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RESEARCH

Effect of Ageing on Dry Sliding Wear Behaviour of Al-MMC for Disc Brake

B.M. Viswanatha[a], M.P. Kumar[b], S. Basavarajappa[c], T.S. Kiran[a]

[a] *Kalpataru Institute of Technology-Tiptur, India.*
[b] *Bapuji Institute of Engineering and Technology-Davanagere, India.*
[c] *University BDT College of Engineering, Davangere, India.*

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Corresponding author:

B.M. Viswanatha
Kalpataru Institute of Technology-Tiptur, India
E-mail: vishwanathabm@rediffmail.com

A B S T R A C T

The present investigation shows the wear behaviour of as-cast and heat treated, A356 aluminium alloy reinforced with SiC and Graphite particles subjected to different ageing durations. The liquid metallurgy technique was used to fabricate the composites. The reinforcement content was varied from 0 to 9 % by weight in steps of 3 % of SiC_p and fixed quantity of 3 % by weight of graphite particles. The castings were machined to ASTM standard and T6 heat treatment was carried out at 540 ^{0}C ± 5 for 12 hrs and quenched at 60 ^{0}C in water. All the specimens were artificially aged at different durations of 3, 6, 9 and 12 hrs at a temperature of 155 ^{0}C ± 5. The wear tests were performed for alloy and composites by varying load, speed and sliding distance for both aged and as-cast conditions by using a pin on disc wear testing machine. The results reveal that the wear rate of composites was less than that of non-reinforced alloy. It was found that the wear resistances of A356-9 SiC_p-3 Gr composites aged at 9 hrs showed better wear resistance compared with other samples. However in both aged and as-cast materials, the wear rate was increased with the increase in load, speed and sliding distance. The tested samples were examined and analyzed using Scanning Electron Microscope (SEM) and X-ray energy-dispersive spectrometry (EDX).

1. INTRODUCTION

Metal Matrix Composites are most preferred among the fastest growing families of new materials and have potential properties. There is a continuous development and usage of particulate composites in the making of appliances such as brake rotors, engine parts, cylinder liners, etc., which are regarded as high performance components, due to their superior mechanical and tribological properties [1,2]. In addition to mechanical and physical properties the particulate composites also exhibit isotropic properties [3-5]. Most common Metal Matrix Composites (MMCs) are based on aluminium (Al), magnesium (Mg) and titanium (Ti) alloys reinforced with silicon carbide particles (SiC_p), alumina (Al_2O_3), carbon or graphite particles (Gr) [6].

Aluminium alloys are majorly used in automotive and aerospace industries because of their high specific strength, modulus and high thermal conductivity. These materials display poor tribological properties that lead to seizure under adverse conditions. Hence there was a need to develop new materials with greater resistance to wear and good tribological properties which ultimately led to the development of aluminium metal matrix composites [7-10]. A good number of works have been carried out on using SiC_p, Al_2O_3 and soft graphite particles as reinforcements individually. The wear resistance and mechanical properties of MMCs increased with the increase in the content of hard ceramic particles, but the machining property was decreased [3].

Tjong et al. [11] studied on the addition of a low volume fraction of SiC_p from 2-8 vol. % to Al-Silicon alloys. He observed that the significant increase in wear resistance with increase in content of reinforcement. Miyajima et al. [12] investigated the different volume fraction of reinforcements such as SiC whisker of 5-29 %, Al_2O_3 fibres of 3-26 %, and SiC particles of 2-10 % with Al-2024 matrix materials and investigated the dry sliding wear behaviour by using pin-on-disk apparatus. Improvement in wear behaviour was observed with reinforcement by particles. Pramila Bai et al. [13] observed that wear resistance improved with the addition of SiC_p when compared with non-reinforced aluminium alloy. The increase of SiC_p from 15 to 25 wt. % does not change any mechanisms and only quantitative improvement was observed. Ravikiran et al. [14] carried out the effect of sliding speed on wear behaviour of A356 aluminium reinforced with 30 wt. % SiC_p. The wear rate reduced continuously with increasing speed.

Sahin. [15] studied the effect of 10 wt. % of SiC_p with average particle size of 100 µm reinforced with Al 2014 alloy using orthogonal arrays and analysis of variance of the tribological behaviour. The results indicated that, the reinforcement exhibited greater effect on abrasive wear followed by applied load, whereas sliding distance had the least effect.

Straffelini et al. [16] studied the friction and wear behaviour of two aluminium metal matrix composites reinforced with 10 and 20 vol. % of SiC_p for dry sliding against a semi-metallic friction material. For an applied load of lower than 200 N, friction coefficient was found to be 0.45. Zhang et al. [17] in his study found out that the Al-MMCs containing small sized SiC_p were not suitable for fabrication of the brake rotor and drums. Friction parameter strongly depends on the size of SiC_p. The small sized reinforcements used, could be easily pulled out from the matrix material, which would then form a thin tribofilm and abrades the brake material, whereas, the large sized reinforcements form a thick tribofilm that protects the brake material from abrasion and reduces the specific wear rate. Constantin et al. [18] worked on the dry sliding wear of aluminium matrix composites reinforced with different volume fraction of particles. Even for small volume fraction of reinforcement, increase in the wear resistance of the composites was observed. Bindumadavan et al. [19] reported that the porosity content increased with the increase in the reinforcement percentage of SiC_p. However, for lower content of SiC_p, porosity interaction was greater when compared with higher SiC_p content.

