Alexandria Engineering Journal (2016) 55, 19–36

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ORIGINAL ARTICLE

Wear behaviour of Al 2618 alloy reinforced with Si_3N_4, AlN and ZrB_2 in situ composites at elevated temperatures

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Received 29 December 2015; accepted 14 January 2016
Available online 15 February 2016

KEYWORDS

Aluminium matrix composites (AMC);
Wear;
Taguchi method;
ANOVA;
Genetic Algorithm (GA)

Abstract Al 2618 matrix material was mixed with the Silicon Nitride (Si_3N_4), Aluminium Nitride (AlN) and Zirconium Boride (ZrB_2) reinforced particles. AMC was synthesized successfully by the stir casting method with the various X-wt.% of reinforcements ($X = 0, 2, 4, 6, 8$). Tribological behaviour was studied in this composite with various temperature conditions. The working conditions were Temperature (°C), Load (N), Velocity (m/s) and Sliding Distances (m). Before wear testing the mechanical behaviour has been analysed. EDAX was confirmed by the matrix material composition. The Al 2618 alloy and the reinforcement mixers were confirmed by the X-ray Diffraction analysis. Wear rate (mm^3/m), Wear resistance (m/mm^3), Specific Wear rate (m/Nm) and Co-efficient of friction (μ) were analysed with various conditions. The worn surfaces were analysed before and after wear testing by Scanning Electron Microscope (SEM). Influence of process parameters and Percentage of contribution were analysed by Taguchi and Analysis of Variance (ANOVA) methods. Genetic Algorithm (GA) was adopted for optimizing the best and mean of the wear rate and to identify the exact influence of input parameters.

1. Introduction

Aluminium metal matrix composites (AMC) has the wide range of application for its high mechanical properties, high corrosion resistances and low density [1] for its superior qualities. In AMC fabrication method is the main important for evenly distributing the reinforcements. There are many ways to produce the AMC in powder metallurgy route, and also achieve the even distribution of the reinforcements [2–4].

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.01.017
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Commonly the reinforcements are used to improve the mechanical properties and structural properties of the composite materials [5,6]. Recently in situ process has used the successful method to producing composites. In this method matrix material and reinforcements are mixed together and thus giving the excellent results and also better adhesion is achieved between the matrix and reinforcements [7–14]. In situ process has the fine mixture of the composite and the advantages of uniform distribution, fine grain size, clear interface and thermodynamically stable of reinforcements compared with ex situ process [15,16]. In this study Al 2618 is taken as the matrix material and Silicon Nitride (Si_3N_4), Aluminium Nitride (AlN) and Zirconium boride (ZrB_2) were selected as the reinforcement particles. The matrix material and reinforcement particles are mixed by the stir casting method to make the Al 2618 composites. The addition of reinforcement particles with matrix material percentage of weight 0, 2, 4, 6, 8. The mechanical properties such as hardness test, tensile test and compression test were conducted. In this investigation Pin-on-Disc apparatus was used to find the sliding wear behaviour of Al 2618 composites with various wt.% of reinforcements at various temperature conditions. Microstructure, EDAX and X-ray Diffraction analyses were analysed to find the formed different phases of Al 2618 composites. The before wear and after wear of Al 2618 composite worn surfaces were analysed by Scanning Electron Microscope (SEM). The input process parameters are optimized by Taguchi, ANOVA and Genetic Algorithm (GA).

2. Experimental details

2.1. Material selection and sample preparation

In this investigation, however, the previous studies reported the influence of scandium and zirconium on the typical age-hardenable Al–Cu–Mg series alloys. Compared to other 2XXX series alloys, alloy 2618 (Al–Cu–Mg–Fe–Ni series) has good strength at elevated temperature [17]. Aluminium metal matrix composite was produced with various weight percentages of reinforcement particles. Al 2618 is considered as the base metal and Silicon Nitride (Si_3N_4), Aluminium Nitride (AlN) and Zirconium boride (ZrB_2) are acted as the reinforcement particles because their hard ceramics is used to improve the properties of materials. ZrB_2 was synthesized with the two powders namely $K_2Z_rF_6$ and KBF_4 by in situ method. The chemical composition of Al 2618 is shown in Table A.1.

The stir casting method is adopted for making the metal matrix composites in this study. The Al 2618 alloy was melted inside the crucible with its melting temperature. After that the reinforcement powders about Si_3N_4, AlN and ZrB_2 particles were mixed with the wt.% of 0, 2, 4, 6, 8 according to the Al 2618 alloy wt.%. In this method the iron stirrer with zirconium coated is used to stir the mixture of matrix and reinforcement for fine mixing of particulates. After that the mixture was poured into the round mould at room temperature which is already prepared for required dimensions for making samples. After cooling the mould the samples are taken out from the mould and they are prepared as 10 mm diameter and 20 mm length cylinder.

Table A.1 Chemical composition of Al 2618 alloy in wt.%.

Element	Cu	Mg	Fe	Ni	Si	Ti	Al
wt.%	2.30	1.60	1.1	1.0	0.18	0.07	Bal

2.2. Mechanical properties

The mechanical properties analysed the Al 2618 composites with various amount of reinforcements. The mechanical properties are used to prove the Al 2618 composites strength.

Hardness test has been conducted by the micro Vicker's hardness testing machine. As per ASTM E10-07 standards the hardness test was conducted on the samples. Totally five specimens are taken from each wt.% of reinforcements, and the test has been conducted on various surfaces on the samples. It helps to attain the average hardness value and also the indent has to stroke the reinforcement.

As per the ASTM EO8-8 standard the tensile test was conducted by the Universal Testing Machine. The samples are well prepared for the test, and they were polished with 1200 grade sic paper to reduce the machining scratches and reduce the outer surface defects of the specimens. The tensile test has been carried out with 10 kN load and the cross head speed of 2.5 m/min in the Universal testing machine.

The compression test is carried out on the Al 2618 composites with various wt.% of reinforcements by the computerized Universal testing machine. The test was carried out as per the ASTM E9-09 standard. The ultimate compressive test was calculated by the applied force adjacent to the deformation in the universal testing machine.

2.3. PIN-ON-DISC wear test

The dry sliding wear tests were conducted by the high temperature Pin-on-Disc apparatus. The tests were conducted as per ASTM G99 G95a standards. The Al 2618 composites with various amounts of reinforcements were used as the test samples with the dimensions of 10 mm diameter and 25 mm height. Before doing the test the contacting surfaces of disc and samples were cleaned with acetone and ultrasonic cleaner. The weights of pin and disc are noted before and after the test with the help of electronic balance in the accuracy of 0.0001 mg. The test was conducted with all the weight percentage (wt.%) of Al 2618 samples, the input parameters of different temperature conditions (°C) 150, 200, 250, 300, 350, and various applied loads (N) 10, 20, 30, 40, 50. The sliding distances (m) were changed in the range of 500, 1000, 1500, 2000 and 2500 and velocity (m/s) 1, 2, 3, 4, 5. Each sample was possessed with five tests at various conditions. The mass loss was calculated from each test and to find the volume loss of samples. Wear rate (mm^3/m), Wear resistance (m/mm^3), Specific wear rate (mm^3/Nm) and Co-Efficient of Friction (μ) were calculated from the volume loss.

2.4. Characterization of the Al 2618 composites

The electronic optical microscope was used to capture the microstructure for Al 2618 composites with various amount of reinforcements at various magnifications to analyse the blend of both matrix material and reinforced particles. The samples are prepared with square shape of each wt.% of reinforced composites using hacksaw blade. The cold setting powder and Liquid were used to cold set the specimens. After that the scratches were removed partially with help of Dry belt and dual disc polisher machines. For obtaining the enhanced microstructure, the chemical etchant called Kellers (Distilled water – 190 ml, HNO_3 – 5 ml, HCl – 3 ml, HF – 2 ml) [18] is applied on the upper surface of the specimen and it is made to dry in hot air by using gun for 30 s. Energy-dispersive X-ray spectroscopy (EDX) is used to identify the composition of Al 2618 alloy. X-ray Diffraction (XRD) was taken to confirm the reinforced particles were successfully mixed with the matrix material. Before and after test samples were examined using Scanning Electron microscopy (SEM) for the analyses of worn surfaces.

2.5. Optimization techniques

In a wear experiment wear rate was the output result and the composites, temperature conditions, load, velocity and sliding distances were considered as the input parameters [19]. In this study three optimization techniques were used namely Taguchi method, Analysis of Variance (ANOVA) and Genetic Algorithm (GA).

2.5.1. Taguchi method

Taguchi method is the simple way arranging the design of experiment to draft the orthogonal arrays. And also the method is very accurate, easy and the systematic approach of the optimizing techniques [20,21]. In this investigation L_{25} orthogonal array was selected. Al 2618 alloy with addition of various wt.% of Si_3N_4, AlN and ZrB_2 particles (0, 2, 4, 6, 8), Temperature (°C), Load (N), Velocity (m/s) and Sliding distance (m) were taken as input parameters. The condition "Smaller is better" was used to attain the minimum wear rate of Al 2618 composites. The Input parameter and L_{25} Orthogonal array are shown in Tables A.2 and A.3 respectively.

