International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 06 Issue: 09 | September - 2022 Impact Factor: 7.185 ISSN: 2582-3930

VARIATION OF TWO BODY ABRASIVE WEAR AND THREE BODY ABRASIVE WEAR IN ALUMINIUM ALLOY (6063)

Mohd Shadab Khan, Riyan Ahmad

Associate Professor, Department of Mechanical Engineering, Integral University, Lucknow, U.P, India

Abstract

This study aims to correlate the abrasive wear performance with mechanical properties, considering AA6063 Al-Mg-Si alloy as the model material. The selected alloy specimens are subjected to artificial ageing at 150 °C for an ageing duration ranging from 1 to 672 h, covering severely under-aged (SUA) to peak-aged (PA) to severely over-aged (SOA) states. Apart from the hardness and tensile properties, two-body abrasive wear properties are also evaluated for differently aged alloys in terms of wear rate, coefficient of friction, and roughness of the abraded surfaces. Furthermore, the generated wear debris, surface, and sub- surface of the abraded specimens are critically examined to reveal the micro-mechanisms of abrasion. The lowest amount of wear rate is observed for a PA alloy with maximum hardness, while the OA alloy exhibits a slightly lower wear rate than the UA alloy at a similar level of hardness. Statistical analyses of wear rate and various mechanical properties of all heat-treated alloys establish a strong negative linear correlation between the wear rate and hardness, yield strength, tensile strength, and strength coefficient; whereas, a positive linear correlation with the strain hardening exponent. Relationships between wear rate and different roughness parameters are also discussed. Under the investigated wear condition, the aged alloys endure significant plastic deformation; micro-plowing, micro-cutting, and delamination are found to be the predominant mechanisms during abrasion.

1. Introduction

The emission of greenhouse gases and global warming are the potential threats to the sustainable development of the human race. Hence, from the last few decades, continuous efforts are being made to cut down the fuel consumption and the emission rate of greenhousegases in transportation sectors; this has led to the emergence of light alloys, *e.g.*, aluminium, magnesium, and titanium alloys, for structural and rotating components in automobile and aerospace industries [1–4]. Age-hardenable aluminium alloys are the most preferred ones in this field due to their excellent ageing response, high specific strength, and good corrosion resistance [5–8]. Al-Mg-Si alloys, especially the low Cu content members, are currently the economical ones employed for these applications [9]. The progress of age-hardening depends on the amount of added trace elements which can precipitate as per the kinetics of the alloy [10,11]. Additionally, Al-Mg-Si alloys undergo several microstructural alterations during the process of ageing; such microstructural changes have profound effects on the mechanical properties [12].

One of the significant drawbacks of Al alloys in the transportation sectors is their poor wear performance [13,14]. Several investigators [15–20] have attempted to understand the wear behavior of age-hardenable Al-alloys. Reports related to the wear of Al-alloys are primarily directed at understanding the adhesive wear behavior [15,16], although the frequently encountered mode of wear during industrial applications is abrasion. Wear causes damage to the material surface when it comes in contact with other materials like solid, liquid, and gas [21]. Abrasive wear removes the material on the surface in the form of debris when a hard surface slides against a softer surface under normal loading conditions [22]. Earlier investigations related to the abrasive wear behavior of Al-Mg-Si are primarily focused on the effect of Si content [17] and the temperature of ageing [16]. Kaushik et al. [23,24] have investigated the influence of applied pressure and the abrasive grit size on the high-stress abrasive wear resistance of hybrid 6082 Al-Mg-Si composites and compared them with the unreinforced alloy in both as-cast as well as in T6 conditions. The authors have observed that the abrasive wear resistance is the highest under lower applied pressures and grit size and gradually decreases with increasing the same for both as-cast and the aged conditions. At the same time, comparatively, the aged specimen has shown higher abrasion resistance at any particular applied pressure and grit sizes.

However, from the tribological perspective, besides understanding the type of wear encountered, wear behavior, and their mechanisms, studying the correlation between the wear and mechanical properties are also equally important in enhancing the entire life cycle of mechanical components by defining the abrasive wear losses [5]. Few earlier researchers have attempted to correlate the abrasive wear performance with mechanical properties of materials. Baldoni et al. [25] have examined the abrasive wear resistance of three different classes of cutting tool materials (brittle, brittle-ductile, and ductile) in correlation with the hardness and fracture toughness. Wear by fracture is dominant for the brittle materials, which indicates the abrasive wear resistance depends on the fracture toughness of the material. For brittle-ductile material like cemented carbide, wear can cause a large amount of plastic deformation, which is less prone to fracture toughness; whereas, for ductile metals, low hardness and fracture toughness results in less abrasive wear resistance. Jha et al. [26] have studied the correlation between the hardness, microstructure, and tensile properties of high-strength low alloy steel. These researchers have optimized the microstructural features and other mechanical properties to achieve superior wear characteristics and suggested that apart from hardness, ductility is also equally important in defining the abrasive wear performance of the steel. In a different study, Das et al. [27] have investigated the wear resistance of the aluminium alloys and hard particle composites. This research group has established an equation to define the wear rate as a function of hardness, strength, and young’s modulus and has suggested that the wear resistance is being entirely dependent on hardness, even though other mechanical properties like strength and elongation have a minor influence on it.

One can find a gap in the existing literature regarding the correlation between the abrasive wear characteristics and the mechanical properties of materials in contact. This study focuses on understanding two-body abrasive wear behavior and its correlation with the mechanical properties of artificially aged AA6063 alloy. Apart from establishing the hardness and tensile properties, the two-body abrasive wear behavior is examined in terms of wear rate, coefficient of friction, and roughness of the abraded surfaces. The operative wear mechanisms are identified by characterizing the abrasive paper, generated debris, surfaces, and sub-surfaces of abraded specimens using SEM and EDS apart from surface topography using a 3D optical profilometer. Finally, an attempt to correlate the wear rate with mechanical properties and some roughness parameters is made for Al-Mg-Si alloy specimens subjected to different ageing conditions.

REVIEW OF LITERATURE

- **Saurabh Kumar [1**] published three body abrasive wear behaviour on six aluminium alloys (AA1050, AA2014-T6, AA3003, AA5052, AA6061-T6 and AA6351-T6).Research shows abrasive wear increases with increase in load. Interaction of abrasive wear rate with hardness, ultimate strength and percentage elongation at break are reported. Wear mechanisms involved in material removal process were studied with the aid of optical microscope and scanning electron microscope (SEM).

- **Monil Salot [2]** This study focuses on the evaluation of abrasive wear resistance of Al-Si alloys with and without chromium oxide coating. It states that the wear resistance of Al-Si alloys increases with the increase in the amount of Si in the alloy.

- **Tadashi Ohtani [3]** Two-body wear and three-body abrasive wear test of katsura wood were carried out using abrasive paper and moving abrasive grains. it is reported that two-body abrasive wear is more affected by yield stress and surface microstructure, and three-body abrasive wear is more affected by the cutting action of moving abrasive grains.

- **A.P. Harsha [4**] Investigates the three-body abrasive wear behavior of polyaryletherketone composites.It includes the study the effect of reinforcement fibres, solid lubricants, mass of abrasives and load in three-body abrasive wear situations on various polyaryletherketone (PAEK) matrix. He inspected that fibre reinforcement is detrimental to the abrasive wear resistance of neat PAEK matrix. Scanning electron microscopy was used to detect worn surfaces and to know the functioning involved in it.

