Multi-Objective Optimization of Dry Sliding Wear Parameters of Aluminium Matrix Composites (AA7068/TiC) using Grey Relational Analysis

Syed Altaf Hussain, Naresh Poppathi, Md. Alamgir

***Abstract:** Metal matrix composites are supplanting conventional materials due to their prevalent properties like high strength of weight ratio, high specific stiffness, high fracture toughness, high thermal stability and wear resistance etc. In this investigation, Al-TiC composites consist of TiC particles of an average size 4μm whose wt% of reinforcement varied from 2 to 10 wt% in steps of 2 wt%, composites have been prepared using the stir casting technique. Dry-sliding wear experiments have been performed on pin-on-disc apparatus according to Taguchi's L_{25} in the design of experiments. The parameters considered are wt% of TiC, rotational speed (Nr), load (P) and sliding velocity (Vs). Optimum combinations of parameters have been identified based on grey relational grade (GRG) to solve the wear response of AA7068/TiC MMCs. Also, analysis of variance (ANOVA) is applied to recognize the main factors affecting the wear response. Confirmation experiments with optimum conditions show that the results were nearer to the anticipated outcomes.*

***Keywords:** AA7068/TiC MMCs, Grey Relational Analysis, Taguchi Design, ANOVA, Optimization.*

I. INTRODUCTION

In recent years Aluminium alloy based composite materials are used in various applications of engineering due to their superior advantages and properties over other engineering materials. The combination of matrix and reinforcing phases produce an unusual combination of properties that cannot be found in traditional materials. In this investigation, AA7068/TiC Metal matrix composites were fabricated using the stir casting method [1]. Most of the studies are apparent that for auto and aviation applications the material used for components should possess good toughness combined with better tribological properties. Therefore, to meet the automotive applications an attempt is made to develop AA7068 aluminium alloy reinforced with Titanium Carbide (TiC) particles. Dissolving magnesium alloy to the melt guarantee great holding between the matrix and reinforcement [2]. Several ceramic reinforcing particles have been identified, but titanium carbide (TiC) has got the attention over the others duo its high hardness, stiffness and high wear resistance. Usages of MMCs have reached several areas other than automobiles such as recreation, sports, marine and infrastructure [3]. Most of the commercially used composites are made using micron size reinforcements [4, 5]. TiC particle reinforced aluminium matrix composites are lightweight and thermodynamically stable. Al-TiC MMCs can also be produced by different processes, casting is practically attractive and economical [6, 7]. Wear is the progressive loss of material from reaching surfaces that have relative movement under load. An unrivalled perception of different sorts of wear because of sliding and abrasive phenomena. Hardness is the main property that controls wear. Various strategies that improve the hardness and wear resistance of Al alloy include solid solution hardening, dispersion hardening and precipitation hardening. Dispersion hardening involves reinforcing the hard particles or combination of hard particles (increases abrasive resistance) and/or soft particles (yield less friction) in a soft matrix material [8-11]. The tribological properties of AA6063 / clay composites for brake disc rotor applications. It was accounted that the sliding speed and applied load primarily affect the wear rate [12]. Multiple parameters attributed to wear resistance of metal matrix composites different decision-making techniques such as grey relational analysis (GRA) and the technique for order of preference by similarity to ideal solution (TOPSIS), Analysis hierarch process (AHP), Data envelopment analysis,) [13]. Grey relational analysis (GRA) is one of the prominent techniques applied when the nature of information is deficient and unsure, GRA coupled with a Taguchi orthogonal array to determine the optimal level of multiple control parameters of EDM [14]. Multi-factor experiments of dry sliding on AA6531 MMCs using Taguchi L_9 orthogonal array. The experimental analysis shows that the applied load and sliding velocity are the most predominant factors [15]. Taguchi method combined with GRA for multi-objective optimization of milling parameters [16].

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II. MATERIALS AND METHODS

AA7068 is one of the industrially accessible strongest aluminium alloys that was taken as a matrix material and the reinforcement is titanium carbide (TiC) particles of 4 µm size The mechanical properties of matrix and reinforcement materials are also presented in Table 1.