2.5.2. Analysis of variance (ANOVA)

Analysis of variance (ANOVA): the method was commonly used statistically identifying the significant process parameters and also investigating the contribution [22] which obtains the minimum wear rate of Al 2618 composites. MINITAB software was used to calculate the percentage of contribution in each process parameters.

2.5.3. Genetic Algorithm

Genetic Algorithm (GA) is one of the optimization techniques which give the exact and approximate solution [23]. In this study GA was used to find out the exact contribution parameters of wear. GA has some advantages: (1) the variables are generated by the codes to optimize. These codes are used to generate the chromosome and genes to help the optimization. (2) GA method can be performed only by the objective functions and need not to derive the auxiliary knowledge. (3) GA is the nontraditional technique to identify the multi point function to give the exact optimized results compared with one point traditional techniques. (4) GA is commonly adopting the best probability search technique in simple and easy way [24]. GA adopted this investigation to find the best and mean values of wear rate and exact affecting input parameters.

Table A.2 Factors and levels of L_{25} orthogonal Array.

Factor	Levels				
	1	2	3	4	5
Composites (wt.%)	0	2	4	6	8
Temperature (°C)	150	200	250	300	350
Load (N)	10	20	30	40	50
Velocity (m/s)	1	2	3	4	5
Sliding distance (m)	500	1000	1500	2000	2500

3. Results and discussions

3.1. Mechanical properties

3.1.1. Hardness test

The micro Vicker's hardness was conducted on Al 2618 composites with various amounts of reinforcement particles such as Si_3N_4, AlN and ZrB_2. The test was conducted on the each sample of Al 2618 composites with various surfaces to obtain the average hardness value. Due to its fine distribution of reinforcement matrix material has to increase the hardness. The Al 2618 has the high hardness value in higher wt.% of reinforcement (8%) due to the decrease in plastic deformation by the reinforcement particles. AlN particles are dissolved with the effect of hard binder to decline the particle size to increase the aluminium with reinforced particles having the higher hardness strength. The results to addition of Si_3N_4 particles have to resist the dislocation of particles and to reduce the plastic deformation to improve the mechanical properties. The results are shown in Fig. A.1.

3.1.2. Tensile test

Tensile strength is performed by Universal testing machine on Al 2618 alloy reinforced by Si_3N_4, AlN and ZrB_2 particles with the weight percentage (wt.%) of 0, 2, 4, 6, 8. The samples are prepared before to conduct the test and the samples cleaned with 1200 grade emery sheet to reduce the scratches to get the accurate result. The dispersion of reinforcements is evenly distributed and thus having continuous locations and having the high strength [25]. Particle volume process increases the elongation significantly the addition of ZrB_2 particles to improve the tensile strength. The addition of Si_3N_4 particles has the brittleness to help decrease the ductility content of composites. AlN particles have the superior hard ceramics and improve the wear properties also. Finally the tensile strength was increased with increase in reinforcements. The observed tensile test results are shown in Fig. A.2.

3.1.3. Compressive test

The compression test was conducted with five specimens along various amounts of reinforcements. The ultimate compressive strength is high due to the reinforcement particles acting as a second phase in the phase and resisting the movement of dislocation in the matrix composite [26]. At each stage of wt.% of (0, 2, 4, 6, 8) reinforcement material with matrix Al 2618 possess higher value compressive strength due to the hybrid composites are greater than those of base alloy [27]. The compression test proved the Al 2618 composite has the higher compression

Table A.3 L_{25} orthogonal array of input process parameters.

Experiment number	Input parameters				
	Composites (wt.%)	Temperature (°C)	Load (N)	Velocity (m/s)	Sliding distance (m)
1	0	150	10	1	500
2	0	200	20	2	1000
3	0	250	30	3	1500
4	0	300	40	4	2000
5	0	350	50	5	2500
6	2	150	20	3	2000
7	2	200	30	4	2500
8	2	250	40	5	500
9	2	300	50	1	1000
10	2	350	10	2	1500
11	4	150	30	5	1000
12	4	200	40	1	1500
13	4	250	50	2	2000
14	4	300	10	3	2500
15	4	350	20	4	500
16	6	150	40	2	2500
17	6	200	50	3	500
18	6	250	10	4	1000
19	6	300	20	5	1500
20	6	350	30	1	2000
21	8	150	50	4	1500
22	8	200	10	5	2000
23	8	250	20	1	2500
24	8	300	30	2	500
25	8	350	40	3	1000

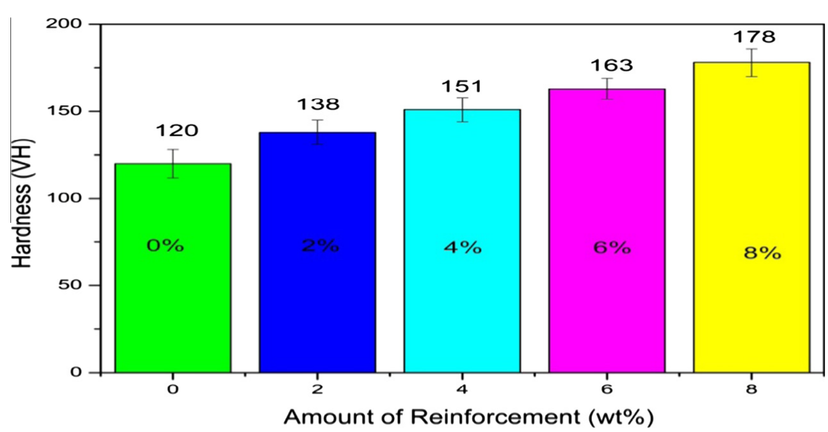

Figure A.1 Hardness results (amount of reinforcement vs hardness).

strength with increasing reinforcements compared with base alloy. The compression strength and amount of reinforcement are shown in Fig. A.3.

3.2. Characterization of Al 2618 composites

3.2.1. Microstructural studies

In Fig. A.4 five micrographs for the composite alloy of various weight percentages are shown. In the same Fig. A.4 (0 wt.%) the micrograph of matrix Al 2618 without reinforcement materials such as Si_3N_4, AlN and ZrB_2 is also shown. It reveals the grains of matrix phase in which its base metal particles are uniformly distributed. In the same Fig. A.4 the microstructure of matrix metal reinforced with increasing reinforcement particles is shown. The grain size of matrix phase refines on in situ for motions of these particles are implied. The bond strength is enhanced at the interface between the matrix and the reinforcement particles. By stir casting method the homogeneous distribution of the reinforcement particles is achieved. The

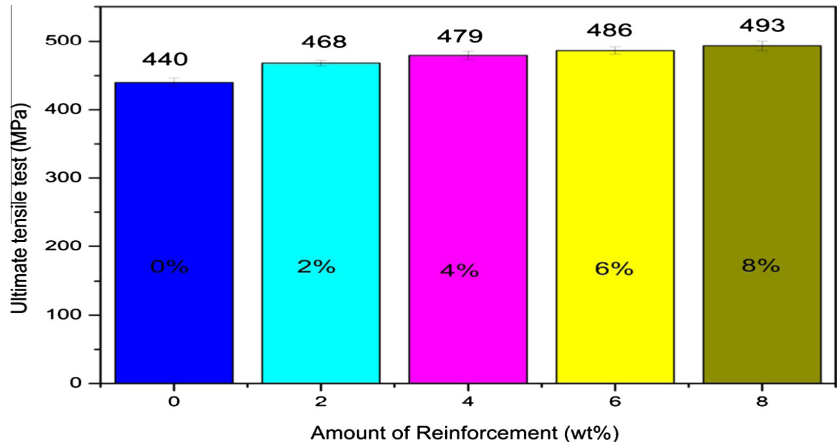

Figure A.2 Tensile results (amount of reinforcement vs ultimate tensile strength).

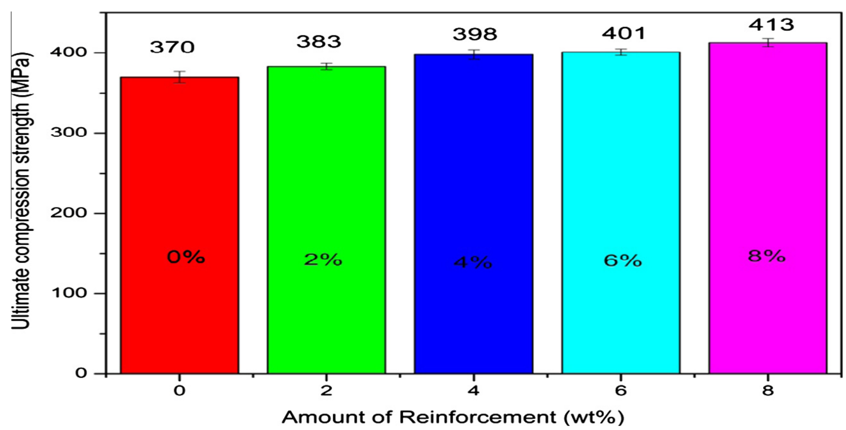

Figure A.3 Compression test results (amount of reinforcement vs ultimate compression strength).

reinforcement fracture might be severe in spite of it, and the improvement of the state of the dispersion of the reinforcement had a good influence on the mechanical properties of the metal matrix composites [28].