- **Mohd Shadab Khan [5]** conducted a research on Abrasive wear behavior of Silicon Polyethylene vinyl Acetate copolymer using a pin-on-disc arrangement. Load and angular speed are the two parameters which are taken into consideration .Results showed that the wear increases as the load and angular speed(rpm).

- **Mohd shadab Khan** [6] inspected the Abrasive wear behavior of Organopolysiloxane and concluded that the wear varies with applied load and and mechanical parameters .The wear increases with increasing load and angular speed.

- **N. Mohan [7**] investigates the Two-Body Abrasive Wear Behavior of Silicon Carbide Filled Glass Fabric-Epoxy Composites. The effect of silicon carbide (SiC) fillers inclusion on two-body abrasive wear behaviour of Glass Fabric - Epoxy (GE) composites was observed and results are examined. He states that the appreciably decrement in wear loss and specific wear rates were observed after introducing of SiC filler into GE composites.

- **Gaoqi Wang [8**] examined the Two-Body and Three-Body Wear Behavior of a Dental Fluorapatite Glass-Ceramic. Results obtained that good mechanical properties of fluorapatite glass-ceramic can be achieved by the sintering process. In both two-body and three-body modes, the fluorapatite glass-ceramic had a smaller friction coefficient and wear rate and caused less damage on antagonistic teeth than the feldspathic glass-ceramic.

- **Vishwas Mahesh [9]** performed research on two-body and three-body abrasive wear behavior of jute-natural rubber flexible green composite. The wear trend of the composites follows a similar pattern in the case of two- and three-body wear, the mechanisms governing the wear are found to be different. The morphology of the worn surface is studied with the aid of a scanning electron microscope.

EXPERIMENTAL PROCEDURES

Material

Experimentation

In this chapter, details of material used in the present investigation and its preparation has been described and the details of the experimentation on wear studies in the material of present investigation have been given.

In order to carry out the experimental work, the procedure is as follows.

(i) Fabrication of Pin on Disc

(ii) Specimen‘s Materials

(iii) Wear characterization

Fabrication of Pin on Disc

Numerous researches have been done in the field of abrasive wear. This work is also anexperimental design in the field of abrasive wear Pin on Discvia a newly designed wear Pin on Disc. In view of the objective a set-up was needed to be designed which can calculate wear rate at different speed (rpm) of work piece with respect to the main frame (horizontal position).

The wear machine used for Pin on Disc wear properties was designed by **Prof. (Dr.) Zahir Hasan** and fabricated by **Dr. Mohd Shadab Khan.** A pin on disc wear test technique was adopted to test the wear behavior of specimens.

Wear rate and wear mass were Pin on Disc at different orientation of the specimen. The tests were conducted for seven different orientations namely **100 rpm , 150 rpm, 200 rpm .** The wear mass of above said specimen Pin on Disc test at a constant time of **2min (120 sec).**

The set-up has following different parts-:

(1)Controller (2)D.C Motor (3)Flange Coupling (4)Bearing (5)Main Frame (6)Frame(Angular) (7)AcrylicSheet (8) Grinding Wheel (9) Specimen (10) Screw Jack (11) Load Cell (12) Angular Lever.

The designed setup is shown in the fig. 4.1 and 4.2

Experimental Setup of Wear Pin on Disc

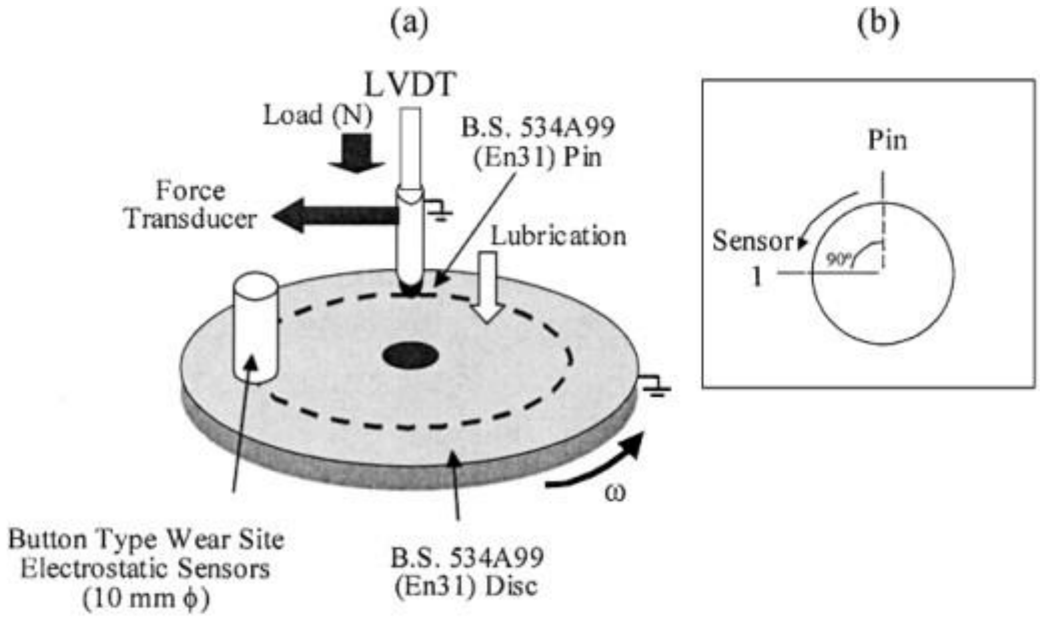


Fig- 4.1 Experimental Setup (Front View)