Table 1. Mechanical properties of constituent materials

Material	Type	Tensile Strength, σ_u (MPa)	Young's modulus (GPa)	Density, ρ (g/cm^3)	Melting temperature (C°)
AA7068	Matrix	710	73.1	2.85	635
TiC	Reinforcement	2580	451	4900	3,160

A. Preparation of Aluminium Matrix Composites using Stir Casting

In this investigation, aluminium metal matrix composites were fabricated using the stir casting method. Stir casting is a liquid state technique of fabrication of composites in this, the reinforcing particles are mixed with molten metal using mechanical stirring. According to Surappa & Rohatgi (1981) and Miracle (2005), stir casting is the best method of liquid state fabrication. The ingots of Aluminium alloy AA7068 were put in a refractory crucible and heated in an electric furnace to a temperature of 850°C. The molten metal was stirred to create a vortex and titanium carbide (TiC) particles were introduced. The slurry was mixed at 300 rpm for 15 minutes. The weight percentage of titanium carbide particles added was 2, 4, 6, 8 and10%. During the process, magnesium strips are added to the liquid metal for better wettability and to eliminate the residue particles from the liquid metal.

This investigation presents a successful strategy to find the significant process parameters that influence the wear response of AA7068/TiC MMCs by integrating Grey relational analysis and statistical methods. Furthermore, it is feasible to obtain the combination of process parameters to optimize the multi-responses of wear viz, Wear, Wear rate and coefficient of friction using GRA.

III. EXPERIMENTAL DETAILS

The dry Wear test has been conducted on a pin-on-disc test rig at room temperature. The sliding wear test determines the abrasive wear of AMCs against EN32 steel disc. The counter steel disc is having a hardness of 62 RC. The sliding exists between the rotating steel disc and stationary pin.

The test specimen was prepaid as per ASTM standard and is fixed on a pin holder is bring contact with the disc. A frictional force exists between the pin disc and determines the values of wear by obstructing the pin deflection against the load cell. The wear can be estimated by changing the different input parameters of the pin-on-disc machine. The disc is rotated with the help of a DC motor having the track diameter and 30-50mm in length and maximum load applied up to 200N with the sliding speed from 0-10 m/sec. The photo of the original experimental setup is shown in Figure 1. Process parameters and their levels used for dry sliding wear are recorded in Table 2.

Table 2. Process parameters and levels used for dry sliding wear.

Levels / Parameters	Notations	Units	Levels				
			1	2	3	4	5
Weight percentage of TiC	wt. %	%	2	4	6	8	10
Rotational sped	Nr	RPM	200	300	400	500	600
Load	P	N	9.81	19.62	29.23	39.24	49.05
Sliding Velocity	Vs	m/s	0.6	1.2	1.8	2.4	3

The experiments have been planned and executed by Taguchi's L25 orthogonal array in the design of experiments. The combination of process parameters and the observed wear responses were shown in Table 3.

Fig.1. Experimental set-up

The dimensions of the specimen utilized in this investigation are 10 mm diameter and 30 mm length as per ASTM G-99. The test was performed under the dry sliding condition at ambient temperature and atmospheric conditions for 5min. Experiments are executed according to the design matrix set by Taguchi's L25 orthogonal array. At the point when the load is applied, the frictional force is exerted and can be read by the controller. The 25 experimental runs have been conducted with various input parameters. Each test was done 3 times and noticed the average value for analysis. The weight loss of the sample is determined for each test using an electronic weight balance with an accuracy of 0.001grams. Pin specimens were cleaned with acetone before testing. The wear rate and coefficient of friction were calculated by the following formulae.

$$\text{Wear rate} = \frac{\text{Volume loss}}{\text{sliding distance}}\ \text{mm}^3/\text{m}. \qquad (1)$$

The Coefficient of friction (Cof) was determined by taking the proportion of the kinetic frictional force (Ff) to the normal applied load (Fn) as represented by equation 2.

$$\text{Coefficient of friction (Cof)} = \frac{\text{Kinetic frictional force (Ff)}}{\text{Normal applied force (Fn)}} \qquad (2)$$

