC/7% Gr. hybrid composite exhibited 57.83% decrease in wear rate has compared to non-reinforced Al-Zn-Mg alloy. SEM images of worn-out surface shows scratching, ploughing, delaminated layer and plastic deformation.

Keywords: Al-Zn-Mg alloy; Stir casting; Wear rate; SEM image; Graphite; Microstructure

1. Introduction

Essential part of any engineering industry is selection of material for a specific application to meet as per suitable engineer design. In general, higher strength of material will have higher density[1)]. Al alloy have better physical and mechanical behaviour upon loading hence, which will suit the automotive application and exhibit poor adhesive wear[2)]. The structure and reinforcement properties of metal will influence in control of mechanical characterization of MMCs[3)]. For automobile and aerospace application Al 7075 are preferred due to their high toughness and high tensile strength[4)]. For solid lubricant graphite is commonly used due to its properties like chemical inertness, low friction, film forming ability. Wear rate for aluminum-based composite may be reduced by adding suitable quantity of graphite particles[5)]. MMCs is one of the crucial materials in recent decades due to their significant consideration of low density, stiffness and higher strength[6)]. Hybrid composites are the group of composites which has two different types of metal particles were added as reinforcement in the matrix alloy and are used in satellite bearings, inertia navigation and laser reflectors[7)]. The fabrication process commonly adopted to produce MMCs are powder metallurgy, squeeze casting and stir casting which is extensively used due to cost effective, flexible and simple in operation[8-10)]. Different method can be used to prepare MMCs like squeeze casting, compo casting, spray deposition and stir casting[11,12)]. Improved wear results are obtained for aluminium alloy produced by using FSP[13)]. B_4C particles in AA2024 alloy improves the mechanical property and maximum tensile properties was observed for 4 wt.% of boron carbide[14,15)].

MMCs have achieved better mechanical properties over ordinary material and compounds which will have a potential constructive material for automotive and marine applications[16,17)]. Wear properties for Al7075 alloy reinforced with Al_2O_3/SiC is understood by using L_9 standard orthogonal array[18-20)]. Composite materials are produced by mixing whiskers, fibers and metal particles, ceramic to achieve the enhanced features of conventional materials[21)]. Effort has been made on AW2024/B_4C composite by stir casting route and determined the influence of process parameter on tensile strength and hardness of formed composite[22]. Work has been reported on effect of SiC particles on Al7075 alloy on tribological properties[23]. Work on nickel alloy base hybrid composite[24] was done on thermal properties, microstructure evaluation and wear characteristics through sand mould technique[25-30]. Experimental work has been reported on short carbon fiber reinforced composite on its characterization and analysis[31]. Tribological Behavior[32] of Organic Anti-Wear and Friction Reducing Additive of ZDDP under Sliding Condition: Synergism and Antagonism Effect was done and reported the outcomes[33]. Effect of carbon fiber Content on the tensile, flexural, and thermal properties of the Sisal/PMMA Composites was reported in their research outcomes[34]. Mechanical behaviour and fractured surface analysis was done and reported in their finding that the hybrid composite under gone ductile type of fracture[35]. Research work has been done on Al-Cu based composite through stir casting method. Experimental hardness was predicted and validated through linear regression and machine learning method[36]. Investigation on friction stir welding[37] reinforced with nanoparticle joint has been done to know the microstructural and macrostructural review and also comparative analysis followed by mechanical characteristics[38]. Influence of Al_2O_3 and TiO_2 nanoparticles on AA6061-T6 joint for mechanical and microstructural characteristics of FSW nanocomposites has been done by volume fraction. The respective wear and mechanical properties were correlated with the fractography and microstructure study[39-40]. AA6061-T6/ Al_2O_3 reinforced composite with friction stir welding[41] are produced which results in reduction in granular size. Tensile strength, wear properties are notably increased[42-43]. By considering above fact for the present investigation work Al-Zn-Mg alloy is chosen as matrix and SiC and Gr. as reinforcements. Thus, the aim of this current work is to deal with the effect of reinforcements on Al-Zn-Mg alloy on surface examination and wear study of Al-Zn-Mg/SiC/Gr. hybrid composites.

2. Material selection and fabrication method

2.1 Matrix Material selection

In the existent investigation, the hypo eutectic Al-Zn-Mg alloy ingot as received from the Fenfe Metallurgical, Bangalore is selected as matrix material. Zinc and its alloy are commonly employed in rail cars, tennis racket, construction of aircraft due to its superior strength, higher wear resistance, greater stiffness and dimensional stability. Table 1 demonstrate, the elemental composition of Al-Zn-Mg alloy as supplied by the supplier.

Table 1. Al-Zn-Mg alloy chemical composition

Element	Wt. %
Al	91.2
Zn	3.25
Mg	1.9
Cr	0.8
Cu	1.8
Mn	0.4
Fe	0.5
Ti	0.15
Si	0.5

2.2 Selection of reinforcement material

Greatest improvement on wear characteristic is due to the influence of silicon carbide particles in Al alloy. Silicon carbide which acts as obstacles to the motion of indentation thereby achieving the improved hardness in Al alloy composite material[13]. By adding graphite (Gr.) particles in Al alloy, coefficient of friction is observed to be declined however, it will enhance the resistance to wear in hybrid composite[8]. Average particle size of SiC and Gr. are 156µm and 165µm. SEM images and photograph of (a) SiC and (b) Graphite particle reinforcement is represented in Fig. 1 and Fig. 2.