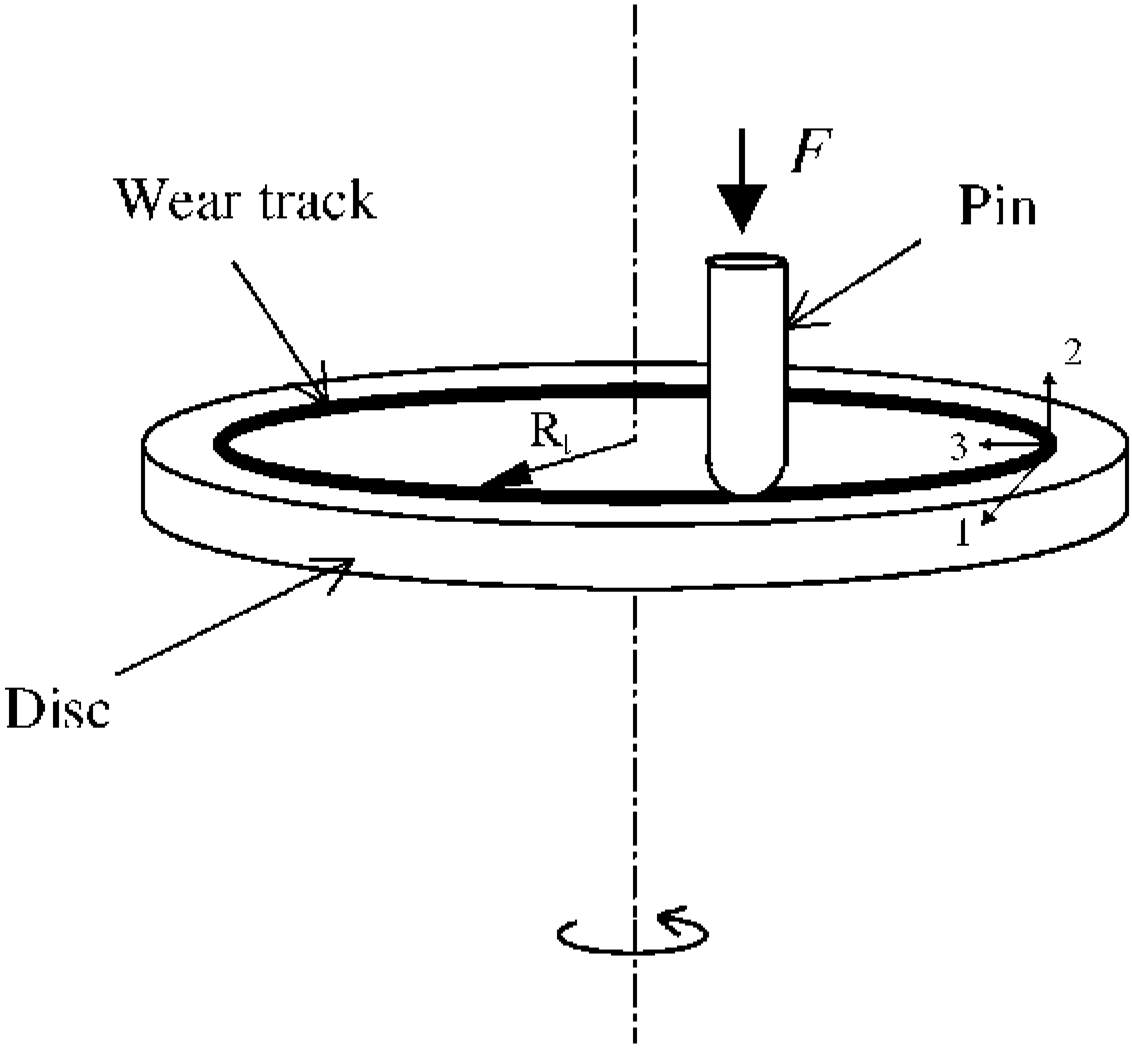


Fig- 4.1 Experimental Setup (Top View)

Working of Set-Up

The pin-on-disc sliding tests were conducted in the following manner. The pins, measuring 5 mm in diameter and 5 mm in length, were made of hardened bearing steel (AISI 52100) and polished to a surface roughness of Ra 0.05 micron. The disc measured 35 mm in diameter and 2.5 mm in thickness and was made of carburized steel. The three pins were secured to prevent them from rotating and were pressed against the toric sliding surface of the rotating disc at a position that was 20 mm in diameter from the center of the disc. Contact at the sliding interfaces was in the shape of lines under high Hertzian pressure of 700 MPa due to a normal force of 500 N, Lubrication was provided by an oil bath heated to 353 K. The sliding speed was varied in a range of 0 to 1 ms^{-1} for the tribological experiments and the sliding time was 60 minutes..

Description of the Parts of the Wear Pin on Disc

DC Motor

The D.C. Motor having following specifications:

Power – 1 H.P, Rotation – 1 rpm to 3000 rpm

Regulator of a direct current motor is used to regulate and control the speed of motor. It has ammeter to measure current and voltmeter to measure volt attached to it. The characteristic features of regulator are:

Regulated Voltage – 0-260 V , Least Count – 2V The technical parameters of Ammeter are:Current
Range: 0 – 10 ampere
Least Count: o.4 ampere
The technical parameters of Voltmeter are: Voltage Range : o – 300V , Least Count: 20 V

Frame

The main frame is just like chassis to the engine ,it hold all the parts such as motor , shaft , coupling , screw jack and all its related attachment. The dimensions of the main frame are as follows:
Length – 105 cm , Width – 21 cm Dimensions of angular frame are as follows :Length – 115 cm Width – 35 cm

Acrylic Disc

The acrylic disc is used as a fixture of specimen holder. The disc is drilled with multiple holes at differentradius. This is done so that every specimen gets fresh abrasive surface. This makes synchronization in the calculation of wear rate of the entire specimen. The dimensions of the acrylic disc are as follows:

Diameter – 26 cm
Radius of the first hole (r1) = 8 cm Radius of the second hole (r2) = 16 cm Radius of the thirdhole (r3) = 24 cm

Grinding Wheel

A grinding wheel used in the design as an abrasive media to produce abrasive wear on thespecimen selected. The dimensions of the grinding disc are as follows:
Diameter – 20 cm

Speed Of Grinding Wheel

Generally all the abrasive processes are performed with the wheel speed in between the range of300 to 2000 rpm with the maximum work speed from 0 to 60 m/min.

Shaft

Two shafts were used , the first shaft connects motor to the abrasive disc and second shaft connects accrylic disc to screw jack. Load is applied with help of second shaft , it pushes the specimen against the rotating abrasive disc.

The dimensions of the shaft are as follows :

Diameter – 25mm Length (First) – 20 cm Length (Second) – 30 cm

Screw Jack

The screw jack is used to apply the load gradually turn wise. The screw jack is connected to the shaft, which is further connected to the acrylic disc and specimen fixture.As the screw jack unfolds, it pushes the shaft and acrylic sheet which holds the specimen against the abrasive disc.

Weighing Machine

The weighing machine used in the design to calculate mass loss (wear) of the specimen. Theweighing machine used had following parameters:

Least Count – 0.001gm Max. Capacity – 5 Kg

Diagram of Experimental Setup

Fig-4.2 Experimental Setup –With Controller

Fig-4.3 Experimental setup (Front View)

Fig-4.4 Experimental set up (Top View)

Fig-4.6 Specimen

RESULTS AND DISCUSSION

Table 1: Variation in Two-body and Three Abrasive Wear of Aluminiumalloy(6063) at 5N Load

SET NO.1(100rpm,5N)					
TEST NO.	MASS BEFORE TEST (gm)	MASS AFTER TEST (TWO BODY test) (gm)	Wear by mass (Two BODY WEAR) gm	Mass after three body test (gm)	Wear by Mass(three Body wear
1.	54.921	54.458	0.463	54.344	0.114
2.	55.139	54.711	0.428	54.529	0.182
3.	53.673	53.215	0.458	53.020	0.195
4.	54.116	53.787	0.329	53.568	0.219
5.	53.545	53.326	0.219	53.200	0.126
MEAN			0.379		0.167

Table 2:

SET NO.2(150rpm,5N)					
TEST NO.	MASS BEFORE TEST(gm)	MASS AFTER TEST (TWO BODY test) (gm)	Wear by mass gm	Mass after three body test	Wear by mass
1.	54.344	53.600	0.744	53.335	0.265
2.	54.529	53.955	0.574	53.670	0.285
3.	53.020	52.530	0.490	52.200	0.330

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 06 Issue: 09 | September - 2022 Impact Factor: 7.185 ISSN: 2582-3930

4.	53.568	52.830	0.738	52.535	0.295
5.	53.200	52.650	0.550	52.355	0.295
MEAN			0.619		0.294

Table 3:

SET NO.3(200RPM,5N)

TEST NO. MASS BEFORE TEST mass after test WEAR BY MASSmass after three (gm) (two body test) (gm) body test(gm)					Wear by mass
1.	53.300	52.575	0.725	52.100	0.475
2.	53.655	52.800	0.855	52.350	0.450
3.	52.200	51.455	0.745	50.970	0.485
4.	52.530	51.700	0.830	51.235	0.465
5.	52.355	51.600	0.755	51.225	0.375
mean			0.782		0.450

SET NO.4(100RPM,10N)