In Table A.4, the average grain size of different composites is shown. For composite of 0%, 2%, 4%, 6% and 8% the average values of the grain size are 39.2 μm, 43.8 μm, 30.95 μm, 26.85 μm and 21.9 μm respectively. Due to the restriction in the movement of solidification the main advantages in the presence of reinforced and refine of grains are achieved. They also act as nucleation sites for matrix phase in increasing the number of grains. By solidification front the particles have greater tendency to the push towards grain boundary. Grain boundaries can suppress the grain growth, due to the pinning effect of reinforced particles. The pushed particles have produced the grain refinement and it is commonly observed in reinforcement particles in dispersed particles [29].

3.2.2. EDX analysis

To perform qualitative and quantitative elemental analyses of materials the EDX spectrometer acts as a powerful instrument. It is performed by measuring the characteristics of re-emitted X-rays [30]. From the EDX spectrograph of the composite fillers, the results are obtained. These results consume a number of varying compositions of different types of particles. The EDX analysis of the wear surface after wear being tested is shown in Fig. A.5 and all aluminium alloy peaks are observed. Surface of the alloy contains the content of iron and the presence of oxygen also indicates the reaction of the oxidation and it is one of the remarkable features O peak's presents conforms the oxidation driven wear in variably in all cases. The transmission of iron from the wearing counter face by a mechanical alloying results in the Mechanically Mixed Layer (MML) on the wearing surface [31]. It shows that the iron transfer layer inhibits contacts between the surfaces and so it improves the wear resistance. This behaviour goes hard with the results of Rosenberger et al. [32]. Due to the iron transmit layer restraining contact between the surfaces, the wear resistance is increased.

3.2.3. X-ray diffraction analysis

In Fig. A.6 the reinforcement particles such as Si_3N_4, AlN and ZrB_2 with the results of the X-ray diffraction (XRD) for the

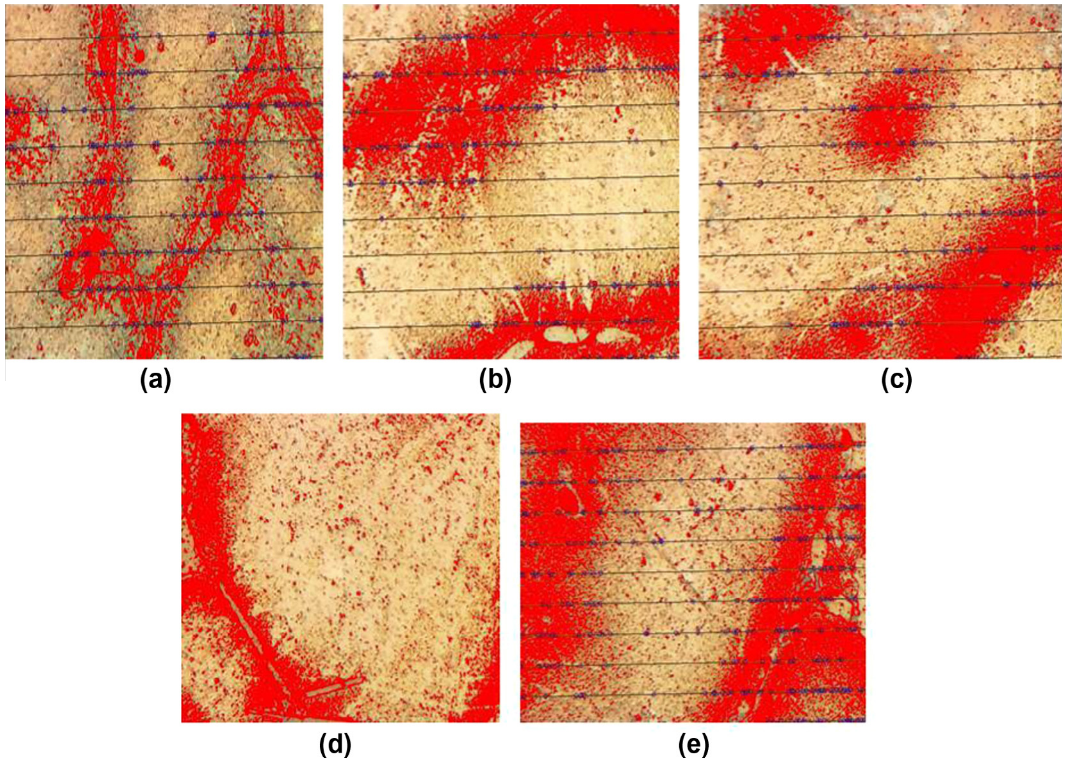

Figure A.4 Micrographs at various wt.% of composites ($a = 0\%$, $b = 2\%$, $c = 4\%$, $d = 6\%$, $e = 8\%$).

Table A.4 Average grain size of the composite alloy.

S. No.	Weight percentage (%)	Grain size of matrix phase (μm)
1	0	39.2
2	2	43.8
3	4	30.95
4	6	26.85
5	8	21.9

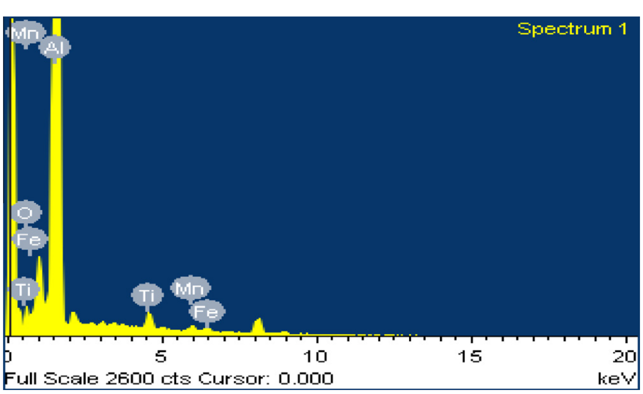

Figure A.5 EDX spectrum of Al 2618 composite.

matrix metal Al 2618 are shown. Al, Si_3N_4, AlN and ZrB_2 phases and their peaks of diffraction are observed. In XRD result that has been obtained reveals that the presence of Aluminium is in form of the largest peaks. At the level below to each other, the mixture of nitride and Aluminium particles in the composite particles occurs. Minor peaks indicate the presence of Zirconium boride and silicon nitride particles. It is evident that there is an increase in the amount of reinforcement particles with the increasing in the intensity of reinforcement particles in the composite. It is also evident that the increases in the weight percentage of the reinforcement ZrB_2 with the measured shift of the Al particles to higher angles are proved. In this analysis, during the sintering process samples are not subjected to oxygen reaction.

4. Analysis of variation graphs

4.1. Wear rate of the composite as a function of amount of reinforcement and temperature, load, sliding distance

The graphs are analysed with various parameters. Figs. A.7a–A.7c indicates the wear rate of the composite as a function of amount of reinforcement and Temperature, Load and Sliding Distance. In Fig. A.7a the wear rate and the Amount of Reinforcement were compared. The various wt.% of Al 2618 composite has involved the wear test as various different temperature conditions. The wear rate was decreased along with the increasing wt.% of reinforcement. The higher wt.% of reinforcement has the minimum wear rate in all the conditions of experiment. In the higher wt.% of reinforcement particles have the greater bonding strength and thus improving the resistance of movement of the particles within the matrix material. Figs. A.7b and

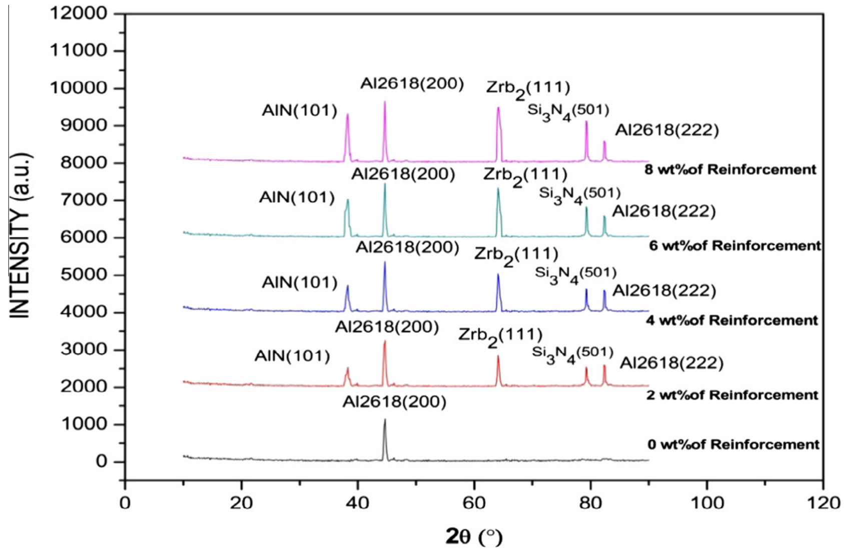

Figure A.6 XRD results for the prepared composites.