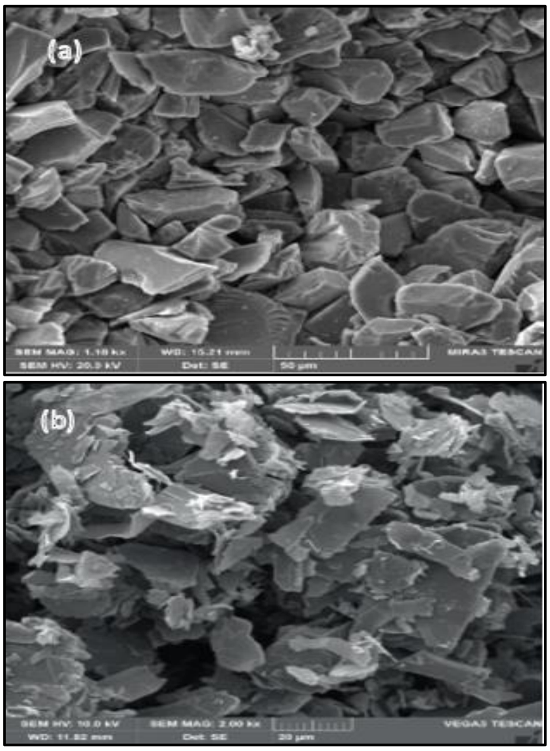


Fig. 1: SEM images of (a) SiC and (b) Graphite particles.

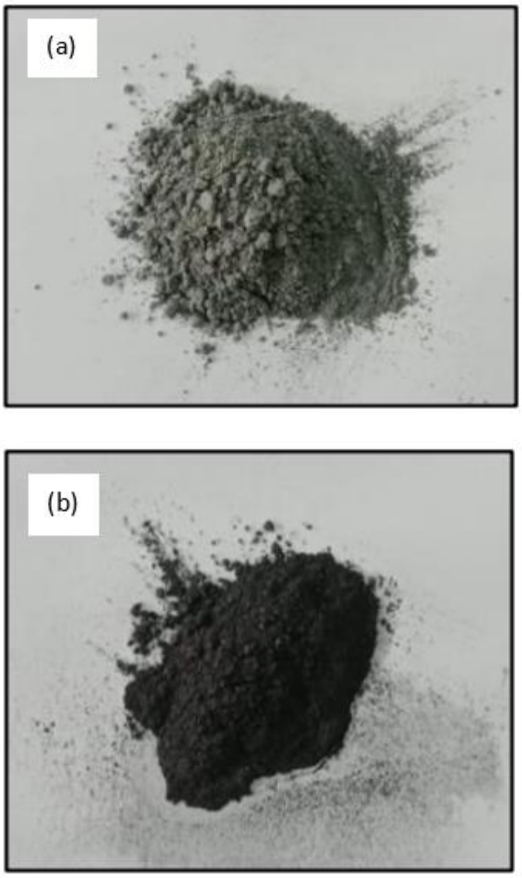


Fig. 2: Photograph of (a) SiC and (b) Graphite particles.

2.3 Preparation of hybrid composites

Hybrid composites were fabricated as per the composition in wt.% as represented in Table 2. Formation of Al-Zn-Mg/SiC/Gr. hybrid composites are done by choosing split die (graphite material) having dimension of 26mm diameter and 300mm length. To eliminate the slag and oil contamination, pre-heating was done at the inner surface area of the split die at 250°C. Coating material (14ESS) was used at the inner surface area of the split die which act as protective grade to absorb moisture and produce smooth surface.

Electric furnace which is prepared by using cast iron material is preheated to 650°C and aluminium matrix alloy along with reinforcements were melted in the electric furnace. The electric furnace was heated up to 1500°C and Al-Zn-Mg alloy is melted in the graphite crucible. The reinforcements which was pre-heated at 750°C to eliminate the impurity present on the particle surface and to promote the wettability. Mechanical stirrer (stainless steel) was adopted to obtain homogenous mixing of hybrid composite by adding graphite reinforcement from 1 wt.% to 7 wt.% in step of 2 wt.% for constant 2 wt.% of silicon carbide.

Degassing tablet (1/4th portion) was introduced into the mixture to takeout the entrapped gas and other contamination. The slag formed on the surface of the molten metal is removed out by using skimmer tool and the hybrid composite is poured into the split die which is pre heated and followed to natural air cooling for solidification. Once the split die attains ambient temperature the cast specimen is removed out from the split die. As per ASTM E3 and G99-17 standards microstructure and wear test specimens were prepared through conventional lathe machine tool as represented in Fig.3.

Table 2. Different test specimens prepared as per the chemical composition.

Test Specimen	Chemical composition (wt.%)		
	Al-Zn-Mg alloy	**Silicon Carbide (SiC)**	**Graphite (Gr)**
TS1	100	-	-
TS2	97	2	1
TS3	95	2	3
TS4	93	2	5
TS5	91	2	7

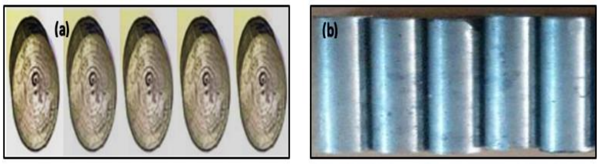


Fig. 3: Photograph of (a) Microstructure specimen and (b) Wear specimen.

