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Optimisation of process parameters for minimum volumetric wear rate on AA7075-TiC metal matrix composite

***V. RamakoteswaraRao[1], N. Ramanaiah[2], M. Srinivasa Rao[2], M.M.M. Sarcar[3] and G. Kartheek[1]**

[1]Mechanical Engineering Dept., R.V.R & J.C College of Engineering (A), Guntur, 522019, India
[2]Mechanical Engineering Department, Andhra University College of Engineering, Visakhapatnam, 530003, India
[3]JNTUA, Anantapur, 520002, India
* Corresponding author, Email: vrkrao112880@gmail.com

ABSTRACT

Aluminium matrix material reinforced with particulates constitutes a material matrix composite with low wear rate and substantial hardness, owing to which it has marked its path in many engineering applications. The sub-sequential design and selection of new variants of composites can be done to improve its tribological performance. In the present work, the wear behaviour of aluminium metal matrix composites (AA7075 as matrix material and titanium carbide (TiC) particulates as reinforced material) fabricated through stir casting method was studied. The wear rate was investigated on a pin-on-disc machine and analysis of variance was used to identify the effect of control parameters such as sliding velocity, sliding distance and wt.% of reinforcement on the volumetric wear rate at a fixed load of 20 N. The hardness and wear resistance of the composites were found to be strengthened with the TiC particles reinforced into the AA7075 matrix material. Results show that volumetric wear rate decreases with increasing sliding velocity but increases with increasing sliding distance, irrespective of the wt.% of TiC particles added to composites. Confirmation tests were carried out to verify the experimental results and the worn-out surfaces of selected samples were analysed with scanning electron microscopy.

Keywords: AA7075- TiC; Taguchi optimisation; metal matrix composites; stir casting; wear.

INTRODUCTION

The continuous and increasing demand for lightweight materials in aerospace, automotive and defence applications has resulted from the drive to increase fuel economy. It has drawn the attention of researchers in the development of metal matrix composites (MMCs), which has been the major innovation in the field of composite materials [1-4]. MMCs have an outstanding benefit in producing materials with various combinations of stiffness and strength, wherein particulate composites are widely used owing to their easy fabrication and low cost through stir casting process [5]. The use of ceramic materials as reinforcements for the matrix Al7075 in various properties can lead to more effective MMCs that exhibit improved mechanical and tribological properties [6-8]. Aluminium is utilised in many engineering fields; however, its use has rendered critical factors because of its poor wear and corrosion resistance [9-12]. Al7075 alloy and their composites have been successfully developed through the stir casting-based liquid processing route, which significantly improves the hardness, yield strength and ultimate tensile strength of Al7075 [13, 14]. A modified stir casting method was employed to fabricate Al7075 alloy reinforced with particles. It includes a three-stage process where finally the dissolution rate and growth rate of a-Al reached equilibrium [15]. By using the stir casting method, an Al7075–flyash composite was successfully fabricated by adding Mg to improve the wettability of the ash particles [16]. Heat treatment of specimens generated hard and unbrittle phases in the top coat, owing to which increased hardness and wear resistance were observed and mass loss was decreased when compared to the untreated substrate [17].The wear rate of the quenched specimen is very low owing to the presence of a protective oxide coating layer formed during heat treatment and also owing to the presence of an acicular martensitic structure (retained beta) in its microstructure [18]. The dry sliding wear behaviour of Al7075 reinforced with titanium carbide (TiC) was studied in previous article [19, 20]. The Taguchi method is a most useful tool for improving product performance, process, design and system with a significant reduction in experimental time and cost [21].This method defines the lower-the-better, the larger-the-better and the nominal-the-better categories of quality characteristics in the analysis of signal/noise ratio [22]. Taguchi's robust design method was used to analyse the dry sliding wear problem of the metal matrix composites [23].

The present work investigates the effect of sliding distance, sliding velocity and wt.% of reinforcement on the volumetric wear rate of AMMCs (AA7075 as matrix material and TiC particulates as the reinforced material) on pin on disc apparatus and identifies the most effective control parameter from the reference variables by using the Taguchi method.