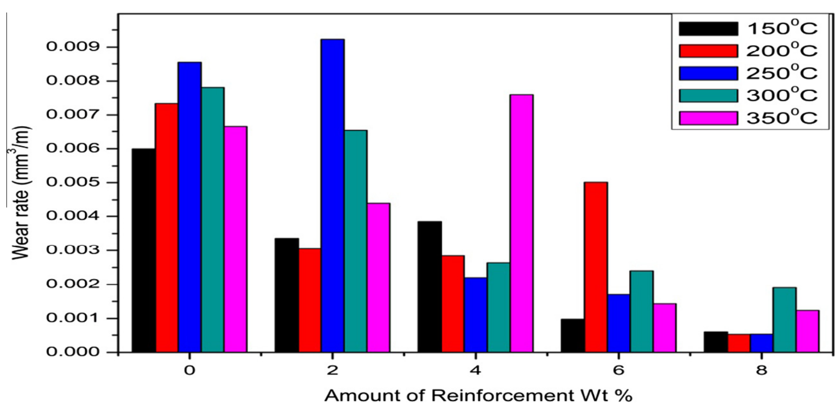

Figure A.7a Wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and temperature (°C).

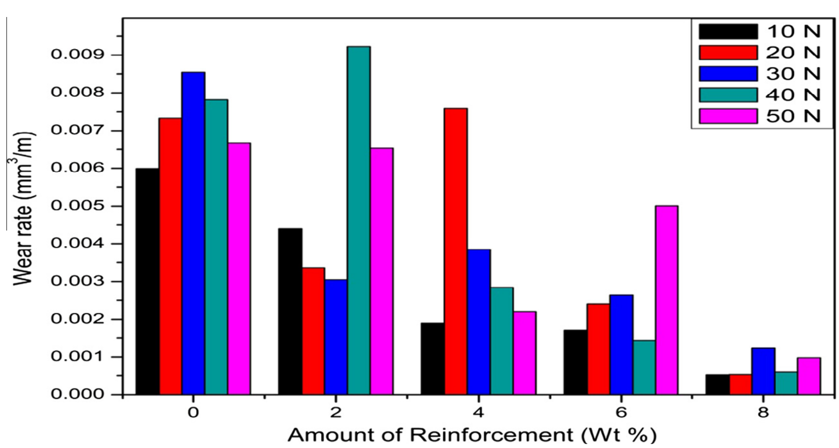

Figure A.7b Wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and load (N).

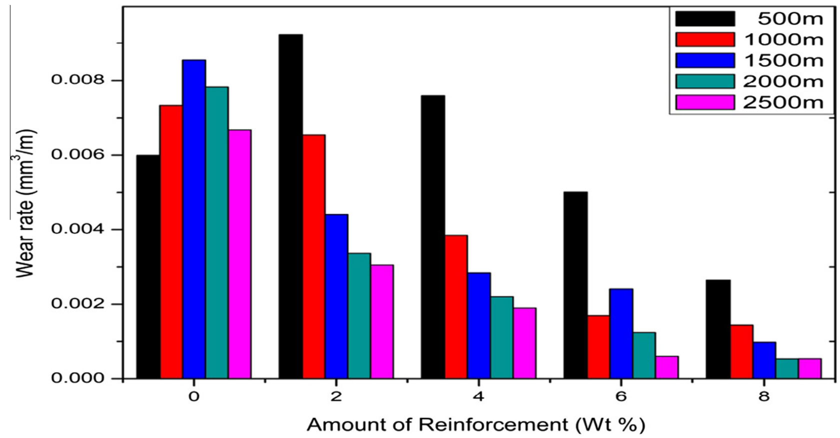

Figure A.7c Wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and sliding distance (m).

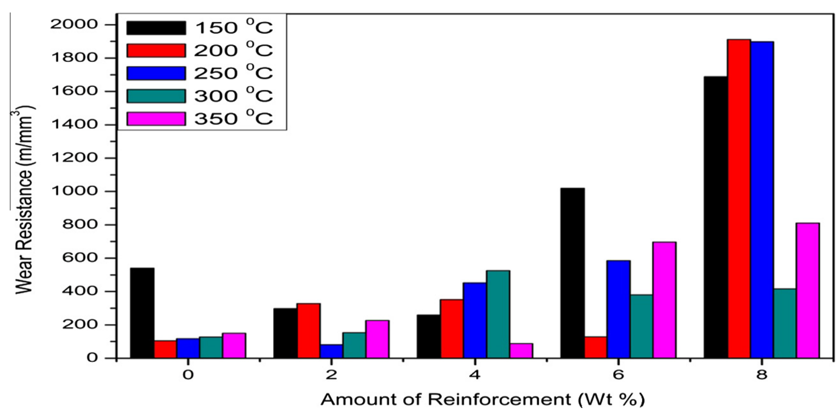

Figure A.8a Wear resistance of the Al 2618 composites as a function of amount of reinforcement (wt.%) and temperature (°C).

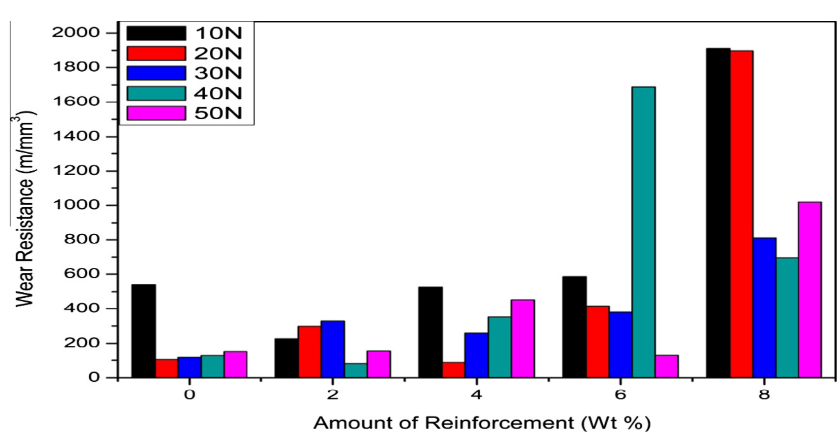

Figure A.8b Wear resistance of the Al 2618 composites as a function of amount of reinforcement (wt.%) and load (N).

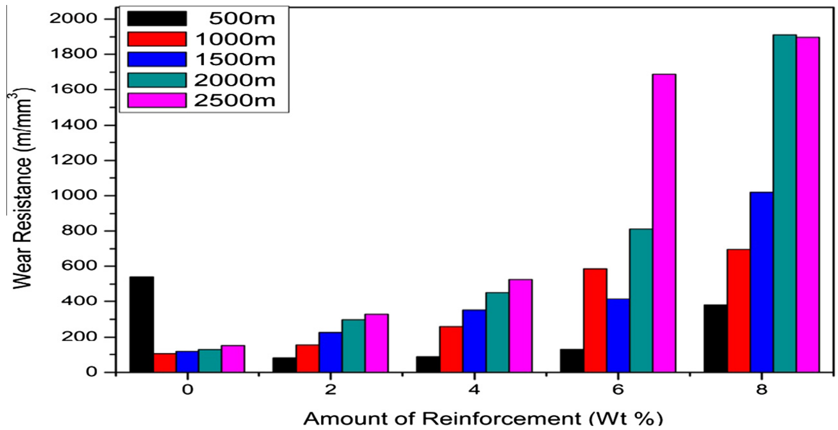

Figure A.8c Wear resistance of the Al 2618 composites as a function of amount of reinforcement (wt.%) and sliding distance (m).

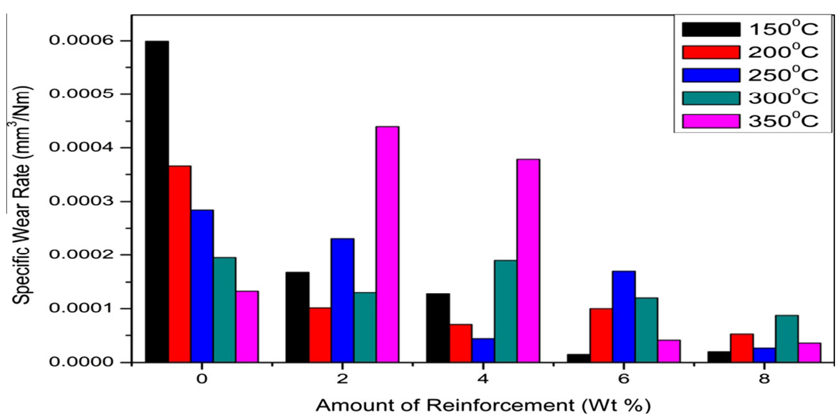

Figure A.9a Specific wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and temperature (°C).