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Table 3: Experimental results

Exp. No	The weight percentage of TiC, wt.%	Rotational speed, Nr (RPM)	Load, P (N)	Sliding Velocity, Vs (m/s)	wear (µm)	Wear Rate mm^3/m	Coefficient of friction (f)
1	2	200	9.81	0.6	40	0.036	0.3686
2	2	300	19.62	1.2	20	0.045	0.3895
3	2	400	29.23	1.8	12	0.036	0.3332
4	2	500	39.24	2.4	17	0.033	0.3822
5	2	600	49.05	3	54	0.038	0.5664
6	4	200	19.62	1.8	49	0.056	0.4141
7	4	300	29.23	2.4	29	0.04	0.3671
8	4	400	39.24	3	32	0.025	0.4663
9	4	500	49.05	0.6	32	0.033	0.6285
10	4	600	9.81	1.2	29	0.092	0.3681
11	6	200	29.23	3	50	0.043	0.4941
12	6	300	39.24	0.6	32	0.015	0.5464
13	6	400	49.05	1.2	19	0.048	0.4532
14	6	500	9.81	1.8	13	0.065	0.348
15	6	600	19.62	2.4	32	0.102	0.4283
16	8	200	39.24	1.2	33	0.053	0.3296
17	8	300	49.05	1.8	17	0.074	0.3705
18	8	400	9.81	2.4	12	0.037	0.3961
19	8	500	19.62	3	23	0.064	0.5556
20	8	600	29.23	0.6	32	0.086	0.4920
21	10	200	49.05	2.4	24	0.034	0.3499
22	10	300	9.81	3	49	0.056	0.4941
23	10	400	19.62	0.6	15	0.037	0.3723
24	10	500	29.23	1.2	8	0.095	0.3391
25	10	600	39.24	1.8	20	0.171	0.4255

IV. MULTI-RESPONSE OPTIMIZATION USING GRA

Taguchi's technique is sufficient to decide the ideal setting of process parameters for a single response characteristic. On account of at least two or more responses, with different quality attributes, multi-response optimization using GRA is the favoured strategy. Grey analysis can also be used to decide the likeness between apparently sporadic finite data. Henceforth, multi-response optimization of wear parameters in this investigation is performed utilizing the following steps in GRA

A. Data- Pre-processing

Pre-processing or grey relational generation of collected data requires normalization by dividing the data in original series by their average. In this investigation, the data to be normalized are wear, wear rate and coefficient of friction. If these responses convey different units of measurement, the GRA may lead to wrong results, therefore they need to be brought under units dimensionless. It is the transformation of the original sequence series to an equivalent series therefore, the experimental values are normalized between the ranges 0 to 1 [17-18]. In this investigation for processing the wear responses viz., wear, wear rate and coefficient of friction Lower-the better rule utilized and is given by equation 3.

$$x_i^*(k) = \frac{Max\ x_i^0(k) - x_i^0(k)}{Max\ x_i^0(k) - Min\ x_i^0(k)} \qquad (3)$$

Where *xi* (K) is the value after the grey relational generation, $Min\ x_i^0(k$ is the smallest value of $x_i^0(k)$ for the Kth response,

and $Max\ x_i^0(k)$ is the largest value of x_i^0 (K) for the K_{th} response.

After the data processing, it is expected to calculate the grey relational coefficient, which is derived by using equation 4.

$$\xi_i(k)\ \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{0i}(k)+\zeta\Delta_{max}} \qquad (4)$$

$\Delta_{0i} = \left| x_0^*(k) - x_i^*(k) \right|$ deviational sequence
Δ_{0i} = minimum value in deviational sequence
$\underset{\forall j \in i}{min}\ \underset{\forall k}{min} \left\| x_0^*(k) - x_j^*(k) \right\|$
Δ_{0i} = Maximum value in deviation sequence
$\underset{\forall j \in i}{max}\ \underset{\forall k}{max} \left\| x_0^*(k) - x_j^*(k) \right\|$
ζ = Identification sequence
$\zeta\ \varepsilon\ [0,1];$ Generally consider $\zeta = 0.5$