3. Testing of prepared hybrid composite material

Prepared hybrid composites which are machined as per the ASTM standard size for microstructure and wear rate study. Microstructure inspection was made by using optical microscope (Model: Lx-047) as represented in Fig.4 (a) to understand how the dispersion of reinforcements particles in the Al-Zn-Mg alloy. Wear test was conducted on a pin-on-disc wear testing equipment (NTS-POD-V01) as presented in Fig. 4 (b) by varying speed and load at constant sliding velocity according to ASTM G99-17 standard. The volume loss technique was adopted to determine the rate of wear from Equation (1-3). Wear rate was obtained for prepared hybrid composite specimen and plotted graph between wear rate v/s speed and also for wear rate v/s load for five different samples. The Volume loss and wear rate was then found out by using the formula:

- Cross sectional area $A = \pi r^2$ (mm^2) ………. (1)

Where Radius of test specimen (r) in mm.

- Volume loss V= Area x Height loss (mm^3) …. (2)

Where Height loss (H) in mm.

- Wear rate = Volume loss / Sliding distance (mm^3/N-m) ……… (3)

Where sliding distance in m.

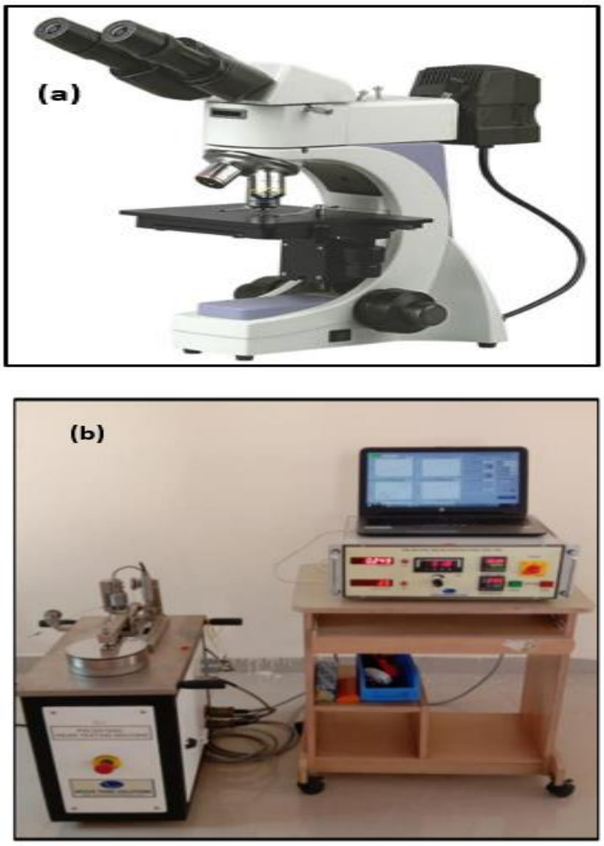


Fig. 4: Photograph of (a) Microscope and (b) Wear testing machine.

4. Results and discussion

4.1 Microstructure study

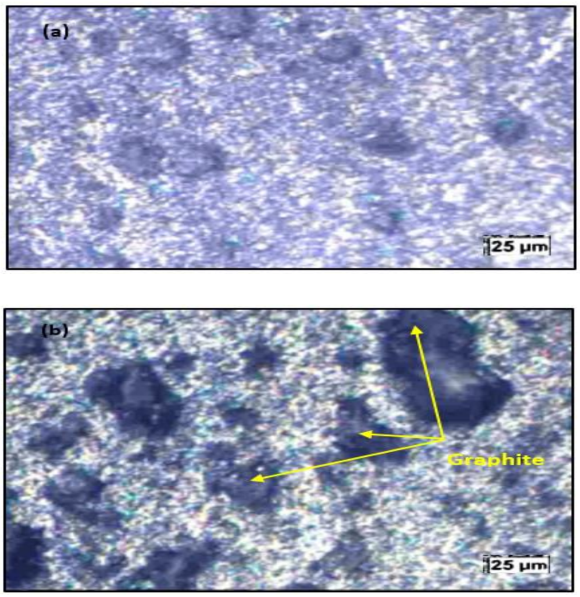


Fig. 5: Microstructure images for (a) Unreinforced Al-Zn-Mg matrix, (b) Al-Zn-Mg alloy/2 wt.% SiC/7 wt.% Gr. hybrid composite.

Figure 5 (a and b) demonstrate the microstructure photographs of Al-Zn-Mg alloy and Zn-Mg alloy-based hybrid (Al-Zn-Mg/SiC/Gr) hybrid composites. Figure 5 (a) shows the pure Al-Zn-Mg alloy having some porous which may occur during the production of Al7075 alloy. The chief factor for occurring porous in Al-Zn-Mg alloy is might be the insufficient of degasification and prolonged pouring time. Similar outcomes were found in their research findings by Kumaraswamy Jayappa et al [21]. Figure 5 (b) shows the incorporation of 2% of SiC and 7% of graphite particles in the soft Al-Zn-Mg alloy and uniform spreading of silicon carbide which is due to right stirring of reinforcements in the mixture. Due to the incorporation of reinforcements (SiC and Gr.) in the soft Al-Zn-Mg alloy results in improved hardness value and strength of hybrid composites. However, the ductility of fabricated hybrid composite is declined. The reason behind for decline in ductility is due to the several factors which includes splitting of reinforcements particle, conductivity of matrix material, restriction on grain boundary, thermal expansion of reinforcement, pouring temperature of the mixture into the die etc. during fabrication of the hybrid composite. Bond quality between matrix alloy and reinforcements is observed to be good which is maybe due to right stirring of the mixture and addition of pre-heated reinforcements into the vortex of the mixture. Figure 6 (a-b) shows the EDX spectrum image of Al-Zn-Mg alloy showing the evidence of presence of Aluminum, Zinc, Magnesium and other basic elements within the selected area.