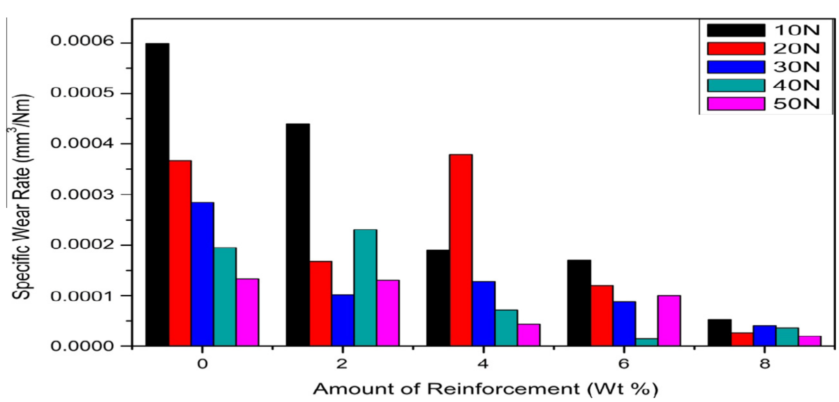

Figure A.9b Specific wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and load (N).

A.7c conforms the minimum wear rate achieved to the various load and sliding Distances.

4.2. Wear resistance of the composite as a function of amount of reinforcement and temperature, load, sliding distance

Al 2618 composites with the various wt.% of the reinforcement have the higher wear resistance along with increasing the reinforcement. The 8 wt.% of composite has the higher wear resistance compared with other mixer of reinforcement. In Figs. A.8a–A.8c the wear resistance Vs Temperature, Load and Sliding distance is shown and it proves the higher wear resistance of the composite with the increase in reinforcement. Reinforcement particles such as Si_3N_4, AlN and ZrB_2 are the hard particles uniformly distributed with the matrix material. The higher resistance of dislocation was avoided in the composites

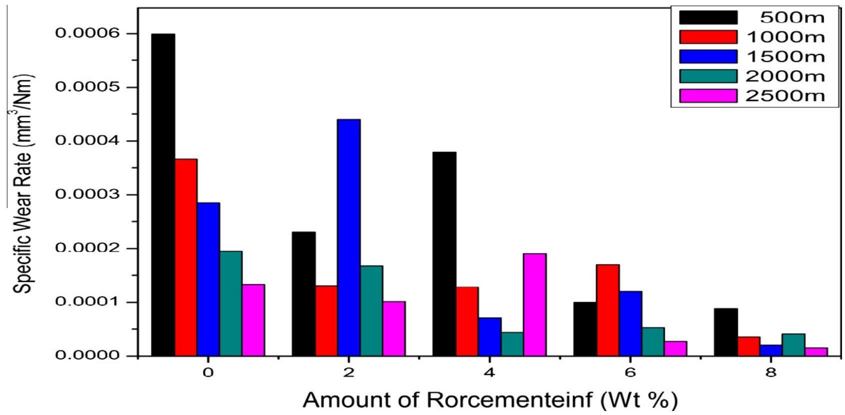

Figure A.9c Specific wear rate of the Al 2618 composites as a function of amount of reinforcement (wt.%) and sliding distance (m).

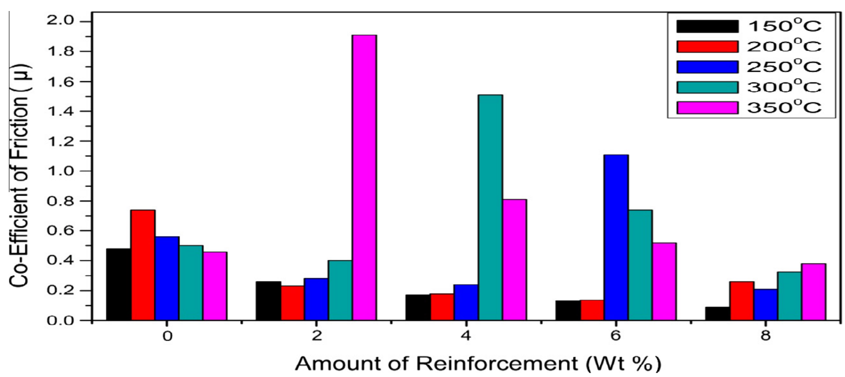

Figure A.10a Co-efficient of friction of the Al 2618 composites as a function of amount of reinforcement (wt.%) and temperature (°C).

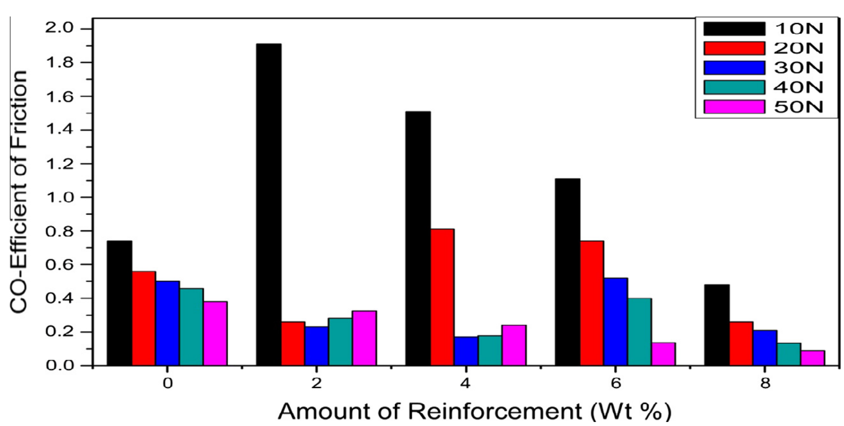

Figure A.10b Co-efficient of friction of the Al 2618 composites as a function of amount of reinforcement (wt.%) and load (N).

to improve the wear properties. The hard particles have to improve the mechanical properties of the composite.

4.3. Specific wear rate of the composite as a function of amount of reinforcement and temperature, load, and sliding distance

Specific wear rate was compared with various wear testing conditions such as Temperature, Load and Sliding distance of the Al 2618 composites with various wt.% of reinforcements. Figs. A.9a–A.9c proves the minimum specific wear rate in all conditions. By the stir casting method the reinforcements were mixed successfully and achieved the uniform distribution to improve the wear properties. The various testing conditions were performed to observe the specific wear rate, the reinforcement contents were increased and the specific wear rate was decreased simultaneously.

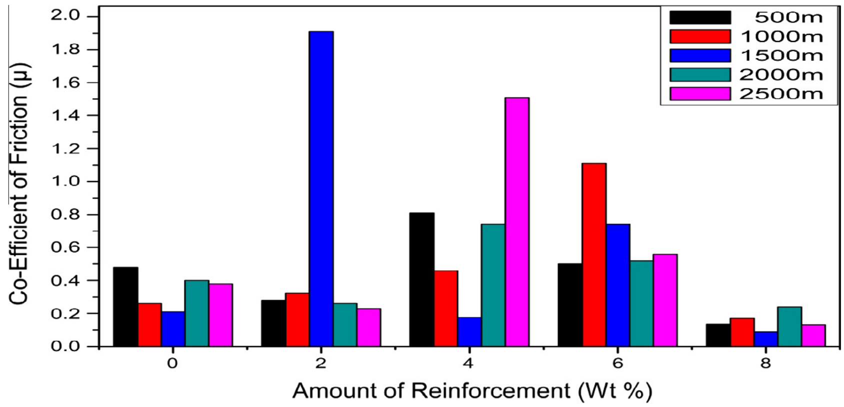

Figure A.10c Co-efficient of friction of the Al 2618 composites as a function of amount of reinforcement (wt.%) and sliding distance (m).

