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Abrasive Wear Model for Al_2O_3 Particle Reinforced MMCs Using Genetic Expression Programming

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Abstract: In this investigation, a new model was developed to predict the wear rate of Al_2O_3 particle-reinforced aluminum alloy composites by Genetic Expression Programming (GEP). The training and testing data sets were obtained from the well established abrasive wear test results. The volume fraction of particle, particle size of reinforcement, abrasive grain size and sliding distance were used as independent input variables, while wear rate (WR) as dependent output variable. Different models for wear rate were predicted on the basis of training data set using genetic programming and accuracy of the best model was proved with testing data set. The two-body abrasive wear tests of the specimens was performed using a pin-on-disc abrasion test apparatus where the sample slid against different SiC abrasives under the loads of 2N at the room conditions. The test results showed that GEP model has produced correlation coefficient (R) values about 0.988 for the training data and 0.987 for the test data. The predicted wear rate results were compared with experimental results and found to be in good agreement with the experimentally observed ones.

Keywords: Metal matrix composites; Wear modeling; Sliding wear; Two-body abrasion; Genetic Expression Programming

1 Introduction

Metal-matrix composites (MMCs) reinforced with ceramic particles have received substantial attention from the aerospace, automotive, chemical and transportation industries because of their improved strength, high elastic modulus and increased wear resistance over conventional base alloys [Warren and Hunt (2000)]. Among

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the various types of MMCs as an important class of high performance materials, the aluminium based composites reinforced with particles of SiC or Al_2O_3 exhibit better mechanical and tribological properties compared to unreinforced aluminium alloys [Raghumatham et al (1991); Shibata and Ushio (1994)] and have been used as tribological parts in some vehicles due to their high ratio of strength/density and better wear resistance [Chellman and Langenbeck (1993); Prasad and Rohatgi (1987)]. Particulate reinforced aluminium alloy composites have shown a significant improvement in tribological properties including sliding and abrasive wear resistance, and seizure resistance [Rana and Stefanescu (1989); Surappa et al (1982)]. Thus, increased attentions have been directed towards particulate reinforced aluminium MMCs for tribological applications due to their excellent wear resistance, high load carrying capacity and light weight. Some research works show that these composites have potential for applications subjected to abrasive wear conditions [Banerjee et al (1982); Bhansali and Mehrabian (1982); Prasad et al (1992)]. For aluminium alloy matrix composites reinforced with Al_2O_3 or SiC particles, it has been generally agreed that increasing the particle content can enhance wear resistance [Jasim and Dwarakadasa (1987); Kanth et al (1990); Kök (2006)]. High wear resistance of particle reinforced MMCs is due to the ceramic particle content, which protects the metal matrix from wear. Therefore, the application of these composites in automotive and aircraft components is gradually increasing for pistons, cylinder heads, connecting rods, brake drum etc. where the tribological properties of the material are very important [Dellis et al (1991); Ma et al (1996); Deuis et al (1996)]. Out of different wear processes, these components primarily suffer either from abrasive or sliding wear.

Wear is one of the most commonly encountered industrial problems, leading to frequent replacement of components, particularly abrasion. Abrasive wear behaviour of aluminium alloy matrix composites reinforced with various particles such as Al_2O_3, SiC, boron, zircon etc. has been investigated experimentally by many investigators [Alpas and Zhang (1992); Moustafa (1995); Straffelini et al (1997); Hassan et al (2009); Das et al (2007)]. Survey of previous abrasive wear studies reveals that particular efforts were devoted to the determination the most precise model for abrasive wear prediction. Most of the studies propose the multiple regression method and statistical analysis to predict abrasive wear [Prasad et al (1997); Mondal et al (1998); Modi et al (2001); Sahin (2003, 2005, 2007); Sahin and Özdin (2008); Esteban Fennandez et al (2003); Basavarajappa et al (2007); Kumar and Balasubramanian (2008, 2010)]. However, there is a limited number of research study carried out on the abrasive wear of particle reinforced aluminium alloy composites using genetic programming. Prasad et al. [Prasad et al (1997)] showed that the size of abrasive played a significant role in the wear resistance of the specimens, among the many other parameters affecting the abrasive wear of a zinc-based SiC_p-reinforced composite using a statistical analysis. Deuis et al. [Deuis et al (1996)] indicated that the controlling factors affecting the dry sliding wear behaviour of aluminium alloy based composites were the abrasive grit size, hardness of the counter face and properties of the reinforcement phase. Mondal et al. [Mondal et al (1998)] carried out the two body abrasive wear behaviour of a cast aluminium alloy and 10 wt.% Al_2O_3 particle reinforced composite using statistical analysis of the measured wear rate at different operating conditions. The effect of applied load on the wear rate of the composite was found to be more severe. Later work studied by Modi et al. [Modi et al (2001)] showed that the effect of applied load on the wear rate of both zinc alloy and the 10 wt.% Al_2O_3 particle reinforced composite was more severe as compared to that of the abrasive size at different loads. Sahin [Sahin (2003)] investigated the wear behaviour of SiC_p-reinforced aluminium alloy composites using statistical analysis. The wear rate of the composite and matrix alloy has been expressed in terms of the applied load, sliding distance and particle size using a linear factorial design approach. The results showed that the abrasive size was more effective factor for both matrix alloy and its composites, followed by the applied load. Sahin [Sahin (2005)] also studied the prediction of wear resistance model for the metal matrix composites based on the Taguchi method. The experimental results showed that abrasive grit size was found to be the major parameter among the other control factors on abrasive wear, followed by weight fraction of reinforcement. However, the applied load had a much lower effect while sliding distance was not significant. The later work carried out by Sahin [Sahin (2007)] indicated that type of the work piece due to the introduction of SiC particle into the matrix alloy exerted the greatest effect on abrasive wear, followed by applied load and the sliding distance was found to have a much lower effect. Sahin and Özdin [Sahin and Özdin (2008)] demonstrated the increase of the wear rate with increasing applied load, abrasive size and decreased with sliding distance through established equations. No systematic study has been reported so far incorporating various factors that affect the abrasive wear behavior of MMCs. The desired testing parameters are either determined based on experience or by use of a handbook for any testing process. It, however, does not provide optimal testing parameters for a particular situation and testing cost increased significantly. Therefore, several mathematical models based on statistical regression techniques have been constructed to select the proper testing or cutting conditions [Prasad et al (1997); Sahin (2003); Esteban Fennandez et al (2003)]. GP has not been used to model abrasive wear of MMCs so far.

