Journal of Bio- and Tribo-Corrosion (2019) 5:90
https://doi.org/10.1007/s40735-019-0282-0

An Investigation on Mechanical and Wear Characteristics of Al 6063/TiC Metal Matrix Composites Using RSM

P. Venkateshwar Reddy[1] · P. Rajendra Prasad[2] · D. Mohana Krishnudu[2] · E. Venugopal Goud[2]

Received: 25 May 2019 / Revised: 1 August 2019 / Accepted: 27 August 2019 / Published online: 9 September 2019

Abstract
This paper focuses on the consequences of reinforcement content (TiC particles) on sliding wear behavior of aluminum alloy Al 6063 fabricated by stir casting process. Three different reinforcement percentages (5, 10 and 15) have been considered in the present study. Both hardness and tensile tests have been executed on the fabricated samples. The results of the conducted mechanical tests showed that the increase in reinforcement weight percent increased the tensile strength and hardness. Pin-on-disk tests have been performed on the fabricated composite samples to identify their tribological behavior. Reinforcement weight percent, load and sliding speed with three levels each were taken as the process variables, and specific wear rate is considered as response. Box–Behnken design have been utilized to carry out the experiments and to analyze the results. Moreover, ANOVA is carried out to know the influencing parameter on the response. From ANOVA, it was confirmed that reinforcement weight percent and sliding speed is considered as the influencing parameters on the response.

Keywords Composites · Pin-on-disk · Aluminum alloy · Wear · RSM

1 Introduction

An increase in demand for metal matrix composites (MMCs) is due to enhancement in properties like strength, hardness and stiffness over the base metals. The MMC achieved the improved properties with the mixture of matrix and reinforcement materials. Now a day, much attention has been given for aluminum and its alloys for the fabrication of composites due to their wide range of functions in automotive and aerospace fields. Aluminum-based MMCs are successfully implementing in the automotive industries like Nissan, Honda and General Motors for different components. Reinforcements like oxides, carbides, borides, nitrides, etc. are being utilized as reinforcements for the fabrication of MMCs [1–3]. Several methods are utilized by many researchers for the fabrication of MMCs, but stir casting technique is viewed as the most economic technique for the fabrication of MMCs [4–6]. This process is considered as the best technique in terms of cost aspects, higher yield materials, complicated shapes and less damage [7, 8]. Ünlü [9] compared two fabricating techniques of MMC, i.e., liquid condition (casting) and solid condition (powder metallurgy) on aluminum-based Al_2O_3 and SiC reinforced composites. It was concluded from the work that the casting method had shown better mechanical properties than the powder metallurgical fabrication technique. Several research studies proved that the reinforcements addicted to the matrix improves the mechanical and tribological characteristics of the composites [10–13]. Titanium carbide is considered as a hard reinforcing element with many technical advantages. TiC posses high melting point temperature and high hardness with reasonable thermal and electrical characteristics [14]. Moreover, TiC is resistant to corrosion, abrasion and oxidation [15].

Resistance to wear of the material is one of the factors to be considered for using the material in any engineering applications even though the tribological properties of a

P. Venkateshwar Reddy
mr.pvreddy@gprec.ac.in

P. Rajendra Prasad
prp303@gmail.com

D. Mohana Krishnudu
donimohan@gmail.com

E. Venugopal Goud
goudvenu@gmail.com

[1] Department of Mechanical Engineering, JNT University (GPREC Research Centre), Ananthapuramu, A.P., India

[2] Department of Mechanical Engineering, G Pulla Reddy Enginering College (Autonomous), Kurnool, A.P., India

number of aluminum alloys in both dry and wet conditions are broadly investigated by many researchers. Abrasive wear of the composite samples depends on many controllable factors like load, dimension of the abrasive elements, content of abrasive particles, toughness and hardness of the reinforcement particles [16–19]. Tyagi [20] investigated on the wear characteristics of aluminum-based titanium carbide reinforced composites. It was concluded from the work that the wear conduct decreased as the proportion of the TiC particles raise in the composite sample. Kostornov et al. [21] investigated on the tribological aspects for improving the wear resistance of titanium-based composites. It was concluded from the work that the selected material can be used as an antifriction material at higher sliding velocities. Selvakumar and Narayanasamy [22] investigated on frictional aspects of both TiC and MoS_2 reinforced composites and concluded that the content of TiC and sliding time influence the response (weight loss) of the composites. León-Patiño et al. [23] investigated on nickel-based TiC reinforced composites by considering its wear characteristics. The work concluded that the TiC weight content reduced the dry sliding wear of the composite. Narayanasamy et al. [24] investigated on tribological aspects of magnesium-based TiC reinforced composites and concluded that the higher TiC content directs to lower wear rate of the composite. Jha et al. [25] investigated on nickel-based titanium carbide reinforced composites for finding out its friction and wear behavior. The work concluded that wear pace improved with spindle load increment, whereas addition of reinforcement resists the wear rate.

From the above works, it was confirmed that many studies were conducted on aluminum-based composites and investigated on physical and mechanical properties. However, few works have showed attention on aluminum-based TiC reinforced composites to investigate on the tribological characteristics. Hence, the main plan of the current effort is to study the consequences of reinforcement weight percent on the physical, mechanical and wear performance of the Al 6063 reinforced with TiC. Moreover, the effect of reinforcement weight percent, load and sliding distance on wear characteristics of the composites was also investigated. The morphology of the composites is also studied by scanning electron microscopy (SEM) on the wear samples. ANOVA is also carried out to know the significant parameters on the wear characteristics.