TEST NO. MASS BEFORE TEST mass after test WEAR BY MASSmass after (gm) (two body test)(gm) (two body wear)gm three body test					Wear by mass
1.	52.100	51.525	0.575	51.155	0.370
2.	52.350	51.856	0.494	51.375	0.481
3.	50.970	50.235	0.735	49.800	0.435
4.	51.235	50.560	0.675	50.145	0.415
5.	51.200	50.620	0.580	50.130	0.490
mean			0.611		0.438

SET NO.5(150RPM,10N)

TEST NO. MASS BEFORE TEST mass after test WEAR BY MASSmass after three (gm) (two body test)(gm) (gm) body test(gm)					Wear by mass
1.	51.155	50.550	0.605	50.200	0.350
2.	51.375	50.700	0.675	50.235	0.465
3.	49.800	49.224	0.576	48.835	0.389
4.	50.145	49.450	0.695	49.100	0.350
5.	50.130	49.635	0.495	49.225	0.410
mean			0.609		0.392

SET NO.6(200RPM,10N)

TEST NO. MASS BEFORE TEST mass after test WEAR BY MASs mass after (gm) (two body test)(gm) (gm) three body(gm					Wear by mas
1.	50.200	49.337	0.863	48.900	0.437
2.	50.350	49.755	0.595	49.225	0.530
3.	48.835	48.105	0.730	47.554	0.551
4.	49.100	48.322	0.778	47.883	0.439
5.	49.225	48.445	0.780	47.900	0.545
mean			0.749		0.500

SET NO.7(100RPM,15N)

TEST NO. MASS BEFORE TEST mass after WEAR BY MASS mass after (gm) (two body test)(gm) (gm) three body test					Wear by mass
1.	48.900	48.230	0.670	47.620	0.610
2.	49.225	48.665	0.560	48.223	0.442
3.	47.554	46.882	0.672	46.260	0.622
4.	47.883	47.120	0.763	46.570	0.550
5.	47.900	47.220	0.680	46.600	0.620
mean			0.669		0.568

SET NO.8(150RPM,15N)

TEST NO. MASS BEFORE TEST mass after WEAR BY MASS mass after (gm) (two body test)(gm) (two body wear)gm three body test					Wear by mas
1.	47.620	46.800	0.820	46.210	0.590
2.	47.950	47.177	0.773	46.450	0.727
3.	46.260	45.445	0.815	44.910	0.535
4.	46.570	45.653	0.917	44.950	0.703
5.	46.600	45.775	0.825	45.120	0.655
mean			0.830		0.642

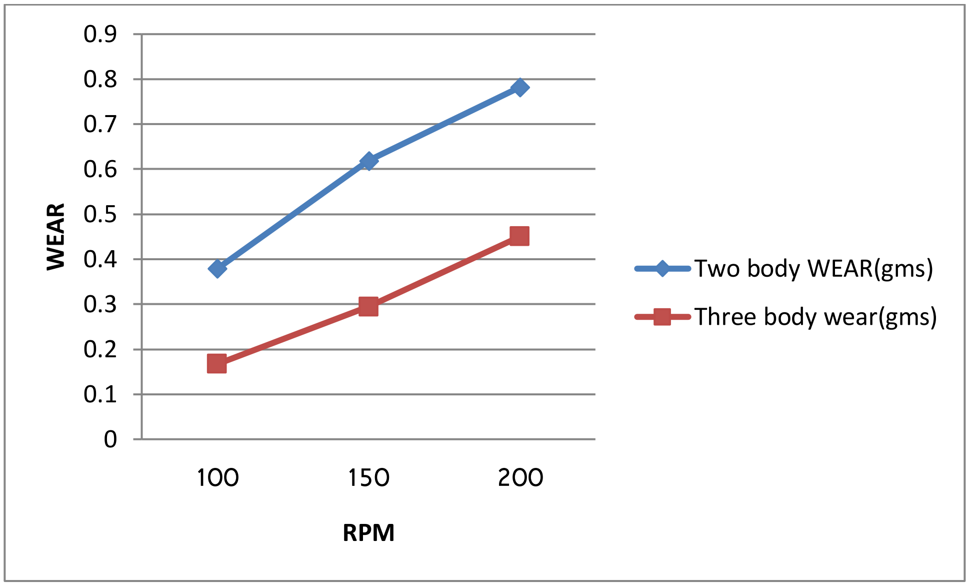
SET NO.9(200RPM,15N)

TEST NO. MASS BEFORE TEST mass after WEAR BY MASSmass after (gm) (two body wear)(gm) (two body wear)gm three body test					Wear by mass
1.	46.210	45.305	0.905	44.665	0.640
2.	46.450	45.571	0.879	44.910	0.661
3.	44.910	44.102	0.808	43.720	0.382
4.	44.950	44.110	0.840	43.620	0.490
5.	45.120	44.250	0.870	43.770	0.480
mean			0.860		0.530

At 5N- RPM vs. WEAR

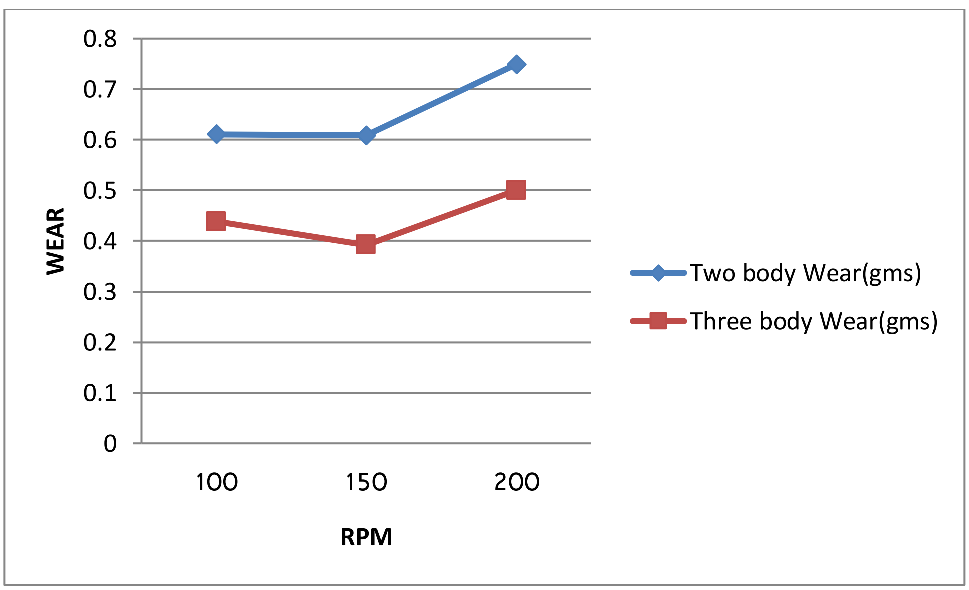
RPM	Two body WEAR(gms)	Three body wear(gms)
100	0.379	0.167
150	0.619	0.294
200	0.782	0.450

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 06 Issue: 09 | September - 2022 Impact Factor: 7.185 ISSN: 2582-3930