MATERIALS AND METHODS

For the fabrication of aluminium material matrix composites, TiC particulates with a mean particle size of 2 µm were used as the reinforcement material and AA7075 as the matrix material. The reinforcement percentage varied from 2 to 10 wt.% in steps of 2%. The chemical composition of the AA7075 alloy is shown in Table l.

Table 1. Chemical composition of AA7075 alloy.

Element	Wt.%
Si	0.08
Fe	0.24
Cu	1.5
Mn	0.06
Mg	2.4
Cr	0.20
Zn	5.8
Ti	0.07
Al	Balance

Fabrication of Composites

Matrix material AA7075 was weighed and fed into the electric furnace for melting at 800 °C. The experimental setup is shown in Figure 1(a). To ensure the even distribution of the reinforcement added to the matrix, magnesium ribbons were added to increase the wettability of the melted AA7075 matrix material. A sufficient amount (2% of the weight of the matrix material) of TiC particles to be added to the molten material is pre-heated to 300 °C to remove the moisture, drift etc. present in it. When the TiC particles are added to the molten material, for uniform mixing of the matrix and reinforcement material, it is stirred thoroughly at a constant speed of 300 rpm with an electrical stirrer for a period of 15 min. The molten composite (AA7075/TiC) was poured in the materialic moulds, which were preheated to 400 °C and then cooled to room temperature. Figure 1(b) shows how the castings were separated from the materialic moulds. The same procedure was followed to obtain the AMMCs of different weight percentages: 4%, 6%, 8% and 10% [24].

Heat Treatment

AA7075 matrix material and AA7075/TiC composites were homogenised at 450 °C for 2 hours and then aged at 121 °C for 24 hours to T_6 condition. The wear specimens of 30 mm length and Ø8 mm were retrieved through wire cut EDM process from the thoroughly homogenised ingots of matrix alloy and composites, as shown in Figure 1(c) [24].

(a) (b) (c)

Figure 1. (a) Electric furnace, (b) casting specimens and (c) wear specimens

Testing Procedure

Cylindrical samples (Ø8 × 30 mm) with a flat surface in the contact region and rounded corners were used to conduct wear tests under a fixed normal load of 20 N at three sliding velocities (1.57 m/s, 2.09 m/s and 2.61 m/s) and at three sliding distances (1, 2 and 3 km) on a pin-on-disc machine (Model TR-19.62LE supplied by M/s Ducom) in dry condition as per ASTM G99 standards. After each test run the pin was removed from the holder and disk was cleaned with acetone to remove wear debris. Microstructure and SEM analysis of the post mechanical tests were carried out to study the worn-out surfaces under different velocities and distances.

Calculation

The volumetric wear rate W_v of the composites was calculated using the relationship between the density (ρ), the mass loss of the specimen after wear test (Δm) and the abrading time (t) shown in Eq. (1):

$$W_v = \frac{\Delta m}{\rho t} \; mm^3/sec \tag{1}$$

Experimental Design

In this work the design of experiments technique is mainly used to identify the effect of control parameters on volumetric wear rate. In Taguchi's approach, optimum design is determined by using design of experiment principles, and consistency of performance is achieved by carrying out the trial conditions under the influence of the noise factors. To determine the effect on volumetric wear rate of AA7075 matrix material reinforced with TiC particles, a combination of three parameters was used. Using Taguchi's technique, the volumetric wear rate is considered as the response variable and the control parameters are wt.% of reinforcement, sliding velocity and sliding distance. The wt.% of reinforcement, sliding distance and sliding velocity are each varied at three levels. These experiments were carried out at a normal load of 20 N. The control parameters along with their levels are presented in Table 2. A total of 27 experiments (L_{27}) were conducted and the experimental combinations were determined using Minitab15 software. The experimental results of volumetric wear rate were collected for each experiment and then analysed [25]. ANOVA is a statistical technique that can infer some important conclusions based on analysis of the experimental data. This method is rather useful for revealing the level of significance of the parameters or their interaction on a particular response [26, 27].

Table 2. Levels of the control parameters used in the experiment.