2 Materials and Methods

2.1 Workpiece Material

The workpiece material used in the present study was A6063-TiCp (5, 10 and 15 p) MMCs of cylindrical shape with a diameter of 30 mm and 100 mm length were made-up by stir casting technique. The chemical composition of matrix material (Al 6063) aluminum alloy utilized as base metal is tabulated in Table 1. The manufacturing steps along with obtained samples are shown in Fig. 1. Density of the samples was determined by rule of mixtures and the obtained values are shown in Fig. 2. The density of the composites enhances with the increase in reinforcement content in the composites [26, 27].

Table 1 Chemical composition of matrix material (Al 6063) aluminum alloy

Elements	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
Composition (wt%)	97.5	0.60	0.35	0.1	0.1	0.9	0.1	0.1	0.1	0.15

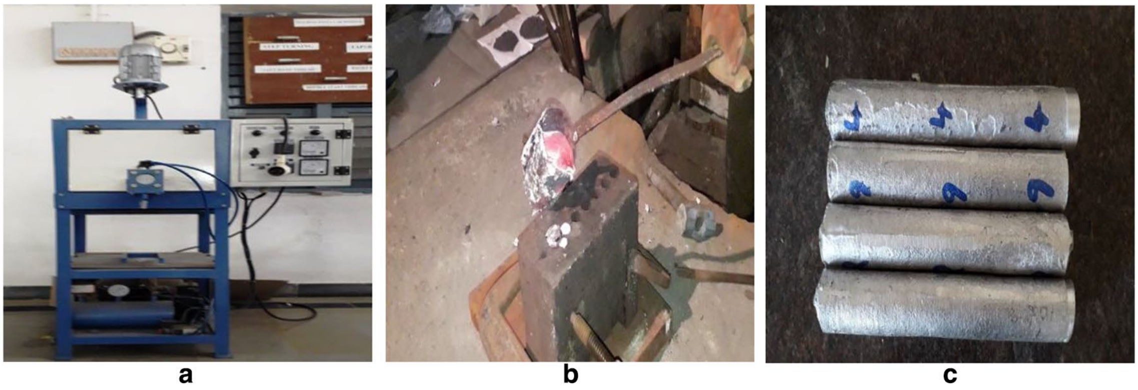


Fig. 1 Fabrication steps of MMC's: **a** stir casting, **b** pouring into mold, **c** fabricated samples

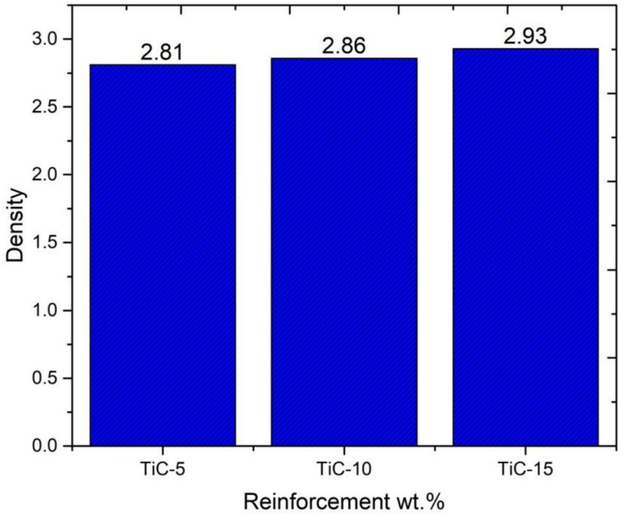


Fig. 2 Density of the fabricated MMCs with variation of reinforcement %

2.2 Hardness Test

Microhardness analysis was performed on the composite samples by taking up of regular testing method as per ASTM: E384−10 [28]. The hardness of the composite was measured by Vickers microhardness tester with diamond indenter with an applied load of 100 N. The test was performed at five various positions over the sample, and an average hardness value was reported.

2.3 Tensile Test

Tensile test was performed on the composite samples as per the ASTM E8/E8M-13a [29] standards using Universal Testing Machine (UTM) at GPREC Kurnool, A.P., INDIA. Before testing, the samples were prepared as per the required dimensions of the ASTM standards using lathe machine.

2.4 Box–Behnken Experimental Design

Box–Behnken designs (BBD) are a class of rotatable second-order designs with incomplete three-level factorial designs. The graphical representation of three-level factorial designs is shown in Fig. 3. BBD is a part of response surface method design, which is very efficient when compared to central composite design for three-level full factorial designs [30]. Moreover, BBD circumvent extremes by allowing the user to work around the extreme factor level arrangements. Since the present work consists of extreme factor level combinations, BBD is considered since it does not have corners and no risk of parametric extreme combinations. The risk of failure updates can be reduced by this design.

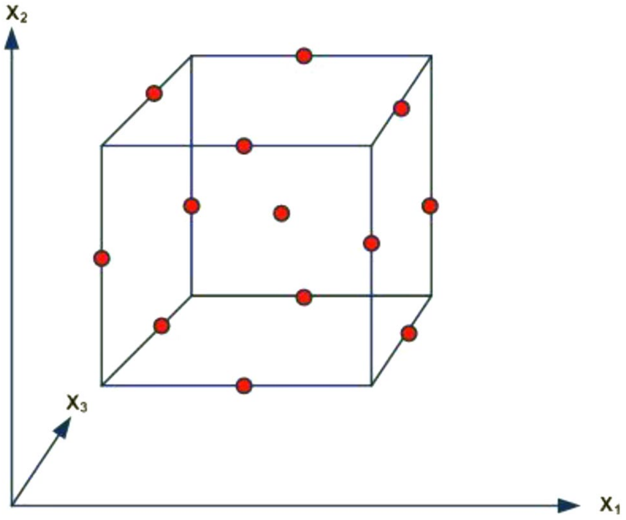


Fig. 3 Cube with central and middle points of the edges

2.5 Sliding Wear Tests

Wear tests were performed on DUCOM made computerized pin-on-disk wear testing machine as per ASTM G99 standards [31] at GPREC Kurnool, A.P., INDIA. The disk material used for the test was EN31 steel. After every experiment, both the pin and disk faces were cleaned properly by means of acetone. In the present study, three controlling factors (reinforcement wt%, load and sliding distance) with three levels each have been considered. The experiments were conducted according to the Box–Behnken design of RSM due to their suitability and applicability for the present work. Considered parameters and their levels are listed in Table 2 and in the present study, output response is considered as the specific wear rate (SWR).