Surappa et al. [20] investigated the wear rate of cast aluminium and Al-Si alloys containing up to 5 wt. % of Al_2O_3 particles with 100 µm size under the conditions of adhesive and abrasive wear. The wear rate of Al-Si alloys decreased with the addition of Al_2O_3 particles. Kumar et al. [21] reported that the wear resistance increased with the increase in garnet content in Zinc-aluminium alloy. Akhlaghi et al. [23] found that the lower addition of graphite 2 to 5 wt. %, showed higher wear resistance compared with higher content of graphite addition 5 to 20 wt. %. Increasing the graphite content in matrix material formed porosity cracks and decreased the mechanical properties, resulting in delamination.

The studies on heat treatment of composites at different ageing durations showed that, the material behaved relatively softer with good formability which improved the mechanical and wear resistance of the composites [24,25]. Liu et al. [26] studied on wear resistance of laser processed Al-Si-graphite composites aged at different temperatures. The wear resistance of laser processed composites showed better results than as-cast matrix material. Yang et al. [27] studied the tribological properties of A356 alloy/Gr with varying graphite content of 2-8 wt % in steps of 2 %. The result showed that 4 or 6 wt. % of graphite exhibited lowest wear compared to the 8 wt. %. Gomez et al. [28] studied the influence of heat treatment on wear resistance of A60692/SiC_{25p} composite material. It was found that, the heat treated MMCs at T6-7 hrs produced maximum hardness and showed good wear resistance. Ames and Alpas [29] reported that, graphite acted as solid lubricant which effectively improved the tribological properties of samples under dry sliding conditions.

Same effort has been carried out for graphite reinforced matrix material which increased the machining property and loss in mechanical properties. Addition of graphite in Al/SiC_p composites resulted in maintaining high mechanical, wear and machining properties [22,41,42]. Suresha and Sridhara [30] have reported that the wear behaviour of Al-SiC-Gr hybrid composites with same % reinforcement of SiC and Gr exhibited better wear resistance compared with composites reinforced with SiC_p alone. Riahi and Alpas [31] studied the sliding wear behaviour of A356-10%SiC-4%Gr and A356-5%Al_2O_3-3%Gr hybrid composites. The graphitic content composites were well suited to seizure resistance applications. Leng et al. [32] reported that the wear resistance of SiC/Gr/Al composites increased with the increase in graphite particle size. The tribolayers improved with the increase in the particle size of graphite, which in turn improved the wear resistance of the composite material.

Zhan et al. [33] studied on the reduction in wear and friction coefficient of Cu-SiC-Gr hybrid composites, compared with Cu–SiC composite material. They reported that the graphite microcrystal layers on worn surface helped to decrease the plastic deformation during adhesion wear. The addition of graphite particles had more effect in high temperature sliding wear applications. Babic et al. [34] studied the tribological behaviour of A356 aluminium alloy reinforced with SiC and Gr hybrid composites. Wear rate of hybrid composites was 0.375 times lower than the wear rate of base A356 alloy. Basavarajappa et al. [35] studied the wear behaviour of Al, Al-SiC_p and Al-SiC_p-Gr composites. The wear resistance increased with the addition of graphite to Al/SiC_p composites. Graphite layer smeared and formed a protective layer at the interface between the pin and counter face. The addition of graphite content in composite material reduced the hardness and coefficient of thermal expansion (CTE), but exhibited a stable wear rate [36]. These contradictory statements are proving out to be more challenging to work with, in the case of addition of graphite particles along with SiC_p reinforcement to aluminium metal matrix material.

Many research works have been carried out to find suitable replacements for traditional materials such as cast iron for brake components. All these efforts have been undertaken with the prime aim of utilization of favourable characteristics of Al-MMCs which results in weight reduction, higher mechanical and tribological properties. The same have been used in producing more efficient products, leading to considerable reduction in pollutant emissions and there by enhance the efficiency of the vehicle [37,38].

In view of the accounts given above, a study is being made by the author on wear behaviour of Al alloy reinforced with SiC and graphite particles, with different ageing durations along with heat treated composites and as-cast material.

2. EXPERIMENTAL PROCEDURES

2.1 Materials and processing

A356 is used as matrix material and its chemical composition is given in Table 1.

Table 1. Composition of A356 Aluminium alloy.

Elements	Cu	Mg	Mn	Si	Fe	Zn	Ti	Al
Wt. %	0.1	0.4	0.06	7.0	0.1	0.04	0.1	Bal.

This matrix material was chosen because it is having good castability, weldability and good resistance to corrosion. The composites were fabricated with SiC_p and Gr particles reinforced with A356 matrix material. The SiC particles content was varied from 0-9 % by weight in steps of 3 % and the average particle size of 25 μm and fixed quantity of 3 wt.% of graphite particle with average particle size of 44 μm. The liquid metallurgy method was used to fabricate the composites [7]. Among all the liquid state processes, stir-casting technology is considered to be the most potential method for engineering applications in terms of production capacity and cost efficiency [40].

The castings were machined to ASTM standard and T6 heat treatment was carried out. The under shown steps were followed during the ageing process.

Solution treatment was carried out at:

- 540 ^{0}C ± 5 ^{0}C for 12 hrs.
- Quenched at 60 ^{0}C in water.
- Stabilised at room temperature for 12 hrs.
- All the specimens were artificially aged at different durations of 3, 6, 9 and 12 hrs, at a temperature of 155 ^{0}C.