This work provides an alternative approach for the modeling of abrasive wear of particle reinforced MMCs depending on testing parameters and characteristics of materials using Genetic Programming. GP based equations are proposed for wear rate of MMCs. The GP models are based on an experimental data, which was conducted to document the abrasive wear behaviour of tested materials. The proposed GP approach has an important advantage because of the simplicity of the formulation and its wide range of applicability to empirical formulation of various materials engineering where sufficient experimental results exist. This method is an efficient and systematic approach to optimize designs for performance and quality.

The present work is aimed at developing a genetic programming model that could predict the wear rate of Al_2O_3 particle reinforced 2024 aluminium alloy composites, produced by the widely used molten metal mixing method, depending on volume fraction of particle, particle size of reinforcement, abrasive grain size and sliding distance factors. Moreover, the analysis of variance (ANOVA) was employed to study the effects of these factors and their interactions on the sliding wear behaviour of MMCs.

2 Experimental Procedure

2.1 Material Details

In this study, 2024 aluminium alloy with the theoretical density of 2800 kg/m^3 was used as the matrix material while α-Al_2O_3 (alumina) particle with particle sizes of 16, 32 and 66 μm, and a density of 3950 kg/m^3 was used as the reinforcements. The materials used in the present work were 2024 Al alloy composites reinforced with 7.3, 15 and 23.3 vol. % Al_2O_3 particles, having a composition (in wt.%) of minimum 93 α-alumina, 1.8 TiO_2, and maximum 0.8 Fe_2O_3, 1.1 CaO and 0.2 other magnetic materials. They were fabricated by molten metal mixing method and subsequently applied pressure, using a 2 kW power resistance-heated furnace under protected argon gases [Kok (2005)]. The chemical composition of the 2024 Al alloy matrix was (wt. %): 3.23 Cu, 0.81 Mg, 0.74 Si, 0.54 Mn, 0.13 Zn and balance Al. Table 1 shows the characteristics and properties of the materials tested in this study. Details of production processes, methods and microstructure of composites are given in the previous studies [Kök (2006); Kok (2005)].

2.2 Plan of Experiments

The experiments were employed to analyze the effects of testing parameters and characteristics of the materials on wear rate of nine different MMCs work pieces. For the modeling algorithms, Gene Expression Programming (GEP) with four factors at three levels was used. Table 2 presents the details of experimental database including the variables to be designed, their range and codes. The parameters and list of function sets used in the GEP models are given in Table 3 and 4 respectively.

Table 1: Characteristics and properties of the materials tested

Material	Volume fraction of Al_2O_3 particles (vol.%)	Average size of Al_2O_3 particles (μm)	Ultimate tensile strength (MPa)	Brinell hardness (BHN)	Density (kg/m^3)
Al-1-16	7.3	16	88	104	2806
Al-2-16	15	16	100	122	2868
Al-3-16	23.3	16	112	135	2911
Al-1-32	7.3	32	90	101	2808
Al-2-32	15	32	97	116	2886
Al-3-32	23.3	32	105	128	2925
Al-1-66	7.3	66	80	95	2819
Al-2-66	15	66	83	110	2895
Al-3-66	23.3	66	88	118	2967

Table 2: The variables used in model construction

	Code	Variable	Abbreviation	Range
Input	d0	Volume Fraction of Particle (%)	Pv	7.3-23.3
Input	d1	Particle Size (μm)	Ps	16-66
Input	d2	Abrasive Grit Size (μm)	Ags	20-60
Input	d3	Sliding Distance (m)	Sd	150-450
Output	F	Wear Rate(mm^3/m)	Wr	0.00157-0.0556

Table 3: Parameters of the GEP models

P1	Function Set	+, -, *, /, $\sqrt{}$, ex, ln, log, tan, X^2, X^3
P2	Number of Genes	1,2,3,4,5,6
P3	Head Size	3, 5, 8, 10, 12, 15
P4	Linking Function	Addition (+), Multiplication (*)
P5	Number of Generation	10000 and 20000
P6	Chromosomes	30-45
P7	Mutation Rate	0.044
P8	Inversion Rate	0.1
P9	One-point Recombination Rate	0.3
P10	Two-point Recombination Rate	0.1
P11	Gene Recombination Rate	0.1
P12	Gene transposition Rate	0,1

Table 4: List of function sets

Code	Function Set
S1	+, -, *, /
S2	+, -, *, /, $\sqrt{}$, ex
S3	+, -, *, /, $\sqrt{}$, ex, ln
S4	+, -, *, /, ln,
S5	+, -, *, /, log, tan
S6	+, -, *, /, $\sqrt{}$, ex, ln, X^2, X^3

The volume fraction and size of particles, abrasive grain size and sliding distance were assigned to the columns as independent input variables while wear rate was used as dependent output variable. Therefore, a mathematical model of wear rate was developed by using GEP. Moreover, a statistical ANOVA, predicted for a 95 % confidence level, was performed to determine the influences of these factors and their interactions on the abrasive wear, and which parameters are the statistically significant using Minitab version 15 software.

2.3 Abrasion wear tests

A pin-on-disc with emery paper apparatus was employed to evaluate the wear characteristics of composites [Kök (2006)]. SiC papers with three different sizes of 20 (600 grit), 46 (320 grit) and 60 μm (240 grit), fixed on a rotating 115 mm diameter and 12 mm thick aluminium disc with the help of a double sided tape, were used as abrasive mediums. Test specimens were cut from the composite disc, and shaped in the form of cylinder 8 mm in diameter and 30 mm in length. Before the abrasion tests, each specimen was ground up to grade 600 abrasive paper for making sure that the wear surface was in complete contact with the surface of the abrasive paper. Samples for wear testing were loaded against the abrasive mediums by a cantilever mechanism. Wear tests were carried out at room temperature. The test parameters were: normal loads on the pin, 2N, equivalent to nominal normal stresses of 0.04 MPa, sliding velocity of 2 ms^{-1} and sliding distance, 150, 300 and 450 m. Nine groups of composites were tested and each test was performed with a new abrasive paper. Before and after every test, the pins and the disc were cleaned in an ultrasonic bath with acetone and then dried. During the wear tests, the end of the pin specimen was pressed against the abrasive paper on the disc, which was rotating at a fixed speed under the applied load. The wear rates were calculated from the differences in weight of the pin specimens measured before and after the tests using an electronic balance with sensitivity of 0.1 mg. For each test condition, at least three tests were performed and the average was used.