Table 2 Considered process parameters and its levels

Factors	Process parameter	Units	Level − 1	Level 0	Level 1
A	Reinforcement	wt%	5	10	15
B	Load	N	10	15	20
C	Sliding distance	m	1000	1500	2000

3 Results and Discussion

3.1 Microhardness Analysis

Harness values were noted at five different positions to overcome the risk of repeatability, and an average value is noted. Actually, the hardness of the cast sample should be uniform throughout the sample but due to the non-uniform distribution of particles, hardness value of the cast sample is different at different locations. Moreover, other factors like gravity of the reinforcements and cooling rate of the casted sample lead to different hardness values at different locations. The results of microhardness tests are shown in Fig. 4 with various wt% of TiC particles. A prominent increase in hardness of the fabricated composite sample is observed by the increase in weight percent of TiC particles. The reason for the improvement is because of higher percent of TiC particles in base material Al 6063. It has been proved that incorporation of reinforcement particles into the matrix material improves the hardness of the composites. Similar results were observed by several researchers [32]. As observed from the SEM micrographs in Fig. 5b, c, the reinforcing particles are uniformly embedded in the matrix material. The reinforcing particles in the matrix material improved the hardness of the composites, since the density of the sample also increased by the reinforcing particles. Reinforcing particles are harder than the matrix material, when both the materials are mixed together to form composite; the hardness of composite is shared by both matrix and reinforcement, which is clearly observed from the results. The increase in hardness value for 10 wt% TiC reinforced composite is 24% when compared to 5 wt% TiC reinforced composite. The improvement in hardness for 15 wt% TiC reinforced composite is 67% and 35% when compared to 5 and 10 wt% TiC reinforced composites, respectively.

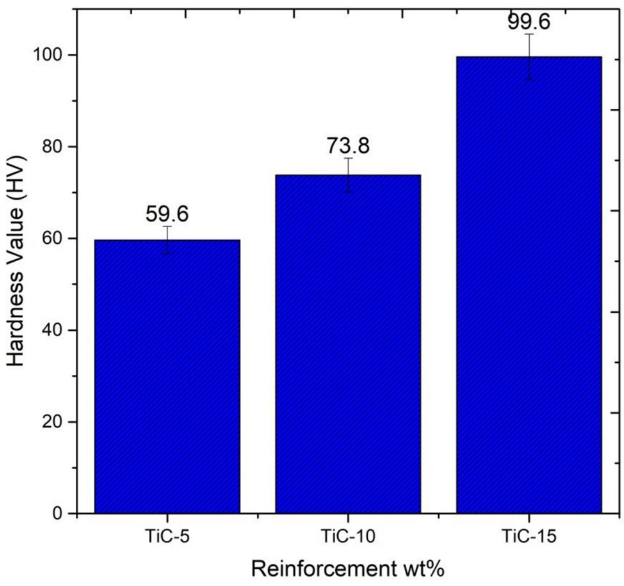


Fig. 4 Effect of reinforcement % on microhardness of MMC

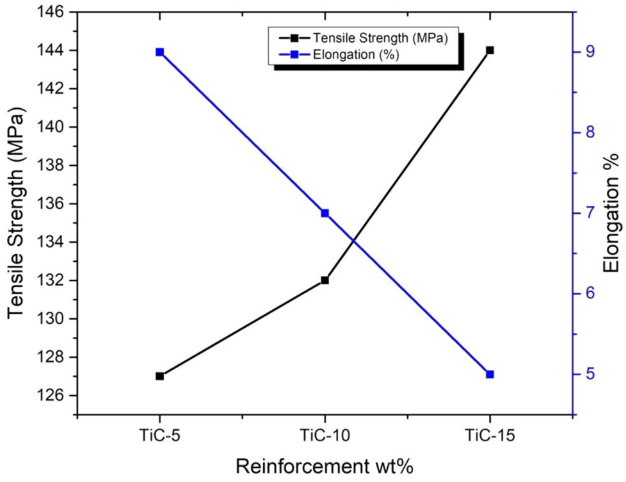


Fig. 5 Effect of reinforcement on tensile strength of MMC

3.2 Tensile Strength Analysis

The tensile strength and elongation percent of Al 6063 reinforced with various portions of TiC particles are shown in Fig. 5, which was interpreted from stress vs strain curves. From Fig. 5, it is observed that the tensile strength of the composite sample increased as the reinforcement percent into the sample increases. Similar results were observed from the previous researchers as well to validate the present results [33, 34]. The elongation percent of the composite sample was declined with enhance in reinforcement weight percent in the sample, which is observed from Fig. 5. It is because of the presence of TiC particles in composite made the composite brittle. Similar outcomes were experiential by additional researchers supporting the present study results [34]. Presence of hard reinforcing particles (TiC) into the matrix made the composite stronger as the bonding within the matrix and reinforcement improved, which is clearly visible from Fig. 6 c. Incorporation of TiC particles made the composite brittle, since the elongation percent of the composite decreased and tensile strength increased. The load sharing capability of both matrix and reinforcement for 15 wt% TiC reinforced composite is high as observed from Fig. 5. The increase in tensile strength for 10 wt% TiC reinforced composite is 4% when compared to 5 wt% TiC reinforced composite. The improvement in tensile strength for 15 wt% TiC reinforced composite is 14% and 12% when compared to 5 and 10 wt% TiC reinforced composites, respectively. The decrease in elongation percent for 10 wt% TiC reinforced composite is 28% when compared to 5 wt%