Control parameter	Level			Units
	I	II	III	
Reinforcement	0	8	10	Wt.%
Sliding distance	1	2	3	km
Sliding velocity	1.57	2.09	2.61	m/s

RESULTS AND DISCUSSION

Mechanical Properties

Table 3 shows the mechanical properties of AA7075 matrix material and composites with different wt.% of TiC. Previously an attempt had been made to investigate the properties of TiC reinforced AA7075 metal matrix composites [24, 28]. It can be observed that hardness and measured density ($\rho_{MMC} = (m) / ((m-m_1) \times \rho_{H2O})$) shows an increasing trend with increasing percentage of TiC particulates; owing to the increased strain energy, the hardness of the composite is increased at the periphery of the particles dispersed in the matrix (Sylvia Cruz et al. 2014). An increase of hardness was observed from 181 VHN for the matrix material to 202 VHN for the 8 wt.% TiC reinforced composite at T_6 condition. However, a decline of hardness was observed for the 10 wt.% TiC composite owing to agglomeration and casting defect [29]. The same trend was observed for tensile strength but a significant decrement in the percentage of elongation from 8.341% to 7.14% was observed. It was observed that the 8 wt.% TiC composite shows better mechanical properties than the matrix material and all other composites. Owing to the Orowan mechanism, the addition of TiC particles improves the mechanical properties mainly by stress transference from the aluminium matrix to the reinforced particles, through which a dislocation bypasses impenetrable obstacles where a dislocation bows out considerably to leave a dislocation loop around a particle [29].

Table 3. Mechanical properties of composites.

Wt.% of reinforcement	Hardness, VHN	Density, g/cc	Tensile strength, N/mm^2	% elongation
AA7075/0 wt.% TiC	181.0	2.810	471.3	8.34
AA7075/2 wt.% TiC	188.7	2.820	557.7	8.14
AA7075/4 wt.% TiC	193.0	2.830	563.9	7.86
AA7075/6 wt.% TiC	196.4	2.845	571.2	7.57
AA7075/8 wt.% TiC	202.1	2.853	602.0	7.14
AA7075/10 wt.% TiC	195.1	2.862	587.9	7.37

Table 4. Experimental conditions and machining response.

Test number	Wt.% of reinforcement	Sliding distance, km	Sliding velocity, m/s	Volumetric wear rate, mm^3/sec	S/N ratio
a.	0	1	1.57	1584.34	-63.997
b.	0	1	2.09	1071.67	-60.6012
c.	0	1	2.61	815.66	-58.2302
d.	0	2	1.57	4986.72	-73.9563
e.	0	2	2.09	3405.69	-70.6441
f.	0	2	2.61	2446.98	-67.7726
g.	0	3	1.57	9520	-79.5727
h.	0	3	2.09	6986.51	-76.8852
i.	0	3	2.61	4486.12	-73.0374
j.	8	1	1.57	1070.03	-60.5879
k.	8	1	2.09	720.43	-57.1519
l.	8	1	2.61	535.58	-54.5764
m.	8	2	1.57	3572.04	-71.0583
n.	8	2	2.09	2348.05	-67.4142
o.	8	2	2.61	1606.73	-64.1189
p.	8	3	1.57	6764.49	-76.6047
q.	8	3	2.09	4018.23	-72.0807
r.	8	3	2.61	2811.78	-68.9796
s.	10	1	1.57	1111.11	-60.9151
t.	10	1	2.09	801.68	-58.08
u.	10	1	2.61	560.59	-54.9729
v.	10	2	1.57	3649.83	-71.2455
w.	10	2	2.09	2608.18	-68.3267
x.	10	2	2.61	1788.54	-65.05
y.	10	3	1.57	7077.04	-76.997
z.	10	3	2.09	4406.15	-72.8812
aa.	10	3	2.61	3163.31	-70.0028