Table 5: The best and the worst results obtained from the GEP test

P1	P2	P3	P4	P5	R^2 Error	
					Training Data	Test Data
S1	1	3	+	18724	0.593	0.597
S1	2	5	+	18414	0.939	0.938
S1	3	8	+	10552	0.976	0.971
S1	4	10	+	11913	0.967	0.912
S1	5	12	+	19366	0.973	0.976
S1	6	15	+	19742	0.971	0.970
S1	1	3	*	17399	0.567	0.578
S1	2	5	*	15283	0.924	0.917
S1	3	8	*	14567	0.936	0.912
S1	4	10	*	14154	0.964	0.970
S1	5	12	*	13700	0.957	0.959
S1	6	15	*	13717	0.958	0.967
S2	1	3	+	17565	0.717	0.711
S2	2	5	+	19127	0.959	0.955
S2	**3**	**8**	**+**	**18178**	**0.976**	**0.974**
S2	4	10	+	19174	0.966	0.964
S2	5	12	+	18216	0.973	0.887
S2	6	15	+	15219	0.966	0.960
S2	1	3	*	17620	0.727	0.715
S2	2	5	*	17720	0.880	0.890
S2	3	8	*	15404	0.963	0.966
S2	4	10	*	19789	0.861	0.884
S2	5	12	*	17591	0.968	0.976
S2	6	15	*	18601	0.698	0.690
S3	3	8	+	19603	0.899	0.892
S3	4	10	+	18655	0.973	0.978
S3	5	12	+	17264	0.902	0.880
S3	3	8	*	18033	0.956	0.967
S3	4	10	*	18858	0.919	0.908
S3	5	12	*	17536	0.889	0.902
S4	3	8	+	18806	0.848	0.860
S4	4	10	+	11481	0.967	0.967
S4	5	12	+	19179	0.914	0.906
S4	3	8	*	19429	0.947	0.960
S4	4	10	*	18045	0.959	0.951
S4	5	12	*	17111	0.970	0.972
S5	3	8	+	18842	0.949	0.954
S5	4	10	+	17939	0.959	0.960
S5	5	12	+	18139	0.957	0.947
S5	3	8	*	18060	0.914	0.922
S5	4	10	*	17576	0.971	0.961
S5	5	12	*	17219	0.803	0.839
S6	3	8	+	16072	0.967	0.965
S6	4	10	+	15820	0.974	0.979
S6	5	12	+	16212	0.965	0.960
S6	3	8	*	19937	0.937	0.941
S6	4	10	*	18970	0.949	0.942
S6	5	12	*	18999	0.731	0.708

3 Results and Discussion

The plan of tests was developed with the aim of relating the effects of the volume fraction of particle (Pv), particle size (Ps), abrasive grain size (Ags) and sliding distance (Sd) with the Wr.

The statistical treatment of the data was made in two steps. The first step was to obtain a mathematical model for wear rate with respect to the parameters affecting the abrasive wear of composites using genetic programming based on experimental results. The second step was related to the ANOVA and the effects of the factors and the interactions. Afterwards, the values calculated using the equation generated for the wear rate models were compared with the experimental measurements, for the purpose of determining the total average errors. Lastly, a correlation graph was performed to do a comparison between the foreseen values from the model developed with the values obtained experimentally.

3.1 Numerical Application and GEP Formulations

Table 5 shows all tried combinations of GEP tests obtained from the experimental results. There are many different combinations of the GEP parameters, which mean as lots of GEP models. Running the GEP algorithm for all of these combinations requires a huge amount of computational time. Therefore, a subset of these combinations is selected intuitively to investigate the performance of the GEP algorithm in predicting the wear rate (Wr). The maximum value of coefficient of correlation in optimal setting is pointed out with bold characters as shown in Table 5. Therefore, this optimal setting was used for the prediction of Wr. Figure 1 shows the training and test evaluation of the GEP method for the Wr prediction.

Table 6: Statistical values of the best results of GEP formulation

Statistical parameter	Training set	Test set
MSE	0.0000034	0.0000081
MAE	0.0013777	0.0023748
R^2	0.976	0.974

To achieve generalization capability for the formulations, the experimental data is divided into two sets as training and test sets. The formulations are based on training sets and are further tested by test set values to measure their generalization capability. Statistical parameters of test and training sets of GEP formulations are given in Table 6 where R^2, MSE and MAE correspond to the coefficient of correlation, mean square error and the mean absolute error of proposed GEP model, respectively. In the literature [Eskil and Kanca (2008); Baykasoglu et al (2009);

Table 7: Results of GEP formulation versus training results

No:	Pv	Ps	Ags	Sd	Wr (mm^3/m)	Wr (mm^3/m)	Wr Test/ Wr GEP
	(vol.%)	(μm)	(μm)	(m)	Test	GEP	
1	7,3	16	20	150	0,0272	0,0270	1,0041
2	7,3	16	20	300	0,0239	0,0209	1,1416
3	7,3	16	46	150	0,0411	0,0429	0,9572
4	7,3	16	46	300	0,0337	0,0360	0,9365
5	7,3	16	46	450	0,0288	0,0333	0,8656
6	7,3	16	60	150	0,0556	0,0530	1,0494
7	7,3	16	60	450	0,0406	0,0417	0,9741
8	7,3	32	20	150	0,0179	0,0165	1,0839
9	7,3	32	20	300	0,0135	0,0141	0,9538
10	7,3	32	20	450	0,0119	0,0132	0,9066
11	7,3	32	46	300	0,0273	0,0252	1,0813
12	7,3	32	46	450	0,0243	0,0229	1,0593
13	7,3	32	60	150	0,0309	0,0368	0,8391
14	7,3	32	60	300	0,0297	0,0304	0,9775
15	7,3	66	20	150	0,0145	0,0153	0,9448
16	7,3	66	20	300	0,0119	0,0127	0,9366
17	7,3	66	20	450	0,0108	0,0117	0,9274
18	7,3	66	46	150	0,0284	0,0242	1,1703
19	7,3	66	46	450	0,0213	0,0174	1,2207
20	7,3	66	60	150	0,0274	0,0276	0,9901
21	7,3	66	60	300	0,0238	0,0224	1,0589
22	7,3	66	60	450	0,0222	0,0201	1,1039
23	15	16	20	300	0,0063	0,0070	0,9029
24	15	16	20	450	0,0061	0,0058	1,0452
25	15	16	46	150	0,0110	0,0119	0,9212
26	15	16	46	300	0,0091	0,0099	0,9182
27	15	16	60	150	0,0144	0,0147	0,9814
28	15	16	60	300	0,0145	0,0124	1,1673
29	15	16	60	450	0,0121	0,0117	1,0332
30	15	32	20	150	0,0017	0,0027	0,6223
31	15	32	20	450	0,0016	0,0030	0,5306
32	15	32	46	150	0,0068	0,0068	1,0040
33	15	32	46	300	0,0064	0,0060	1,0508
34	15	32	46	450	0,0047	0,0058	0,8054
35	15	32	60	300	0,0084	0,0071	1,1832
36	15	32	60	450	0,0071	0,0069	1,0270
37	15	66	20	150	0,0040	0,0029	1,3979
38	15	66	20	300	0,0026	0,0029	0,8985
39	15	66	46	150	0,0042	0,0037	1,1206
40	15	66	46	300	0,0035	0,0038	0,9141
41	15	66	46	450	0,0027	0,0039	0,6960
42	15	66	60	150	0,0032	0,0033	0,9718
43	15	66	60	450	0,0027	0,0041	0,6646
44	23,3	16	20	150	0,0068	0,0081	0,8433
45	23,3	16	20	300	0,0057	0,0046	1,2477
46	23,3	16	20	450	0,0053	0,0034	1,5375
47	23,3	16	46	300	0,0082	0,0054	1,5299

