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RESEARCH

Abrasive Wear Behavior of Centrifugally Cast Al Alloy Composites with TiB_2 Reinforcement

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A B S T R A C T

Materials are graded with some particles by centrifugal casting so that they can be provided a high service life in engineering applications such as pulley, flywheel and cam disc. This study aims to investigate of abrasive wear behavior of centrifugally cast Al alloy composites with Titanium diboride (TiB_2) reinforcements. Microstructure, hardness and abrasive wear behavior of composites has been examined from the outer wall to the inside. The abrasive wear properties of the composites were investigated with the Taguchi technique considering factors such as, Al alloy type, a layer of composite, abrasive particle size, sliding distance, sliding speed and applied load factors. It has been observed that the composites have two distinct layers as TiB_2-reinforced and non-reinforced layers. In addition, it has been observed that the wear properties of the TiB_2-reinforced layers are 63% better than the non-reinforced layers

1. INTRODUCTION

Aluminum alloys have a great demand in the aircraft and marine industries due to their low densities and high mechanical properties [1]. But, their wear properties are relatively poor. Therefore their use is limited to the manufacture of machine parts exposed to wear. Tribological and mechanical properties of aluminum alloys can have been enhanced by adding Al_2O_3, SiC, TiB_2, TiC, and ZrC particles [2-5].

The addition of the particles increases the wear resistance, but decreases the fracture toughness. Functionally graded material (FGM) provides a specific function of performance for engineering applications where both higher superficial wear resistance and sufficiency internal fracture toughness are required [6-8].

TiB_2 reinforced aluminum matrix composites can be produced by centrifugal casting technique [9,10]. TiB_2 particles are formed by a chemical reaction between boron and titanium within molten aluminum. In this way, it can obtains easily and economically. L. LU et al. [11] and C.S. Ramesh et al. [12] reported that they synthesized TiB_2 particles by the reaction of Al-10Ti and Al-3B mater alloys. S. Kumar et al. [13] stated that TiB_2 particles, K_2TiF_6, were formed by the reaction of

KBF_4 with molten aluminum. To produce the FGM composites, M. F. Forster [9] et al first created a liquid aluminum alloy containing TiB_2 particles, and then applied a centrifugal force to the alloy and separated the TiB_2 towards the outer wall of the mold. They also expressed that the composition gradient in FGM can be controlled by centrifugal force. O. Savaş [10] produced functionally graded TiB_2/Al and TiB_2/Al–Cu composites under 1500 rpm throwing force at 900 ºC. It was determined that the TiB_2 ratio varied between 0 and 27 vol.% from the inner region to the outer region of the composites.

Abrasive wear is a damage that occurs on the surface of materials caused by abrasive particles. It reduces the life of machine parts in engineering applications. It is a complex type of damage that is affected by many factors such as abrasive size [14], abrasive type [14,15], abrasive shape [16], applied load [17], sliding distance [18], sliding speed [3], material hardness [5], material toughness [19], etc.

Taguchi Technique is a statistical method that is based on process optimization. It is seen that many researchers using effectively the Taguchi technique to determine the wear behavior of composites [20-24]

Centrifugally cast Al and Al-Cu alloy composites with TiB_2 reinforcements were produced in small sizes in order to determine their properties and abrasion behavior in previous studies [10,15]. To advance to the next level, in this study, centrifugally cast Al, Al-Cu and Al-Si alloy composites with TiB_2 reinforcements were produced as cylindrical and large mass for using in engineering applications such as pulley, flywheel and cam disc. The abrasive wear properties of the produced materials were investigated with the Taguchi technique by applying many wear parameters.

2. EXPERIMENTAL STUDIES

Pure aluminum (99.5% purity) and Al-3wt.% B and Al-10wt.% Ti alloy ingots were cut at a rate to obtain a solution containing 5wt.%TiB_2 particles. In order to dissolve Al_3Ti, AlB_2, AlB_{12} and other structures in the master alloys, the ingots were melted in a crucible at 1200 ºC for 1 hour. At this temperature, the semi-solid "$Al_{(l)}$ - $TiB_{2(s)}$" solution was prepared in three different crucibles in order to obtain different matrix types. One of them has not been processed for producing pure aluminum matrix functionally graded material. Two of them were individually alloyed with 4wt.% Cu and 4wt.% Si for producing Al-Cu and Al-Si matrix functionally graded composites, respectively. The temperature of the solutions was cooled down to 800 ºC waited for 30 minutes to allow the TiB_2 particles to develop in liquid aluminum. Afterwards, '$Al_{(l)}$ - $TiB_{2(s)}$' solution was solidified under a centrifugal force after alloying with 4%Si and 4%Cu to obtain different aluminum alloys.