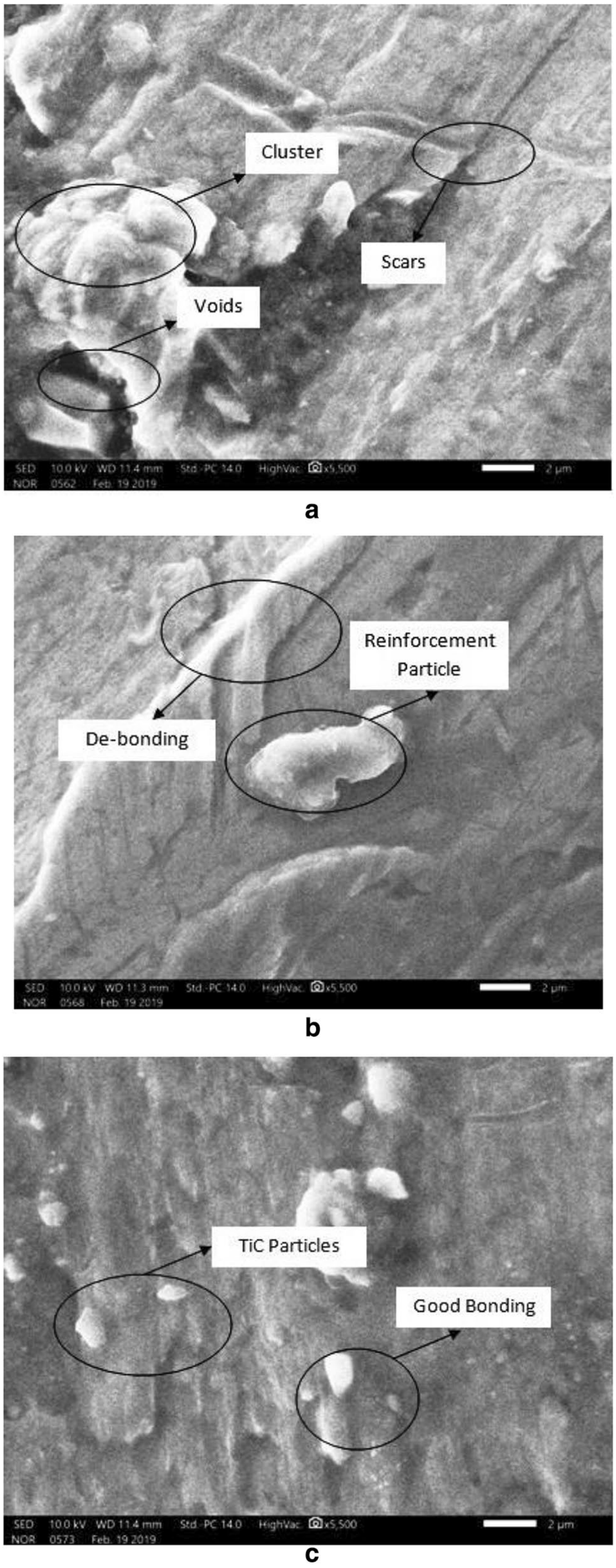


Fig. 6 SEM images TiC reinforced composites: **a** 5 wt%, **b** 10 wt%, and **c** 15 wt%

TiC reinforced composite. The decrement in elongation percent for 15 wt% TiC reinforced composite is 44% and 22% when compared to 5 and 10 wt% TiC reinforced composites, respectively.

3.3 SEM Analysis

The morphology of the samples after conducting the wear test for TiC particles reinforced Al 6063 alloy is exposed in Fig. 6 with a magnification of 2 μm. All the wear samples were observed that there is a scratches over the wear surfaces which propose that the samples undergone an abrasive wear. Figure 6a shows the SEM images at 5 wt% TiC reinforced composite and observed a large voids, scars, cracks and delaminations, the reason might be the improper stirring or insufficient wettability. Moreover, cluster formation takes place in 5 wt% TiC reinforced composite surface which lacks the interfacial bonding with the matrix material. The cluster formation in the matrix due to the reinforcement particles leads to porosity and poor interfacial bonding. The reason for lesser tensile strength for 5 wt% TiC reinforced composites is because of these void defects. All the fabricated composites sample are free from general casting defects like shrinkages and porosities. Moreover, the void contents are reduced for 10 wt% TiC reinforced composites as observed from Fig. 6b when compared to Fig. 6a. Figure 6a, b shows little wear scars over the surfaces which are highlighted; moreover, there are plowing grooves over the wear surface, which seems to be very common phenomenon in metal matrix composites due to improper bonding. This improper bonding leads the composites for delamination cracks; but in the present case, no significant delamination cracks are observed but only a small wear scars and plowing are observed from Fig. 6. The void contents in Fig. 6c are almost reduced due to higher presence of TiC particles, thereby a good bonding is observed such that higher mechanical properties have attained [34, 35]. The load bearing capability of the composite can be increased only if there is a good interface between matrix and reinforcement, such its mechanical and tribological properties can be improved.