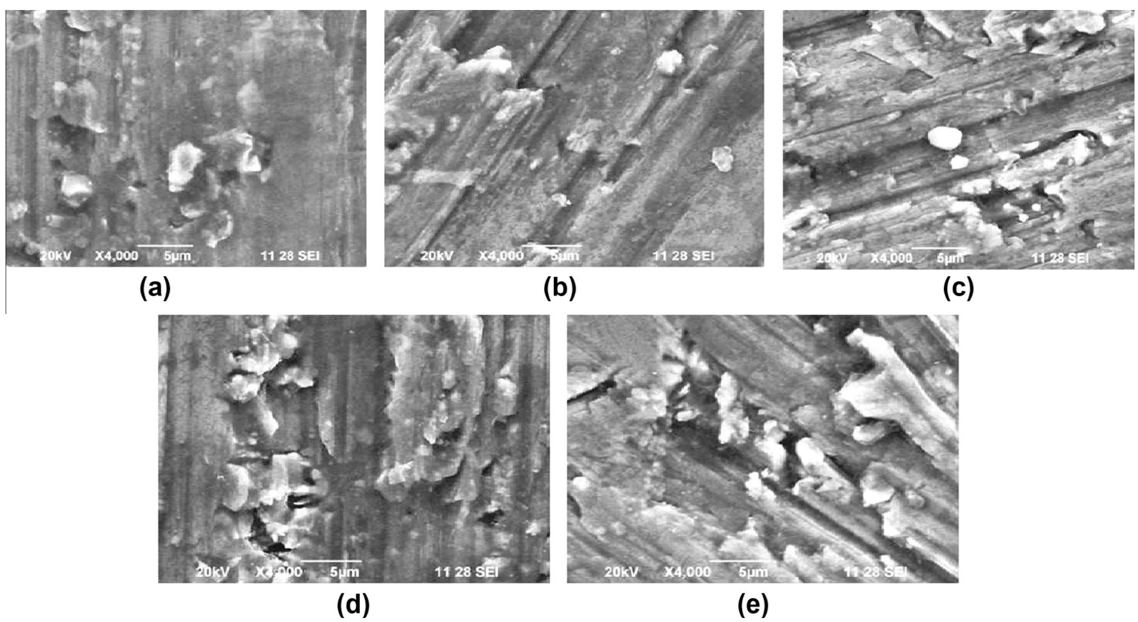

Figure A.11 Before SEM micrographs of worn surfaces ($a = 0\%$, $b = 2\%$, $c = 4\%$, $d = 6\%$, $e = 8\%$).

4.4. Co-efficient of friction of the composite as a function of amount of reinforcement and temperature, load, and sliding distance

The wear test was performed by the design of experiment of input and output conditions. Figs. A.10a–A.10c shows the co-efficient of friction of the Al 2618 composite as a function of amount of reinforcement and temperature, load and sliding distances. The effect of reinforcement particles the Co-efficient of friction gets minimum along with increase in reinforcements. An addition of the hard particles such as Si_3N_4 and AlN with fine mixing of matrix material makes the hard surface of the composite. Hard surface has to avoid the friction during the various input conditions. The 8 wt.% of Al 2618 composite has the minimum Co-efficient of friction proving all various testing conditions.

5. Worn surfaces analysis

In Fig. A.11 the powder mixture of reinforcement particles such as Si_3N_4, AlN and ZrB_2 along with the SEM micrograph of the matrix material Al 2618 is shown. Due to the stir casting process a uniform and homogeneous microstructure of the composite is successfully formed and it is revealed by the micrograph commonly the wear resistance of metal matrix composites. Simultaneously the size and shape of the reinforcement particles are also increasing [33]. The matrix material Al 2618 attains round and cylindrical shapes. Size selection of the reinforcement particles depends upon its potential applications and tribological features [34,35]. The presence of Aluminium and ZrB_2 particles in their corresponding phases is combined by the spotted image of dark and light regions and it is shown in Fig. A.11. It also brings to light the presence of Si_3N_4

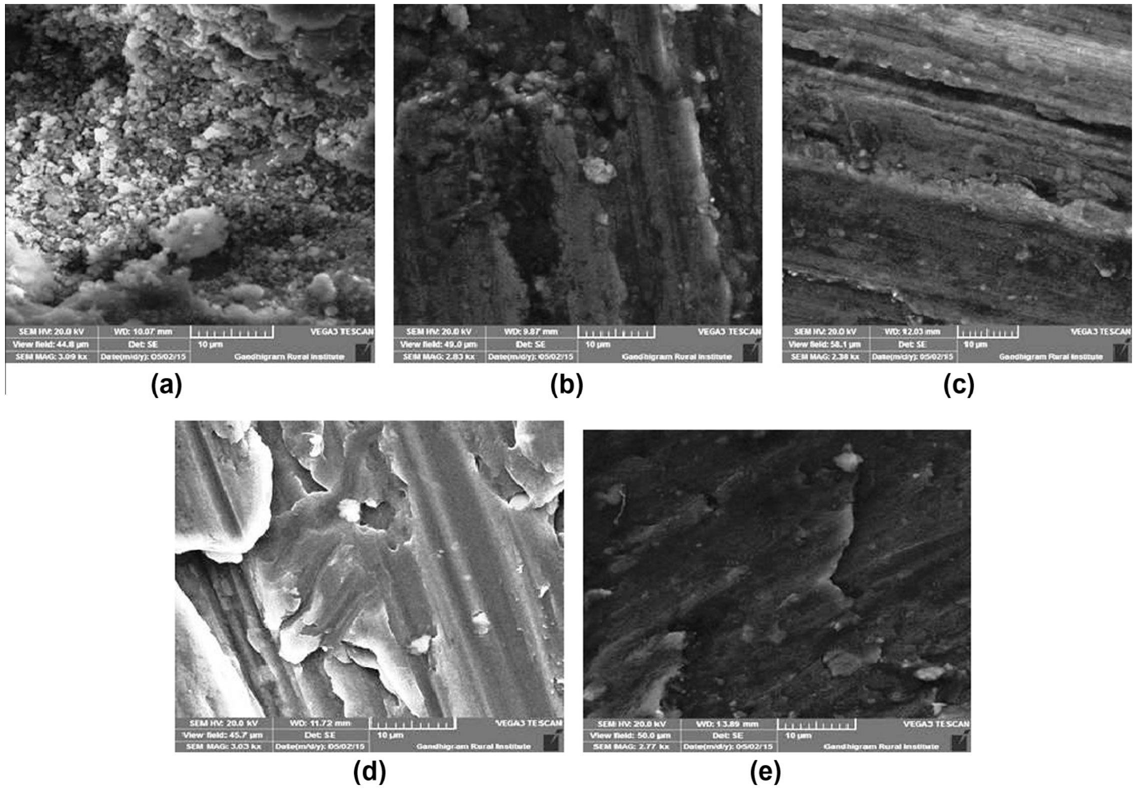

Figure A.12 After SEM micrographs of worn surfaces (*a* = 0%, *b* = 2%, *c* = 4%, *d* = 6%, *e* = 8%).

Table A.5 Input and output parameters L_{25} orthogonal array.

Experiment number	Input parameters					Output parameters
	Composites (wt.%)	Temperature (°C)	Load (N)	Velocity (m/s)	Sliding distance (m)	Wear rate (mm^3/m)
1	0	150	10	1	500	0.005993
2	0	200	20	2	1000	0.007332
3	0	250	30	3	1500	0.008542
4	0	300	40	4	2000	0.007814
5	0	350	50	5	2500	0.006666
6	2	150	20	3	2000	0.003361
7	2	200	30	4	2500	0.003048
8	2	250	40	5	500	0.009232
9	2	300	50	1	1000	0.006537
10	2	350	10	2	1500	0.0044
11	4	150	30	5	1000	0.003851
12	4	200	40	1	1500	0.002844
13	4	250	50	2	2000	0.0022
14	4	300	10	3	2500	0.0019
15	4	350	20	4	500	0.007585
16	6	150	40	2	2500	0.000592
17	6	200	50	3	500	0.005009
18	6	250	10	4	1000	0.0017
19	6	300	20	5	1500	0.0024
20	6	350	30	1	2000	0.001234
21	8	150	50	4	1500	0.000981
22	8	200	10	5	2000	0.000523
23	8	250	20	1	2500	0.000527
24	8	300	30	2	500	0.002634
25	8	350	40	3	1000	0.001434

Table A.6 Response table for means.

Level	Composites (wt.%)	Temperature (°C)	Load (N)	Velocity (m/s)	Sliding distance (m)
1	0.0072694	0.0029556	0.0029032	0.0034270	0.0060906
2	0.0053156	0.0037512	0.0042410	0.0034316	0.0041708
3	0.0036760	0.0044402	0.0038618	0.0040492	0.0038334
4	0.0021870	0.0042570	0.0043832	0.0042256	0.0030264
5	0.0012198	0.0042638	0.0042786	0.0045344	0.0025466
Delta	0.0060496	0.0014846	0.0014800	0.0011074	0.0035440
Rank	1	3	4	5	2

Table A.7 The response table for S/N ratio.

Level	Composites (wt.%)	Temperature (°C)	Load (N)	Velocity (m/s)	Sliding distance (m)
1	42.8353	53.3853	53.4048	52.5603	45.0270
2	46.2616	51.1143	50.5060	51.8239	49.3873
3	49.8375	51.2345	49.9477	49.6277	50.3967
4	55.3038	48.8487	51.0361	50.0842	53.7137
5	59.9641	49.6194	49.3077	50.1062	55.6776
Delta	17.1287	4.5366	4.0971	2.9327	10.6506
Rank	1	3	4	5	2

particles in the Aluminium composites. The particles possess a cluster on the space, which leads to deposition of these particles. It occurs because of high density of Si_3N_4 particles than Aluminium and Si_3N_4 particles possess a good interface between them and it is revealed by the SEM micrograph.

