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Research Article

ABRASIVE WEAR BEHAVIOR OF FUNCTIONALLY GRADED AIB_2/AI COMPOSITE

Ömer Savas [1], İlknur Keskin Öner *[2]

[1] Yildiz Technical University, Faculty of Naval Architecture and Maritime, Departmant of Marine Engineering, İstanbul, Türkiye
ORCID ID 0000 – 0001 – 7454 – 1457
osavas@yildiz.edu.tr

[2] Yildiz Technical University, Faculty of Naval Architecture and Maritime, Departmant of Marine Engineering, İstanbul, Türkiye
ORCID ID 0000 – 0003 – 1584 – 4479
keskin@yildiz.edu.tr

* Corresponding Author
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ABSTRACT
Functionally graded composites (FGM) can combine high surface wear resistance and high toughness. For this reason, it has been seen to be preferred in many regions, especially in the defense and maritime sectors, in recent years. This study is an experimental study on the investigation of the wear properties of functionally graded AlB_2 boride reinforced composite materials, which can be an alternative in the manufacturing of ship machinery parts exposed to repeated loads and wear. This study aims to increase the industrial usability of the boron element, which has strategic importance for our country. Pin-On-Disk technique and abrasive wear method were used to determine the wear properties of composites. In the wear tests, a total of 5 factors consisting of wear factors such as the region of the composite (% reinforcement ratio), abrasive particle diameter, application load, sliding distance and sliding speed were selected as test parameters with 3 levels. In wear tests, the "Taguchi Experimental Design" method was used. As a result of the study, it was seen that the hardness and wear resistance of aluminum increased with the addition of AlB_2 into the aluminum matrix. It was observed that the load had an effect of 33.98%, the abrasive particle diameter had an effect of 31.68% and the AlB_2 reinforcement ratio had a 10.73% effect on the wear resistance of the composites. As a result of the study, linear equations predicting 'wear resistance in different conditions' were obtained.

Keywords: *Wear, AlB_2, Functionally Graded Composite*

1. INTRODUCTION

Composite materials are defined as a new type of material created by combining two or more different materials at a macro level and they carry the best properties of the materials that form them(Miracle 2006; Rohatgi and Paper 2001; Pramod et al. 2015; Kumar et al. 2008). In general, metal matrix composites consist of a matrix with low strength and ductility and a reinforcement material with high hardness and wear resistance. The need for lightweight and high-performance metals has paved the way for the research and development of Aluminum Matrix Composites.

Compared to conventional aluminum alloys, aluminum matrix composites have high specific strength, superior wear resistance and stability at high temperatures (Rosso 2006; Kane et al. 2016; Radhika and Raghu 2018). Silicon carbide (SiC) and Alumina (Al_2O_3) are preferred as strengthening phases due to their high wettability by aluminum and their low prices (Ozdin 2007). The development and discovery of new production processes have shown that there are various ceramic and intermetallic reinforcers with high potential for Aluminum Matrix Composites (Tjong and Ma 2000; Ma et al. 1999). The mechanical properties of composite materials increase with increasing reinforcement ratio and increasing aspect ratio (width/thickness ratio of the reinforcement phase) (Kayikci and Savaş 2015; Tjong and Mai 2008).

There are very limited studies on aluminum matrix AlB_2 boride reinforced composite materials (Kayikci and Savaş 2015; Deppisch et al. 1997). AlB_2 reinforced composites can be produced easily and cheaply with the in-situ production method. Since it is produced with this method, it exhibits a number of superior properties desired in composite production, such as wettability, homogeneous distribution, thermodynamic stability and high aspect ratio (length/thickness) (Hall and Economy 2000; Deppisch et al. 1997). Boric acid (H_3BO_3), boric oxide (B_2O_3), borax ($Na_2B_4O_7.10H_2O$), potassium chloride and commercial Al-B master alloys are used as boron source in the production of AlB_2 composites (Kayikci and Savaş 2015; Hall and Economy 2000). Commercial Al-B alloys are widely used as grain refiners in the casting of aluminum alloys and in the production of conductive wires with high conductivity.