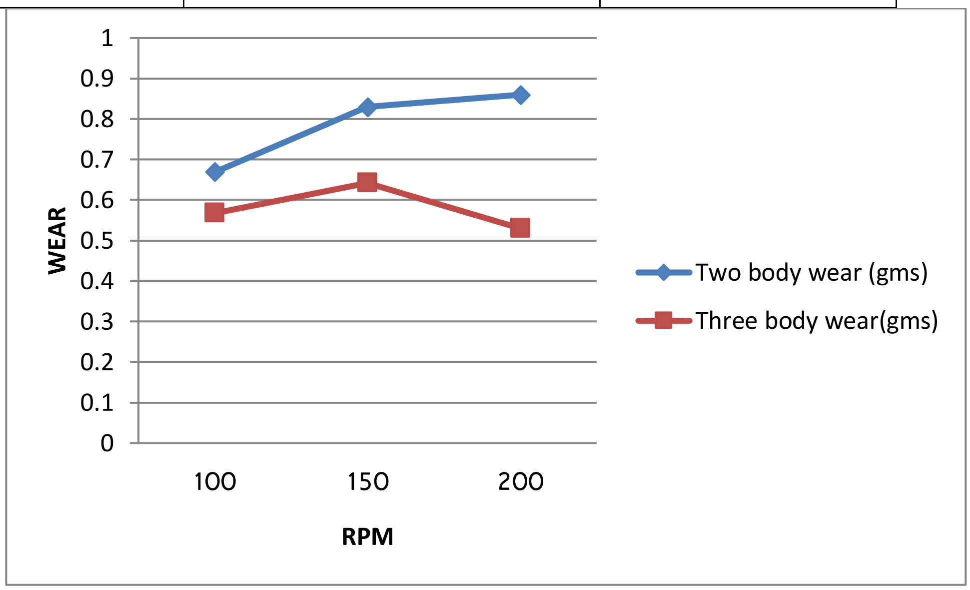
At 10 N- RPM vs. WEAR

rpm	Two body Wear(gms)	Three body Wear(gms)
100	0.611	0.438
150	0.609	0.392
200	0.749	0.500



At 15 N- RPM vs. WEAR

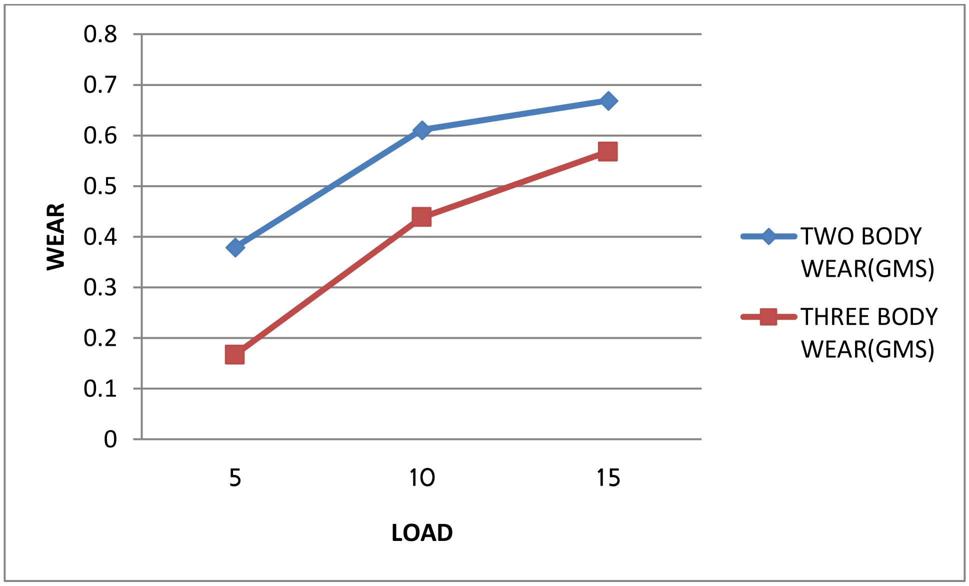
RPM	Two body wear (gms)	Three body wear(gms)
100	0.669	0.568
150	0.830	0.642
200	0.860	0.530



Effect of Speed (rpm) On Abrasive Wear of ALUMINIUM AL6063 AT CONSTANT ANGULAR SPEED

LOAD VS WEAR (100RPM)

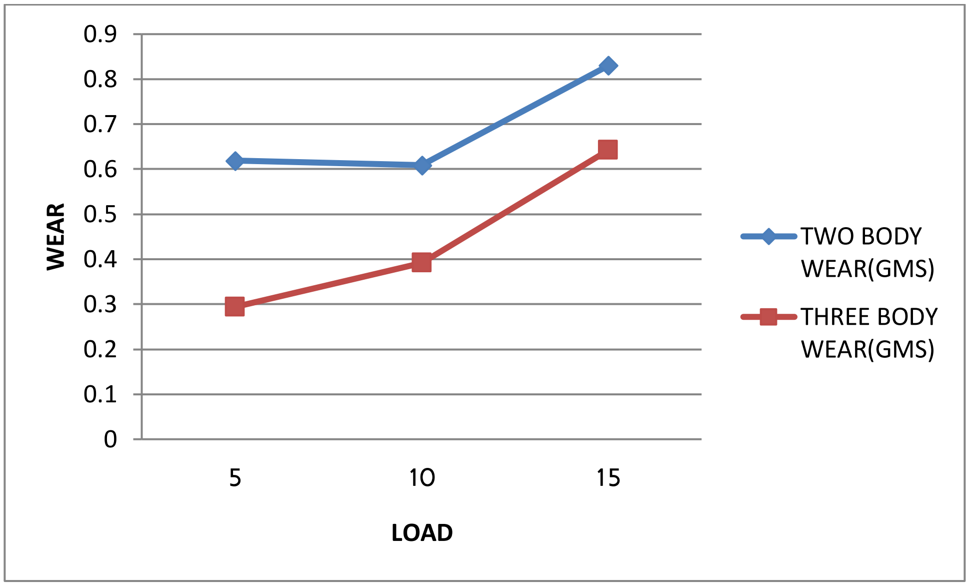
LOAD(N)	TWO BODY WEAR(GMS)	THREE BODY WEAR(GMS)
5	0.379	0.167
10	0.611	0.438
15	0.669	0.568



GRAPH

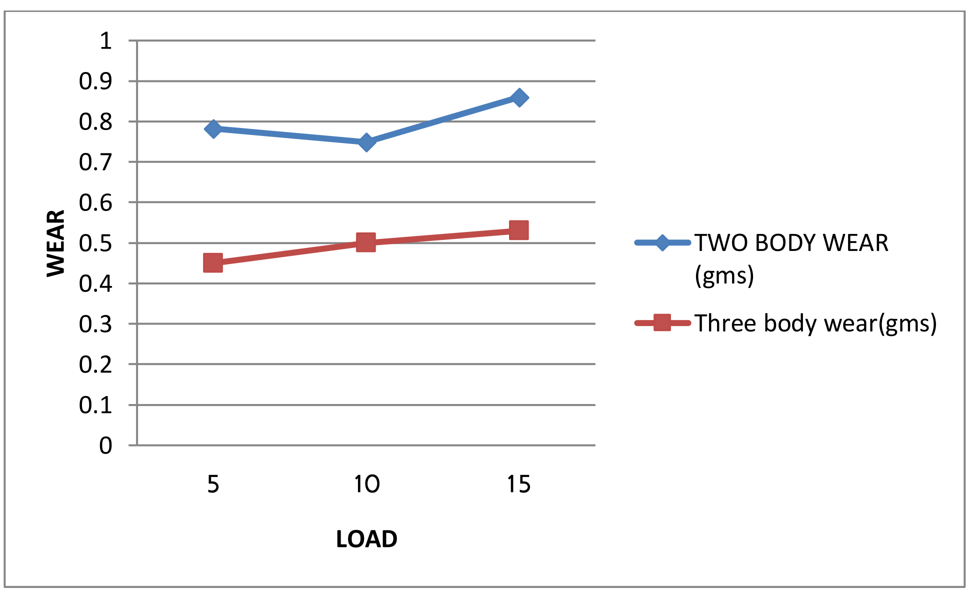
LOAD VS WEAR (150RPM)

LOAD(N)	TWO BODY WEAR(GMS)	THREE BODY WEAR(GMS)
5	0.619	0.294
10	0.609	0.392
15	0.830	0.642



LOAD VS WEAR(200RPM)

LOAD(N)	TWO BODY WEAR (gms)	Three body wear(gms)
5	0.782	0.450
10	0.749	0.500
15	0.860	0.530



DISCUSSION

The main findings of the investigation have been listed out. The suggestion for the future work have also been indicated. The specimen do not get fresh abrasive surface,due to this wear resistance increases. Following results are discussed below:

GRAPH-5.1

This graph shows RPM vs WEAR at 5 N. The wear loss increases while RPM increases. The graph is not linear in nature.