The micrographs of the worn surfaces of Al 2618 alloy slide various temperatures are shown in Fig. A.12. The proper interfacial bonding without any cracking on the surface between Al matrix is illustrated by the phases and it is revealed in the Fig. A.12 (0 wt.%). The Al 2618 composites are restricted with the temperature difference and different loading conditions of 150–350 °C and 10–50 N respectively. Both wear mechanisms of materials abrasive and adhesion wear mechanism occur on the surface. As the temperature and loading conditions are increased randomly the wear rate of the composite is increased and it implies more wear mechanisms as a result transaction from mild to severe wear becomes possible. The presence of Si_3N_4 particles reflects the density of the Aluminium composites and it is shown in Fig. A.12 (2–8 wt.%) [36]. AlN particles are seen in the micrographs and the particles have the sharp edges of abrasive particles. Due to effect of AlN particles scratches, grooves and number of pits are seen in the composites. The less material removal was achieved due to the coarse particles presence cannot easily penetrate on the worn surfaces. The hardness of the composites in various amounts of reinforcements has increased with the addition of AlN particles. Because of the absence of residual particles interface between Aluminium and reinforcement particles were having strong. The thermal expansion of Aluminium and ZrB_2 particles in the microstructure and the small pores was existed. According to the higher reinforcement of the composites there was good strength, bonding between grains and free from micro cracks in the structure. Due to increase in conflict of the dislocation movement across grain boundaries, it is believed that the grain boundaries act as micro cracks nucleation sites and it is due to residual stresses [37]. Further due to subsequent deformation abrasive wear was found in higher temperature condition and adhesion wear was found in lower temperature and loading conditions.

6. Optimization techniques

6.1. Taguchi method

In this investigation, composites (wt.%), Temperature (°C), Load (N), Velocity (m/s) and Sliding Distance (m) are taken as the input parameters. L_{25} orthogonal array was used with the help of Design of Experiment (DOE) in the software of MINITAB. The wear test was conducted with various input process parameters. Totally 25 samples were tested with various amount of reinforcements to obtain the minimum wear rate. The minimum wear rate was 0.000523 mm^3/m. The process parameters were influenced such as composites 8%, Temperature 200 °C, Load 10 N, velocity 5 m/s and the sliding distance 2000 m. The above results have conformed the higher wt.% of reinforcement has the minimum wear rate. Table A.5 shows the input parameter and output results of L_{25} orthogonal array.

6.2. Signal-to-noise ratio

The MINITAB software was employed to find the Signal to Noise ratio of the wear rate of the Al 2618 composites with various amounts of reinforcements. The response tables for means and S/N ratio are shown in Tables A.6 and A.7 respectively. Smaller is a better condition was taken to find the influence of process parameters found. The statistical software is used to find the mean effect and S/N ratio for minimum wear rate of Al 2618 composites. Figs. A.13 and A.14 show the main

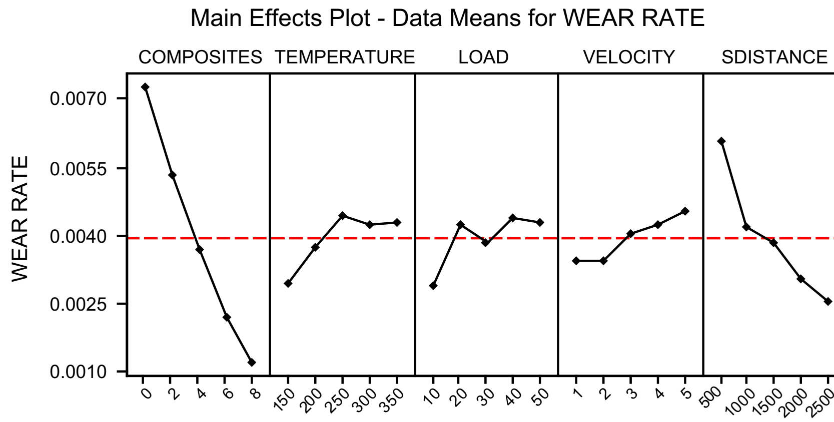

Figure A.13 Main effects plot for means.

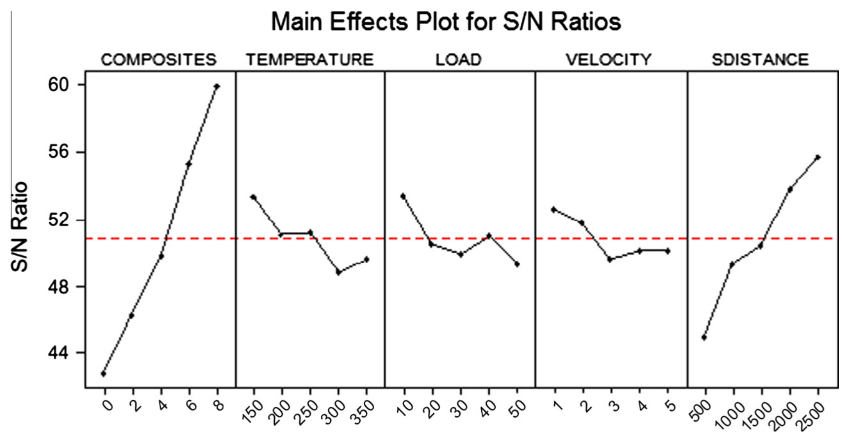

Figure A.14 Main effect plot for S/N ratio.

Table A.8 Results obtained from ANOVA.

Source	DF	Adj. SS	Adj. MS	*F*	*P*	Percentage of contribution
Composites (wt.%)	4	0.0001176	0.0000294	12.04	0.017	63.84
Temperature (°C)	4	0.0000098	0.0000024	0.75	0.608	5.32
Load (N)	4	0.0000074	0.0000019	0.76	0.602	4.01
Velocity (m/s)	4	0.0000073	0.0000018	0.50	0.743	3.96
Sliding distance (m)	4	0.0000373	0.0000093	3.82	0.111	20.2
Error	4	0.0000048	0.0000012			2.60
Total	24	0.0001842				

Adj. SS, adjusted sum of squares; Adj. MS, adjusted mean squares; *F*. statistical test; *P*. statistical value.

effect plots for means and S/N ratio respectively. And the tables explain the ranking of input process parameters such as Composites, Sliding distance, Temperature, Load and Velocity orderly.

The wear of the friction composite materials shows that the composition of the alloy possesses low wear rate due to the presence of more weight percentage of reinforcement materials. The wear rate of the composite will be decreased when the composition of reinforcement increases in the matrix material.

6.3. ANOVA (Analysis Of Variance)

Analysis of Variance method (ANOVA) was used to identify the percentage of contribution of each process parameters and to find the significant influence of the parameters. The ANOVA results are shown in Table A.8. From the ANOVA results composites have the higher percentage of contribution 63.84% influencing the wear rate of the Al 2618 composites and it is followed by Sliding Distance 20.2% and Temperature 5.32%, Load 4.01%, and Velocity 3.96%. Fig. A.15 represents

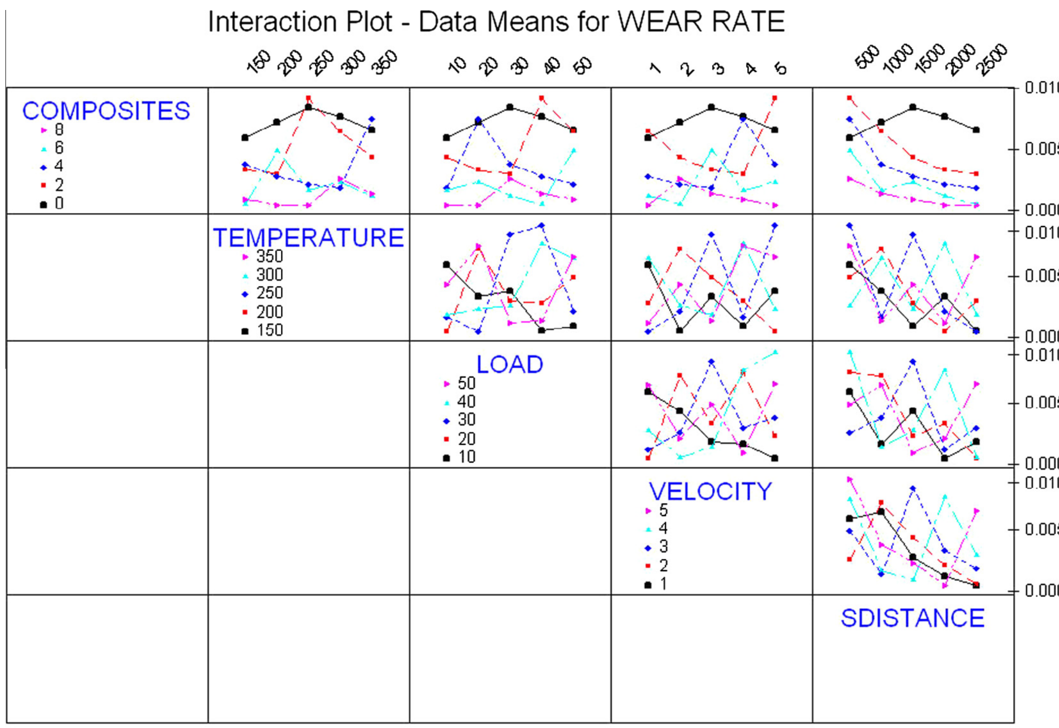

Figure A.15 Interaction plot – data means for wear rate.