Since the highest reinforcement ratio was provided using a horizontal centrifugal casting process at 800 °C at 1500 rpm in the optimization studies, all composites have been produced by under these conditions.

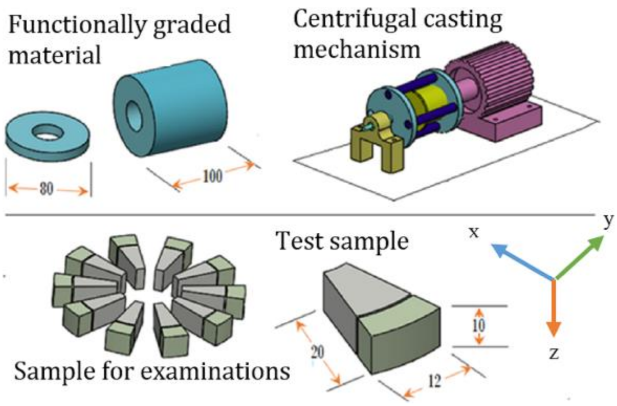

Fig. 1. Sample preparation for experimental studies.

Cylindrical steel mold with a diameter of 80 mm and a height of 100 mm was used only for centrifugal casting. After the composites are produced by centrifugal casting method, they are divided into equal parts for X-ray diffraction (XRD) and scanning electron microscope (SEM) analyzes, Brinel hardness and wear test as seen in Figure 1.

X-ray diffraction (XRD) analysis was performed on the materials using a CuK_α radiation at 40mA and 45 kV to determine phase components and the ratios of TiB_2 and other particles. The ratios of phases were determined on the basis of intensity of diffraction peaks. Then microstructure images are taken using scanning electron microscope (SEM) to study the distribution and morphology of TiB_2 particles in materials. The Brinell hardness was measured with 31.25-kg load on z-direction of the composite sanded up to 1500 grit sandpaper levels.

Abrasive wear tests have been done on x-direction of the sample using a pin-on-disc apparatus at a room temperature and relative humidity of 75% according to the ASTMG99-05 standard.

SiC-sandpaper with particle size of 45, 25, and 18µm were chosen as the wear medium. Wear tests have been carried out on reinforced and non-reinforced layers in the centrifugally cast Al, Al-Si and Al-Cu alloy composites. Three different loads of 1, 2 and 3 N, three different sliding velocities of 7.00, 3.00 and 1.10 m/s, and three different sliding distance of 100, 200 and 300 m were chosen as the wear parameters. Wear test recipes have been designed using L_{18} ($1^2 5^3$) orthogonal array according to Taguchi's experimental design are shown in Table 1 (A, B, C, D, and E column).

Table 1. Abrasive wear trial recipes designed according to L_{18} ($1^2 5^3$) orthogonal array.

Exp. No	Layer of composite	Abrasive Particle Size	Aluminum alloy type	Sliding speed	Applied load	Sliding distance	Average hardness	Wear rates	S/N
Unit	-	µm	-	m/s	N	m	HB	$x10^{-3}$ mm^3/m	dB
Columns	A	B	C	D	E	F	G	H	I
1	Non-reinforced layer	46	Pure Al	7.00	3	100	34.3±8	251.63	-48.02
2			Al-Si	3.00	2	200	70.2 ±12	169.05	-45.19
3			Al-Cu	1.10	1	300	80.2±15	104.54	-41.93
4		26	Pure Al	7.00	2	300	34.3±8	180.16	-45.12
5			Al-Si	3.00	1	100	70.2 ±12	49.66	-35.25
6			Al-Cu	1.10	3	200	80.2±15	157.01	-45.92
7		18	Pure Al	3.00	3	300	34.3±8	92.68	-39.57
8			Al-Si	1.10	2	100	70.2 ±12	33.95	-32.83
9			Al-Cu	7.00	1	200	80.2±15	22.25	-27.13
10	TiB_2-reinforced layer	46	Pure Al	1.10	1	100	51.0±6	35.30	-32.72
11			Al-Si	7.00	3	200	115.3±15	41.07	-32.29
12			Al-Cu	3.00	2	300	103.4±13	35.09	-31.18
13		26	Pure Al	3.00	1	200	51.0±6	28.63	-29.43
14			Al-Si	1.10	3	300	115.3±15	15.80	-27.25
15			Al-Cu	7.00	2	100	103.4±13	18.64	-25.54
16		18	Pure Al	1.10	2	200	51.0±6	23.40	-29.78
17			Al-Si	7.00	1	300	115.3±15	1.71	-4.87
18			Al-Cu	3.00	3	100	103.4±13	17.09	-25.24

The wear test of each test recipe was performed at least three times. Since the wear rate is the best way to express the wear performance of materials, the Wear rate of each wear recipe is calculated using Eq. (1) [22,25].

$$\text{Wear rate} = \frac{\text{Volume loss}}{\text{Sliding distance}} \left(\frac{mm^3}{m} \right) \qquad (1)$$

ANOVA table was prepared by determining S/N ratios according to the lower-the-better quality characteristic (Eq-(2)). The results has been evaluated by using Minitab software.

$$S/N = -10\log\left(1/n \sum_{i=1}^{n} yi^2 \right) \qquad (2)$$

Where; *n* is the number of measurements in a trial and *y* is the value of measurement in a trial.