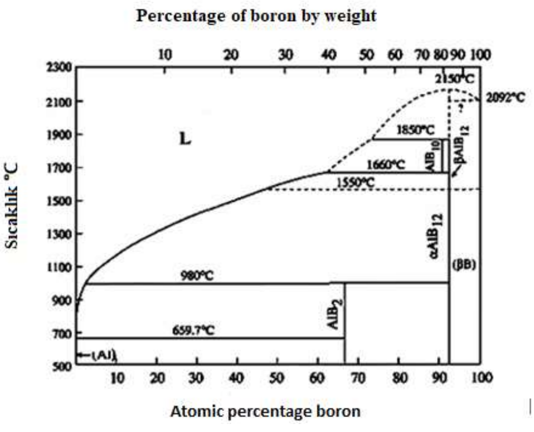

Figure.1. Al–B binary phase diagram [16]

In order to produce AlB_2 boride reinforced composites properly, the Al-B phase diagram must be well understood (Hall and Economy 2000; Hall and Economy 2000). As can be seen in the phase diagram given in Fig. 1, it is seen that the boron element does not dissolve in aluminum at room temperature and exists in the form of AlB_{12} and AlB_2 boride compounds. Additionally, it is seen that the Al-B phase diagram has a peritectic reaction line at approximately 980°C. It is noteworthy that AlB_{12} boride structures are stable above the peritectic reaction temperature and AlB_2 below it. While AlB_2 boride structures have high aspect ratio and high mechanical properties, AlB_{12} boride structures are coaxial, unstable at room temperature, brittle and have low mechanical properties. For this reason, AlB_{12} is not desired to be present in the structure in the production of boride structured composites.

In functionally graded composites (FGM), the reinforcement ratio varies from the inner region to the outer region of the mold. For this reason, the physical and mechanical properties of composites vary depending on the change in reinforcement ratio (Kayikci and Savaş 2015; Melgarejo et al. 2008; Naebe and Shirvanimoghaddam 2016; Nadu 2016). FGM can combine high surface wear resistance and high toughness (Karun 2017).

Tjong and Lau (2000) showed that the wear resistance increased dramatically with the increase in the proportion of reinforcement particles in the composite. In their study to investigate the abrasive wear behavior of functionally graded TiB_2 reinforced aluminum matrix composites, Savaş et al. (2020) reported that the weight losses of the composites increased with increasing load and sliding speed, and that the weight losses decreased significantly with increasing reinforcement ratio.

Radhika and Raghu (2016) examined the abrasive wear behavior of functionally graded AlB_2/Al composites. In the study, the effects of test parameters such as load, sliding distance and abrasive type (SiC and Al_3O_2) on the wear behavior of composites were examined. Wear test results showed that the wear rate decreased with increasing AlB_2 reinforcement ratio in the aluminum matrix and SiC particles had more abrasive properties.

Previous studies conducted to investigate the wear behavior of AlB_2/Al composites reported that wear resistance increased with increasing AlB_2 reinforcement ratio in the aluminum matrix (Ficici, 2016; Ficici and Koksal, 2016; Ficici et al., 2011).

For wear tests, functionally graded AlB2 reinforced aluminum matrix composites, which were produced and characterized in our previous study, were used (Savaş and Karataş 2022). In another previous study, the wear behavior of these composites was examined in a limited way (Öner and Savaş, 2022). In this study, the wear behavior of composites was examined by using more comprehensive and more advanced analysis techniques in order to take previous studies to a further stage.