3.4 Wear Analysis

Figure 7 shows the wear against time graphs for all the three weight percent of TiC particle reinforced composites. From Fig. 7, it is observed that the wear is highest for the 5 wt% of TiC reinforced composite sample than the other two reinforced composite samples. Wear of the composite sample increased by increase in time. Moreover, the wear of the composite samples enhances with raise in load as is observed from Fig. 7a–c. The wear of the composite samples with 15 wt% TiC particles are observed to be constant for the first 5 min (300 s.) and from then non-uniform wear took

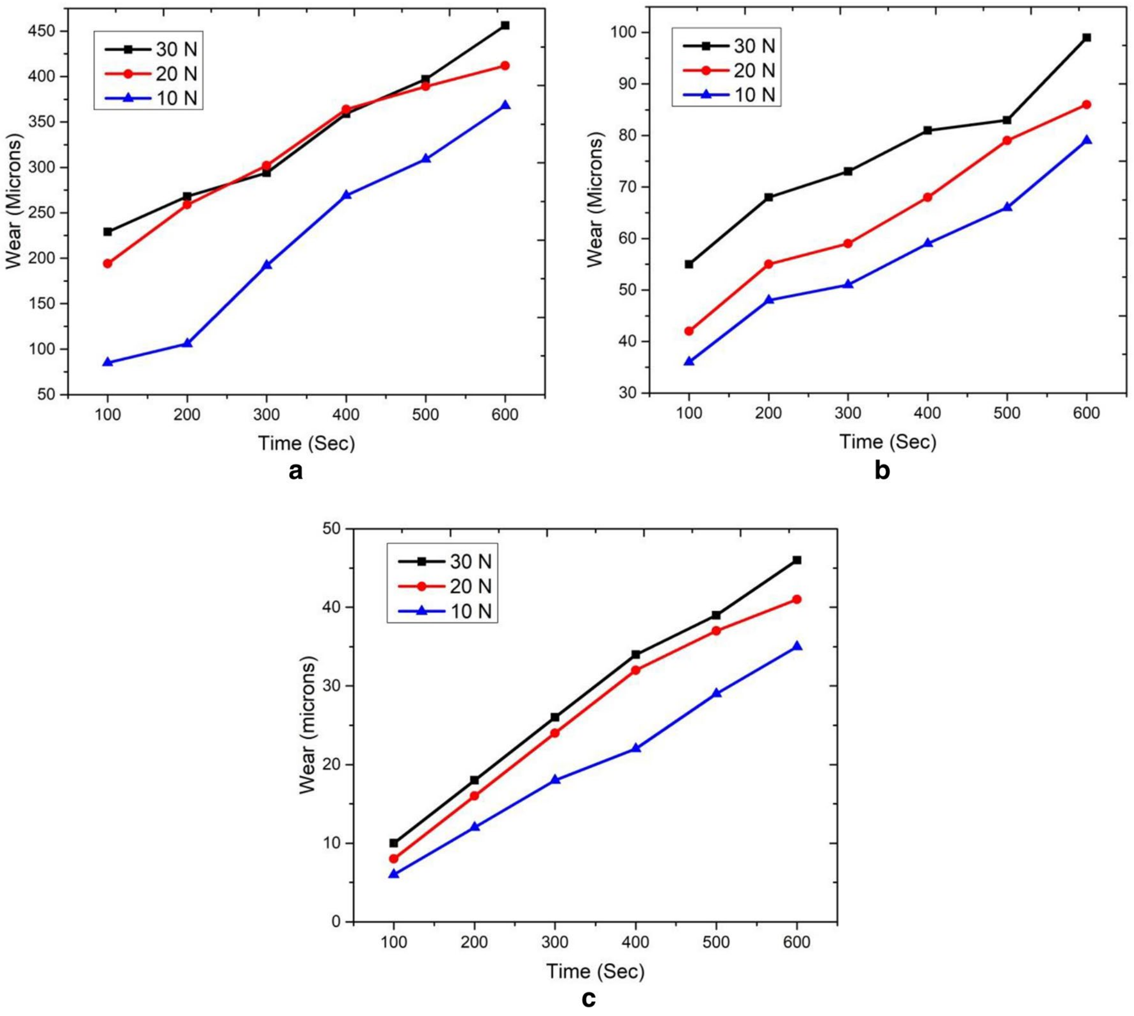


Fig. 7 Wear of the composite sample at various loads of TiCp reinforcements: **a** 5 wt%, **b** 10 wt%, and **c** 15 wt%

place. Whereas for the 5 and 10 wt% reinforced composite samples, non-uniform wear took place right from the starting as observed from Fig. 7a, b. The increase in wear loss due to increase in load is due to the generation of higher plastic deformation zones. Moreover, at higher loads delamination wear takes place, this can also be one of the reasons for the increase in wear loss. High loads can also create fracture between matrix and reinforcement during sliding of the disk. Analogous consequences were experiential by others investigators as well [35]. The decrease in wear for 15 wt% of TiC reinforced particles than the 5 wt% of TiC particles is because of presence of more TiC particles, which restricts the composite against wear.

Figure 8 illustrates the influence of reinforcement content and load on frictional coefficient of the composite sample. From Fig. 8, it is concluded that the coefficient of friction enlarges as the load raise. Similar consequences were concluded by other researchers [36–38]. Moreover, the coefficient of friction enlarges with reinforcement content into