After the determination of grey relation, the coefficient assesses grey relation grade by taking the average value of grey relational coefficients. The grey relation grade could be processed utilizing equation 5.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (5)$$

Where γ_i the grey relational grade for Ki_{th} experiments and ‘n’ is the number of wear responses. Based on the grey relational grade the optimum process parameters could be identified. The grade of grey relations shows the relationship between the sequences and the effect of the compatibility sequence and the reference sequence. When both the sequences are equal, then the grey relational grade will be unity. The higher the value of the grey relational grade means that the corresponding process parameters are closer to optimal.

As such, the optimization of the complicated multi-responses will be converted into the optimization of a single grey relational grade. Once the optimal combination of process parameters are found using GRG, the last step is to anticipate and confirm the GRG utilizing equation 6.

$$\gamma_{Predicted} = \gamma_m + \sum_{i=1}^{q} \gamma_o - \gamma_m \qquad (6)$$

Where γ_o denotes the maximum of average GRG at the optimal level of parameters and γ_m represent the mean GRG. The quantity ‘q’ represents the number of parameters influencing response values.

V. RESULTS AND DISCUSSIONS

In this research work wear responses of AA7068/TiC MMCs are investigated. Experiments are planned according to Taguchi's L25 orthogonal array in the design of experiments and are executed on Pin-on-Disc apparatus. The wear phenomena depend on various factors, it is more affected by the parameters such as wt.% of TiC, rotational speed (Nr), load (P) and sliding velocity (Vs). In this study, to bring down the values of wear, wear rate and coefficient of friction are the objectives. Therefore, the data sequences have the smaller-the better characteristics. The values of wear, wear rate and coefficient of friction are set to be reference sequences.

The data processing of each response was determined using equation 3 and the grey relational coefficients and grey relational grades for each wear response are calculated using equations 4 and 5 and are shown in Table 4.

From Table 4, it is inferred that experiment number 3 which is at (wt%-2, Nr-400rpm, P-29.23N, Vs-1.8m/s) has the highest grey relational grade of 0.872. The relative effect and significant process parameters were also determined accurately using response graphs and statistical analysis (ANOVA) for GRG.

Table 4: Grey relational coefficients and Grey relational grade for each wear response

Exp. No	**Data processing of each wear response**			**Grey relational coefficient**			**Grey Relational Grade (GRG)**
	Wear	Wear rate	Coefficient of friction	Wear	Wear rate	Coefficient of friction	
1.	0.304	0.865	0.870	0.418	0.788	0.793	0.666
2.	0.739	0.808	0.800	0.657	0.722	0.714	0.698
3.	0.913	0.865	0.988	0.852	0.788	0.976	0.872
4.	0.804	0.885	0.824	0.719	0.813	0.740	0.757
5.	0.000	0.853	0.208	0.333	0.772	0.387	0.498
6.	0.109	0.737	0.717	0.359	0.655	0.639	0.551
7.	0.543	0.840	0.875	0.523	0.757	0.799	0.693
8.	0.478	0.936	0.543	0.489	0.886	0.522	0.633
9.	0.478	0.885	0.000	0.489	0.813	0.333	0.545
10.	0.543	0.506	0.871	0.523	0.503	0.795	0.607
11.	0.087	0.821	0.450	0.354	0.736	0.476	0.522
12.	0.478	1.000	0.275	0.489	1.000	0.408	0.632
13.	0.761	0.788	0.586	0.676	0.703	0.547	0.642
14.	0.891	0.679	0.938	0.821	0.609	0.890	0.774
15.	0.478	0.442	0.670	0.489	0.473	0.602	0.521
16.	0.457	0.756	1.000	0.479	0.672	1.000	0.717
17.	0.804	0.622	0.863	0.719	0.569	0.785	0.691
18.	0.913	0.859	0.778	0.852	0.780	0.692	0.775
19.	0.674	0.686	0.244	0.605	0.614	0.398	0.539
20.	0.478	0.545	0.457	0.489	0.523	0.479	0.497
21.	0.652	0.878	0.932	0.590	0.804	0.880	0.758
22.	0.109	0.737	0.450	0.359	0.655	0.476	0.497
23.	0.848	0.859	0.857	0.767	0.780	0.778	0.775
24.	1.000	0.487	0.968	1.000	0.494	0.940	0.811
25.	0.739	0.000	0.679	0.657	0.333	0.609	0.533