2. EXPERIMENTAL STUDIES

2.1. Composite Production and Characterization

Wear test samples measuring 10x10x20 mm were taken to be used in wear tests. When looking at the cross-sectional image of the test sample, it can be seen that it has two regions in the direction of spinning, one reinforced with AlB_2 and one that is not reinforced. In the previous study, wear experiments were conducted separately on these two region. In order to determine the regional wear behavior of the composite, the reinforced region in the direction of blowing was divided into two. As seen in Fig. 2, the region corresponding to the outside of the mold is named A, and the inner region (the part between region A and the unreinforced region C) is named B.

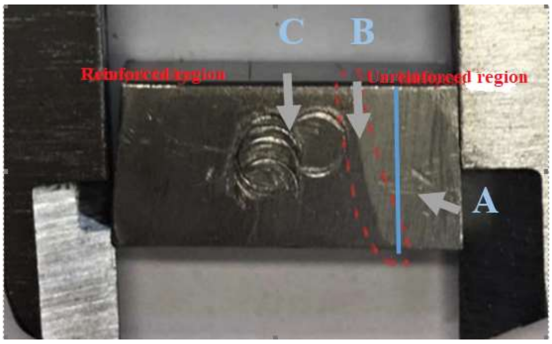

Figure 2. Wear test sample

In order to speed up the wear process, abrasive wear technique was used in the wear analysis of composites. Abrasive wear tests of composites were carried out with the 'Pin-On-Disk' method given in Fig. 3 (Melgarejo, 2008). Fig. 3 shows that the abrasive media is placed on the disc and the composite pin is pressed onto the abrasive media by the applied load. In abrasion tests, the weights of the samples before and after the test were measured with a scale with a sensitivity of 0.0001 g, and the wear amounts were determined by taking the difference of these measurements. The average wear resistance of each test recipe was calculated by considering the weight losses.

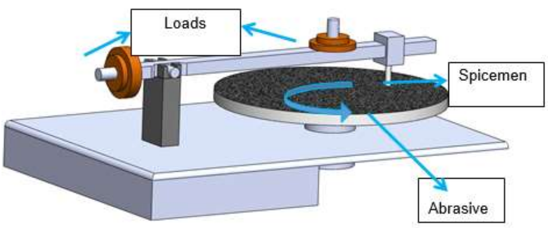

Figure 3. Schematic representation of the experimental setup

Water sandpapers of 1000, 1200 and 1500 grit with particle sizes of 18, 15 and 12 µm were determined as the abrasive medium. Wear tests were carried out at a sliding distance of 100-200-300 meters, at sliding speeds of 1-3-4.5 m/s and under 1-2-3 N loads. Factor and level values determined for wear tests are given in Table 1 considering the factors and levels given in Table 1, if all combinations are tried, a total of '3x3x3x3x3' = 243 experiments are required. Although conducting such a large number of experiments is negative in terms of cost and time, conducting too many experiments means making too many mistakes. For this reason, Taguchi experimental approach was used in this study.

Table 1. Factors selected for wear tests and their level abrasive medium particle size

	Factor	Factor level		
		Level 1	Level 2	Level 3
A	Region % AlB_2 ratio	0,0 (Region C)	5,0 (Region B)	7,5 (Region A)
B	Abrasive Particle size, µm	18	15	12
C	Load, N	1	2	3
D	Sliding speed, m	100	200	300
E	Sliding distance, m/s	1,0	3,0	4,5

The Taguchi method, which is preferred to improve a process or a system with a small number of trials, was developed by Dr. Genichi Taguchi in the 1950s. It is an effective design method for product quality, customer satisfaction and pre-production planning. The Taguchi method has been used effectively in many studies conducted to examine the wear behavior of materials (Unal et al., 2008; Melgarej, 2018; Koksal et al., 2014.

As a result of the preliminary examinations made according to the Taguchi approach, it was seen that the most suitable series for the factors and levels given in Table 1 was the L_{27} orthogonal series. In Table 2, 27 experimental prescriptions determined by considering the $L_{27}{}^{(35)}$ orthogonal series are given.