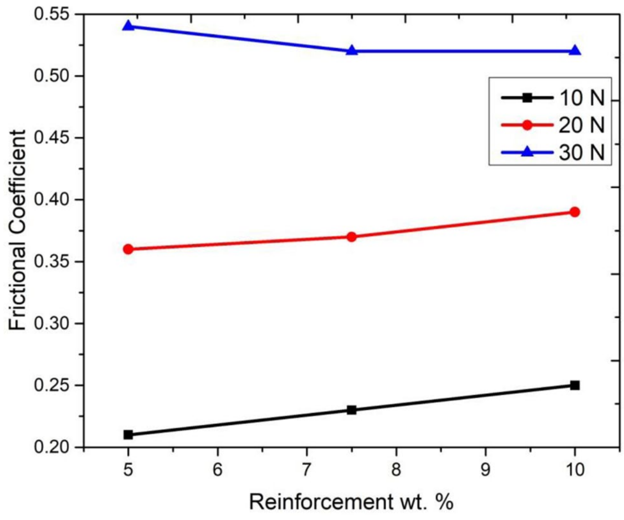


Fig. 8 Image of reinforcement wt% and load against frictional coefficient

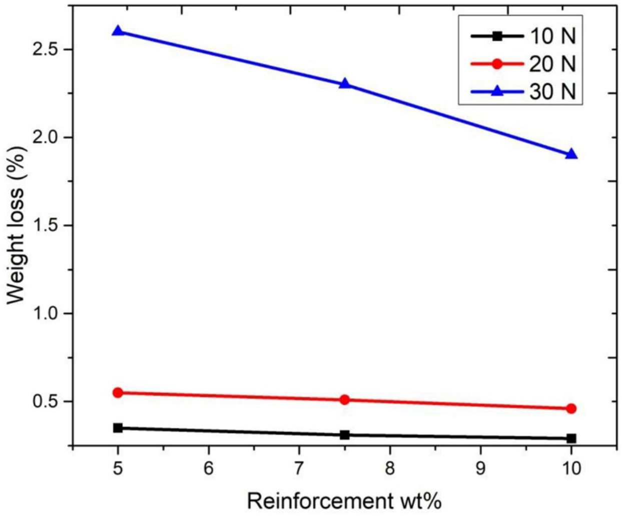


Fig. 9 Result of reinforcement wt% and load on weight loss percentage

the composite sample. The reason for these results is due to the presence of more hard particles into the composite samples. Figure 9 represents the weight loss percentage based on the effect of reinforcement weight percent and load. From Fig. 9, it was noted that only a minute weight loss percent is observed for 10 and 20 N, whereas at 30 N load weight loss percent is more when compared to other two loads. Reinforcement content into the material has an influence on the weight loss percent, as higher the reinforcement content lower the weight loss percent. For the first two loads (10 N and 20 N), the reinforcement content has not shown much influence on the weight loss percent as observed from Fig. 9.

3.5 Specific Wear Rate

The experimental test results and forecasted results of specific wear rate based on Box–Behnken design by response surface methodology (RSM) are shown in Table 3. Specific wear rate (SWR) is calculated by using Eq. (1):

$$\mathrm{SWR} = \frac{\Delta W}{\rho \times F_{\mathrm{n}} \times S_{\mathrm{d}}}, \tag{1}$$

whereas ΔW is the weight loss, ρ is the density of the specimen, F_{n} is the normal load, and S_{d} is the sliding distance.

3.6 Validation

The correlation between experimental and predicted results of the specific wear rate is illustrated in Fig. 10. It is observed from Fig. 10 that the produced model is more than enough as the calculated results are in good agreement with the experimental outcomes. The coincidence of points 1, 3 and 7 with the fitted line confirms that the model is efficient with minimum errors.

3.7 Analysis of Variance (ANOVA)

The ANOVA is used to test the created model for finding out its significance. R^2 value of 98.22 for SWR is considered that the model has high predictive capability. Figure 11 represents the contour plots to know the interaction between the process parameters. The contour plots based on SWR were generated utilizing the model equation obtained by regression analysis using Minitab 16 statistical software. Figure 11 concluded that there is

Table 3 Box–Behnken experimental design and response

Test No.	Reinforcement wt%	Load	Sliding distance	Expt. specific wear rate (mm^3/N-m)	Pred. specific wear rate (mm^3/N-m)
1	7.5	10	2000	9.96E−05	8.0500E−05
2	10.0	10	1500	5.64E−05	3.8000E−05
3	5.0	30	1500	1.25E−04	1.8300E−04
4	10.0	20	2000	7.56E−05	6.8000E−05
5	10.0	30	1500	5.94E−05	9.8000E−05
6	5.0	10	1500	1.25E−04	1.2300E−04
7	7.5	20	1500	9.65E−05	1.1050E−04
8	7.5	10	1000	8.85E−05	8.0500E−05
9	7.5	30	2000	9.25E−05	1.4050E−04
10	5.0	20	1000	1.27E−04	1.5300E−04
11	7.5	20	1500	1.02E−04	1.1050E−04
12	10.0	20	1000	4.95E−05	6.8000E−05
13	7.5	20	1500	9.65E−05	1.1050E−04
14	5.0	20	2000	1.39E−04	1.5300E−04
15	7.5	30	1000	9.06E−05	1.4050E−04

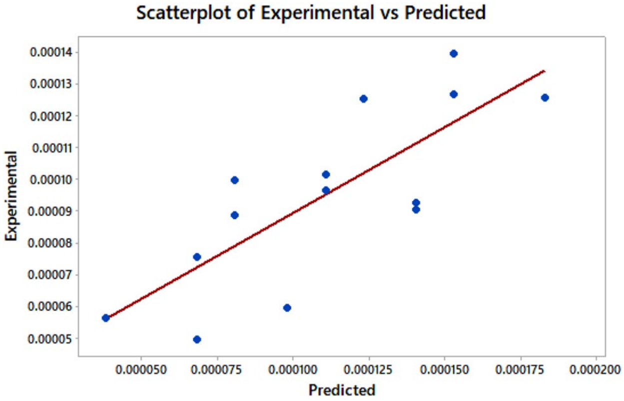


Fig. 10 Correlation of experimental and calculated SWR

an interaction between A and B and A and C, but there is no much interaction between B and C. From the contour plots it was concluded that SWR is optimized at a parameter combinations of reinforcement wt% – 7.5, load – 20 and sliding distance – 1500. Interaction between load and sliding distance for SWR is very less as observed from the contour plot. The ANOVA of the SWR is shown in Table 4. The predictive capability of the model is better for SWR at 99% confidence interval, since the *p* is less than 0.05. The predicted results fit well with experimental results as is observed from Fig. 10. The *p* value is less than 0.05 for reinforcement weight percent and sliding speed, which specify that the two parameters are statistically significant and have influence on the response [39].