GRAPH-5.2

This graph shows RPM vs WEAR at 10 N. The wear loss increases while RPM increases. The graph is not linear in nature.

GRAPH-5.3

This graph shows RPM vs WEAR at 15 N. The wear loss increases while RPM increases. The graph is not linear in nature. In this graph wear loss is more as compare to graph 1 and graph 2.

GRAPH-5.4

This graph shows LOAD vs WEAR at 5 N. The wear loss increases while load increases. The graph is linear in nature , this shows linear relationship between load and wear.

GRAPH-5.5

This graph shows LOAD vs WEAR at 10 N. The wear loss increases while load increases. The graph is linear in nature , this shows linear relationship between load and wear.

GRAPH-5.6

This graph shows LOAD vs WEAR at 15 N. The wear loss increases while load increases. The graph is linear in nature , this shows linear relationship between load and wear. In this graph wear loss is more as compare to graph 1 and graph 2.

CONCLUSION

It is concluded from the above discussion that wear is function of applied load. Initially, it was understood that wear depends upon applied load, surface parameters and mechanical properties such as hardness, toughness etc. Thus it can be concluded that:

- There is a linear relationship between wear and load
- The wear loss increases while load increases. Wear loss is more at 15 N load as compare to 5N and 10 N load.
- The wear loss increases while RPM increases.
- The wear loss in first minute is more as compare to last minute while increasing the RPM

REFERENCES

REFERENCES

[1] Langille, M., Diak, B. J., De Geuser, F., Guiglionda, G., Meddeb, S., Zhao, H., Gault, B., Raabe, D., and Deschamps, A., 2019, “Understanding the Role of Cu and Clustering on Strain Hardening and Strain Rate Sensitivity of Al-Mg-Si-Cu Alloys,” Light Metals, C. Chesonis, ed., Springer, Cham, pp. 143–151.

[2] Tisza, M., and Czinege, I., 2018, “Comparative Study of the Application of Steels and Aluminium in Lightweight Production of Automotive Parts,” Int. J. Light. Mater. Manuf., 1(4), pp. 229–238.

[3] Holmberg, K., and Erdemir, A., 2017, “Influence of Tribology on Global Energy Consumption , Costs and Emissions,” 5(3), pp. 263–284.

[4] Panigrahi, S. K., and Jayaganthan, R., 2011, “Development of Ultrafine-Grained Al 6063 Alloy by Cryorolling with the Optimized Initial Heat Treatment Conditions,” Mater. Des., 32(4), pp. 2172–2180.

[5] Burger, G. B., Gupta, A. K., Jeffrey, P. W., and Lloyd, D. J., 1995, “Microstructural Control of Aluminum Sheet Used in Automotive Applications,” Mater. Charact., 35(1), pp. 23–39.

[6] Sekhar, A. P., Nandy, S., Ray, K. K., and Das, D., 2016, “Comparative Assessment of Strength Models for AA6063 Alloy,” Materials Science Forum, Trans Tech Publications, Switzerland, pp. 83–89.

[7] Sato, Y. S., Kokawa, H., Enomoto, M., and Jogan, S., 1999, “Microstructural Evolution of 6063 Aluminum during Friction-Stir Welding,” Metall. Mater. Trans. A Phys. Metall. Mater. Sci., 30(9), pp. 2429–2437.

[8] Vishwakarma, D. K., Kumar, N., and Padap, A. K., 2017, "Modelling and Optimization of Aging Parameters for Thermal Properties of Al 6082 Alloy Using Response Surface Methodology," Mater. Res. Express, 4(4), p. 046502.

[9] Heinz, A., Haszler, A., Keidel, C., Moldenhauer, S., Benedictus, R., and Miller, W. S., 2000, "Recent Development in Aluminium Alloys for Aerospace Applications," Mater. Sci. Eng. A, 280(1), pp. 102–107.

[10] Ringer, S. P., and Hono, K., 2000, "Microstructural Evolution and Age Hardening in Aluminium Alloys: Atom Probe Field-Ion Microscopy and Transmission Electron Microscopy Studies," Mater. Charact., 44(1–2), pp. 101–131.

[11] Dumitraschkewitz, P., Gerstl, S. S. A., Stephenson, L. T., Uggowitzer, P. J., and Pogatscher, S., 2018, "Clustering in Age-Hardenable Aluminum Alloys," Adv. Eng. Mater., 20(10), p. 1800255.

[12] Nandy, S., Kumar Ray, K., and Das, D., 2015, "Process Model to Predict Yield Strength of AA6063 Alloy," Mater. Sci. Eng. A, 644, pp. 413–424.

[13] Blau, P. J., 1997, "Fifty Years of Research on the Wear of Metals," Tribol. Int., 30(5), pp. 321–331.

[14] Barwell, F. T., 1958, "Wear of Metals," Wear, 1(4), pp. 317–332.

[15] Gavgali, M., Totik, Y., and Sadeler, R., 2003, "The Effects of Artificial Aging on Wear Properties of AA 6063 Alloy," Mater. Lett., 57(24–25), pp. 3713–3721.

[16] Meriç, C., Atík, E., and Kaçar, H., 2006, "Effect of Aging on the Abrasive Wear Properties of AlMgSi1 Alloy," Mater. Des., 27(10), pp. 1180–1186.

[17] Sharma, R., Anesh, and Dwivedi, D. K., 2005, "Influence of Silicon (Wt.%) and Heat Treatment on Abrasive Wear Behaviour of Cast Al-Si-Mg Alloys," Mater. Sci. Eng. A, 408(1– 2), pp. 274–280.

[18] Büyükdoğan, S., Gündüz, S., and Türkmen, M., 2014, "Influence of Ageing Treatment on Microstructure, Mechanical Properties and Adhesive Wear Behaviour of 6063 Aluminium Alloy," Ind. Lubr. Tribol., 66(4), pp. 520–524.

[19] Mahajan, Y., and Peshwe, D. R., 2018, "Effect of Temper Conditions on Abrasive Wear Behavior of AA7010 Alloy," Trans. Indian Inst. Met., 71(4), pp. 1025–1032.

[20] Sekhar, A. P., and Das, D., 2021, "Influence of Artificial Aging on Mechanical Properties and High Stress Abrasive Wear Behaviour of Al–Mg–Si Alloy," Met. Mater. Int., 27, pp. 337–351.

[21] Kaçar, H. U., Atik, E., and Meriç, C., 2003, "The Effect of Precipitation-Hardening Conditions on Wear Behaviours at 2024 Aluminium Wrought Alloy," J. Mater. Process. Technol., 142(3), pp. 762–766.