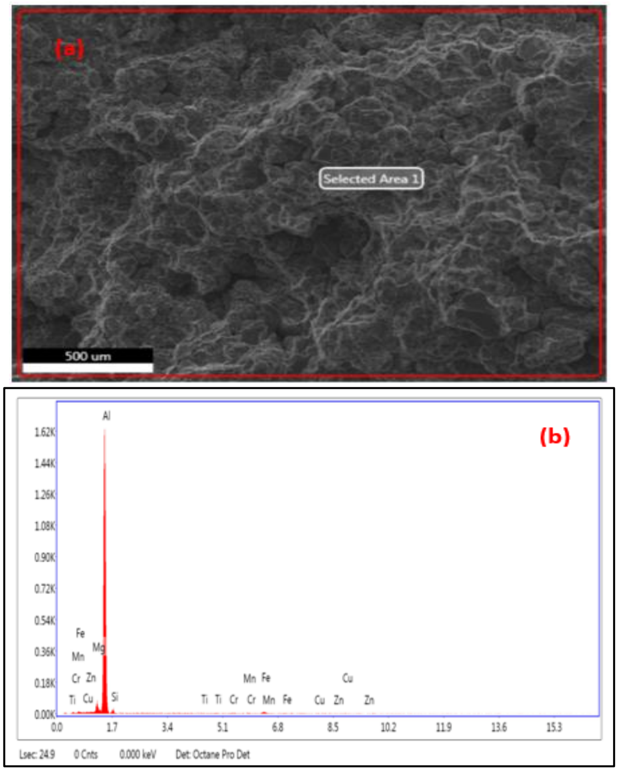


Fig. 6: (a) Selected arear for EDX spectrum(b) SEM-EDX image of Al-Zn-Mg alloy

4.2 Wear rate analysis

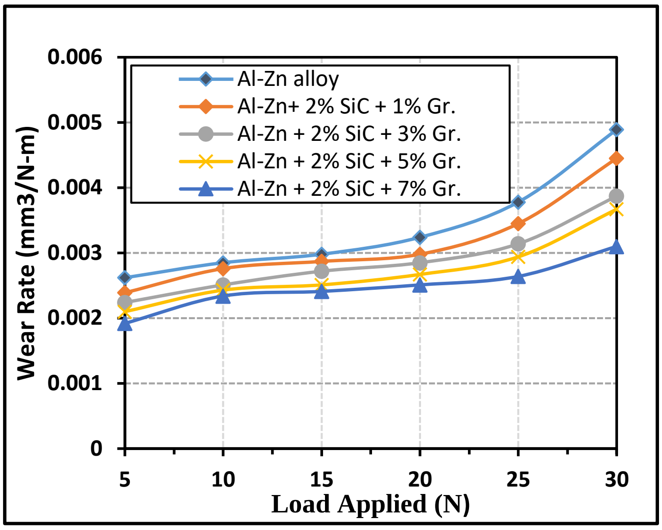


Fig. 7: Wear rate of Al-Zn-Mg/SiC/Gr. hybrid composite for different load applied.

Wear rate analysis has been exemplified in Fig. 7 showing increase in wear rate for all combination of produced hybrid composites when the applied load increases through pin and disc wear testing equipment. Reason for increase in wear rate is maybe due to the contact specimen surface area and normal load applied on to it. Further, frictional force between the specimen surface and the steel disc surface have contributed for increase in loss of material resulting for greater wear rate. Higher wear rate value was observed to be for Al-Zn-Mg alloy for all loading condition however, the lesser wear rate value was observed for Al-Zn-Mg/2% of SiC/7% of Gr. hybrid composite. On addition of reinforcements (SiC/Gr.) in soft Al-Zn-Mg alloy led to increase in hardness value for hybrid composites. Intensity of wear rate was observed to be decreased as hardness of hybrid composite increased. From the prior review study on composite material, reported that TiC particle reinforcement exhibits the stack to matrix resulting slowing the loss of material. Similar trend has been obtained on wear characteristic on AA6061-T6/Al_2O_3 reinforced nanocomposite using friction stir welding by Tanvir Singh and other[39-43].

Figure 8 illustrate the wear behavior[44] for Al-Zn-Mg/SiC/Gr. hybrid composites for different speed condition. It is clear that, as increase in speed from 250rpm to 1500rpm wear rate observed to be increase for all combination of hybrid composites. The impact of hard reinforcements in Al-Zn-Mg alloy have resulted lower wear rate as compared to Al-Zn-Mg alloy. It is seen that, wear rate is seen to be more for higher speed which is might be the increase in temperature, frictional force, lack of lubrication and normal force between test sample surface and rotating steel disc. Greater wear rate is observed to be Al-Zn-Mg alloy for all varying speed however, lesser wear rate is seen to be for Al-Zn-Mg/2% of SiC/7% of graphite hybrid composites. Upon adding reinforcement into the matrix material contributed in enhancing the hardness property of Al-Zn-Mg alloy conversely intensity of wear is lowered as hard particles will restrict the loss the material[44-46].