Table 2. Hardness values of composites.

Composition	As-Cast	3 hrs	6 hrs	9 hrs	12 hrs
A356	94	98	99	126	105
A356-3SiC_p-3Gr	99	103	111	142	120
A356-6SiC_p-3Gr	101	105	108	137	110
A356-9SiC_p-3Gr	102	108	121	144	124

2.2 Wear tests

Wear tests were carried out on Aluminium alloy and composites by varying applied load, sliding speed and sliding distance on both aged and as-cast conditions by using a pin on disc wear testing apparatus to investigate the dry sliding wear behavior as per ASTM G98-99 standard. The test was carried out by rubbing a testing specimen against rotating disc of EN-36 steel with hardness of 65 HRC. The surface roughness of both the specimens were about 0.3µm. Wear specimens of size, 10 mm diameter and height 30 mm, were prepared from cast samples by machining and polishing metallographically. The weight of specimens were measured on a single pan electronic weighing machine with accuracy of 0.0001 gm. After each test, the specimens were cleaned with acetone to remove the debris from the disc and then dried. The tests were conducted with varying applied load from 10 to 50 N at a sliding speed of 1.25, 2.5, 3.77, 5.03 and 6.28 m/s and with 1500, 3000, 4500, 6000 and 7500 m. The difference in the weights of the specimen between before and after the test, gives the weight loss of the specimen. All these experiments were conducted at room temperature.

3. RESULTS AND DISCUSSION

3.1 Effect of Sliding Distance on Wear Rate

The wear rate of as-cast and heat-treated hybrid composites was carried out on pin-on-disc technique to verify the wear resistance characteristics. The specimen aged at 9 hrs showed highest wear resistance in all the sliding distance conditions. The high wear resistance was attained at T6-9 hrs durations due to hardening precipitation in composites. The wear resistance decreased at T6-12 hrs due to lack of formation of hardening phase in composite. The as-cast experienced highest wear compared to the aged specimens. The wear rate is a function of sliding distance for A356-3Gr-(0, 3, 6 and 9) SiC_p of different ageing durations as shown in Fig. 1.

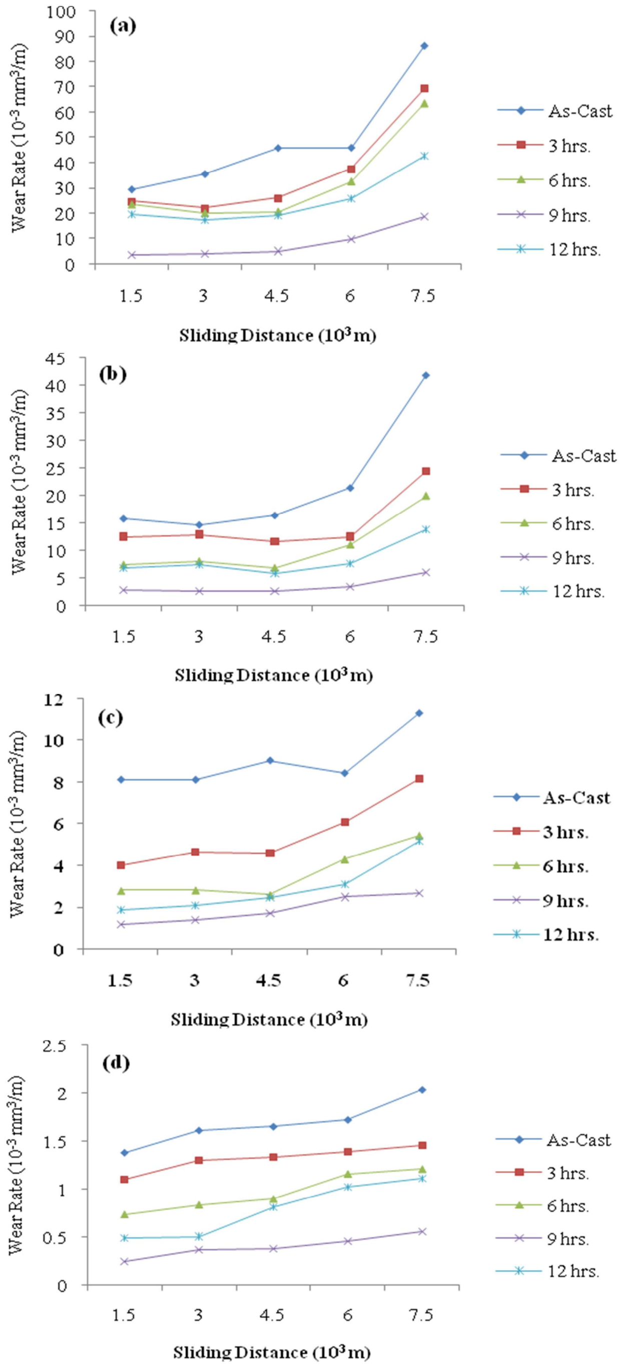
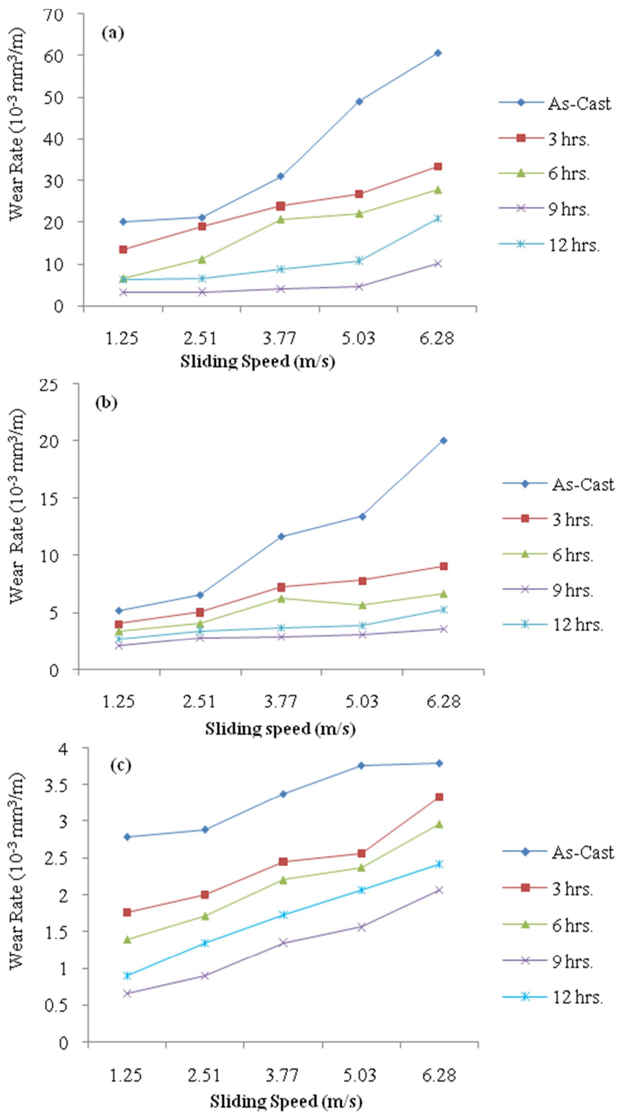