Table 2. $L_{27}{}^{(35)}$ orthogonal series and test recipes selected for wear experiments

Test number	% AlB_2 ratio	Load, N	Abrasive particle diameter, µm	Speed, m/s	Distance, m
	A	B	C	D	E
1	7,5	1	18	1	100
2	7,5	1	15	3	200
3	7,5	1	12	4,5	300
4	7,5	2	18	3	200
5	7,5	2	15	4,5	300
6	7,5	2	12	1	100
7	7,5	3	18	4,5	300
8	7,5	3	15	1	100
9	7,5	3	12	3	200
10	5	1	18	3	300
11	5	1	15	4,5	100
12	5	1	12	1	200
13	5	2	18	4,5	100
14	5	2	15	1	200
15	5	2	12	3	300
16	5	3	18	1	200
17	5	3	15	3	300
18	5	3	12	4,5	100
19	0	1	18	4,5	200
20	0	1	15	1	300
21	0	1	12	3	100
22	0	2	18	1	300
23	0	2	15	3	100
24	0	2	12	4,5	200
25	0	3	18	3	100
26	0	3	15	4,5	200
27	0	3	12	1	300

Wear tests were carried out in a way to minimize environmental and systemic errors, taking into account the 27 different test recipes given in Table 2. Each experimental recipe was repeated at least three times in order to minimize systemic and environmental errors.

3. RESULTS

In Fig. 4 (A, B and C regions), SEM images of AlB_2 reinforced and non-reinforced regions are given. Approximately 30 µm long AlB_2 structures are seen in AlB_2 reinforced regions. It is also noteworthy that there is no intermetallic compound between the matrix and AlB_2 boride structures. It is noteworthy that there is no significant difference in terms of AlB_2 reinforcement ratio between regions A and B. However, it is clearly seen that there are no AlB_2 boride structures in the unreinforced regions. As a result of the SEM analysis, no significant micro porosity was found in both reinforced and unreinforced regions.

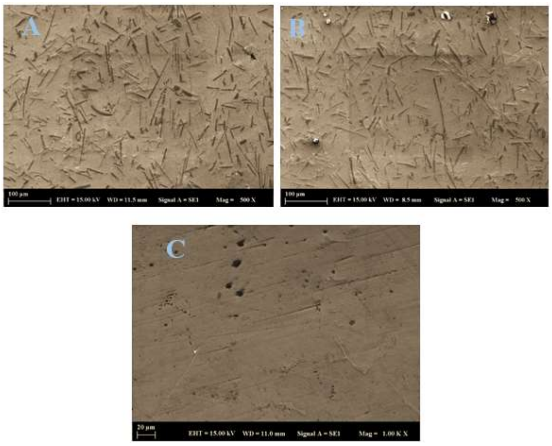

Figure 4. SEM image of a) A region, b) B region and c) C region of the composite material to be subjected to wear

The % AlB_2 ratio, density and hardness values of the composite regions to be exposed to AlB_2 wear are given in Table 3.

Table 3. Composite material properties

Region	Reinforcement ratio	Density,gr/cm^3	Hardness, HB
A	%7,5	2,72	79,17
B	%5,0	2,71	55,05
C	%0,0	2,70	45,05

In Table 3, it is seen that the AlB_2 reinforcement ratio in the reinforced region of the composites varies between 7.5% and 5%. Additionally, the table shows that the density and hardness values of the composite increased with increasing AlB_2 in the aluminum matrix. The table shows that the highest hardness value was measured as 79.17 HB in the region reinforced with 7.5% AlB_2.