Table 4 ANOVA of SWR

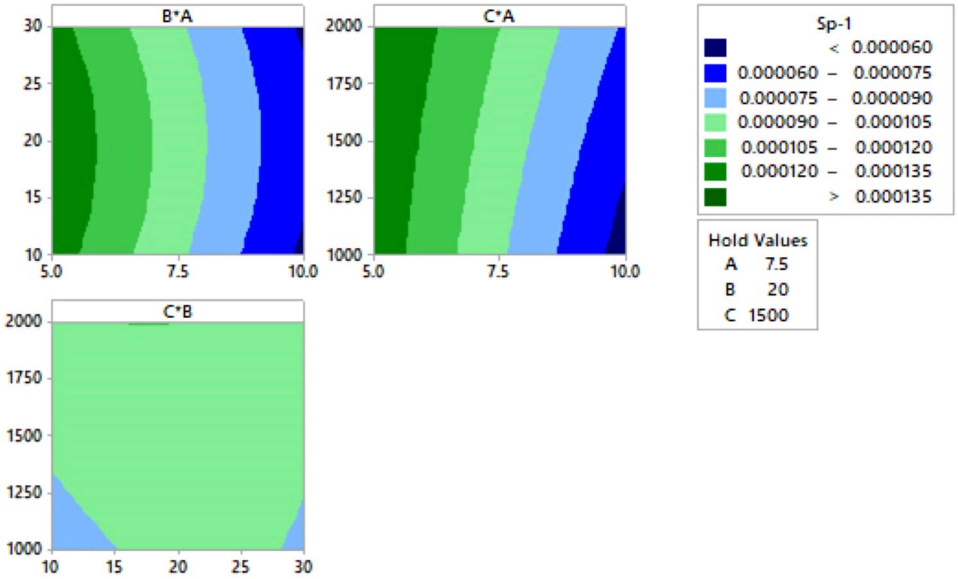
Source	DF	Adj SS	Adj MS	*F* value	*p* value
A	2	0.000000	0.000000	210.95	0.000
B	2	0.000000	0.000000	2.76	0.122
C	2	0.000000	0.000000	7.40	0.015
Error	8	0.000000	0.000000		
Lack-of-fit	6	0.000000	0.000000	3.28	0.252
Pure error	2	0.000000	0.000000		
Total	14	0.000000			
Model summary					
S	R^2	R^2(adj)	R^2(pred)		
0.0000048	98.22%	96.89%	93.18%		

4 Conclusions

In the present study, physical and mechanical properties of Al 6063 reinforced with 5, 10 and 15 wt% of TiCp were investigated. The consequence of TiCp weight percent on wear characteristics has been estimated, and the following conclusions were drawn:

- The physical and mechanical properties of Al 6063-based MMCs improved with enhancement in reinforcement weight percent.
- The abrasive particles present in the composite made the wear characteristics of MMC behave different from conventional materials. Wear of composite reduced with enhancement in reinforcement weight percent.
- Box–Behnken design of RSM was used effectively for developing the model with high predictive capability at 99% confidence level.

Fig. 11 Contour plots of SWR among the considered parameters



- ANOVA was also applied to verify the competence of the developed model and there was a good agreement subsists between the experimental and predicted results.
- From ANOVA, it was confirmed that reinforcement weight percent and sliding speed had influence on the response.
- The developed model in the present study had good capability such that it can be used to predict the results with minimum error.