Fig. 1. Cumulative wear rate of as-cast and different ageing treated composites as a function of sliding distance at constant sliding speed of 3.77 m/s and applied load of 30 N. (a). A356 alloy (b). A356-3%SiC_p-3%Gr (c). A356-6%SiC_p-3%Gr (d). A356-9%SiC_p-3%Gr.

The wear rate increased linearly with the increase in sliding distance in the order of T6-3hr, T6-6hr and T6-12 hr heat treated composites at T6-9hr showed less wear rate in all the cases. This is due to improper precipitation to form good hardening characteristics in composite and alloy materials. From the Table 2, it is observed that the ageing durations increase with the increase in the hardness and also increase in wear resistance.

3.2 Effect of Sliding Speed on Wear Rate

Effect of sliding speed on the wear rate is shown in Fig. 2, in which the tests were conducted at constant load of 30 N and sliding distance of 4500 m. The wear rate is low for A356-9SiC$_p$-3Gr aged at T6-9 hrs compared with different aged materials. Sliding speed is increased with the increase in the wear rate.



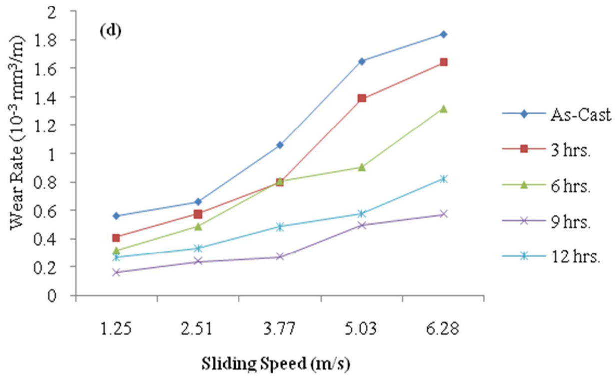


Fig. 2. Cumulative wear rate of as-cast and different ageing treated composites as a function of sliding speed at constant sliding distance of 4500 m and applied load of 30 N. (a). A356 alloy (b). A356-3%SiC$_p$-3%Gr (c). A356-6%SiC$_p$-3%Gr (d). A356-9%SiC$_p$-3%Gr.

The specimen at T6-12 hrs composite showed slight increase in wear, when compared with 9 hrs aged specimen. It produced intense noise and seizing was observed during tests at sliding speed from 3.7 m/s to 5.03 m/s for as-cast material. But smooth running was observed with no seizing for heat treated specimens. At lower sliding speed, the rate of formation of protective layer is slow on the pin surface. The damage has been experienced due to the fracture of SiC$_p$ in all the test cases up to 5.05 m/s and wear rate increases drastically beyond that. At lower speed the SiC$_p$ was fractured and removed. When the sliding speed increased, the quantity of fracture decreased. As the percentage of reinforcement increases, it increases the area of fracture,which decreses the wear rate of the composites.

3.3 Effect of Applied Load on Wear Rate

The variation of wear rate on applied load at a constant sliding speed of 3.77 m/s and sliding distance of 4500 m is shown in Fig. 3. When the applied load is low, the wear rate is small and it increases with the increasing of applied load. As load was increased from 10 to 30 N, wear was minimum, after 40 to 60 N, wear increases drastically for all the cases. For alloy, above 40 N load, seizure was observed. The composite A356-9SiC$_p$-3Gr, at T6-9 hrs aged specimen showed less wear rate without the effect of seizing. The increase in content of SiC$_p$ in A356-3%Gr composites showed better wear resistance due to increasing of hard reinforcement SiC$_p$. It acted as load bearing member which could enhance the higher load carrying capacity in composite material. The composites aged at T6-9 hrs showed better mobility of SiC_p in graphite reinforced composites which gives strength and enhances the wear resistance capacity of the composite material.