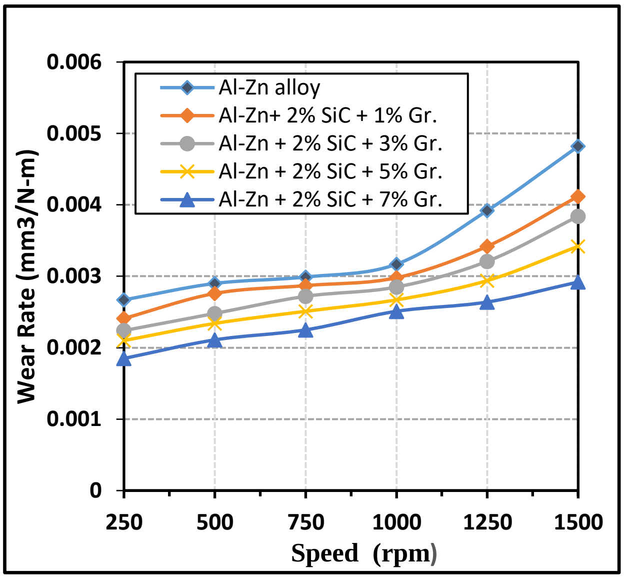
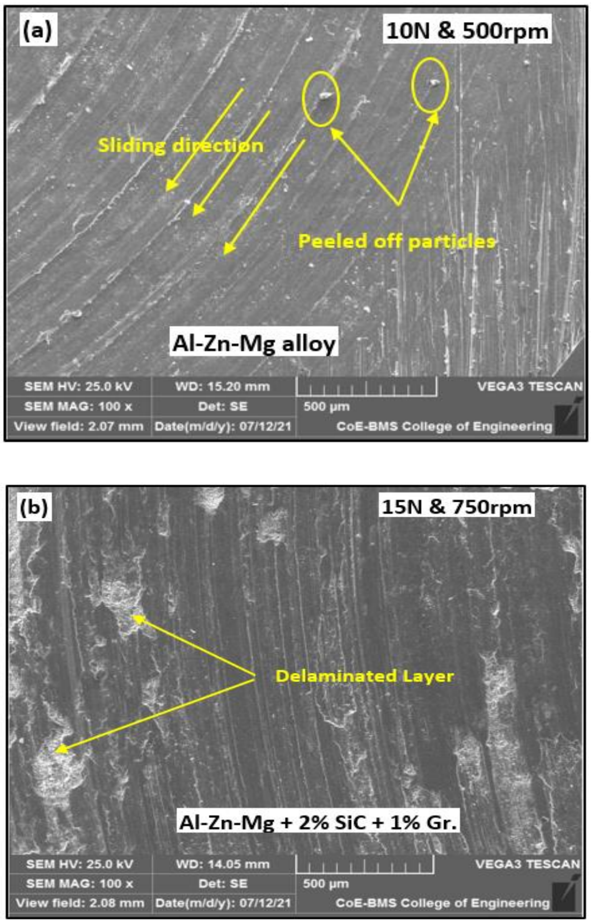


Fig. 8: Wear rate of Al-Zn-Mg/SiC/Gr. hybrid composites for different speed applied.

4.3 Study on worn-out surface



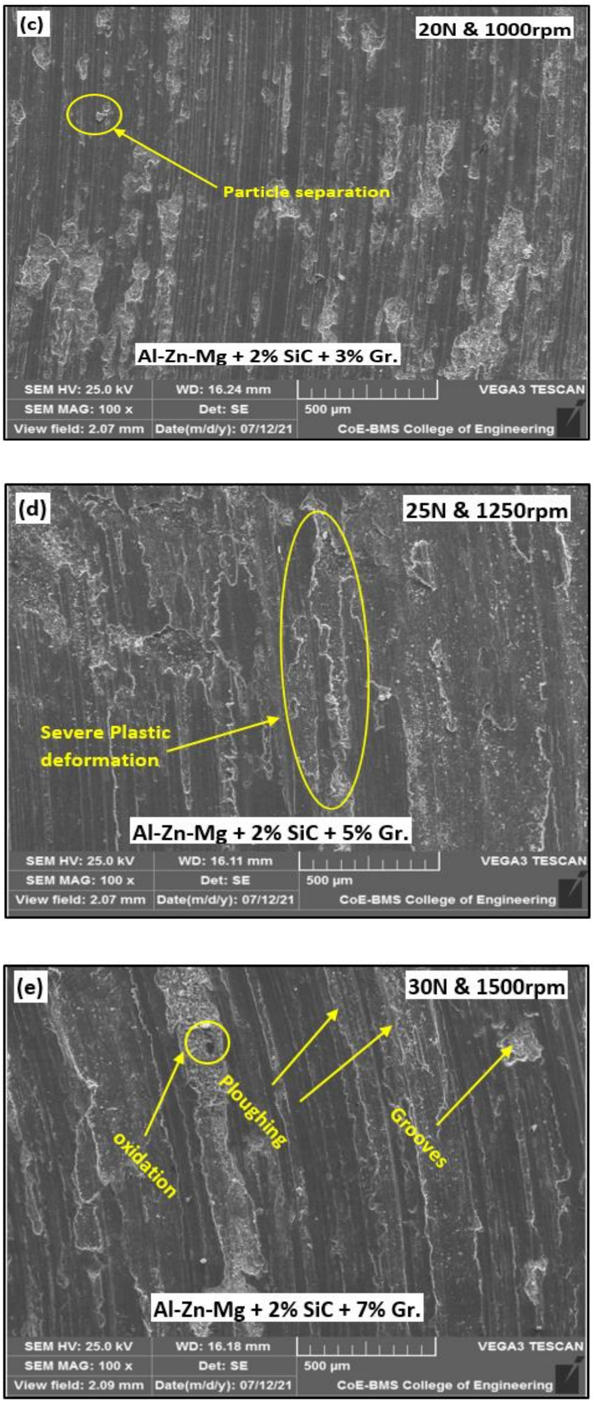


Fig. 9 (a-e): SEM photographs of worn-out surfaces for samples examined at v = 1.5m/sec