Table 4 shows the wear resistance results obtained as a result of the wear tests of 27 test recipes. The last column of the table shows the S/N ratios of the wear results calculated according to the "highest is best" quality characteristic. In the experiments carried out in the table, it is seen that the wear resistance values vary between 35400 m/g and 2290 m/g. The highest abrasion resistance was observed as 14181 m/g on average in the 2nd test recipe. The lowest abrasion resistance was observed in the 22nd test recipe with 2417 m/g. It is noteworthy that, in general, the wear resistance of regions with low reinforcement ratio is low, while it is higher in regions reinforced with AlB_2. Additionally, the table shows that S/N ratios vary between 91.9 dB and 67.7 dB.

Table 5 shows the ANOVA table prepared taking into account S/N ratios. The sum of squares, variance, F and P values of each factor and its interactions are given in the Table 5. Statistically, P values in the ANOVA table below 0.05 indicate that that factor is effective, while values above 0.05 indicate that it is not effective. The table shows that load, abrasive particle diameter and reinforcement ratio are effective on the wear of composites. It shows that sliding speed, distance and factor interaction are not important. When looking at the percentage effects of the factors on wear, it is seen that the load factor has the highest effect with 33.98%, followed by the abrasive particle diameter factor with 31.68% and the Reinforcement ratio factor with 10.73%. It is seen that the sliding speed factor, which does not have a significant effect, has an effect of 3.36% and the sliding distance factor has an effect of 0.45%. It shows that uncontrollable factors on wear have a total effect of 19.8%.

Fig. 5 shows the 'main effect graph' drawn for wear resistance. The graph shows the wear resistance changes with the factor level change of each factor. In the graph, the factor level that gives the highest wear resistance value shows the optimum test conditions. Accordingly, it shows that the highest wear resistance of composites can be achieved by abrading the regions with 7.5% reinforcement ratio under 1 N load, in an abrasive particle environment of 12 µm diameter, at a sliding speed of 4.5 m/s and at a sliding distance of 200 m. However, it should be noted that speed and road factors do not have a significant effect here. According to Fig. 5, the optimum test recipe is $A_3B_1C_1D_3E_2$.

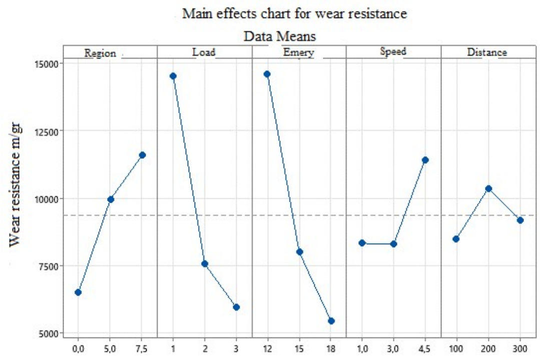

Figure 5. Key effects graphs for wear resistance

Table 4. Experimental prescriptions and wear resistance results and their S/N ratio

No	% AlB_2 ratio	Load, N	Abrasive particle diameter,μm	Speed, m/s	Distance, m	1. Measuring m/gr	2. Measuring m/gr	3. Measuring m/gr	Average wear resistance, m/gr	S/N ratio, dB
1	7,5	1	18	1	100	11656	8272	11652	10526,7	80,1
2	7,5	1	15	3	200	14181	14170	14192	14181,0	83,0
3	7,5	1	12	4,5	300	42269	35400	42268	39979,0	91,9
4	7,5	2	18	3	200	5941	5053	4677	5223,7	74,2
5	7,5	2	15	4,5	300	6784	6038	4684	5835,3	75,0
6	7,5	2	12	1	100	8843	7542	8852	8412,3	78,4
7	7,5	3	18	4,5	300	3500	3087	3351	3312,7	70,4
8	7,5	3	15	1	100	4346	4838	4931	4705,0	73,4
9	7,5	3	12	3	200	12929	10722	12932	12194,3	81,6
10	5	1	18	3	300	8792	8795	8779	8788,7	78,9
11	5	1	15	4,5	100	10990	10775	10760	10841,7	80,7
12	5	1	12	1	200	16027	18506	16027	16853,3	84,5
13	5	2	18	4,5	100	3663	4995	6106	4921,3	73,3
14	5	2	15	1	200	19726	17860	19726	19104,0	85,6
15	5	2	12	3	300	7327	7341	8454	7707,3	77,7
16	5	3	18	1	200	2290	2699	2397	2462,0	67,8
17	5	3	15	3	300	3461	4778	4352	4197,0	72,2
18	5	3	12	4,5	100	16652	16648	10990	14763,3	82,9
19	0	1	18	4,5	200	10368	8326	8335	9009,7	79,0
20	0	1	15	1	300	5028	5035	5018	5027,0	74,0
21	0	1	12	3	100	14653	16281	16182	15705,3	83,9
22	0	2	18	1	300	2419	2410	2424	2417,7	67,7
23	0	2	15	3	100	3960	4627	3960	4182,3	72,4
24	0	2	12	4,5	200	9314	12211	9425	10316,7	80,1
25	0	3	18	3	100	2376	2365	2836	2525,7	68,0
26	0	3	15	4,5	200	3434	3536	5132	4034,0	71,7
27	0	3	12	1	300	5575	5469	5602	5548,7	74,9