[22] Hutchings, I. M., 2002, "Abrasion Processes in Wear and Manufacturing," Proc. Inst. Mech. Eng. Part J J. Eng. Tribol., 216(2), pp. 55–62.

[23] Kaushik, N. C., and Rao, R. N., 2016, "The Effect of Wear Parameters and Heat Treatment on Two Body Abrasive Wear of Al-SiC-Gr Hybrid Composites," Tribol. Int., 96, pp. 184–190.

[24] Kaushik, N. C., and Rao, R. N., 2016, "Effect of Grit Size on Two Body Abrasive Wear of Al 6082 Hybrid Composites Produced by Stir Casting Method," Tribol. Int., 102, pp. 52–60.

[25] Baldoni, J. G., Wayne, S. F., and Buljian, S. T., 1986, "Cutting Tool Materials : Mechanical Properties — Wear- Resistance Relationships," A S L E Trans., 29(3), pp. 347–352.

[26] Jha, A. K., Prasad, B. K., Modi, O. P., Das, S., and Yegneswaran, A. H., 2003, "Correlating Microstructural Features and Mechanical Properties with Abrasion Resistance of a High Strength Low Alloy Steel," Wear, 254(1–2), pp. 120–128.

[27] Das, S., Mondal, D. P., and Dixit, G., 2001, "Correlation of Abrasive Wear with Microstructure and Mechanical Properties of Pressure Die-Cast Aluminum Hard-Particle Composite," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., 32(3), pp. 633–642.

[28] 2016, Standard Test Method for Tension Testing of Metallic Materials, West Conshohocken.

[29] 2005, "ASTM G99-05, Standard Test Method for Wear Testing with a Pin-on-Disc Apparatus," ASTM Int.

[30] Mondal, D. P., Das, S., Jha, A. K., and Yegneswaran, A. H., 1998, "Abrasive Wear of Al Alloy-Al2O3 Particle Composite: A Study on the Combined Effect of Load and Size of Abrasive," Wear, 223(1–2), pp. 131–138.

[31] Sardar, S., Karmakar, S. K., and Das, D., 2018, "Tribological Properties of Al 7075 Alloy and 7075/Al 2 O 3 Composite under Two-Body Abrasion: A Statistical Approach," J. Tribol., 140(5).

[32] Gadelmawla, E. S., Koura, M. M., Maksoud, T. M. A., Elewa, I. M., and Soliman, H. ., 2002, "Roughness Parameters," J. Mater. Process. Technol., 123, pp. 133–147.

[33] Rendón, J., and Olsson, M., 2009, "Abrasive Wear Resistance of Some Commercial Abrasion Resistant Steels Evaluated by Laboratory Test Methods," Wear, 267(11), pp. 2055–2061.

[34] Guo, M. X., Li, G. J., Sha, G., Zhang, J. S., Zhuang, L. Z., and Lavernia, E. J., 2019, "Influence of Zn on the Distribution and Composition of Heterogenous Solute-Rich Features in Peak-Aged Al-Mg-Si-Cu Alloys," Scr. Mater., 159, pp. 5–8.

[35] Liu, H., Zhao, G., Liu, C., and Zuo, L., 2007, "Effects of Different Tempers on Precipitation Hardening of 6000 Series Aluminium Alloys," Trans. Nonferrous Met. Soc. China (English Ed., 17, pp. 122–127.

[36] Siddiqui, R. A., Abdullah, H. A., and Al-Belushi, K. R., 2000, "Influence of Aging Parameters on the Mechanical Properties of 6063 Aluminium Alloy," J. Mater. Process. Technol., 102(1), pp. 234–240.

[37] Panigrahi, S. K., and Jayaganthan, R., 2008, "A Study on the Mechanical Properties of Cryorolled Al-Mg-Si Alloy," Mater. Sci. Eng. A, 480(1–2), pp. 299–305.

[38] Jin, S., Ngai, T., Li, L., Jia, S., Zhai, T., and Ke, D., 2018, "Aging Response and Precipitation Behavior after 5% Pre-Deformation of an Al-Mg-Si-Cu Alloy," Materials (Basel)., 11(8).

[39] Cavazos, J. L., and Colás, R., 2003, "Quench Sensitivity of a Heat Treatable Aluminum Alloy," Mater. Sci. Eng. A, 363, pp. 171–178.

[40] Jiang, D. M., Hong, B. D., Lei, T. C., Downham, D. A., and Lorimer, G. W., 1991, "Influence of Aging Condition on Tensile and Fatigue Fracture Behaviour of Aluminium Alloy 6063," Mater. Sci. Technol., 7, pp. 1010–1014.

[41] Zhang, D. L., and Zheng, L., 1996, "The Quench Sensitivity of Cast Al-7 Wt Pet Si-0.4 Wt Pct Mg Alloy," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., 27(12), pp. 3983–3991.

[42] Nandy, S., Bakkar, M. A., and Das, D., 2015, "Influence of Ageing on Mechanical Properties of 6063 Al Alloy," Mater. Today Proc., 2(4–5), pp. 1234–1242.

[43] Zhen, L., Fei, W. D., Kang, S. B., and Kim, H. W., 1997, "Precipitation Behaviour of Al-Mg- Si Alloys with High Silicon Content," J. Mater. Sci., 32(7), pp. 1895–1902.

[44] Demir, H., and Gündüz, S., 2009, "The Effects of Aging on Machinability of 6061 Aluminium Alloy," Mater. Des., 30(5), pp. 1480–1483.

[45] Gupta, A. K., and Prasad, B. K., 2013, "Effects of Microstructural Features and Test Parameters on the Abrasive Wear Response of an Al-Si Alloy," J. Mater. Eng. Perform., 22(7), pp. 2089–2097.

[46] Edwards, G. A., Stiller, K., Dunlop, G. L., and Couper, M. J., 1998, "The Precipitation Sequence in Al-Mg-Si Alloys," Acta Mater., 46(11), pp. 3893–3904.

[47] Gupta, A. K., Lloyd, D. J., and Court, S. A., 2001, "Precipitation Hardening Processes in an Al–0.4%Mg–1.3%Si–0.25%Fe Aluminum Alloy," Mater. Sci. Eng. A, 301(2), pp. 140–146.

[48] Vissers, R., van Huis, M. A., Jansen, J., Zandbergen, H. W., Marioara, C. D., and Andersen, S. J., 2007, "The Crystal Structure of the B′ Phase in Al-Mg-Si Alloys," Acta Mater., 55(11), pp. 3815–3823.

[49] Marioara, C. D., Andersen, S. J., Friss, J., Engler, O., and Aruga, Y., 2018, "The Nature of Solute Clusters and GP-Zones in the Al-Mg-Si System," The Proceedings of 16th International Aluminum Alloys Conference (ICAA16), McGill University, Montreal, QC.

[50] Pink, E., Kumar, S., and Tian, B., 2000, "Serrated Flow of Aluminium Alloys Influenced by Precipitates," Mater. Sci. Eng. A, 280(1), pp. 17–24.

[51] Chmelík, F., Pink, E., Król, J., Balík, J., Pešička, J., and Lukáč, P., 1998, “Mechanisms of Serrated Flow in Aluminium Alloys with Precipitates Investigated by Acoustic Emission,” Acta Mater., 46(12), pp. 4435–4442.

[52] Bourget, J. P., Fafard, M., Shakeri, H. R., and Côté, T., 2009, “Optimization of Heat Treatment in Cold-Drawn 6063 Aluminium Tubes,” J. Mater. Process. Technol., 209(11), pp. 5035–5041.