3. RESULTS AND DISCUSSION

Figure 2 shows cross-sectional pictures of centrifugally cast Al alloy composites. It is seen that there are two layers which are dark and light colors. The dark layer surrounded the outer surfaces of the composites with a thickness of 3 mm.

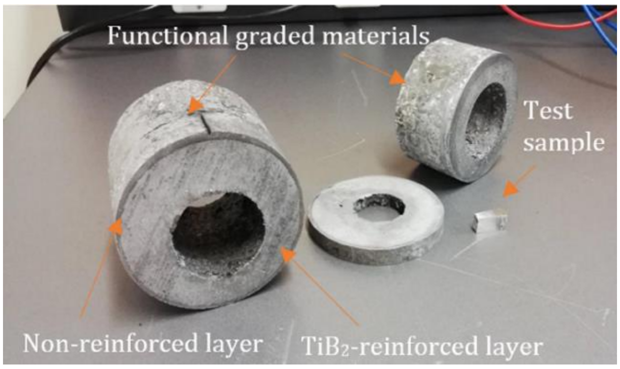

Fig. 2. A photography of centrifugally cast Al alloy composites.

Figure 3(a) and 3(b) show x-ray diffraction analyzes of dark and light layers of Al alloy composites. In Figure 3(a), Al, TiB_2, and Al_3Ti phases can be seen in x-ray diffraction analyzes of the dark layer. Only the peaks of the Al phase are seen in the light layer in Figure 3(b). This result shows that all of TiB_2 and Al_3Ti particles are dragged by the effect of the centrifugally force and form 3 mm dark layer in the outer wall of the composites.

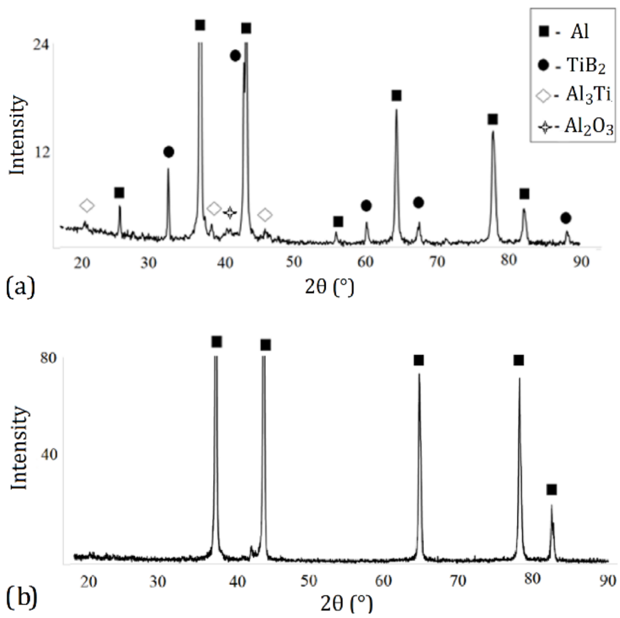

Fig. 3. The XRD patterns taken from (a) TiB2-reinforced and (b) non-reinforced layers of composite.

It was concluded that the dark layer contains 15.12wt.% TiB2, 1.45wt% Al3Ti and 86.2wt% Al phase, while the light layer contains only 98.6wt% Al phase. These results indicate that dark and light layers are two distinct layers as TiB_2-reinforced and non-reinforced layers, respectively. Al_2O_3 peak was observed in both samples, but it was neglected because it was too small.

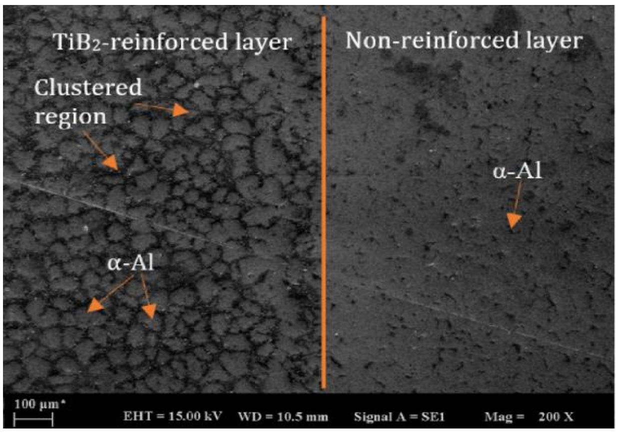

Fig. 4. A SEM image containing both TiB2-reinforced and non-reinforced layers.