Table 5. ANOVA tables

Factors	Column	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Reinforcement ratio	A	2	88,22	88,22	44,112	4,61	0,047	10,73%
Load	B	2	314,68	314,7	157,34	16,43	0,001	33,98%
Abrasive particle diameter	C	2	333,22	333,2	166,61	17,4	0,001	31,68%
Speed	D	2	20,16	20,16	10,078	1,05	0,393	3,36%
Distance	E	2	34,45	34,45	17,224	1,8	0,226	0,45%
Region*Load		4	34,42	34,42	8,605	0,9	0,508	
Load*Emery		4	55,39	55,39	13,849	1,45	0,304	
Residual Error		8	76,59	76,59	9,574			19,80%
Total		26	957,14					100,00%

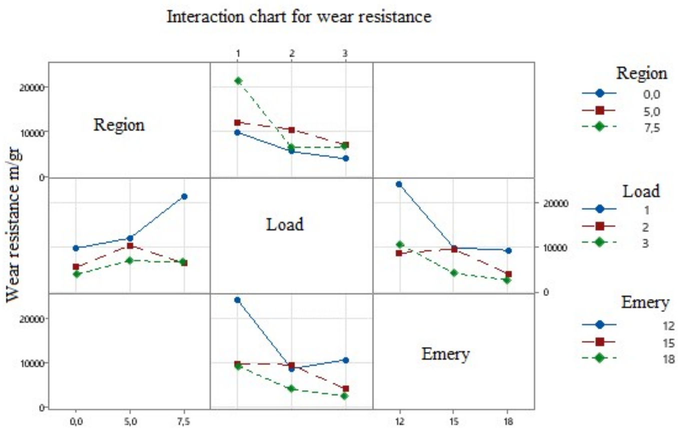

Figure 6. Interaction graphs for wear resistance

In the graph in Fig. 6, the relationships between the Reinforcement Ratio-Load and Abrasive Particle Diameter (sandpaper)-Load factors were examined, but it was observed that there was no significant relationship.

In this study, test recipe number 3 in Table 4 has the optimum test recipe (A3B1C1). Therefore, instead of conducting an extra experiment, the results of experiment number 3 were used for validation experiments. The average S/N ratio, estimated confidence interval and verification experiment average S/N ratios calculated according to optimum conditions are given in Table 6.

Table 6. Predictive and verification test results

Quantity	Results
Optimum experimental conditions	A3B1C1
Estimated average S/N ratio	92,1 dB
Confidence interval for α= 0,05	91,0 $< \mu <$ 94,2 dB
Verification test S/N ratio	91,9 dB

In Table 6, the S/N ratio of the verification test result is 91.9 dB. This value is within the estimated confidence interval calculated as seen in the table. This result shows that the experiments were carried out correctly.