Effect of Control Parameters on Volumetric Wear Rate

The design matrix for the three control factors each at three levels along with the results of the volumetric wear rates and S/N ratios are presented in Table 4. The effect of each control parameter on the volumetric wear rate can be analysed with the main effects plot and interaction plot. The S/N ratio is calculated for each level of each parameter and then a plot is generated, as shown in Figure 2. The level at which the S/N ratio is highest gives a higher signal for the required response, volumetric wear rate in this case. That particular level of each parameter is taken as the optimal parameter for volumetric wear rate, as per Taguchi optimisation. It can be seen from Figure 2 that: (i) as the wt.% of reinforcement increases, the volumetric wear rate decreases up to level 2 (8 wt.%) and then increases slightly to level 3; (ii) as the sliding velocity increases, volumetric wear rate decreases; and (iii) as the sliding distance increases, volumetric wear rate increases. it can be observed that the sliding velocity and sliding distance have a significant effect on the volumetric wear rate. This is in agreement with the laws of adhesive wear and Archard's equation [30]. It is known that as the tensile strengths of the alloys increase, their volumetric wear rate decreases [31]. In view of the above, AA7075/8 wt.% would be expected to exhibit the lowest volumetric wear rate. The main effects plot (Figure 2) indicates that optimal values of the parameters for minimising the volumetric wear rate occurred when the wt.% of reinforcement was at level 2 (8 wt.%), the sliding velocity was at level 3 (2.61 m/s) and the sliding distance was at level 1 (1 km).The interaction plot for volumetric wear rate is illustrated in Figure 3. It is well understood that interactions do not occur when the lines on the interaction plots are parallel and strong interactions occur when the lines cross [32]. Figure 3 reveals a small interaction between the test parameters.

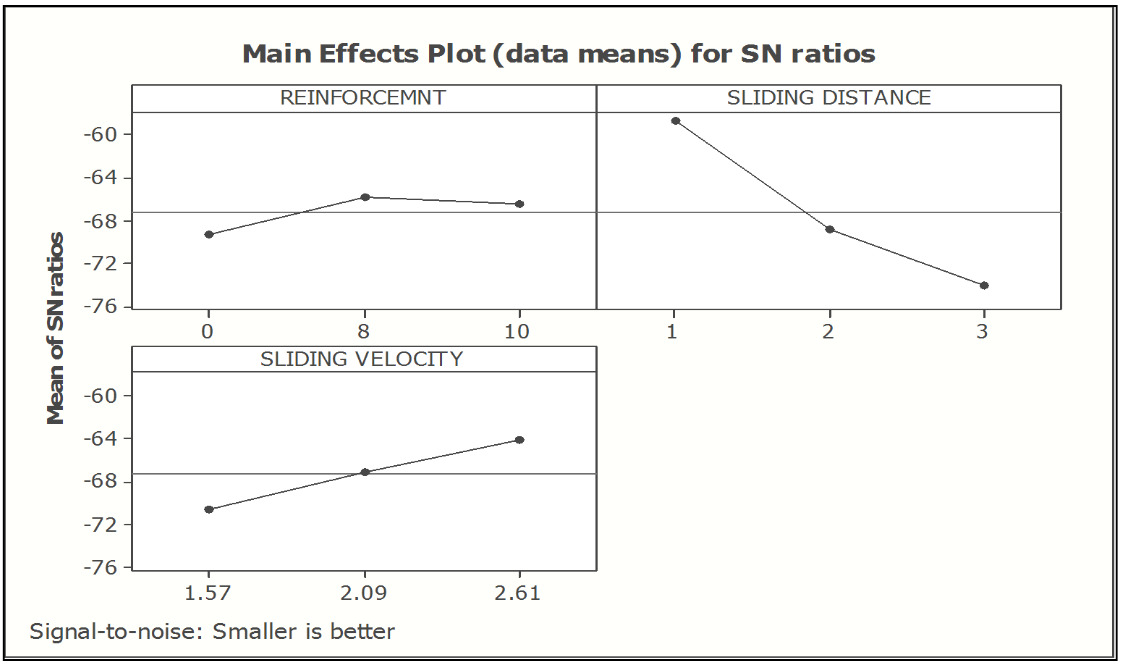


Figure 2. Main effects plot for volumetric wear rate of AA7075/TiC composites.

Statistical Analysis of Variance

The ANOVA results for means of volumetric wear rate are given in Table 5. It can be observed that the percentage contributions to volumetric wear rate were sliding distance (80.99%) followed by sliding velocity (13.97%) and wt.% of reinforcement (4.82%). From the present analysis, it is also observed that sliding distance is the most influential parameter for the volumetric wear rate of AA7075-TiC particulate composites followed by sliding velocity and wt.% of reinforcement. The interactions between the sliding velocity and sliding distance (0.076) and wt.% of reinforcement and sliding velocity (0.041) are the significant interaction model terms. The interaction effect between wt.% of reinforcement and sliding distance (0.033) is only nominal.