Figure 4 shows the SEM image of TiB_2-reinforced and non-reinforced layers. It is seen that both layers clearly separate from each other. Although there are not any particles in the non-reinforced layer, it is noteworthy that TiB_2 particles are very dense in the TiB_2-reinforced layer. It is seen that TiB_2 particles exhibit a clustered distribution along the grain boundaries in the aluminum matrix.

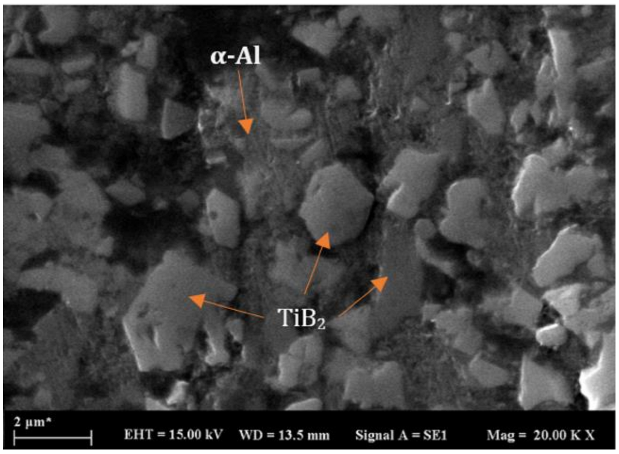

Fig. 5. SEM image taken from a clustered region.

Figure 5 shows the SEM image taken from a clustered region to examine the morphology of TiB_2 particles. It is seen that the TiB_2 particles are not agglomerated and exhibit a homogeneous distribution at the aluminum grain boundaries. The approximate size of TiB_2 particles varies between 0.50 µm and 2.00 µm.

Average hardness measurement results obtained from TiB_2-reinforced and non- reinforced of pure Al, Al-4%Si and Al-4%Cu composites are given in Table 1 (G column). It is seen that the hardness values of the TiB_2-reinforced layers are higher than the non-reinforced layers. It shows that the hardness values of Al-Si and Al-Cu composites are higher than Al composite. The highest hardness value was observed at 115.3 HB in the TiB_2-reinforced layer of the Al-Si composite. The lowest hardness value was measured at 34.3 HB in the non-reinforced layer of Al composite. Also, the results show that the addition of 15 wt. % TiB_2 particles into Al alloys caused an increase in hardness values.

In Table 1, column H and I show the average volumetric wear rates and S / N ratios for each trial recipe, respectively. Table 1 shows that the lowest volumetric wear rate is average 1.71 x10^{-3} mm^3/m at 17-trial recipe and the highest volumetric wear rate is average 251.63 x10^{-1} mm^3/m at 1-trial recipe.

The analysis of variance statistical method (ANOVA) prepared by considering the S/N ratios is given in Table 2. It shows that the layer of composite factor (A) is the most effective factor on the volumetric wear rate and is accompanied by Abrasive particle size (C), applied load (E) aluminum alloy type (B) and sliding speed (D) factors, respectively. The layer of composite, abrasive particle size and applied load factors has an insignificant effect at least 99% confidence levels. Sliding speed factor is a significant effect at %95 confidence levels. However, in the ANOVA table, it is seen that the sliding distance (F) factor hasn't been a significant effect on the volumetric wear rate of the composites.

Since the variance value of the error factor (5.24) is very small in the ANOVA table, it shows that the uncontrolled factors do not have a significant effect.

Table 2. The analysis of variance statistical method (ANOVA)

Factors	Column	Sum of squares (SS)	Degrees of freedom (v)	Variance (V)	F_{factor}	Percent effect, %
+ layer of composite	A	835.70	1	835.70	159.54	63,56
* Aluminum alloy type	B	185.81	2	92.90	17.74	17,11
*Abrasive particle size	C	449.93	2	224.96	42.95	7,07
& Sliding speed	D	72.10	2	36.05	6.88	2,75
*Applied load	E	208.15	2	104.07	19.87	7,92
-Sliding distance	F	32.79	2	16.39	3.13	1,25
Total		1784.47	11	162.22		
e		31.43	6	5.24		

+At least 99% confidence ($F_{(table)}$ value 13.75 for A factor)

*At least 99% confidence ($F_{(table)}$ value 10.92 for B, C and E factors)

& At least 95% confidence ($F_{(table)}$ value 5.14 for D factor)

- At least 90% confidence ($F_{(table)}$ value 3.14 for F factor)

The best working conditions can be determined using the Taguchi method. These conditions can be established by plotting a response graph which is drawn using the average of the levels of each factor. Figure 6 shows the response graph prepared for this study. The highest level of each factor gives an optimum trial recipe which provides the lowest the volumetric wear rate. Optimal trial recipe was determined as A_2,B_2,C_3,D_1,E_3,F_3 conditions. Namely, TiB_2-reinforced layer of the Al-Si composite (A1, C2) should be used in the wear test conditions, carried out under 1 N applied load (E3) using 18 µm of abrasive particle size (C3) at 7.00 m/s of sliding speed (D1) in 300 m of sliding distance (F3) to achieve the lowest volumetric wear rate.