As a result of the statistical analysis, a linear regression equation was prepared for each region of the composite material (Table 7). Thanks to this equation, the wear resistance of the composite material can be predicted under predetermined wear conditions.

Table 7. Regression equations

3. Region %0 AlB_2	SNRA1	=	103,50 - 4,53 Load - 1,370 Abrasive Particle Diameter + 0,934 Hiz - 0,0059 Distance
2. Region %5 AlB_2	SNRA1	=	106,83 - 4,53 Load - 1,370 Abrasive Particle Diameter + 0,934 Hiz - 0,0059 Distance
1. Region %7,5 AlB_2	SNRA1	=	107,58 - 4,53 Load - 1,370 Abrasive Particle Diameter + 0,934 Hiz - 0,0059 Distance

In order to test the regression equation, the wear resistance value and S/N ratios that would occur under spesific wear conditions were calculated. Estimated wear resistance values and S/N ratios are given in Table 8.

Table 8. Control test recipes and test results

Reinforcement ratio, %	Load, N	Abrasive particle size, µm	Speed, m/s	Distance, m	S/N ratio	Wear resistance m/gr
7,5	1	12	4,5	100	88,93	23258,4
0	1	12	4,5	100	84,86	18191,4
7,5	1	12	4,5	200	90,50	25124,5

In order to thin the wear surfaces of the composites, the composite regions reinforced with 0% and 7.5% AlB_2 were exposed to wear under equal conditions under a load of 1 N, in an abrasive particle environment of 12 µm diameter, at a sliding speed of 4.5 and at a sliding distance of 100 m.

Fig. 7 shows the worn surface SEM image of the unreinforced region, and Fig. 8 shows the worn surface SEM image of the region reinforced with 7.5% AlB_2. When the surface images are examined, deep wear marks and material losses as a result of plastic deformation are observed in the worn surface image of the undisturbed region. On the other hand, in the worn surface image of the reinforced region strengthened with 7.5% AlB_2, it is seen that the wear marks are few and shallow. However, no significant plastic deformation was observed on the worn surfaces of the reinforced region.

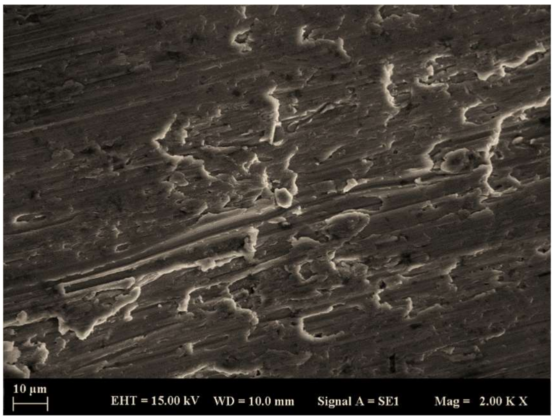

Figure 7. SEM image of the abraded surface of the not reinforced region with AlB_2

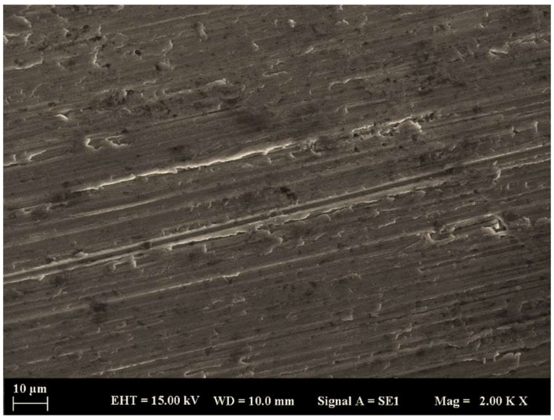

Figure 8. SEM image of the abraded surface of the reinforced region with AlB_2

4. EXAMINATION OF THE RESULTS

The 'Surface Graph' showing the change in wear resistance depending on load and reinforcement is given in Fig. 9. The graph shows that wear resistance decreases with increasing load, similar to previous studies (Pramod et al., 2015; Kumar et al., 2008; Kane et al., 2016). The probable reason for this is that the amount of wear was increased due to the increased wear and tear deterioration with the applied load, which caused the wear resistance to deteriorate.