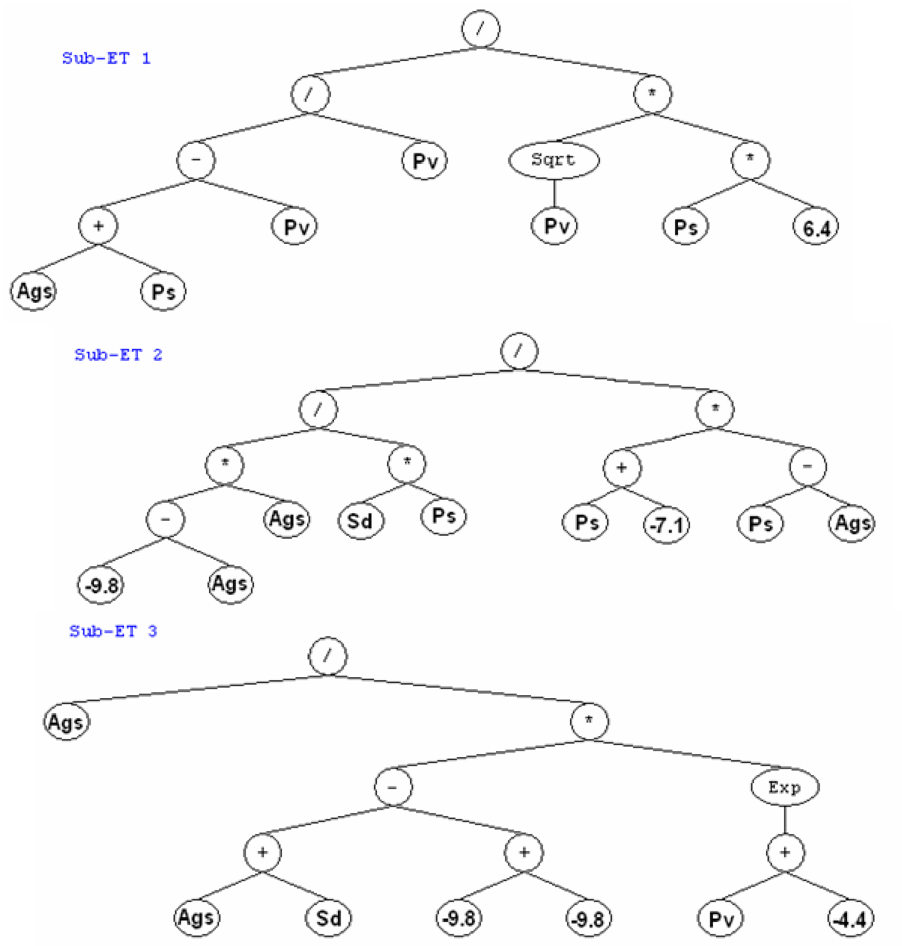


Figure 1: Expression tree for wear rate

Ozbay et al (2008); Kanca and Eskil (2009)], this type of studies includes test sets as 20-30% of the training sets. The patterns used in test and training sets are selected in randomly. The experiments were sorted as the formation order. Sixteen of this experiment numbers were selected randomly. These sixteen experiments were accepted as test set and the others were accepted as training set. Regarding the wear rate (Wr) formulation, 65 training and 16 tests were used as training and test sets presented in Table 7 and 8 respectively. It should be noted that the proposed GEP formulation is valid for the ranges of training sets given in Table 2. Figures 2 and 3 present the training and test evaluation of the GEP method for the wear rate