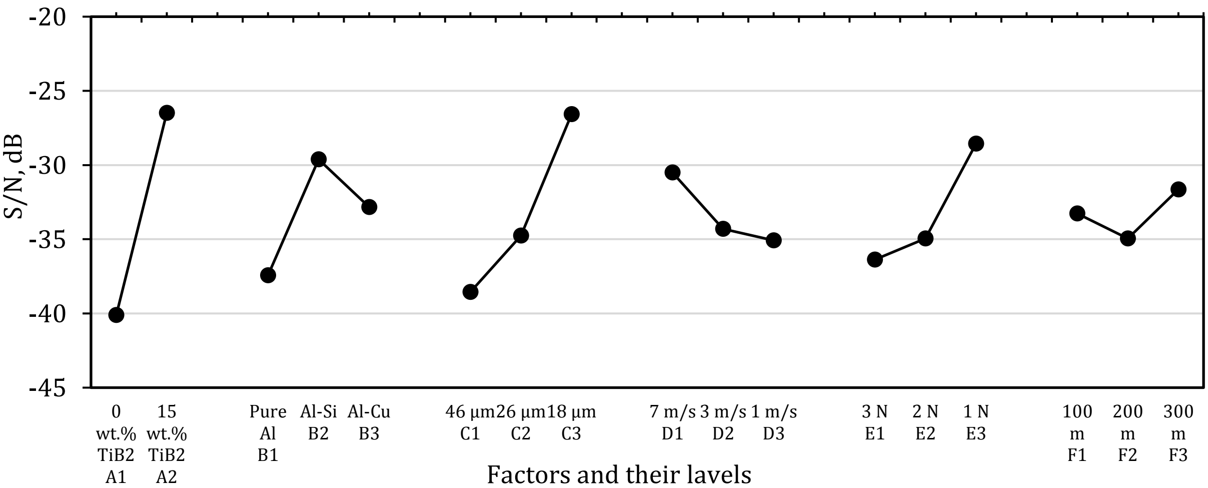

Fig. 6. Main effect plot for S/N ratios (Responses graph).

According to the Taguchi method, a confirmation experiment needs to be done to test that the experiments were done correctly. Confirmation experiments include two parts. In the first part, an estimated confidence interval must be determined for the optimal trial recipe. In the second part, an additional test should be carried out according to optimal test conditions. The results of the additional test must be within the calculated estimation confidence interval for the study to be accurate.

For this study, Confirmation test was performed and the results are given in Table 3.

Table 3. Verification test results with the estimated test results.

Description	
Optimal trial recipe	A_2,B_2,C_3,D_1,E_3,F_3
Estimated average S/N ratio,dB	-6.90
Estimated S/N ratio range,dB	$-11.27 < \mu < -2.54$
Average S/N ratio of additional test, dB	-4.26
Estimated average wear rate, x 10^{-3} mm^3/m	2.203
Estimated wear rate range, x 10-3 mm^3/m	$3.653 > \mu > 1.330$
Average wear rate of additional test, x 10^{-3} mm^3/m	1.711

Additional test results and estimated confidence interval values are given in Table 3. The wear rate of the additional test is average 1.711 x 10^{-3} mm^3/m and their S/N are -4.26 dB as saw Table 3. The estimated confidence interval was calculated between –2.54 dB and -11.27 dB. It is seen that both the mean wear rate and the S/N ratio of the additional test are within the expected confidence interval in Table 3. This result shows that the experiments were done correctly.

Figure 7 shows the worn surface images of the TiB_2-reinforced and non-reinforced layers in Al alloy composite. For a more accurate comparison, both surfaces were abraded under a load of 3 N at a sliding speed of 7.00 m/s using a particle size of 18 μm and then SEM images were taken from the worn surfaces.

In Figure 7(a), intense and deep wear marks are striking in the worn surface of non-reinforced layers. Figure 7(a) also shows black clustered regions containing TiB_2 particles. In Figure 7(b), it is seen that there are traces of shallow wear in the worn surface of the TiB_2-reinforced layer. The reason why the wear marks are more superficial in the worn surface of TiB_2-reinforced layer is due to the fact that 15 wt.% TiB_2 particles added to the Al alloys increase the hardness, making it difficult for the abrasive particles to penetrate the wear surface. On the other hand, in Figure 7(b), it is seen that the abrasive particles penetrate the wear surface more due to the lower hardness value of non-reinforced layer. The average hardness value of the TiB_2-reinforced and non-reinforced layers can be seen in Table 1.