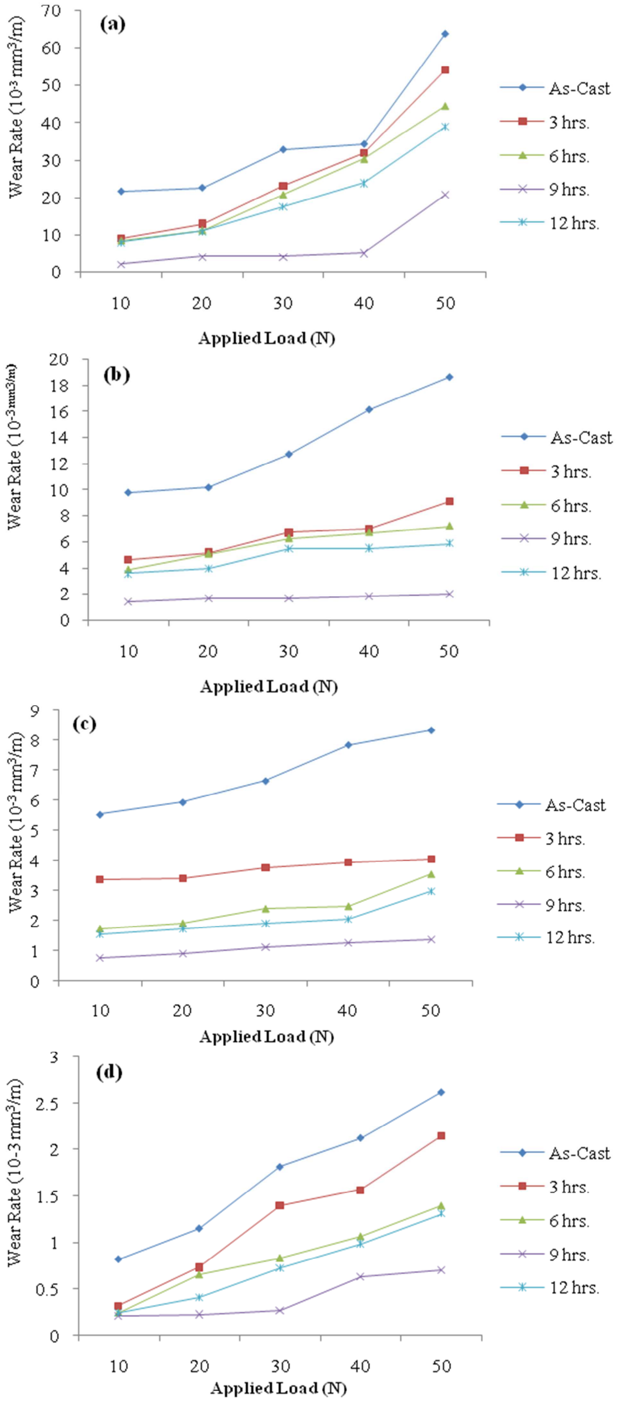


Fig. 3. Cumulative wear rate of as-cast and different ageing treated composites as a function of load when sliding speed of 3.77 m/s and sliding distance of 4500 m. (a). A356 alloy (b). A356-3%SiC_p-3%Gr (c). A356-6%SiC_p-3%Gr (d). A356-9%SiC_p-3%Gr.

4. WORN SURFACES

The SEM micrographs of the worn surface of as-cast and heat-treated hybrid composites specimens are shown in Fig. 4.

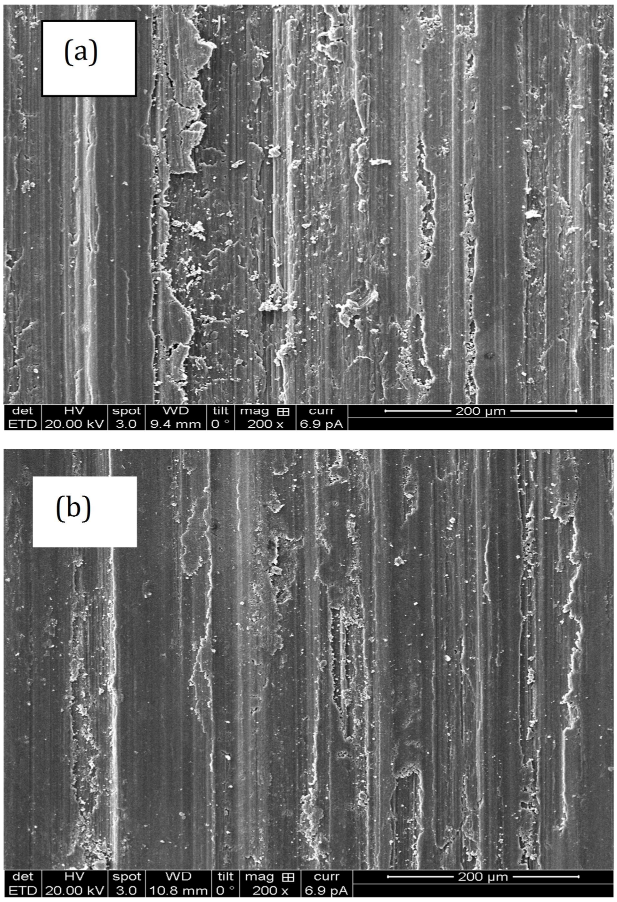


Fig. 4. SEM worn surfaces of (a) as-cast (b) heat-treated hybrid composites as a function of constant variables such as load (30 N), sliding speed (3.77 m/s) and sliding distance (4500 m).