Figure 3. Interaction plot for volumetric wear rate of AA7075/TiC composites.

Table 5. ANOVA table for volumetric wear rate.

Source	DOF	Seq SS	Adj SS	Adj MS	F	% C
Reinforcement	2	64.98	64.98	32.491	300.53	4.82
Sliding velocity	2	188.37	188.37	94.186	871.18	13.97
Sliding distance	2	1091.18	1091.18	545.590	5046.47	80.982
Wt.% of reinforcement * Sliding velocity	4	0.56	0.56	0.140	1.29	0.041
Wt.% of reinforcement * Sliding distance	4	0.45	0.45	0.113	1.05	0.033
Sliding velocity * Sliding distance	4	1.03	1.03	0.258	2.39	0.076
Error	8	0.86	0.86	0.108		0.063
Total	26	1347.44				100

Wear Analysis

Based on the results for the AA7075 matrix material with 8 and 10 wt.% TiC under constant load (20 N) conditions, various graphs are plotted and presented in Figure 4. Figure 4(a) shows the variation of volumetric wear rate with wt.% of reinforcement for varying sliding distances (1, 2 and 3 km) at a sliding velocity 2.09 m/s. It indicates an increasing trend of volumetric wear rate with increasing sliding distance. The volumetric wear rate is higher for the AA7075 matrix material than for the composites owing to the increased hardness of the composites [32]. During the running period the volumetric wear rate increased very rapidly with increasing sliding distance [33]. It is obvious from the figure that the nature of variation in the volumetric wear rate for both the AA7075 matrix material and AMMCs with lead dispersion is similar, irrespective of their compositions. The 8 wt.% TiC composite enchanting the highest tensile strengths showed the highest wear resistance of all the samples. This is in agreement with the laws of adhesive wear and Archard's equation [31]. It is known that as the tensile strengths of the alloys increase, their volumetric wear rate decreases [32]. In view of the above, the AA7075/8 wt.% would be expected to exhibit the lowest volumetric wear rate. Figure 4(b) shows the variation in the volumetric wear rate with respect to the wt.% of reinforcement for varying sliding velocities (1.57, 2.09 and 2.61 m/s) at a sliding distance of 1 km. The result clearly indicates that an increase in the wt.% of reinforcement decreases the volumetric wear rate. The maximum volumetric wear rate is also observed for the unreinforced alloy. It is observed that the volumetric wear rate is low with a higher value of sliding velocity because at higher velocities the contact plateaus and coefficient of friction are low [34]. Thus, at lower velocities, increased volumetric wear rate is observed.