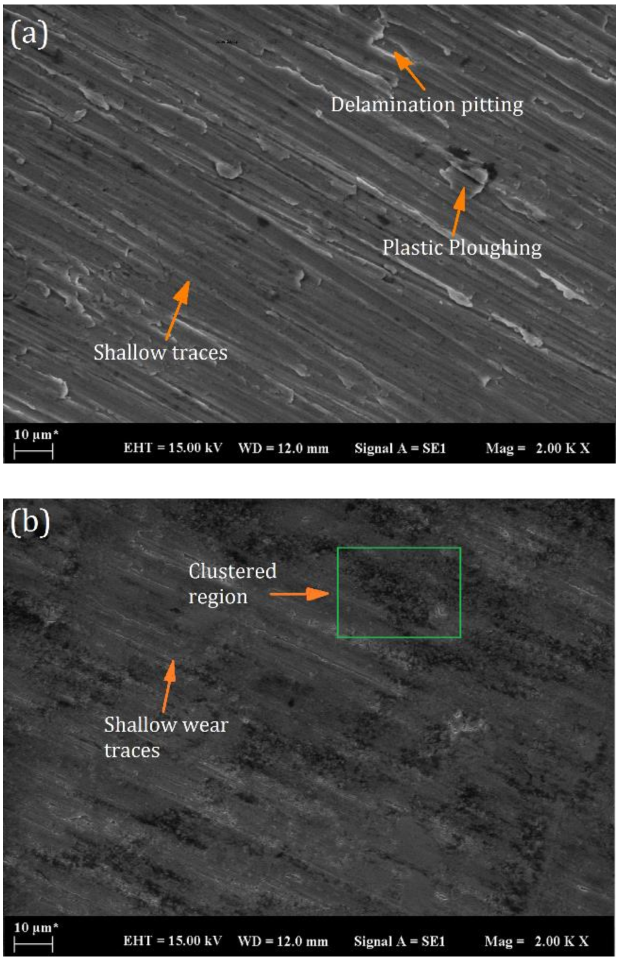

Fig. 7. Worn surface images of the worn surface images of (a) non-reinforced and (b) TiB_2-reinforced layers of aluminum matrix functionally graded materials.

In literature studies, it has been noted that increasing reinforcement ratio increases the wear resistance of materials. This happens because the reinforcing particles increase the hardness of the material. As a result, difficult penetration of abrasive particles on the material surface increases the wear resistance of the materials. [3,8]. In this study, as saw in Figure 6 (A factor), the wear rate decreases with adding TiB_2 reinforcement in Al alloys. The highest of the wear rate value is in Al alloy that does not contain TiB_2 particle, similar to the previous studies [17,26]. This is because TiB_2 particles increased the hardness of the composite.

Figure 6 (B factor) shows that the aluminum alloy type factor affects the wear rate. It is seen that the highest wear rate is in Al composite. The lowest wear rate is in Al-Si composite, followed by Al-Cu composite. This result demonstrates that the alloying of Al with %4Cu and %4Si significantly reduces the wear rate [2,8,21].

Previous studies have reported that the wear rate increase with increasing abrasive particle size and applied load in abrasive wear tests [2,21,26-28]. It is similarly seen that the wear rates increase with increasing the abrasive particle sizes and applied load in this study as can be seen in Figure 6 (C and E factors). This is because the abrasive particle sizes and the applied load increase the sinking depth of the abrasive particles toward the wear surface. Consequently, it was caused that the wear rate increased with increasing load and abrasive particle size.

In Figure 6 (D factor), it is seen that the wear rate decrease with increasing sliding speed. This is thought to be due to the fact that the abrasive particles do not have enough time to penetrate the wear surface with increasing speed. For this reason, the wear rate was less on surfaces abraded at high sliding speed [4,17,22].