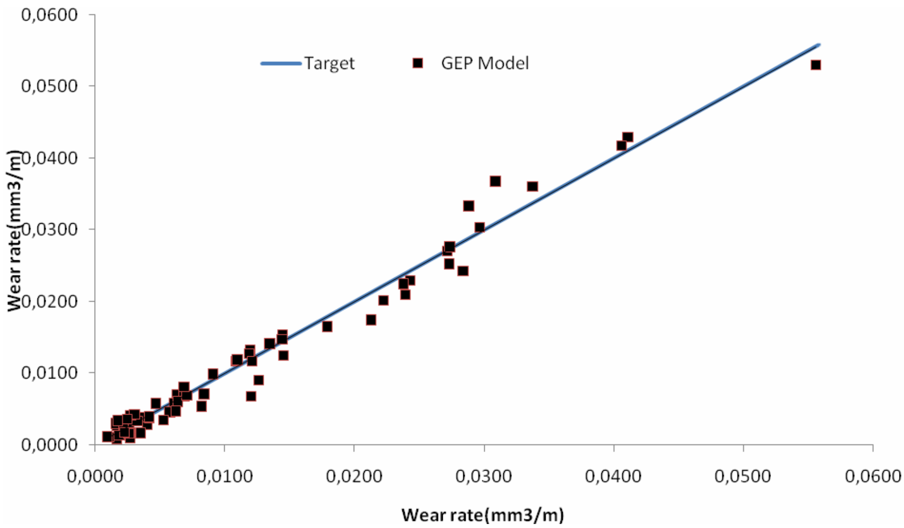


Figure 2: Training evaluation of the GEP method for the wear rate prediction

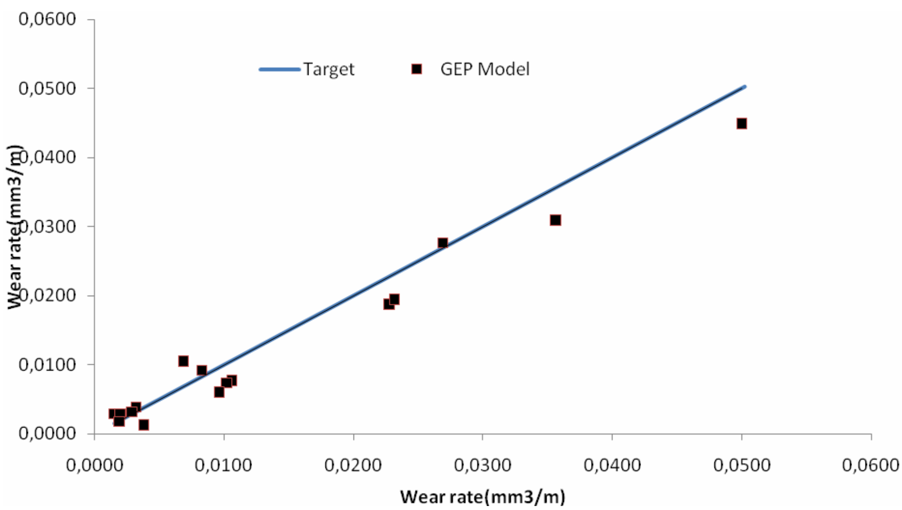


Figure 3: Test evaluation of the GEP method for the wear rate prediction

Table 8: Results of GEP formulation versus training results (Continued)

No:	Pv (vol.%)	Ps (μm)	Ags (μm)	Sd (m)	Wr (mm^3/m) Test	Wr (mm^3/m) GEP	Wr Test/ Wr GEP
48	23,3	16	46	450	0,0062	0,0047	1,3279
49	23,3	16	60	150	0,0126	0,0090	1,3964
50	23,3	16	60	300	0,0120	0,0068	1,7703
51	23,3	32	20	150	0,0016	0,0008	1,9877
52	23,3	32	20	300	0,0011	0,0010	1,0456
53	23,3	32	20	450	0,0009	0,0011	0,8438
54	23,3	32	46	150	0,0042	0,0039	1,0643
55	23,3	32	46	450	0,0022	0,0029	0,7579
56	23,3	32	60	150	0,0030	0,0042	0,7129
57	23,3	32	60	300	0,0025	0,0036	0,6813
58	23,3	32	60	450	0,0017	0,0034	0,5048
59	23,3	66	20	300	0,0024	0,0013	1,8572
60	23,3	66	20	450	0,0018	0,0013	1,4004
61	23,3	66	46	150	0,0035	0,0016	2,1232
62	23,3	66	46	300	0,0026	0,0017	1,5094
63	23,3	66	60	150	0,0027	0,0010	2,8259
64	23,3	66	60	300	0,0026	0,0016	1,6602
65	23,3	66	60	450	0,0023	0,0018	1,2831

prediction. It can be observed that there was a good agreement between the predicted and experimental wear rate within a reasonable percentage of average error (approximately 97.6% and 97.4% for the training and test data, respectively). The obtained expression tree of the formulation is shown in Fig. 1 which corresponds to the following equation:

$$F1 = (Ags + Ps - Pv)/(6.4 * Pv^{3/2} * Ps) \tag{1}$$

$$F2 = -Ags * (9.8 + Ags)/(Sd * Ps * (Ps - 7.1) * (Ps - Ags)) \tag{2}$$

$$F3 = Ags/(e^{Pv-4.4} * (Ags + Sd + 19.6)) \tag{3}$$

$$F = F1 + F2 + F3 \tag{4}$$

Where; Ags: Abrasive grain size, Ps: Particle size, Pv: Volume fraction of particles, Sd: Sliding distance.

3.2 The effects of the variables used in model construction on the wear rate

Analysis of the influence of each factor (Pv, Ps, Ags and Sd) on the wear rate (Wr) has been performed with Taguchi analysis using Minitab version 15 software. The main effects and their interaction plots for the wear rate of the MMCs for mean value are shown in Fig. 4. It can be seen from this figure that the strongest influence was exerted by volume fraction of particles (Pv) and particle size (Ps), respectively.

Table 9: Results of GEP formulation versus test results

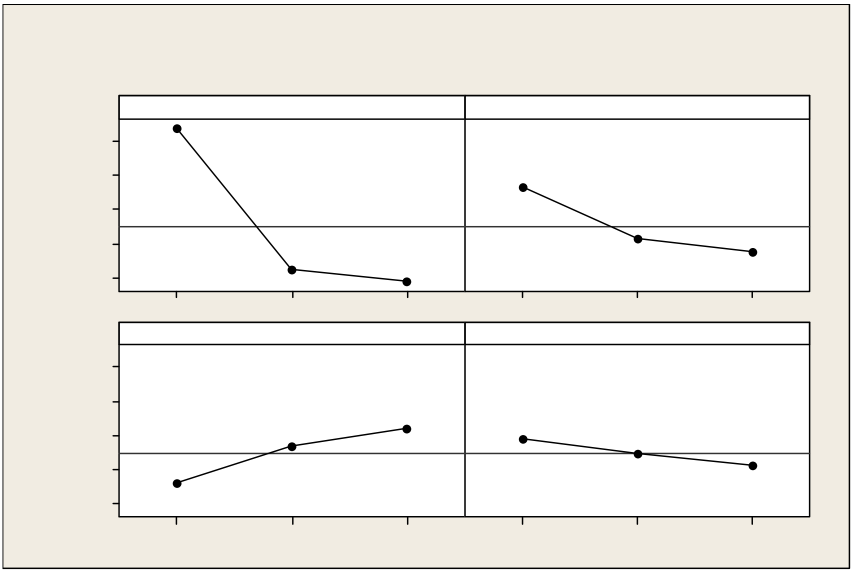
No:	Pv (vol.%)	Ps (μm)	Ags (μm)	Sd (m)	Wr (mm^3/m) Test	Wr (mm^3/m) GEP	Wr Test/ Wr GEP
1	7,3	16	20	450	0,0228	0,0188	1,2121
2	7,3	16	60	300	0,0500	0,0450	1,1123
3	7,3	32	46	150	0,0356	0,0309	1,1517
4	7,3	32	60	450	0,0269	0,0276	0,9734
5	7,3	66	46	300	0,0232	0,0195	1,1920
6	15	16	20	150	0,0069	0,0105	0,6529
7	15	16	46	450	0,0083	0,0092	0,9004
8	15	32	20	300	0,0015	0,0029	0,5328
9	15	32	60	150	0,0106	0,0077	1,3800
10	15	66	20	450	0,0020	0,0029	0,6923
11	15	66	60	300	0,0032	0,0039	0,8236
12	23,3	16	46	150	0,0102	0,0074	1,3843
13	23,3	16	60	450	0,0097	0,0060	1,5979
14	23,3	32	46	300	0,0029	0,0031	0,9163
15	23,3	66	20	150	0,0038	0,0013	2,9568
16	23,3	66	46	450	0,0019	0,0018	1,0696