Acknowledgements The authors would sincerely like to thank the management of G. Pulla Reddy Engineering College (Autonomous), Kurnool, for providing the testing facilities and their constant support.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Ramaswamy A, Perumal AV, Chelladurai SJS (2019) Investigation on mechanical properties and dry sliding wear characterization of stir cast LM13 aluminium alloy-ZrB2-TiC particulate hybrid composites. Mater Res Express 6(6):066578
2. David Raja Selvam J, Dinaharan I, Rai RS, Mashinini PM (2019) Dry sliding wear behaviour of in situ fabricated TiC particulate reinforced AA6061 aluminium alloy. Tribol Mater Surf Interfaces 13(1):1–11
3. Shirvanimoghaddam K, Khayyam H, Abdizadeh H, Akbari MK, Pakseresht AH, Abdi F et al (2016) Effect of B4C, TiB_2 and $ZrSiO_4$ ceramic particles on mechanical properties of aluminium matrix composites: experimental investigation and predictive modelling. Ceram Int 42(5):6206–6220
4. Radhika N, Raghu R (2015) Dry sliding wear behaviour of aluminium Al–$Si_{12}Cu/TiB_2$ metal matrix composite using response surface methodology. Tribol Lett 59(1):2
5. Poria S, Sahoo P, Sutradhar G (2016) Tribological characterization of stir-cast aluminium-TiB_2 metal matrix composites. Silicon 8(4):591–599
6. Bains PS, Sidhu SS, Payal HS (2016) Fabrication and machining of metal matrix composites: a review. Mater Manuf Process 31(5):553–573
7. Suresh S (2013) Fundamentals of metal-matrix composites. Elsevier, Amsterdam
8. Surappa MK (2003) Aluminium matrix composites: challenges and opportunities. Sadhana 28(1–2):319–334
9. Ünlü BS (2008) Investigation of tribological and mechanical properties Al_2O_3–SiC reinforced Al composites manufactured by casting or P/M method. Mater Des 29(10):2002–2008
10. Akbari MK, Baharvandi HR, Shirvanimoghaddam K (2015) Tensile and fracture behavior of nano/micro TiB_2 particle reinforced casting A356 aluminum alloy composites. Mater Des 1980–2015(66):150–161
11. Li M, Ma K, Jiang L, Yang H, Lavernia EJ, Zhang L, Schoenung JM (2016) Synthesis and mechanical behavior of nanostructured Al 5083/n-TiB_2 metal matrix composites. Mater Sci Eng A 656:241–248
12. Sharma BP, Rao GS, Vates UK (2019) Powder metallurgy processing and mechanical characterization of iron-based composite reinforced with alumina and zirconium diboride. In: Shanker K, Shankar R, Sindhwani R (eds) Advances in industrial and production engineering. Lecture Notes in Mechanical Engineering. Springer, Singapore, pp 303–308
13. Tjong SC (2007) Novel nanoparticle-reinforced metal matrix composites with enhanced mechanical properties. Adv Eng Mater 9(8):639–652
14. Akhtar F, Askari SJ, Shah KA, Du X, Guo S (2009) Microstructure, mechanical properties, electrical conductivity and wear behavior of high volume TiC reinforced Cu-matrix composites. Mater Charact 60(4):327–336
15. Rajkumar K, Aravindan S (2011) Tribological performance of microwave sintered copper–TiC–graphite hybrid composites. Tribol Int 44(4):347–358
16. Basavarajappa S, Chandramohan G, Mukund K, Ashwin M, Prabu M (2006) Dry sliding wear behavior of Al 2219/SiCp-Gr hybrid metal matrix composites. J Mater Eng Perform 15(6):668
17. Baskaran S, Anandakrishnan V, Duraiselvam M (2014) Investigations on dry sliding wear behavior of in situ casted AA7075–TiC metal matrix composites by using Taguchi technique. Mater Des 60:184–192
18. El-Aziz KA, Saber D, Sallam HEDM (2015) Wear and corrosion behavior of Al–Si matrix composite reinforced with alumina. J Bio Tribo Corros 1(1):5
19. Vinod B, Ramanathan S, Anandajothi M (2018) Effect of organic and inorganic reinforcement on tribological behaviour of aluminium A356 matrix hybrid composite. J Bio Tribo Corros 4(3):45
20. Tyagi R (2005) Synthesis and tribological characterization of in situ cast Al–TiC composites. Wear 259(1–6):569–576
21. Kostornov AG, Fushchich OI, Chevychelova TM, Varchenko VT, Kostenko AD (2013) Prospects of improving the tribotechnical characteristics of titanium composites. Powder Metall Met Ceram 51(11–12):687–696
22. Selvakumar N, Narayanasamy P (2016) Optimization and effect of weight fraction of MoS_2 on the tribological behavior of Mg-TiC-MoS_2 hybrid composites. Tribol Trans 59(4):733–747
23. León-Patiño CA, Braulio-Sánchez M, Aguilar-Reyes EA, Bedolla-Becerril E, Bedolla-Jacuinde A (2019) Dry sliding wear behavior of infiltrated particulate reinforced Ni/TiC composites. Wear 426:989–995
24. Narayanasamy P, Selvakumar N, Balasundar P (2018) Effect of weight percentage of TiC on their tribological properties of magnesium composites. Mater Today 5:6570–6578
25. Jha P, Gautam RK, Tyagi R (2017) Friction and wear behavior of Cu–4 wt% Ni–TiC composites under dry sliding conditions. Friction 5(4):437–446
26. Kumar GV, Rao CSP, Selvaraj N, Bhagyashekar MS (2010) Studies on Al6061-SiC and Al7075-Al_2O_3 metal matrix composites. J Miner Mater Charact Eng 9(01):43
27. Abdizadeh H, Baghchesara MA (2013) Investigation on mechanical properties and fracture behavior of A356 aluminum alloy based ZrO_2 particle reinforced metal-matrix composites. Ceram Int 39(2):2045–2050
28. Suresh S, Moorthi N, Prema CE (2014) Tribological and mechanical behavior study of Al6061-TiB_2 metal matrix composites using stir casting. In: Diaz PM, Palanikumar K, Ravi Kumar P (eds) Advanced Materials Research. vols 984–5, pp 200–206
29. Standard ASTM (2013) ASTM E8/E8M-13a. Standard test methods for tension testing of metallic materials. ASTM International, West Conshohocken
30. Ferreira SC, Bruns RE, Ferreira HS, Matos GD, David JM, Brandao GC et al (2007) Box-Behnken design: an alternative for the optimization of analytical methods. Anal Chim Acta 597(2):179–186

31. Astm ASTM (2010) G99: standard test method for wear testing with a pin-on-disk apparatus. ASTM Stand G99:1–5
32. Canakci A, Arslan F (2012) Abrasive wear behaviour of B 4 C particle reinforced Al2024 MMCs. Int J Adv Manuf Technol 63(5–8):785–795
33. Sajjadi SA, Ezatpour HR, Parizi MT (2012) Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al_2O_3 composites fabricated by stir and compo-casting processes. Mater Des 34:106–111
34. Mazahery A, Ostadshabani M (2011) Investigation on mechanical properties of nano-Al_2O_3-reinforced aluminum matrix composites. J Compos Mater 45(24):2579–2586
35. Vinod B, Ramanathan S, Anandajothi M (2018) Effect of organic and inorganic reinforcement on tribological behaviour of aluminium A356 matrix hybrid composite. J Bio Tribo Corros 4(3):45
36. Mazahery A, Shabani MO (2012) Study on microstructure and abrasive wear behavior of sintered Al matrix composites. Ceram Int 38(5):4263–4269
37. Suresh S, Gowd GH, Kumar MD (2019) Mechanical and wear characterization of Al/nano-SiC NMMCs by liquid state process. J Bio Tribo Corros 5(2):43
38. Ghorpade SS, Gawande SH, Patil AA (2018) Tribological behaviors of steel and Al alloys for hydroforming components. J Bio Tribo Corros 4(3):49
39. Reddy PV, Reddy BV, Rao PS (2018) A numerical study on tube hydroforming process to optimize the process parameters by Taguchi method. Mater Today 5(11):25376–25381