[53] Munitz, A., Cotler, C., and Talianker, M., 2000, “Aging Impact on Mechanical Properties and Microstructure of Al-6063,” J. Mater. Sci., 35(10), pp. 2529–2538.

[54] Ber, L. B., 2000, “Accelerated Artificial Ageing Regimes of Commercial Aluminium Alloys. II: Al–Cu, Al–Zn–Mg–(Cu), Al–Mg–Si–(Cu) Alloys,” Mater. Sci. Eng. A, 280(1), pp. 91–96.

[55] Urreta, S. E., Louchet, F., and Ghilarducci, A., 2001, “Fracture Behaviour of an A1-Mg-Si Industrial Alloy,” Mater. Sci. Eng. A, 302(2), pp. 300–307.

[56] Shah, K. B., Kumar, S., and Dwivedi, D. K., 2007, “Aging Temperature and Abrasive Wear Behaviour of Cast Al-(4%, 12%, 20%)Si-0.3% Mg Alloys,” Mater. Des., 28(6), pp. 1968– 1974.

[57] Archard, J. F., 1953, “Contact and Rubbing of Flat Surfaces,” J. Appl. Phys., 24(8), pp. 981– 988.

[58] Suh, N. A. M. P., 1981, “The Genesis of Friction*,” Wear, 69, pp. 91–114.

[59] Kato, K., 2000, “Wear in Relation to Friction — a Review,” Wear, 241, pp. 151–157.

[60] Tohkai, M., 1979, “Microstructural Aspects of Friction,” Massachusetts Institute of Technology.

[61] Moore, A. A. J. W., and Tegart, W. J. M., 1952, “Relation between Friction and Hardness R . Wilson (Discussion Meeting),” Proc. R. Soc. London. Ser. A, Math. Phys., 212(1111), pp. 452–458.

[62] Tjong, S. C., and Lau, K. C., 2000, "Abrasion Resistance of Stainless-Steel Composites Reinforced with Hard TiB 2 Particles," Compos. Sci. Technol., 60, pp. 1141–1146.

[63] Dwivedi, D. K., 2004, "Sliding Temperature and Wear Behaviour of Cast Al-Si-Mg Alloys," Mater. Sci. Eng. A, 382(1–2), pp. 328–334.

[64] Zambrano, O. A., Aguilar, Y., Valdés, J., Rodríguez, S. A., and Coronado, J. J., 2016, "Effect of Normal Load on Abrasive Wear Resistance and Wear Micromechanisms in FeMnAlC Alloy and Other Austenitic Steels," Wear, 348–349, pp. 61–68.

[65] Abdel Aziz, M., Mahmoud, T. S., Zaki, Z. I., and Gaafer, A. M., 2006, "Heat Treatment and Wear Characteristics of Al2O3 and TiC Particulate Reinforced AA6063 Al Alloy Hybrid Composites," J. Tribol., 128(4), pp. 891–894.

[66] Sinha, A., and Farhat, Z., 2014, "A Study of Porosity Effect on Tribological Behavior of Cast Al A380M and Sintered Al 6061 Alloys," J. Surf. Eng. Mater. Adv. Technol., 05(01), pp. 1– 16.

[67] Biswas, P., Mondal, M. K., and Mandal, D., 2019, "Effect of Mg2Si Concentration on the Dry Sliding Wear Behavior of Al-Mg2Si Composite," J. Tribol., 141(8), pp. 1–11.

[68] Xu, X., Hipgrave, F., Zwaag, S. Van Der, and Xu, W., 2016, "Correlating the Abrasion Resistance of Low Alloy Steels to the Standard Mechanical Properties : A Statistical Analysis over a Larger Data Set," Wear, 368–369, pp. 92–100.

[69] Subramanian, C., 2010, "Wear Properties of Aluminium-Based Alloys," Surf. Eng. Light Alloy. Alum. Magnes. Titan. Alloy., pp. 40–57.

[70] Sameezadeh, M., Emamy, M., and Farhangi, H., 2011, "Effects of Particulate Reinforcement and Heat Treatment on the Hardness and Wear Properties of AA 2024-MoSi 2 Nanocomposites," Mater. Des., 32(4), pp. 2157–2164.

[71] Xu, L., and Kennon, N. F., 1991, "A Study of the Abrasive Wear of Carbon Steels," Wear, 148(1), pp. 101–112.

[72] Zum Ghar, K. H., 1988, "Modelling of Two-Body Abrasive Wear," Wear, 124, pp. 87–103.

[73] Modi, O. P., Mondal, D. P., Prasad, B. K., Singh, M., and Khaira, H. K., 2003, "Abrasive Wear Behaviour of a High Carbon Steel: Effects of Microstructure and Experimental Parameters and Correlation with Mechanical Properties," Mater. Sci. Eng. A, 343(1–2), pp. 235–242.

[74] Erickson, R. C., 1982, "Effects of Mechanical Properties on the Wear Resistance of Journal Bearing Alloys Effects of Mechanical Properties on the Wear Resistance of Journal Bearing Alloys," A S L E Trans., 25(3), pp. 309–322.

[75] Sundström, A., Rendón, J., and Olsson, M., 2001, "Wear Behaviour of Some Low Alloyed Steels under Combined Impact/Abrasion Contact Conditions," Wear, 250(1–12), pp. 744–754.

[76] Mutton, P. J., and Watson, J. D., 1978, "Some Effects of Microstructure on the Abrasion Resistance of Metals," Wear, 48(2), pp. 385–398.

[77] Sedlacek, M., Podgornik, B., and Vizintin, J., 2009, "Influence of Surface Preparation on Roughness Parameters , Friction and Wear," Wear, 266, pp. 482–487.

[78] Demirci, I., Mkaddem, A., and Khoukhi, D. El, 2014, "A Multigrains ' Approach to Model the Micromechanical Contact in Glass Fi Nishing," Wear, 321, pp. 46–52.

[79] Fan, Z., Lei, X., Wang, L., Yang, X., and Sanders, R. E., 2018, "Influence of Quenching Rate and Aging on Bendability of AA6016 Sheet," Mater. Sci. Eng. A, 730, pp. 317–327.

[80] Jourani, A., and Bouvier, S., 2015, "Friction and Wear Mechanisms of 316L Stainless Steel in Dry Sliding Contact : Effect of Abrasive Particle Size Friction and Wear Mechanisms of 316L Stainless Steel in Dry Sliding Contact : Effect of Abrasive Particle Size," Tribol. Ser., 58(1), pp. 131–139.

[81] Trevisiol, C., Jourani, A., and Bouvier, S., 2017, "Effect of Hardness, Microstructure, Normal Load and Abrasive Size on Friction and on Wear Behaviour of 35NCD16 Steel," Wear, 388– 389, pp. 101–111.

[82] Narayanaswamy, B., Hodgson, P., and Beladi, H., 2016, "Effect of Particle Characteristics on the Two-Body Abrasive Wear Behaviour of a Pearlitic Steel," Wear, 354–355, pp. 41–52.

[83] Alizadeh, A., Abdollahi, A., and Biukani, H., 2015, "Creep Behavior and Wear Resistance of Al 5083 Based Hybrid Composites Reinforced with Carbon Nanotubes (CNTs) and Boron Carbide (B4C)," J. Alloys Compd., 650, pp. 783–793.

[84] Hsu, S. M., Shen, M. C., and Ruff, A. W., 1997, "Wear Prediction for Metals," Tribol. Int., 30(5), pp. 377–383.