Damaged Al-Zn-Mg interface and its silicon carbide (SiC) and graphite particle of hybrid composites represent different class of wear for different wear condition. Aluminium material flow plastically along the sliding direction resulting smoother surface contributing lesser wear loss as presented in Figure 9 (a). Figure 9 (b-c) shows worn surface of Al-Zn-Mg hybrid composite, which is having some scratches, grooves, particle separation and delaminated layer resulting considerable loss of material. The material loss is might be other factors which includes hardness of reinforcements material, bonding between matrix and reinforcement, applied load on to the test specimen, temperature during the test etc. Figure 9 (d-e) represent worn-out surface for Al-Zn-Mg hybrid composites at different wear test condition. It is evidence that as reinforcement added to soft Al-Zn-Mg alloy matrix resistance to wear is enhanced successively decrease in coefficient of friction. Sever plastic deformation, ploughing, narrow grooves, scratches and oxidation was observed on the worm out surface the reason may be the pressure occur between the mating surface of specimen and steel disc, temperature, duration of test, successive loss of material layer, abrasive action. It is knowing fact that the examined hybrid composite material undergone permanent plastic deformation resulting ductile type of failure. Oxidation which occur on material surface undergo some chemical reaction due to the occurrence of atmospheric gases resulting failure of material by creating some internal cracks. Prior investigator in their research article reported that worn out surface of Al-Zn alloy reinforced with aluminum oxide (Al_2O_3) and E-glass shows ductile fracture [26-29].

Based on experimental examination on worn out surface on Al-Zn-Mg alloy, silicon carbide and graphite particles show the considerable wear loss to the Al-Zn-Mg alloy. The wear rate has been considerably decreased for prepared hybrid metal composites material when matched with the matrix alloy alone.

Further, wear resistance and hardness is enhanced with addition of reinforcements into the Al-Zn-Mg alloy subsequently the specimen surface roughness was observed to be increased. It is important to study worn-out surface of developed hybrid composites to know the behavior of hybrid metal matrix composites under different composition and different wear test condition[30-35].

5. Conclusions

In this investigation work on Al-Zn-Mg/SiC/Gr. hybrid composites were produced effectively through die casting method and following notable remarks are drawn as listed below:

- Sound hybrid composites are fabricated by varying silicon carbide (SiC) and graphite particle as reinforcements by conventional die casting technique.
- Microstructure of prepared hybrid composites presented the fairly uniform spreading of reinforcements in the matrix alloy by proper stirring.
- The wear rate was observed to be increased with increase in load applied and rotating speed of wear testing machine for all composition.
- For developed hybrid composite (Al-Zn-Mg/2% SiC/7% Gr.) material shows 57.83% decrease in

wear rate when matched with Al-Zn-Mg alloy. This trend is matched with the previous investigator Tanvir Singh and other in their research finding[39-43].

- It is evident from SEM-EDX image, shows the existence of aluminum, zinc, magnesium and other element authenticating that the selected matrix is Al-Zn-Mg alloy.
- SEM photographs of worn-out surface for different wear test condition shows the direct association between applied load, speed and wear rate.

Declaration statement

We authorize that there is no competing monetary support have been granted for this research work.