A. Microstructural analysis

The microstructural analysis is a powerful tool to investigate the uniform distribution of reinforcing articulates in the matrix. Scanning Electron Microscope (SEM) images are used to investigate the homogeneous distribution of reinforcing particles in the AA7068 matrix. The SEM images are represented in Figure 2 (a-e). From the images, it is inferred that the uniform distribution of TiC reinforcing particles in AA7068 and no traces of clustering of reinforcement particles have not been observed in the composite material. Hence, considered the stirring speed of 300 rpm in stir casting is appropriate to get a homogeneous distribution of reinforcement in AA7068.

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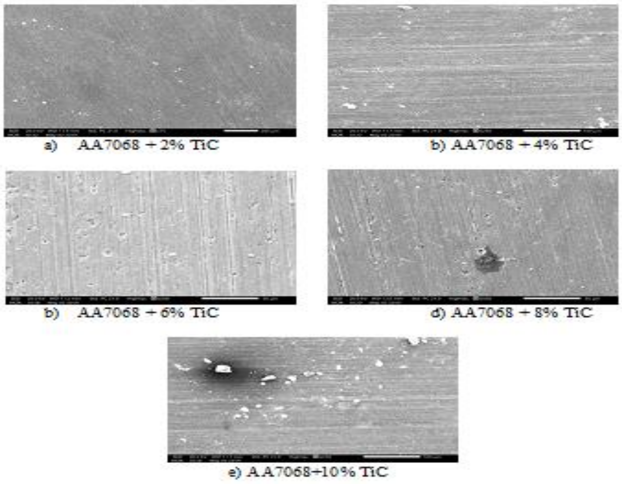
a) AA7068 + 2% TiC
b) AA7068 + 4% TiC
b) AA7068 + 6% TiC
d) AA7068 + 8% TiC
e) AA7068+10% TiC

Fig. 2. (a-e) SEM images of AA70368/TiC MMCs

B. ANOVA for GRG

To discover the importance and % of the contribution of each process parameter for the multi-wear performance characteristics of AA7068/TiC of Metal matrix Composites were carried out for a grey relational grade at a 95% certainty level. Table 5 response table shows the changes in the average values of grey relational grade at each level of process parameters selected. It gives the basis for the optimal setting of process parameters levels by picking the highest values of the grey relational grade.

Table 5 Response table of GRGs

Level	wt% of Reinforcing particles	Rotational Speed Nr	Load P	Sliding Velocity Vs
1	**0.6982**	0.6428	0.6638	0.6230
2	0.6058	0.6422	0.6168	0.6950
3	0.6182	**0.7394**	**0.6790**	0.6842
4	0.6438	0.6852	0.6544	**0.7008**
5	0.6748	0.5312	0.6268	0.5378
Delta	0.0924	0.2082	0.0622	0.1630
Rank	3	1	4	2

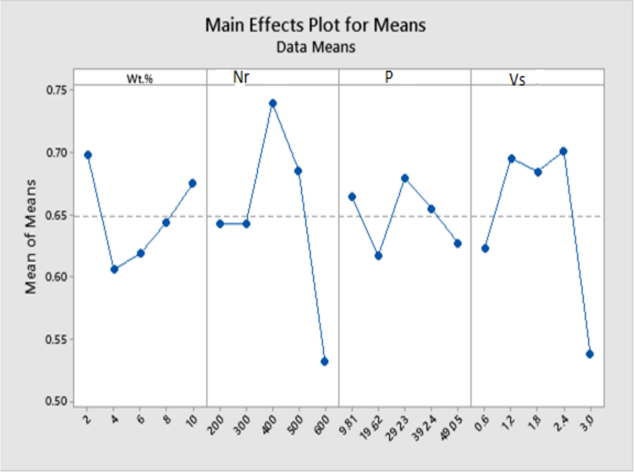

Fig. 3. Response plot of GRG (AA7068/TiC)