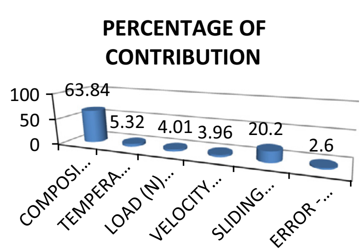

Figure A.16 Percentage contribution of process parameters.

the interaction plot of means for compressive strength and Fig. A.16 represents the respective percentage of contributions graphically.

6.4. Genetic Algorithm

In this investigation, GA is the nontraditional technique used to find the means and best value of wear rate. Al 2618 composites with the various amount of reinforcements have the minimum wear rate with increasing reinforcements. The mathematical equation was formed respective mean and input values using regression equation. The regression and fitness function equations are given in Eqs. (A.1) and (A.2). The Equation was converted to the fitness function. The *X* variables were indicated the input process parameters. In genetic algorithm the input values are given to generate the population and run the chromosomes. The upper and lower values of input parameters were given to optimize the results. The best and mean output vales are generated by the algorithm and also the best input values affecting the wear rate. The comparison of GA results and Experimental results is shown in Table A.9. The obtained input parameters are shown in Fig. A.17 and the mean and best wear are shown in Fig. A.18.

$$\text{Wear rate} = 0.00612 - 0.000761\ \text{COMPOSITES} + 0.000006\ \text{TEMPERATURE} + 0.000029\ \text{LOAD} + 0.000301\ \text{VELOCITY} - 0.000002\ \text{SDISTANCE} \quad (A.1)$$

Fitness Function

$$@(x) + (0.00612 - (0.000761 * x(1)) + (0.000006 * x(2)) + (0.000029 * x(3)) + (0.000301 * x(4)) - (0.000002 * x(5))) \quad (A.2)$$

From the observed results from GA the best output value was found 0.0016458 mm^3/m, and experimental reading is 0.000523 mm^3/m. The best affecting input parameters are

Table A.9 Comparison of optimized results.

	Composites (wt.%)	Temperature (°C)	Load (N)	Velocity (m/s)	Sliding distance (m)	Wear rate (mm^3/m)
GA results	7.999	293.921	20.285	1.001	2165.894	0.0016458
Experimental results	8	200	10	5	2000	0.000523

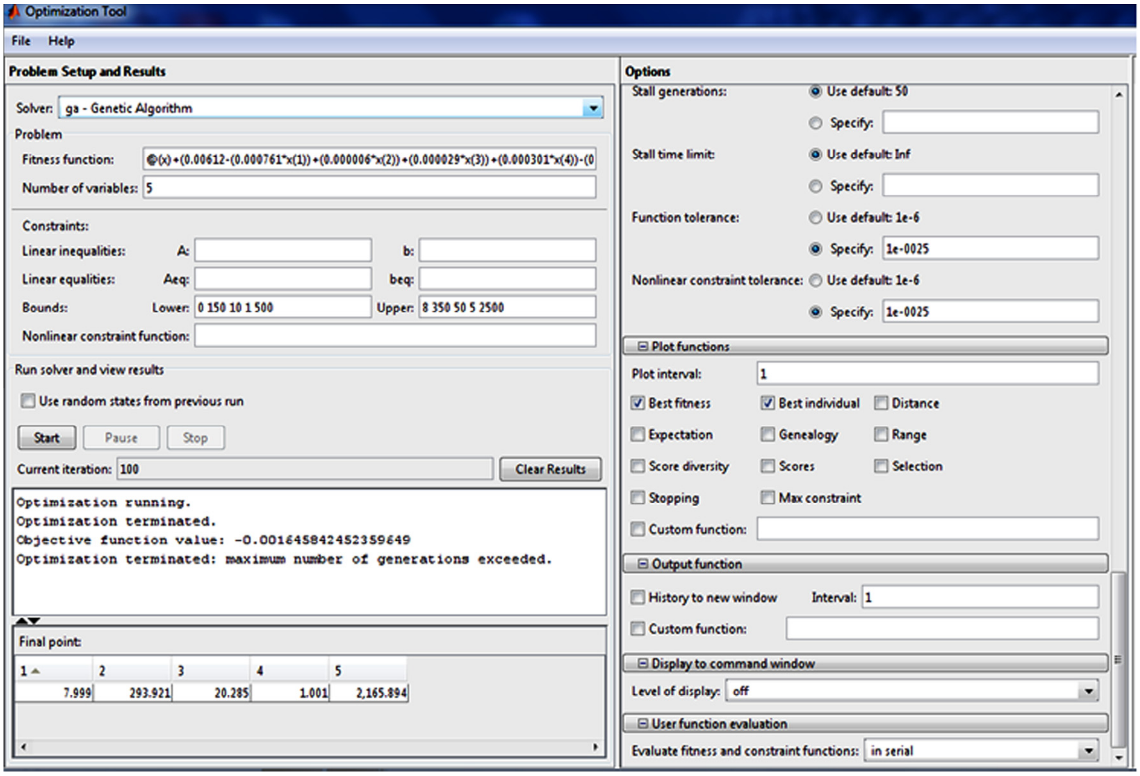

Figure A.17 Optimized process parameters.

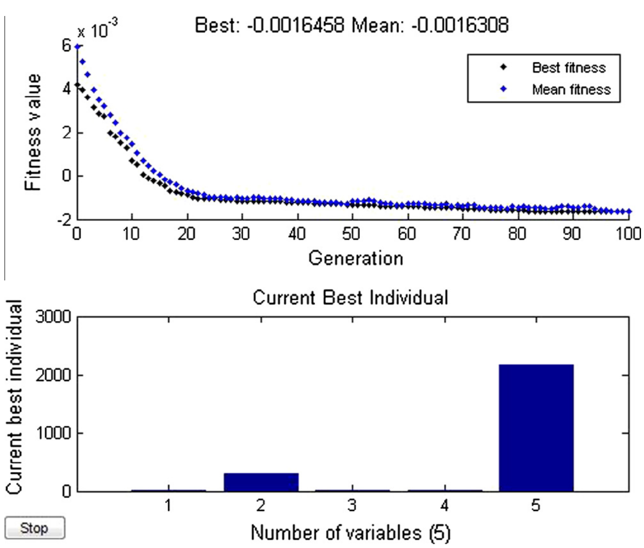

Figure A.18 Best and mean value of wear rate.

composites 7.999 wt.%, Temperature 293.921 °C, Load 20.285 N, Velocity 1.001 m/s and Sliding Distance 2165.894 m.

7. Conclusion

- Al 2618 alloy and Si_3N_4, AlN and ZrB_2 reinforcement particles were mixed successfully with various wt.% by stir casting method.
- The mechanical properties were increased with the increase in reinforcements confirmed by micro Vicker's hardness test, tensile and compressive test.
- The EDAX was proved by the chemical composition of Al 2618 alloy and the XRD was used to confirm the reinforcement presence in the Al 2618 alloy.
- Wear rate (mm^3/m), Specific Wear rate (m/Nm) and Co-Efficient of Friction (μ) were minimized with the various input conditions of wear testing proved by the variation graphs. The maximum wear resistance was achieved in all output conditions in higher wt.% of composite.
- The worn surfaces were analysed before and after wear testing of composites in all wt.% and analyse the movement of particles, presence of reinforcements, mild cracks and porosity were observed.
- The main influence process parameters were analysed by Taguchi method. The minimum wear rate was 0.000523 mm^3/m. The process parameters were influenced such as composites 8 wt.%, temperature 200 °C, load 10 N, velocity 5 m/s and the sliding distance 2000 m observed.
- From the ANOVA results composites have the higher percentage of contribution 63.84% influencing the wear rate of the Al 2618 composites and it is followed by Sliding Distance 20.2% and Temperature 5.32%, Load 4.01%, and Velocity 3.96%.
- The experimental and GA results were compared. The best and mean values of wear rate were 0.0016458 mm^3/m and 0.0016308 mm^3/m. The exact input parameters were composites 7.999%, Temperature 293.921 °C, Load 20.285 N, velocity 1.001 m/s and the Sliding Distance 2165.894 m.

Acknowledgement

The authors like to express our sincere thanks to Research & Development centre for providing us ambient laboratory facilities at RVS School of Engineering & Technology, Dindigul, Tamil Nadu. The authors also wish to acknowledge the Department of Science and Technology, New Delhi, to utilize the facilities under Science and Engineering Research Board (SERB-SB/FTP/ETA-0282/2013) for this research work.

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