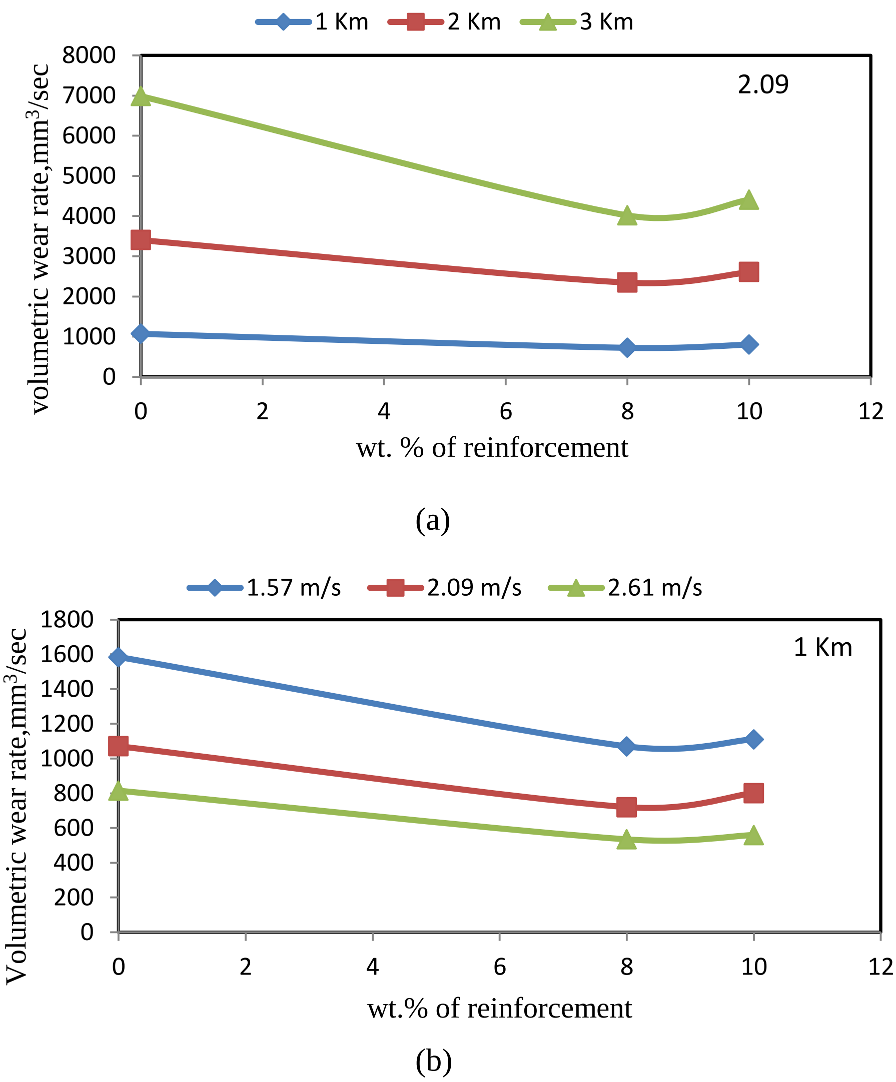
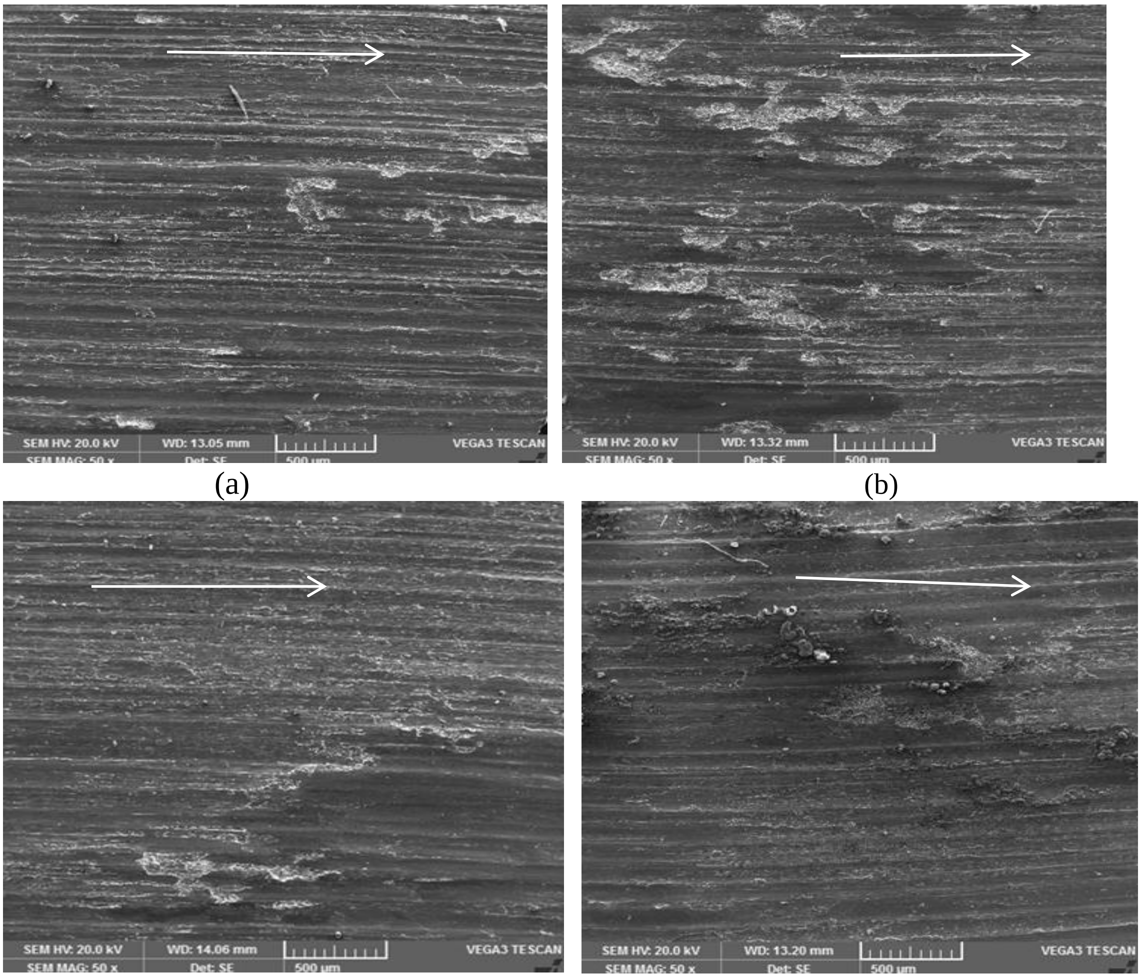