Figure 3 shows the GRG increases with an increase in wt% of reinforcement and applied load. GRG diminishes with an increase in rotational speed and sliding velocity. Because, due to the increase of applied load, the contact area of the specimen with counter disc would be more, so that heat is generated between the contact surfaces, which results in the formation of fine grooves towards the sliding direction. A fine plastic deformity is seen at grooves and craters were observed without cracks confirming abrasive wear mechanisms, which results in more wear. Wear diminishes with the raise of sliding velocity and rotational speed, the reason is the absence of contact is caused at high sliding velocities which prompt less wear of AMCs.

The motivation behind the Analysis of Variance is to figure out the process parameter that strongly influences the wear characteristics of AA7068/TiC MMCs. This can be accomplished by estimating the amount of the sum of squared deviations from the total mean of the grey relational grade for each process parameter and their error variance. The F-test is also conducted to check the relative significance of every process parameter.

Table 6. ANOVA for GRG

Process parameter	DOF	SS	MS	F	Contribution %
Wt.%	4	0.02962	0.007406	1.14	9.62
Nr	4	0.11720	0.029301	4.49	38.08
P	4	0.01337	0.003343	0.51	4.34
Vs	4	0.09538	0.023845	3.66	30.99
Residual Error	8	0.05217	0.006521		16.52
Total	24	0.30775			

From Table 6, it is inferred that the rotational speed (Nr) is the main process parameter has the highest percentage contribution of 38.08% followed by sliding velocity (Vs), wt% of reinforcement, and applied load.

The wear responses like wear, wear rate and coefficient of friction are predicted by equation 7.

Predicted Response = Avg (wt%) + Avg (N) + Avg (W) + Avg (V) – 2 *Yij (7)

Where wt%, Nr, P and Vs are the corresponding process parameters, while Yij is the response value obtained from experiments.

C. Worn surface Morphology

The scanning electron microscopic images of the worn-out surfaces of AA7068/TiC MMCs with various wt.% of TiC particle reinforcement are shown in Figure 4 (a-e). As an assessment of morphological study from the SEM images, it is seen that grooves, craters and sediments are formed because of plastic deformity and unreasonable wear of 2, 4 and 6 wt.% of TiC reinforcement material and relatively mild patches and fine grooves are seen on 8wt.% of TiC and 10wt.% of TiC.

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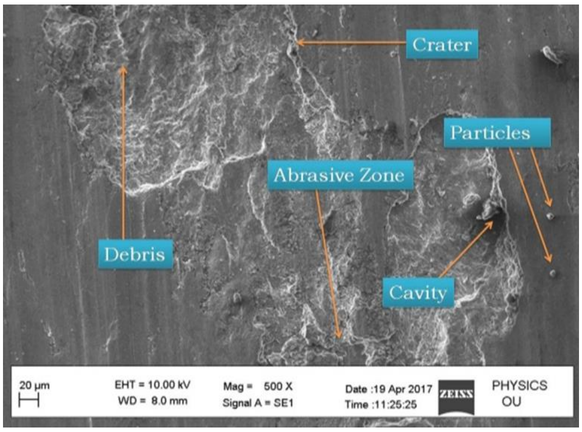
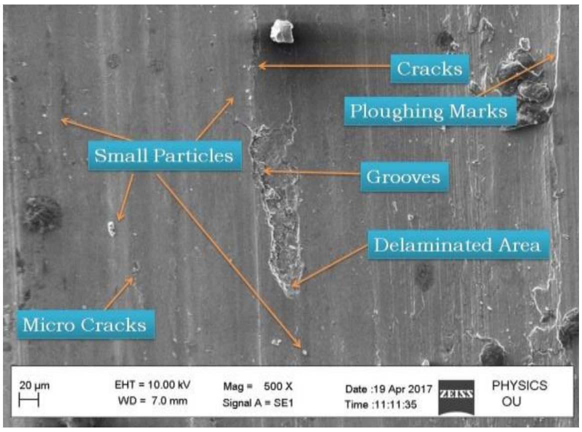
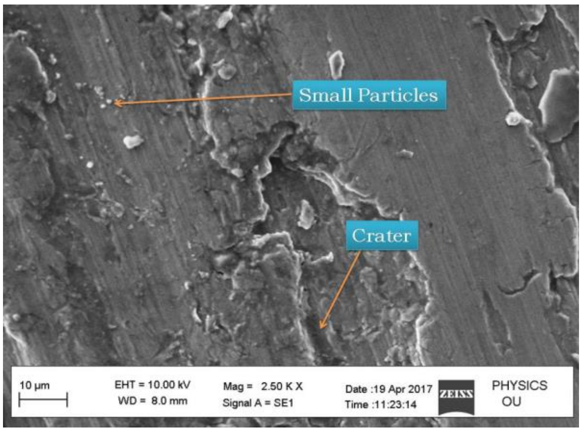