The studies were carried out through SEM for the wear tracks of the composites. For convenience only few micrographs at the same load, speed and sliding distance with different materials were taken.

However the same explanation holds good for other as-cast and aged composite materials. The large amount of plastic deformation was observed on the surface of the as-cast shown in Fig. 4a. In composites and aged specimen, grooves were formed by the hard reinforcement particles SiC_p. The graphitic particle clearly showed interactions with SiC_p and also with surface of hard disc. It formed a lubricant layer. SiC_p projected out from the material and smooth running was observed as shown in Fig. 4b

(A356-3Gr-9SiC$_p$). EDX analysis was employed to find the elements of worn surfaces of A356-3Gr-9SiC$_p$ hybrid composite, as shown in Fig. 5. It is inferred that tribo-layers are combination of fractured SiC and graphite as well as iron oxides and some particles containing aluminium as confirmed by EDX analysis.

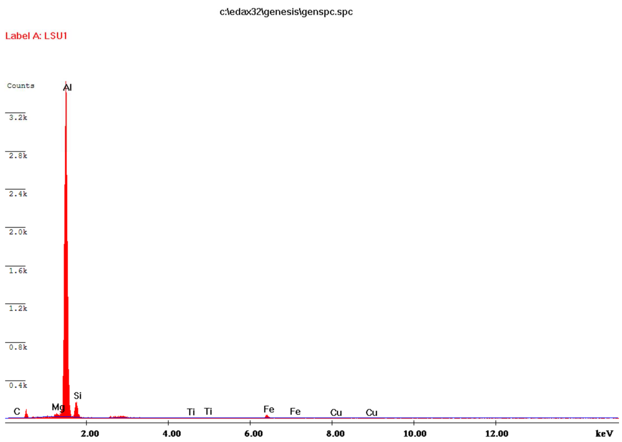


Fig. 5. EDX analysis of worn surface SiC/Gr/Al specimen.

5. DISCUSSIONS

Figures 1, 2 and 3 shows increase in applied load, sliding speed and sliding distance increases the wear rate of as-cast and composite materials.

The composite aged at T6-9 hrs of A356-3Gr-9SiC$_p$ material produces least wear rate. At T6-9 hrs aged in all the materials exhibit better wear resistance compared with different ageing periods of T6-3, T6-6, and T6-12 hrs. At initial stages, wear rate was small and it increased drastically after 5.03 m/s, 4500 m and 40 N. The increase in content of SiC$_p$ in A356-3%Gr composites decreases the wear rate and enhances the tribological property of the composite material. As SiC particles come in contact with sliding disc, it avoids further wear rate and graphite particles help to run smoothly. No seizure and noise of the specimen was observed during the test conditions.

The addition of SiC$_p$ to A356 matrix material leads to mild wear regime and at higher speeds and loads severe wear was observed. The SiC$_p$ assists with retention of oxide transfer layer on composites. It prevents metal-metal contact and keeps wear behaviour within the mild wear regime, resulting in improvement of wear resistance over the non-reinforced alloy [22]. The addition of graphite content in A356-SiC$_p$ composite material decreases the fracture energy and no seizure occurred for composites.

For as-cast and heat treated composites, the friction coefficient reduces with increase of reinforcements. For composites A356-3Gr-9SiC$_p$-9 hrs showed the lowest wear rate. The similar results were obtained by earlier researchers [39].

The content of graphite in matrix material prevents the metal to metal contact and keeps wear behaviour within mild regime. It delays the transition of severe wear and provides best seizure resistance against steel disc [23]. The T6 heat treated composites form quick lubricating film which prevents direct metal-metal contact and seizure. It also reduces the accumulation of Al chips and avoids the plugging effects by improving the tribological property [22].The graphite content on composites is sufficient to form a lubricating film which prevents the metal to metal contact of two surfaces and decreases the plastic deformation on worn surface at higher sliding speed [27].

The addition of SiC$_p$ and graphite ceramic particles into aluminium matrix composites, act as a load bearing member and solid lubricant respectively. The addition of SiC$_p$ in A356-3%Gr composites acts as abrasives and it machines the steel counter face by transferring iron and its oxides on contact surface. It acts as third body abrasion and avoids the metal to metal contact. The formation of iron oxide in the transfer layer reduces the coefficient of friction [32,36]. Few of the abrasives were trapped on the counter face and wear of the matrix occurs and rises the temperature of the surface. The smeared graphite layers helps to slowly reduce the temperature and friction. It also reduces the shear stresses transferred from the surface [29, 30-35]. The coarsening of matrix precipitates reduces the wear resistance in over aged condition. The wear resistance was controlled by the rate at which particulate decohere. The complete precipitation was formed at 9 hrs aged which produces maximum wear resistance in different wt. % of composite and alloy [24,28]. The above said reasons prefer to use of hybrid composites in high load, speed, friction and high temperature applications which can hold multi-task criteria in any circumstances and enhance life span of the component.