Table 10: Results of the ANOVA for wear rate of MMCs

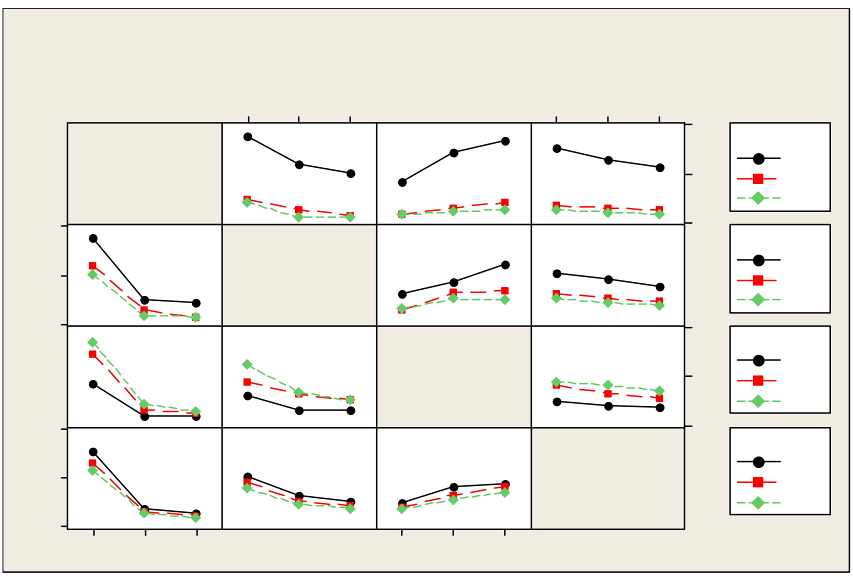
Source of variance	Sum of squares (SS)	Degree of freedom P (%) (DF)	Variance	Test F	Contributions
Pv	0.0084071	2	0.0042035	1358.22	68.77
Ps	0.0013347	2	0.0006673	215.63	10.92
Ags	0.0008974	2	0.0004487	144.98	7.34
Sd	0.0001890	2	0.0000945	30.53	1.55
Pv x Ps	0.0002876	4	0.0000719	23.23	2.35
Pv x Ags	0.0006072	4	0.0001518	49.05	4.97
Pv x Sd	0.0001055	4	0.0000264	8.52	0.86
Ps x Ags	0.0002121	4	0.0000530	17.14	1.74
Ps x Sd	0.0000150	4	0.0000038	1.21	0.12
Ags x Sd	0.0000196	4	0.0000049	1.58	0.16
Error	0.0001486	48	0.0000031		1.22
Total	0.0122237	80			100

Optimal testing conditions of the factors can be very easily determined from these graphs. The optimum condition for tested samples becomes 23.3 % volume fraction of particles, 66 μm particle size, 20 μm abrasive grain size and 450 m sliding distance as shown in Fig. 4. It is evident that volume fraction of particles (Pv) had the greatest effect on influence the optimal testing condition.

Fig. 5 shows the effect of particle size on the wear rate of the composites with respect to the volume fraction of particle and sliding distance based on the GEP results. From this figure, it can be seen that the size of the Al_2O_3 particles had a considerable effect on the abrasion resistance of the composites which increased with increasing the particle size, when the volume fraction of particles was increased from 7.3 to 23.3%. Further, the wear rate of the composites reinforced with 66 μm Al_2O_3 particles is lower than that of the composites reinforced with 16 μm Al_2O_3 particles. This might be due to the lack of microstructural homogeneity, greater porosity and poor interfacial bonding between matrix and Al_2O_3 particles in the latter composites as observed elsewhere [Kok (2005)]. Figs. 6 and 7 show the effects of volume fraction of particles and abrasive grit size on the average wear rate of the composites with three different SiC abrasive grit size. From these figures, it can be seen that the wear rate substantially decreased with increasing Al_2O_3 particles volume fraction from 7.3 vol. % to 23.3 vol. %. This might be because the Al_2O_3 particles have increased the hardness of the matrix alloy considerably as shown in Table 1. As shown in Fig. 7 clearly, the wear rate obviously increased as abrasive grit size increased from 20 μm to 60 μm. This may be since the penetration ability of abrasive increased with increasing the abrasive size and effective stress on the abrasive [22, 38]. In addition, the wear rate decreased with increasing the sliding distance (Fig. 8). This could be attributed to the decreasing cutting efficiency of the abrasive particles during the sliding wear process and increasing wear-induced work hardening of the matrix part of the composites as increasing sliding distance. However, effects of abrasive grit size and sliding distance were much lower compared to those of the volume fraction of particle and particle size (Fig. 4). This is similar to Rabinowicz's classical theory [Sheu and Lin (1996)], claimed that applied load and hardness of materials were most important factors affecting the abrasion process. Similar results were also reported by Esteban et al. [Esteban Fennandez et al (2003)] and Spuzic et al. [Spuzic et al (1997)]. However, Wang and Hutchings [Wang and Hutchings (1989)] reported that coarse abrasive particles and high volume fraction of reinforcement resulting in decreased wear resistance due to breakage and pull out of reinforcement. This is a good agreement with current study because of particle size but it is opposite to the present results because of volume fraction of particles. Banerjee et al. [Banerjee et al (1982)] found similar results for the volume fraction of zircon due to blunting of alumina