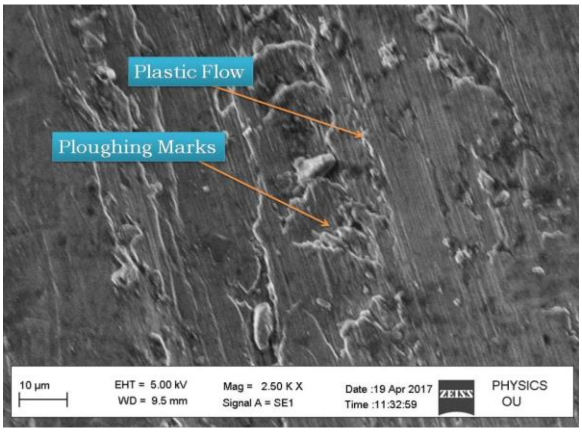
(a) AA7068 +2 % TIC



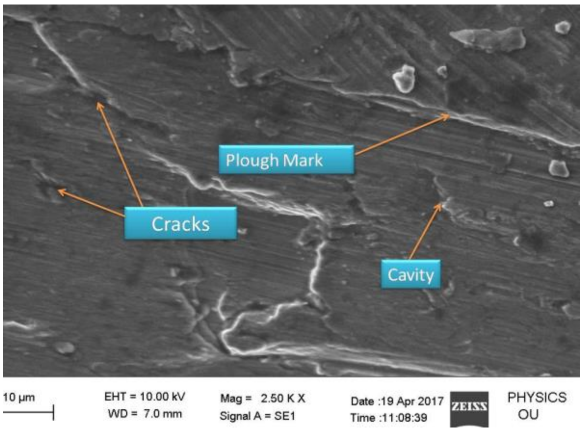
(b)AA7068 + 4. % TiC.



(c) AA7068 + 6 % TiC.



(d) AA7068 + 8 % TiC.



(e) AA7068 + 10 % TiC.

Fig.4. (a-e). SEM images of Warn surfaces of AA7068/TIC MMCs

From the above outcomes, it is seen that the TiC reinforced particle has a positive effect of in decreases the wear rate of AA7068 Metal matrix composites. It can be observed that a significantly low wear rate was exhibited by the composites at a low percentage of TiC reinforced particle as well as at low loads (P), low sliding velocity (Vs.) and low rotational speed (Nr).

VI. CONCLUSIONS

The multi-objective optimization of dry sliding wear parameters of AA7068 / TiC metal matrix composites has been investigated utilizing Taguchi and Grey relational analysis. The rotational speed (Nr) is the main process parameter whose percentage of contribution is 38.08% followed by sliding velocity (Vs) 30.99%. From the Grey relational analysis, it is uncovered that the optimal combination of process parameters for the least wear, wear rate and coefficient of friction are wt.% reinforcement of 2%, rotational speed (Nr) 400 rpm, load (P) 29.23 N and Sliding velocity (Vs.) 2.4 m/s. The confirmation experiments confirm that the proposed GRA can track down the optimal combination of process parameters with multiple quality characteristics.

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