6. CONCLUSIONS

The addition of reinforcement to the aluminium matrix reduces the wear rate. The metal matrix hybrid composites based on aluminium appears to be an attractive alternative for wear resistance applications. Studies have been carried out to find out the effect of T6-heat treatment with different ageing durations on wear resistance of hybrid composite materials and following conclusions were drawn.

- The wear rate of the Al-based hybrid composites is depending on the reinforcement and wear resistance was increased with the increase in the percentage of reinforcement.
- The A356-9SiC_p-3Gr composites show good wear resistance, compared with 3, 6 wt. % of SiC_p.
- The composites aged at T6-9 hrs exhibit better wear resistance, due to proper precipitation and good hardening which were absent in T6-12 hrs.
- Alloy exhibits a sever wear rate by adhesion and in composites show no adhesion and abrasion wear was observed.
- SEM analysis of the worn surfaces of the alloy which exhibits deep grooves cause more wear rate when compared with composites with finer grooves and surfaces appear to be smooth.
- The reinforcements of hard SiC_p and smooth graphite improve the tribological property of the material.

REFERENCES

[1] P.K. Rohatgi: *Metal matrix composites*, Defence Science Journal, Vol. 43, No. 4, pp. 323-349, 1993.

[2] E. Breval: *Synthesis routes to metal matrix composites with Specific Properties: A Review*, Composites Engineering, Vol. 5, No. 9, pp.1127-1133, 1995.

[3] P.K. Rohatgi, Y. Liu, S. Ray: *Friction and wear of metal matrix composites*, ASM Handbook, Friction, Lubrication and Wear Technology, Vol. 18, pp. 801-819.

[4] R.L. Deuis, C. Subramanian, J.M. Yellup: *Dry sliding wear of aluminium composites- A Review,* Composites Science and Technology, Vol. 57, pp. 415-435, 1997.

[5] A.P. Sannino, H.J. Rack: *Dry sliding wear of discontinuously reinforced aluminium composites: review and discussion*, Wear, Vol. 189, No. 1-2, pp. 1-19, 1995.

[6] M.K. Surappa: *Aluminium matrix composites: challenges and opportunities*, Sadhana, Vol. 28, No. 1-2, pp. 319-334, 2003.

[7] S. Basavarajappa, G. Chandramohan: *Application of Taguchi techniques to study dry sliding wear behavior of metal matrix composite*, Materials and Design, Vol. 28, No. 4, pp. 1393-1398, 2007.

[8] A. Vencl, A. Rac, I. Bobic: *Tribological behaviour of Al-based MMCs and their application in automotive industry*, Tribology in Industry, Vol. 26, No. 3&4, pp. 31-38, 2004.

[9] Mihaly Kozma: *Friction and wear of aluminum matrix composites*, in: *Proceedings of National Tribology Conference, ROTRIB `03, DUNAREA DE JOS of Galati, Romania,* 24-26 September 2003, pp. 99-106.

[10] Ye Haizhi: *An overview of the development of Al-si-alloy based material for engine applications*, Journal of Materials Engineering and Performance, Vol. 12, No. 3, pp. 288-297, 2003.

[11] S.C. Tjong, S.Q. Wu Liao, H.C: *Wear behaviour of an al-12% si alloy reinforced with a low volume fraction of SiC particles*", Composite Science and Technology, Vol. 57, No. 12, pp. 1551-1558, 1998.

[12] T. Miyajima, Y. Lwai: *Effects of reinforcements on sliding wear behaviour of aluminium matrix composites*, Wear, Vol. 255, No. 1-6, pp. 606-616, 2003.

[13] B.N. Pramila Bai, B.S. Ramesh, M.K. Surappa: *Dry sliding wear of A356-Al-SiC_p composites*, *Wear*, Vol. 157, No. 2, pp. 295-304, 1992.

[14] A. Ravikiran, M. K. Surappa: *Effect of sliding speed on wear behaviour of A356 Al-30 Wt. % SiC_p MMC*, Wear, Vol. 206, No. 1-2, pp. 33-38, 1997.

[15] Y. Sahin: *Tribological behaviour of metal matrix and its composite*, Materials and Design, Vol. 28, No. 4, pp. 1348-1352, 2007.

[16] G. Straffelini, M. Pellizzari, A. Molinari: *Influence of load and temperature on the dry sliding behaviour of Al-based metal matrix composites against friction material*, Wear, Vol. 256, No. 7-8, pp. 754-763, 2004.

[17] S. Zhang, F. Wang: *Comparison of friction and wear performance of brake material dry sliding against two aluminium matrix composites reinforced with different SiC particles*, Journal of Materials Processing Technology, Vol. 182, No. 1-3, pp. 122-127, 2007.

[18] V. Constantin, L. Scheed, J. Masounave: *Sliding wear of aluminium-silicon carbide metal matrix composites*, Journal of Tribology, ASM, Vol. 121, pp. 787, 1999.

[19] P.N. Bindumadhavan, T.K. Chia, M. Chandrasekaran, H.K. Wah, and L. N. Lam O. Prabhakar: *Effect of particle porosity clusters on tribological behaviour of cast aluminium alloy A356-SiC$_p$ metal matrix composites*, Materials Science and Engineering: A, Vol. 315, No. 1-2, pp. 217-226, 2001.

[20] M.K. Surappa, S.V. Prasad, P.K. Rohatgi: *Wear and abrasion of cast Al-alumina particle composites,* Wear, Vol. 77, No. 3, pp. 295-302, 1982.