4. CONCLUSIONS

In this study, Centrifugal casting Al alloy composites with TiB_2 particles were produced to be used in engineering applications. Wear behavior of composites has been revealed by The Taguchi approach. The current examination concludes that:

1. TiB_2 reinforced centrifugal casting Al, Al-Cu and Al-Si alloy composites were successfully produced. It was observed that the composites had two layers such as TiB_2-reinforced and non-reinforced layers. TiB_2 particle ratio was found to be approximately 15 wt.% in the TiB_2-reinforced layer.
2. It has been determined that the hardness values of Al-Si and Al-Cu composites are higher than Al composite. The highest hardness value was observed at 115.3 HB in the TiB_2-reinforced layer of the Al-Si composite. The lowest hardness value was measured at 34.3 HB in the non-reinforced layer of Al composite.
3. It has been determined that layer of composite (A) factor is the most influential factor on volumetric wear rate, following by abrasive particle size (C), applied load (E) aluminum alloy type (B) factors at least 99% confidence level, respectively. Sliding speed (D) factor was considered to be effective only at the 95% confidence level. It was observed that volumetric wear rate of the composite decrease with increasing TiB_2 particles ratio and sliding speed. However, the volumetric wear rate increases with increasing the abrasive particle size and applied load.
4. It has been determined that the addition of TiB_2 in Al alloys improves the wear properties by 63%. It has been found that alloying aluminum with 4% Cu or 4% Si improves the wear properties by 17%.

Acknowledgments

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REFERENCES

[1] M. Toozandehjani, N. Kamarudin, Z. Dashtizadeh, E. Yee Lim, A. Gomes, C, Gomes *Conventional and Advanced Composites in Aerospace Industry: Technologies Revisited,* American Journal of Aerospace Engineering, vol. 5, iss. 1, pp. 9–15, 2019, doi: 10.11648/j.ajae.20180501.12

[2] S. Kumar, V.S. Sarma, B.S. Murty, *Influence of In-situ Formed TiB_2 Particles on the Abrasive Wear Behavior of Al-4Cu Alloy,* Materials Science and Engineering A, vol. 465, iss. 1–2, pp. 160–164, 2007, doi: 10.1016/j.msea.2007.02.117

[3] S. Kumar, M. Chakraborty, V. Subramanya Sarma, B.S. Murty, *Tensile and Wear Behavior of in situ Al-7Si/TiB_2 Particulate Composites,* Wear, vol. 265, iss. 1–2, pp. 134–142, 2008, doi: 10.1016/j.wear.2007.09.007

[4] A. Sreenivasan, S.P. Vizhianb, N.D. Shivakumarc, M. Munirajua, M. Raguramand, *A Study of Microstructure and Wear Behaviour of TiB_2/Al Metal,* Latin American Journal of Solids and Structures, vol. 8, iss. 1, pp. 1–8, 2011, doi: 10.1590/S1679-78252011000100001

[5] S.L. Pramod, S.R. Bakshi, B.S. Murty, *Aluminum-Based Cast In-Situ Composites: A Review,* Journal of Materials Engineering and Performance, vol. 24, iss. 6, pp. 2185–2207, 2015, doi: 10.1007/s11665-015-1424-2

[6] R. Singh, V. Bhavar, P. Kattire, S. Thakare, S. Patil, R.K.P. Singh, *A Review on Functionally Gradient Materials (FGMs) and Their Applications,* IOP Conference Series: Materials Science and Engineering, vol. 229, pp. 1–9, 2017, doi: 10.1088/1757-899X/229/1/012021

[7] G. Udupa, S.S. Rao, K.V. Gangadharan, *Functionally Graded Composite Materials: An Overview,* Procedia Materials Science, vol. 5, pp. 1291–1299, 2014, doi: 10.1016/j.mspro.2014.07.442

[8] Ö. Savaş, *The Production and Properties Of Al_3Ti Reinforced Functionally Graded Aluminum Matrix Composites Produced by The Centrifugal casting method,* Materials Research Express, vol. 6, no. 12, pp. 1-14, 2019, doi: 10.1088/2053-1591/ab562c

[9] M.F. Forster, R.W. Hamilton, R.J. Dashwood, P.D. Lee, *Centrifugal Casting Of Aluminium Containing In-Situ Formed TiB_2,* Materials Science and Technology, vol. 19, iss. 9, pp. 1215–1219, 2003, doi: 10.1179/026708303225005872

[10] Ö. Savas, *Fabrication and Characterization of TiB_2-reinforced Functionally Graded Aluminum Matrix Material,* Industrial Lubrication and Tribology, vol. 72, iss. 10, pp. 1147–1152, 2020, doi: 10.1108/ilt-12-2019-0538

[11] L. Lu, M.O. Lai, F.L. Chen, *Al-4 wt% Cu Composite Reinforced with In-situ TiB_2 Particles,* Acta Materialia, vol. 45, iss. 10, pp. 4297–4309, 1997, doi: 10.1016/S1359-6454(97)00075-X

[12] C.S. Ramesh, S. Pramod, R. Keshavamurthy, *A Study on Microstructure And Mechanical Properties of Al 6061-TiB_2 In-situ Composites,* Materials Science and Engineering A, vol. 528, iss. 12, pp. 4125–4132, 2011, doi: 10.1016/j.msea.2011.02.024