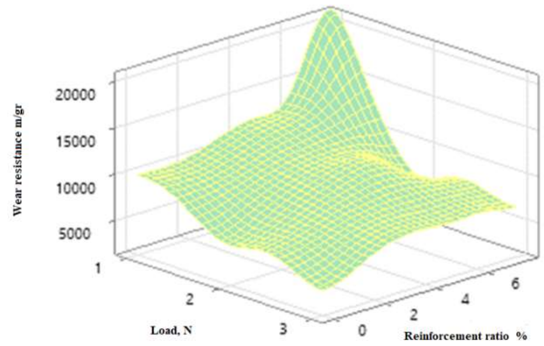

Figure 9. Wear resistance change graph depending on load and reinforcement ratio

The surface graph showing the change in wear resistance depending on the abrasive particle size and reinforcement ratio can be seen in Fig. 10. It has been reported from previous studies that wear resistance decreases with increasing abrasive particle size (Ozdin,2007; Radhika and Raghu, 2016; Radhika and Raghu, 2018). Similarly, in this study, wear resistance decreased with increasing abrasive particle diameter. The probable reason for this is that larger diameter abrasive particles have more sharp corners and therefore are more likely to penetrate the worn surfaces.

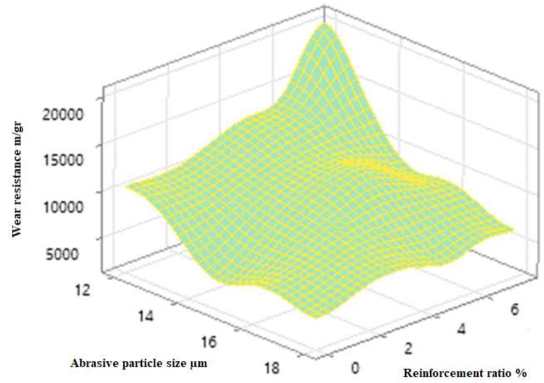

Figure 10. Wear resistance change graph depending on abrasive particle diameter and reinforcement ratio

Fig. 9 and Fig. 10 show that wear resistance increases with increasing AlB_2 ratio in the aluminum matrix. The reason for this is that, as can be seen in Table 1, the hardness value of the reinforced regions with AlB_2 is higher. Previous studies have reported that wear resistance decreases with increasing hardness value (Radhika and Raghu, 2016; Ficici, 2016**;** Kumar et al., 2008). It is thought that the reason why the wear resistance of the reinforced regions with AlB_2 is higher than the hardness of the unreinforced regions is due to the fact that the abrasive particles cannot penetrate the worn surfaces with the increased hardness.

5. CONCLUSION

The results we obtained in this study are summarized below;

1- It has been determined that the most effective factor on the wear resistance of functionally graded AlB2 boride-reinforced aluminum matrix composite materials for a 0.05 confidence level is the load factor, followed by the abrasive particle size and reinforcement ratio factors, respectively.

2- It was observed that sliding speed and distance factors did not have a significant effect on wear resistance.

3- In the worn surface images, it was determined that the wear marks in the unreinforced regions were deeper than in the reinforced regions with AlB_2.

4- It has been determined that the addition of AlB_2 boride particles into aluminum improves the wear resistance of the composites by 10.73%. It was observed that the applied load and the abrasive particle size had an effect on wear resistance of 33.98% and 31.68%, respectively.

5- With the Taguchi approach, a regression equation was obtained with only 27 test prescriptions instead of 243 experiments, and the wear resistance of the composites worn under different conditions was successfully predicted.

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