[21] M. Prasanna Kumar, K. Sadashivappa, G.P. Prabhukumar, and S. Basavarajappa: *Dry sliding wear behaviour of garnet particles reinforced zinc-aluminium alloy metal matrix composites*, ISSN 1392-1320, Materials Science, Vol. 12, No. 3, pp. 209-213, 2006.

[22] C.B. Lin, R.J. Chang, W.P. Weng: *A study on process and tribological behaviour of Al alloy/Gr(p) composite*, Wear, Vol. 217, No. 2, pp. 167-174, 1998

[23] F. Akhlaghi, A.Z. Bidaki: *Influence of graphite content on the dry sliding and oil impregnated sliding wear behaviour of Al 2024-graphite composites produced by in situ powder metallurgy method*, Wear, Vol. 266, No. 1-2, pp. 37-45, 2009.

[24] M.M. Benal, H.K. Shivanand: *Effect of reinforcement content and ageing durations on wear characteristics of Al (6061) based hybrid composites*, Wear, Vol. 262, No. 5-6, pp. 759-763, 2007.

[25] J. Guo, X. Yuan: *The aging behaviour of SiC/Gr/6013Al composite in T4 and T6 treatments*, Materials Science and Engineering: A, Vol. 499, No. 1-2, pp. 212-214, 2009.

[26] Y.B. Liu, J.D. Hu, Z.Y. Cao, P.K. Rohatgi: *Wear resistance of laser processed Al-Si-Graphite composites*, Wear, Vol. 206, No. 1, pp. 83-86, 1997.

[27] J.B. Yang, C. B. Lin, T. C. Wang, H. Y. Chu: *The Tribological Characteristics of A356.2Al Alloy/Gr(P) Composites*, Wear, Vol. 257, No. 9-10, pp. 941-952, 2004.

[28] J.M. Gomez De Salazer, M. I. Barrena: *Influence of heat treatments on the wear behaviour of an AA6092/SiC$_p$ composite*, Wear, Vol. 256, pp. 286-293, 2004.

[29] W. Ames, A.T. Alpas: *Wear mechanisms in hybrid composites of Graphite-20 Pct SiC in A356 Aluminium alloy*, Metallurgical and Materials Transaction, Vol. 26, No. 1, pp. 85-98, 1995.

[30] S. Suresha, B. K. Sridhara: *Effect of addition of Graphite particulates on the wear behaviour in aluminium–silicon carbide-graphite composites*, Materials and Design, Vol. 31, No. 4, pp. 1804-1812, 2010.

[31] A.R. Riahi, A. T. Alpas: *The role of tribo- layers on the sliding wear behavior of graphitic aluminum matrix composites*, Wear, Vol. 251, No. 1-12, pp. 1396-1407, 2001.

[32] L. Jinfeng, J. Longtao, G. Wu, T. Shoufu, G. Chen: *Effect of graphitic particle reinforcement on dry sliding wear of SiC/Gr/Al composites*, Rare Metal materials and Engineering, Vol. 38, No. 1, pp. 1894-1898, 2009.

[33] Y. Zhan, G. Zhang: *The role of graphite particles in the high temperature wear of copper hybrid composites against steel*, Materials and Design, Vol. 27, No. 1, pp. 79-84, 2006.

[34] M. Babic, B. Stojanovic, S. Mitrovic, I. Bobic, N. Miloradovic, M. Pantic, D. Dzunic: *Wear properties of A356/10SiC/1Gr hybrid composites in lubricated sliding conditions*, Tribology in Industry, Vol. 35, No. 2, pp. 148-154, 2013.

[35] S. Basavarajappa, G. Chandramohan M. Prasanna Kumar, M. Ashwin, M. Prabu: *Dry sliding wear behavior of Al 2219/SiC$_p$-Gr hybrid metal matrix composites*, JMEPEG, Vol. 15, No. 6, pp. 668-674, 2006.

[36] M.L.T. Guo, C.Y.A. Tsao: *Tribological behaviour of self-lubricating Aluminium/SiC/Graphite hybrid composites synthesized by the semi-solid powder-densification method,* Composites Science and Technology, Vol. 60, No. 1, pp. 65-74, 2000.

[37] S. Wilson, A.T. Alpas: *Effect of temperature on the sliding wear performance of Al alloys and Al matrix composites*, Wear, Vol. 196, No. 1-2, pp. 270-278, 1996.

[38] N. Natarajan, S. Vijayarangan, I. Rajendran: *Wear behaviour of A356/25 SiC$_p$ aluminium matrix composites sliding against automobile friction material*, Wear, Vol. 261, pp. 812-822, 2006.

[39] S. Wilson, A.T. Alpas: *Wear mechanism maps for metal matrix composites*, Wear, Vol. 212, No. 1, pp. 41-49, 1997.

[40] M.A. Taha: *Practicalization of cast metal matrix composites (MMCCs*), Materials and Design, Vol. 22, No. 6, pp. 431-441, 2001.

[41] M. Babic, S. Mitrovic, R. Ninkovic: *Tribological potential of Zinc-aluminium alloys improvement*, Tribology in Industry, Vol. 31, No. 1&2, pp. 15-28, 2009.

[42] S. Mitrovic, M. Babic, B. Stojanovic, N. Miloradovic, M. Pantic, D. Dzunic: *Tribological potential of hybrid composites based on zinc and aluminium alloys reinforced with SiC and Graphite particles*, Tribology in Industry, Vol. 34, No. 4, pp. 177-185, 2012.