[13] A. Varma, A.S. Rogachev, A.S. Mukasyan, S. Hwang, *Combustion Synthesis of Advanced Materials: Principles And Applications,* Advances in Chemical Engineering, vol. 24, pp. 79–190, 1998, doi: 10.1016/S0065-2377(08)60093-9

[14] M. Kök, *Abrasive Wear of Al_2O_3 Particle Reinforced 2024 Aluminium Alloy Composites Fabricated by Vortex Method,* Composites: Part A, vol. 37, iss. 3, pp. 457–464, 2006, doi: 10.1016/j.compositesa.2005.05.038

[15] Ö. Savaş, *Production and Properties of Functionally Graded Hybrid Composites Containing Al_3Ti and TiB_2,* International Journal of Materials Research vol. 111, iss. 9, pp. 726-732, 2020, doi: 10.3139/146.111941

[16] P. Sharma, D. Khanduja, S. Sharma, *Tribological and Mechanical Behavior of Particulate Aluminum Matrix Composites,* Journal of Reinforced Plastics and Composites, vol. 33, iss. 23, pp. 2192–2202, 2014, doi: 10.1177/0731684414556012

[17] F. Ficici, *The Experimental Optimization of Abrasive Wear Resistance Model for An In-Situ AlB_2/Al-4Cu Metal Matrix Composite,* Industrial Lubrication and Tribology, vol. 68, iss. 6, pp. 632–639, 2016, doi: 10.1108/ILT-12-2015-0198

[18] N. Kumar, G. Gautam, R. Kumar, A. Mohan, *Wear, Friction And Profilometer Studies of In-situ AA5052/ZrB_2 Composites,* Tribology International, vol. 97, pp. 313–326, 2016, doi: 10.1016/j.triboint.2016.01.036

[19] G.Y. Lee, C.K.H. Dharan, R.O. Ritchie, *A Physically-Based Abrasive Wear Model for Composite Materials,* Wear, vol. 252, iss. 3–4, pp. 322–331, 2002, doi: 10.1016/S0043-1648(01)00896-1

[20] O. Savaş, *Investigation of Production and Abrasive Wear Behavior of Functionally Graded TiB2/Al and TiB2/Al–4Cu Composites,* 544 Transactions of the Indian Institute of Metals, vol. 73, iss. 3, pp. 543–553, 2020, doi: 10.1007/s12666-020-01870-7

[21] N. Radhika, R. Raghu, *Effect of Centrifugal Speed in Abrasive Wear Behavior of Al-Si5Cu3/SiC Functionally Graded Composite Fabricated by Centrifugal Casting*, Transactions of the Indian Institute of Metals, vol. 71, iss. 3, pp. 715–726, 2018, doi: 10.1007/s12666-017-1204-9

[22] P. Muthu, *Multi Objective Optimization of Wear Behaviour of Aluminum MMCs Using Grey-Taguchi Method,* Manufacturing Review, vol. 7, no. 16, pp. 1-8, 2020, doi: 10.1051/mfreview/2020013

[23] T. Sathish, S. Karthick, *Wear Behaviour Analysis on Aluminium Alloy 7050 With Reinforced SiC Through Taguchi Approach,* Journal of Materials Research and Technology, vol. 9, iss. 3, pp. 3481–3487, 2020, doi: 10.1016/j.jmrt.2020.01.085

[24] H. Unal, F. Ficici, A. Mimaroglu, A. Demirkol, A. Kırdar, *Prediction And Optimization of Tribological Behavior of Nylon Composites Using Taguchi Analysis Method,* Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 38, iss. 7, pp. 2097–2104, 2016, doi: 10.1007/s40430-015-0398-1

[25] F. Ficici, S. Koksal, *Microstructural Characterization and Wear Properties of In-situ AlB2-reinforced Al-4Cu Metal Matrix Composite,* Journal of Composite Materials, vol. 50, iss. 12, pp. 1685–1696, 2016, doi: 10.1177/0021998315595709

[26] N. Radhika, R. Raghu, *Effect of Abrasive Medium on Wear Behavior of Al/AlB_2 Functionally Graded Metal Matrix Composite,* Tribology Online, vol. 11, iss. 3, pp. 487–493, 2016, doi: 10.2474/trol.11.487

[27] M. Kök, K. Özdin, *Wear Resistance of Aluminum Alloy and Its Composites Reinforced by Al_2O_3 Particles,* Journal of Materials Processing Technology, vol. 183, iss. 2-3, pp. 301–309, 2007, doi: 10.1016/j.jmatprotec.2006.10.021

[28] M. Kok, *Production and Mechanical Properties of Al_2O_3 Particle-Reinforced 2024 Aluminium Alloy Composites,* Journal of Materials Processing Technology, vol. 161, iss. 3, pp. 381–387, 2005, doi: 10.1016/j.jmatprotec.2004.07.068