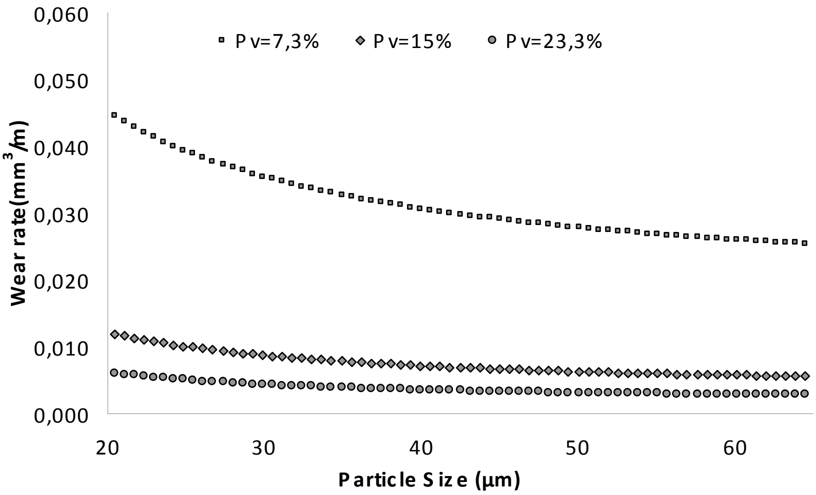


(a)

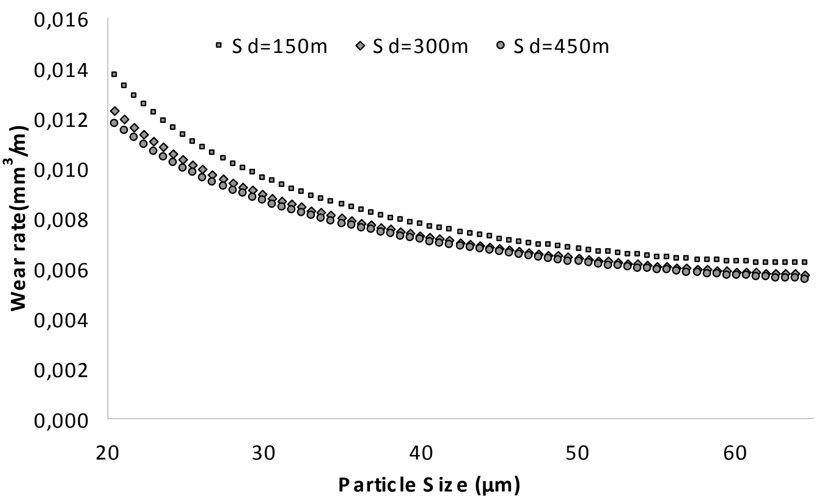


(b)

Figure 4: (a) Main effects plots; (b) Interaction plots for wear rate



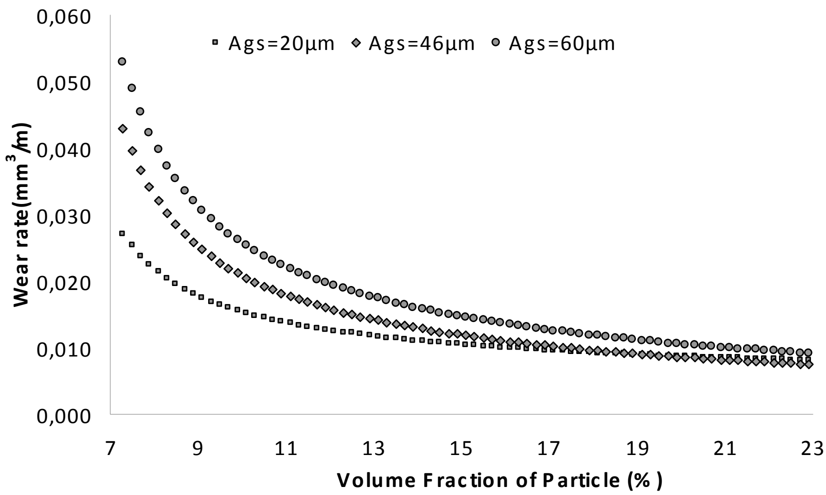
(a)



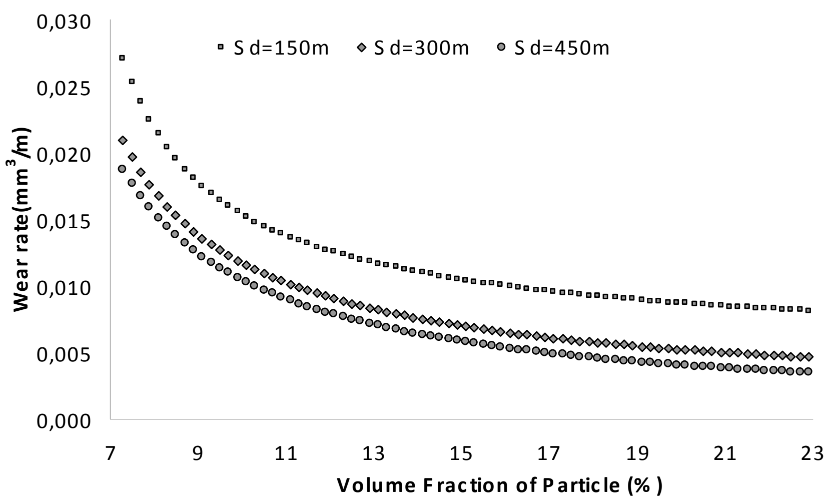
(b)

Figure 5: The effect of (a) Ps and Pv; (b) Ps and Sd on Wr according to GEP results

Figure 5

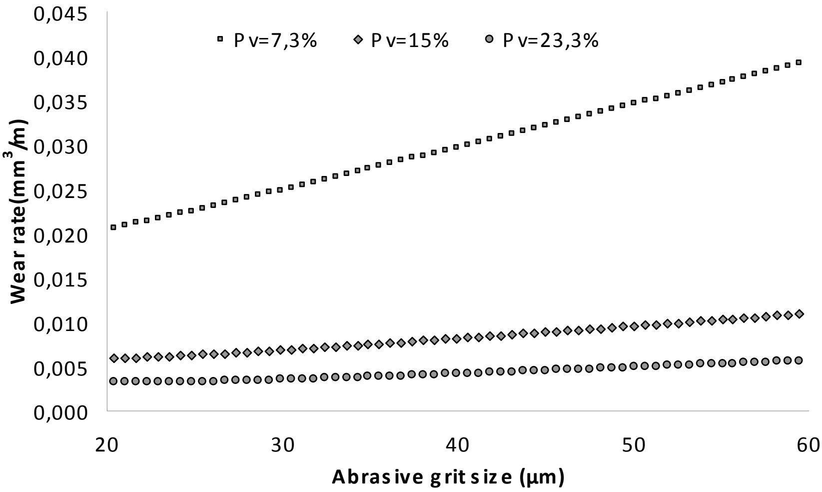


(a)