Figure 4. Variation of volumetric wear rate with wt.% of reinforcement at (a) sliding velocity of 2.09 m/s and (b) sliding distance of 1 km.



(c) (d)

Figure 5. SEM micrographs of worn surfaces at a sliding velocity 2.61 m/s, a sliding distance of 3 km and a normal load of 19.62 N for (a) AA7075, (b) AA7075+2%TiC, (c) AA7075+8%TiC and (d) AA7075+10%TiC

SEM Analysis

Examination of the worn surfaces of the AA7075 and AA7075/TiC composites at a presented magnification of 50× revealed well-defined patterns of grooves and scratches running parallel to one another in the sliding direction (indicated by the white arrows), as shown in Figure 5. It can be seen that the grooves are deeper in the matrix alloy as compared to the composites tested under similar conditions (19.62 N, 2.61 m/s and 3 km) owing to the absence of hard TiC particles. The examination of the wear surface of the AA7075 matrix alloy tested under the above conditions was characterised by smearing and scratches, typical characteristics of sliding wear (Figure 5a) [35].However, the worn surfaces shown in Figures 5b–c reveal that the grooves are much shallower in the composites than those of the matrix alloy owing to the presence of TiC particles [36, 37]. Furthermore, it is evident from Figure 5c exhibits a comparatively smooth worn surface and grooves are much finer and more closely spaced in the AA7075/8 wt.% TiC sample owing to the sliding action of a larger number of hard particles and debris. Owing to an increase in TiC particle on the surface of the matrix, the plastic deformation of the matrix can be resisted with the presence of TiC, which acts as a barrier to the moment of dislocation, thus giving greater wear resistance than that of the matrix alloy [38].This clearly indicates that with increasing weight percentage of reinforcement, the hardness of the specimen greatly improved, resulting in improved wear resistance of the reinforced component. Figure 5d shows the worn surface of the AA7075/10 wt.% TiC composite with small cavities and an increase in the amount of TiC particles led to agglomeration and clustering of TiC particles.

CONCLUSIONS

1. AA7075 reinforced with 2 µm TiC particles showed better mechanical and tribological properties then AA7075 matrix material.
2. The degree of improvement of wear resistance of AMMC is strongly dependent on the kind of reinforcement as well as its weight fraction. There is a definite increase in the wear resistance of the AA7075 matrix alloy with the addition of TiC particles.
3. The volumetric wear rate of AA7075 and AA7075 reinforced with TiC increased with increasing sliding distance and decreased with increasing wt.% of reinforcement and sliding velocity.
4. Sliding distance is the wear factor that has the highest physical as well as statistical influence on the volumetric wear of the composites (80.92%), sliding velocity (13.97%) and reinforcement (4.82%). The interaction between the wt.% of reinforcement and the sliding velocity contributes more (0.041%) and other interactions have less influence.

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