References

1) Anil K C, Kumaraswamy, Mahadeva Reddy, Mamatha K M, “Air Jet Erosion studies on Aluminum -Red Mud Composites using Taguchi Design.” EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 10(1), 130-138, (2023). doi.org/10.5109/6781059
2) Kumaraswamy, J, Vijaya Kumar and Purushotham, G. “A review on mechanical and wear properties of ASTM a 494 M grade nickel-based alloy metal matrix composites”, Materials Today: Proceedings, 37, pp 2027–2032. (2021) Doi: 10.1016/j.matpr.2020.07.499.
3) M. Sreenivasa Reddy, Dr. Soma V. Chetty and Dr. Sudheer Premkumar “Influence of reinforcements and heat treatment on Mechanical and Tribological properties of hybrid composite formed by Al 7075 reinforced with fly ash and EGlass short fibers” International Journal of Advanced Materials Science ISSN 2231- 1211 Volume 3, Number 3, pp. 267-274, (2012).
4) J. Kumaraswamy et al., "Thermal Analysis of Ni-Cu Alloy Nanocomposites Processed by Sand Mold Casting," Advances in Materials Science and Engineering, vol. 2022, Article ID 2530707, 11 pages, 2022. DOI: 10.1155/2022/2530707
5) Jayappa, K., Kumar, V. and Purushotham, G. “Effect of reinforcements on mechanical properties of nickel alloy hybrid metal matrix composites processed by sand mold technique”, Applied Science and Engineering Progress, 14(1), pp. 44–51. (2021). DOI: 10.14416/j.asep.2020.11.001.
6) Sharan kumar, Akash, Anil K C, Kumaraswamy J, “Solid Particle Erosion Performance of Multi-layered Carbide Coatings (WC-SiC-Cr3C_2)” EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 10(2) pp813-819 (2023). doi.org/10.5109/6792833.
7) Uvaraja V C and Natarajan N “Optimization of Friction and Wear Behaviour in Hybrid Metal Matrix Composites Using Taguchi Technique” Journal of Minerals and Materials Characterization and Engineering 11, pp. 757–68, (2012).
8) T Senthilvelan, S Gopalakannan, S Vishnuvarthan and K Keerthivaran “Fabrication and Characterization of SiC, Al_2O_3 and B_4C Reinforced Al-Zn-Mg-Cu Alloy (AA 7075) Metal Matrix Composites: A Study” Advanced Materials Research Vols. 622-623, pp. 1295-1299, (2013).
9) A. Baradeswaran and A. Elaya Perumal“Influence of B4C on the tribological and mechanical properties of Al 7075–B_4C composites” Composites: Part B, pp. 146–152, (2013).
10) A. Baradeswaran, S.C. Vettivel, A. Elaya Perumal, N. Selvakumar, R. Franklin Issac “Experimental investigation on mechanical behaviour, modelling and optimization of wear parameters of B_4C and graphite reinforced aluminium hybrid composites” Materials and Design, 63, pp. 620–632, (2014).
11) M. Sreenivasa Reddy, Dr. Soma V Chetty, Dr. Sudheer Premkumar and Reddappa H N, “Influence of reinforcements and heat treatment on mechanical and wear properties of Al7075 based hybrid composites” Procedia Materials Science 5, pp. 508 – 516, (2014).
12) P. Subramanya Reddy, R. Kesavan, B. Vijaya Ramnath “Investigation of Mechanical Properties of Aluminium 6061-Silicon Carbide, Boron Carbide Metal Matrix Composite”, Silicon, (2018).
13) M. Kumar, G. Balaji & A. Megalingam Murugan “Experimental Investigations on Friction and Wear Behavior and Parameters Optimization of Al7075-T6 Alloy and Al7075/Alumina/ Graphite/ Redmud Hybrid Metal Matrix Composite” Using Grey Relational Analysis” International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) ISSN (P): 2249-6890; ISSN (E): 2249-8001 Vol. 8, Special Issue 7, pp. 1104-1118, (2018).
14) Balasubramani Subramaniam, Balaji Natarajan, Balasubramanian Kaliyaperumal, and Samson Jerold Samuel Chelladurai, “Investigation on mechanical properties of aluminium 7075 - boron carbide - coconut shell fly ash reinforced hybrid metal matrix composites” Overseas Foundry Vol. 15, No 6, pp. 449-456, (2018).
15) Thella Babu Rao “An experimental investigation on mechanical and wear properties of Al7075/SiCp composites: effect of SiC content and particle size” Journal of Tribology ASME, (2017).
16) L. Natrayan and M. Senthil Kumar “Optimization of wear behaviour on AA6061/Al_2O_3/SiC metal matrix composite using squeeze casting technique – Statistical analysis, Materials Today: Proceedings, pp. 1-5, (2017).
17) Abhijit Bhowmik, Dipankar Dey & Ajay Biswas “Comparative Study of Microstructure, Physical and Mechanical Characterization of SiC/TiB_2 Reinforced Aluminium Matrix Composite”, Silicon, (2020).