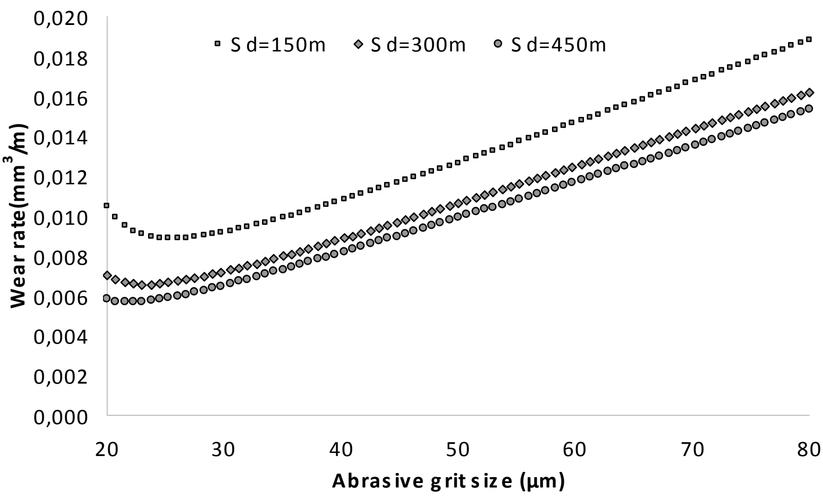


(b)

Figure 6: The effect of (a) Pv and Ags; (b) Pv and Sd on Wr according to GEP results



(a)



(b)

Figure 7: The effect of (a) Ags and Pv; (b) Ags and Sd on Wr according to GEP results

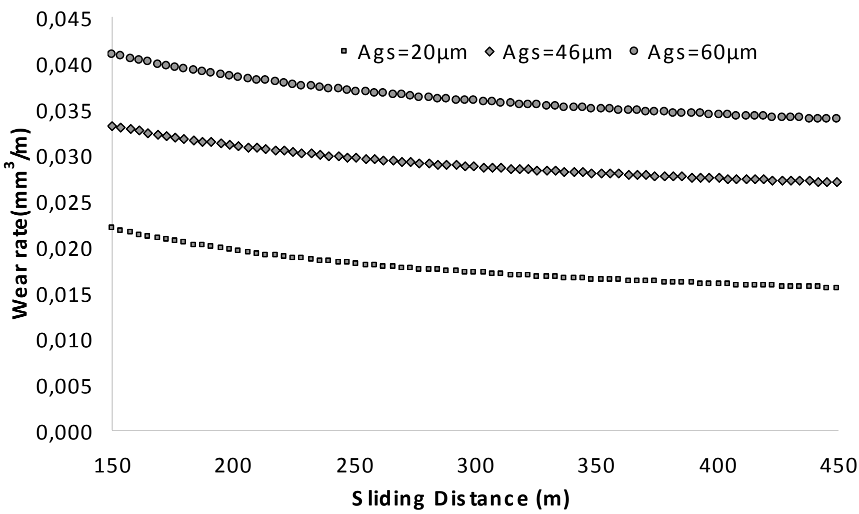


Figure 8: The effect of Sd and Ags on Wr according to GEP results

particles. Mondal et al. [Mondal et al (1998)] reported that the effect of applied load on the wear rate of cast Al alloy and 10 wt.% Al_2O_3 composite was more severe as compared to that of the abrasive grain size, and Prasad et al. [Prasad et al (1997)] showed that the wear rate reduced with sliding distance, whereas it increased with load. These results are similar to the present results.

Previous work carried out by Sahin [Sahin (2003)] found that the abrasive grain size played a significant role on the wear behaviour of MMCs, which is the case for the present work, followed by the applied load. Another study by Sahin [Sahin (2005)] indicated that abrasive grain size was found to be the major parameter among the other control factors on abrasive wear, followed by weight fraction of reinforcement while the applied load had a much lower effect but sliding distance was not significant. As a result, the volume fraction of reinforcement particle played a significant role on the wear behaviour of MMCs in this study, and it is followed by the particle size.

3.3 Analysis of Variance (ANOVA)

The ANOVA is used to investigate as to which design parameters significantly affect the wear behavior. So, ANOVA was carried out on the data corresponding to the wear rate (Wr) for analyzing the effect of volume fraction of particle (Pv), particle size (Ps), abrasive grit size (Ags) and sliding distance (Sd) on the total variance of the results.

Table 9 shows the results of the ANOVA for the wear rate of MMCs. This analysis was carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. The last column of the tables previously shown indicates the percentage of each factor contribution (P) on the total variation, thus indicating the degree of influence on the result.

From the analysis of Table 9, it can be observed that the volume fraction of particle (P=68.77%), the particle size (P=10.92%), the abrasive grit size (P=7.34%) and the sliding distance (P=1.55%) had great influence on the wear resistance property, in particular the volume fraction of particle factor. In other words, examination of the calculated values of variance ratio (F), which is the variance of the factor divided by the error variance, for all factors showed a very high influence of factor Pv and low influence of factor Sd on the wear rate of MMCs, while all of the factors had statistical significance on it. In addition to this, the interactions of Pv x Ps (P=2.35%), Pv x Ags (P=4.97%) and Ps x Ags (P=1.74%) had significant effect on the wear resistance of materials, while the other interactions (P=0.86% for Pv x Sd, P=0.12% for Ps x Sd and P=0.16% for Ags x Sd) were pooled since their percentages of contributions are lower than error associated (1.22%) and had no significant effect on it. Hence, in this study it was found that all factors and the interactions of Pv x Ps, Pv x Ags and Ps x Ags had statistically and physically significant effect on the wear resistance of the tested materials.

4 Conclusions

Using the Taguchi method and ANOVA analysis, the parameters, which have a significant effect on the wear resistance of Al_2O_3 particle reinforced aluminium alloy composites, have been studied. A mathematical model between the parameters was generated by GEP for the purpose of predicting wear rate. Based on the results of this experimental study, the following conclusions have been drawn:

The results indicate that volume fraction of reinforcement particle (Pv) was found to be the most effective factor on abrasive wear, followed by particle size (Ps). The abrasive grit size (Ags) and sliding distance (Sd) also had a significant effect on it, but they exerted much lower effect compared to the other factors.

The wear rate of the composites increased with increasing abrasive grit size while it decreased with increasing volume fraction of particle, particle size and sliding distance.

The interactions of Pv x Ps, Pv x Ags and Ps x Ags had a significant effect on wear resistance, the other interactions had no significant effect on it.

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