18) J. Kumaraswamy, Anil K C, Mahadeva Reddy, "Influence of Particulates on Microstructure, Mechanical and Fractured Behaviour on Al-7075 Alloy composite by FEA", Australian Journal of Mechanical Engineering, 2023
19) Girish G. and Anandakrishnan V, "Tribological behaviour of recursive friction stir processed AA7075, Industrial Lubrication and Tribology, ISSN 0036-8792, (2020).
20) L. Bharath and Suneelkumar N. Kulkarni, "Evaluation of UTS and compression strength of Al2024/B_4C composites by experimental method and validation through regression analysis", Materials Today: Proceedings, (2021).
21) J. Kumaraswamy, V. Kumar and G. Purushotham, "Thermal analysis of nickel alloy/Al_2O_3/TiO_2 hybrid metal matrix composite in automotive engine exhaust valve using FEA method", Journal of Thermal Engineering, Vol. 7, No. 3, March, 2021, pp. 415-428. https://dx.doi.org/10.18186/thermal.882965.
22) L. Bharath, M. Sreenivasa Reddy, H.N. Girisha, G. Balakumar, "Influence of process parameters on tensile strength and hardness of AW2024/B_4C composite using Taguchi's technique" Materials Today: Proceedings, (2021).
23) Mulugundam Siva Surya and G. Prasanthi, "Effect of SiC Weight Percentage on Tribological Characteristics of Al7075/SiC Composites", silicon, springer, (2021).
24) Muhammad Miqdad, Anne Zulfia Syahrial, "Effect of Nano Al2O3 Addition and T6 Heat Treatment on Characteristics of AA 7075 / Al_2O_3 Composite Fabricated by Squeeze Casting Method for Ballistic Application" EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 9(2) pp531-537 (2022). doi.org/10.5109/4794184.
25) J. Kumaraswamy, Vijaya Kumar & G. Purushotham "Evaluation of the microstructure and thermal properties of (ASTM A 494 M grade) nickel alloy hybrid metal matrix composites processed by sand mold casting", International Journal of Ambient Energy, 43 (1), 4899-4908.
26) J Kumaraswamy, Anil K. C., Vidyasagar Shetty & C Shashishekar, "Wear behaviour of the Ni-Cu alloy hybrid composites processed by sand mould casting" Advances in Materials and Processing Technologies, Vol. 9, No. 2, pp. 351–367, (2023).
27) Harish R S, Sreenivasa Reddy M, Kumaraswamy J "Wear Characterization of Al 7075 Alloy Hybrid Composites", Metallurgical and Materials Engineering, Vol 28 (2), pp. 291-303, (2022).
28) Kumaraswamy Jayappa, Kyathasandra Chikkanna Anil and Zulfiqar A. Khan,"Enhancing wear resistance in Al-7075 composites through conventional mixing and casting techniques", Journal of Materials Research and Technology, (2023).
29) Kumaraswamy, J., Anil, K.C., Canbay, C.A., N D Shiva Kumar. Electro-Whirling Stir Casting: a Novel Approach for Fabricating Al7075/SiC MMCs with Enhanced Thermal Characteristics. Silicon (2023). https://doi.org/10.1007/s12633-023-02678-y
30) J. Kumaraswamy, Anil K C, T R Veena, G. Purushotham, Sunil Kumar K, "Investigating the Mechanical Properties of Al 7075 Alloy for Automotive Applications: Synthesis and Analysis" in Scopus indexed EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 10(3), pp.1286-1295, (2023). doi:10.5109/7151674
31) Mr. Dilip Choudhari, Dr. Vyasraj Kakhandki, "Characterization and Analysis of Mechanical Properties of Short Carbon Fiber Reinforced Polyamide66 Composites" EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 8(4), pp768-776, (2021). doi.org/10.5109/4742120.
32) Anthony Chukwunonso Opia, Mohd Kamei Abdul Hamid, Samion, Syahrullail, Charles A. N. Johnson, Abu Bakar Rahim, Mohammed B. Abdulrahman, "Nano-Particles Additives as a Promising Trend in Tribology: A Review on their Fundamentals and Mechanisms on Friction and Wear Reduction" EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 8(4), pp777-798, (2021). doi.org/10.5109/ 4742121.
33) Anthony Chukwunonso Opia1, Mohd Kameil Abdul Hamid, Samion Syahrullail, Audu Ibrahim Ali, Charles N. Johnson, Ibham Veza, Mazali Izhari Izmi, Che Daud Zul Hilmi, Abu Bakar Abd Rahim, "Tribological Behavior of Organic Anti-Wear and Friction Reducing Additive of ZDDP under Sliding Condition: Synergism and Antagonism Effect" EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 9(2) pp246-253 (2022). doi.org/10.5109/4793628.
34) H. Sosiati, N.D.M. Yuniar, D. Saputra, and S. Hamdan, "The Influence of Carbon Fiber Content on the Tensile, Flexural, and Thermal Properties of the Sisal/PMMA Composites" EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 9(1) pp.32-40 (2022). doi.org/10.5109/4774214.
35) Anil, K.C., Kumarswamy, J., Reddy, M., Prakash, B., "Mechanical Behaviour and Fractured Surface Analysis of Bauxite Residue & Graphite Reinforced Aluminium Hybrid Composites", Frattura ed Integrità Strutturale, 16 (62) (2022) 168-179. DOI: 10.3221/IGF-ESIS.62.12
36) L. Bharath, J. Kumaraswamy, T. V. Manjunath and Suneel Kumar N. Kulkarni "Evaluation of microstructure and prediction of hardness of Al–Cu based composites by using artificial neural network and linear regression through machine learning technique" SPRINGER Multiscale and Multidisciplinary Modeling, Experiments and Design,

(2024) DOI: 10.1007/s41939-024-00525-0.

37) Tanvir Singh "Comparative Analysis of Microstructural and Mechanical Characteristics of Reinforced FSW Welds" book editor, (2024) DOI: 10.1002/9781394169467.ch12.
38) Tanvir Singh "Nanoparticles reinforced joints produced using friction stir welding: a review" Engineering Research Express, 5, 022001, (2023) DOI: 10.1088/2631-8695/accb28.
39) Tanvir Singh, S. K. Tiwari and D. K. Shukla, "Effects of Al_2O_3 nanoparticles volume fractions on microstructural and mechanical characteristics of friction stir welded nanocomposites" 6, (2020), pp. 76-84, DOI: 0.1080/20550324.2020.1776504.
40) Tanvir Singh, S. K. Tiwari and D. K. Shukla, "Influence of Nanoparticle Addition (TiO_2) on Microstructural Evolution and Mechanical Properties of Friction Stir Welded AA6061-T6 Joints" (2020), pp. 219-228, DOI: 10.1007/978-981-15-5519-0_18.
41) Tanvir Singh, S. K. Tiwari and D. K. Shukla, "Effect of nano-sized particles on grain structure and mechanical behavior of friction stir welded Al-nanocomposites" 234, Issue 2, (2019), DOI: 10.1177/1464420719885.
42) Tanvir Singh, S. K. Tiwari and D. K. Shukla, Production of AA6061-T6/Al_2O_3 reinforced nanocomposite using friction stir welding" 1, 025052, (2019), DOI: 10.1088/2631-8695/ab5e27.
43) Tanvir Singh, S. K. Tiwari and D. K. Shukla, "Friction-stir welding of AA6061-T6: The effects of Al_2O_3 nano-particles addition" 1, 100005, (2019), DOI: 10.1016/j.rinma.2019.100005.
44) Antony, A. Godwin, V. Vijayan, S. Saravanan, Saravanan Baskar, and Marappan Loganathan. "Analysis of wear behaviour of aluminium composite with silicon carbide and titanium reinforcement." Int. J. Mech. Eng. Technol. 9 (2018), pp. 681-691.
45) Karikalan, L., M. Chandrasekran, S. Ramasubramanian, and S. Baskar. "Hybridization of composites using natural and synthetic fibers for automotive application." International Journal of Scientific Research in Science and Technology 7 (2017), pp. 916-920.
46) Santhanam, V., R. Dhanaraj, M. Chandrasekaran, N. Venkateshwaran, and S. Baskar. "Experimental investigation on the mechanical properties of woven hybrid fiber reinforced epoxy composite." Materials Today: Proceedings 37 (2021), pp. 1850-1853.