Optimising the wear performance of HVOF thermal spray coated Ti-6Al-4V alloy by grey relational approach

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Abstract: In this present investigation, wear studies on uncoated Ti-6Al-4V alloy and HVOF coated alloy was studied. For improving the wear resistance of titanium alloy, SiC coating is performed with the help of HVOF thermal spray coating method. Characterisation of uncoated and coated surface was also made by means of micro hardness and tensile test. Dry sliding wear behaviour is studied with the help of pin-on-disc apparatus. The experiments were designed by using Taguchi's DoE; an L_{16} (4^4) OA is selected, four parameters (load, speed, distance and track diameter) varied through four levels. To optimise the measured output responses, grey relational analysis is applied. From experimental results; wear loss decreased by 35.71% due to SiC coating. From, ANOVA results, among all four parameters speed contributes by 54% on coated, and track diameter contributes by 42.97% on uncoated alloy. To investigate the wear surfaces SEM micrographs and EDS analysis was carried out.

Keywords: Ti-6Al-4V alloy; high velocity oxy-fuel; HVOF; pin-on-disc; Taguchi's DoE; grey relational analysis; GRA; analysis of variance; ANOVA.

Reference to this paper should be made as follows: Thirumalvalavan, S. and Senthilkumar, N. (2020) 'Optimising the wear performance of HVOF thermal spray coated Ti-6Al-4V alloy by grey relational approach', *Int. J. Rapid Manufacturing*, Vol. 9, No. 1, pp.25–47.

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1 Introduction

Titanium is 40% lighter than steel and 60% heavier than aluminium (Faller and Froes, 2001). Titanium and its alloys have been an attractive material in biomedical implants, aerospace through defence, chemical, petrochemical, marine and offshore fields due to high strength to weight ratio and having greater corrosion-resistance (Boyer, 1996; Maehara et al., 2002; Leyens and Peters, 2003a; Thirumalvalavan and Malliga, 2017). The corrosion resistance of the titanium is due to its ability to form an oxide-layer on its surface while exposed in the environment. This oxide layer is thin and brittle in nature (Saravanan et al., 2015). Ti-6Al-4V, known as grade 5 is the most commonly and widely used titanium alloy (Brewer et al., 1998) accounting about 50% of the full world production of titanium alloys (Leyens and Peters, 2003b). Ti-6Al-4V alloy can be made weldable and machined with ease when heat treated to different strength levels (Ezugwu and Wang, 1997). On the contrary, Ti alloys have a low hardness, load bearing capacity and poor wear resistance, so that a process of coating is often necessary in those applications that involve high contact stresses and severe sliding wear (Budinski, 1991). The vital reasons behind poor tribological properties of Ti alloys are due to lower thermal conductivity of the alloys. During sliding, the generated heat dissipates slowly and rises up the interface temperature that successively deteriorates the tribological performance of sliding titanium (EI-Tayeb et al., 2010). Hence, Ti-Al6-V4 alloy requires surface modification to enhance its wear resistance, and a coating is essential for titanium alloys (Guleryuz and Cimenoglu, 2005; Norazman et al., 2017). By this procedure, an extensive economic profit might be achieved by reducing the loss of material in the action of wear and tear (Perumal et al., 2013).

The objective of performing thermal coating is to get better mechanical and tribological properties (Heimann and lehmann, 2008), which were mainly used for elevated temperature applications (Pawlowski, 1995) such as like gas turbine, petroleum, chemical, paper/pulp, automotive and producing industries (Davis, 2004). Thermal spray may be a technology that uses torches/flames at elevated temperatures (above 2,500ºC) for melting a feed stock material that's finally propelled towards a substrate to produce a coating layer by layer (Espallargas and Mubarok, 2014). High velocity oxy-fuel (HVOF) is one of the important and foremost thermal spray techniques widely used in industries (Al-Bashir et al., 2009), whose advantage over thermal spray technique is the ability to accelerate with the massive velocity of the melted powders (Bemporad et al., 2005). HVOF method is performed in short duration within the flame with higher kinetic energy of the particles impacting, which is capable of producing coatings with higher hardness, superior bond strength and fewer decarburising throughout spraying than different thermal spraying techniques (Sahraoui et al., 2010; Marahno et al., 2012). HVOF spraying technique, are the well-liked strategies for manufacturing coatings with low porosity and high adhesion, with reduced porosity levels, hardness increases (Karagoz et al., 2011). From literature studies performed, it is identified that poor wear resistance of Ti-Al6-V4 alloy is limiting its applications (Ganesh et al., 2012), and hence a ceramic coating will improve the resistance to heat, corrosion, and wear surface composites having additional excellent surface properties than the substrate (Oh et al., 2003; Lakshmipathy and Kulendran, 2014).

Silicon carbide (SiC) has been widely engaged in tribological systems for many years due to it's their stability in chemical and structural properties. SiC ceramic coatings have significant attention due to improved tribological properties without affecting the corrosion and wear resistance of the alloy (Wielage et al., 2000). Coatings of SiC were extensively used in applications requiring high wear resistance. Metals, carbides, ceramic and cermets are the foremost widely used coating materials. Most ceramic coatings are done by HVOF thermal spraying technique (Takadoum et al., 1994; Ward et al., 2011), and are revealed that the decrease in powder size will increase the coating performance because of both reduction of the porosity and increase in the mechanical properties (Dong et al., 1995).

2 Experimental procedure and methodologies

The foremost objective of this work is to investigate and optimise the dry sliding wear parameters in pin-on-disc apparatus for uncoated and SiC coated specimens of Ti-6Al-4V alloy. Micro hardness and tensile tests were conducted to research its mechanical properties. Scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were used to study the coating morphology and phase composition of the coating. The most influencing parameters on the wear loss of the tested specimen are identified by Taguchi-grey relational analysis (GRA) technique. Different steps and process involved in this work is listed in methodology flowchart as shown in Figure 1.

2.1 Material selection and specimen preparation

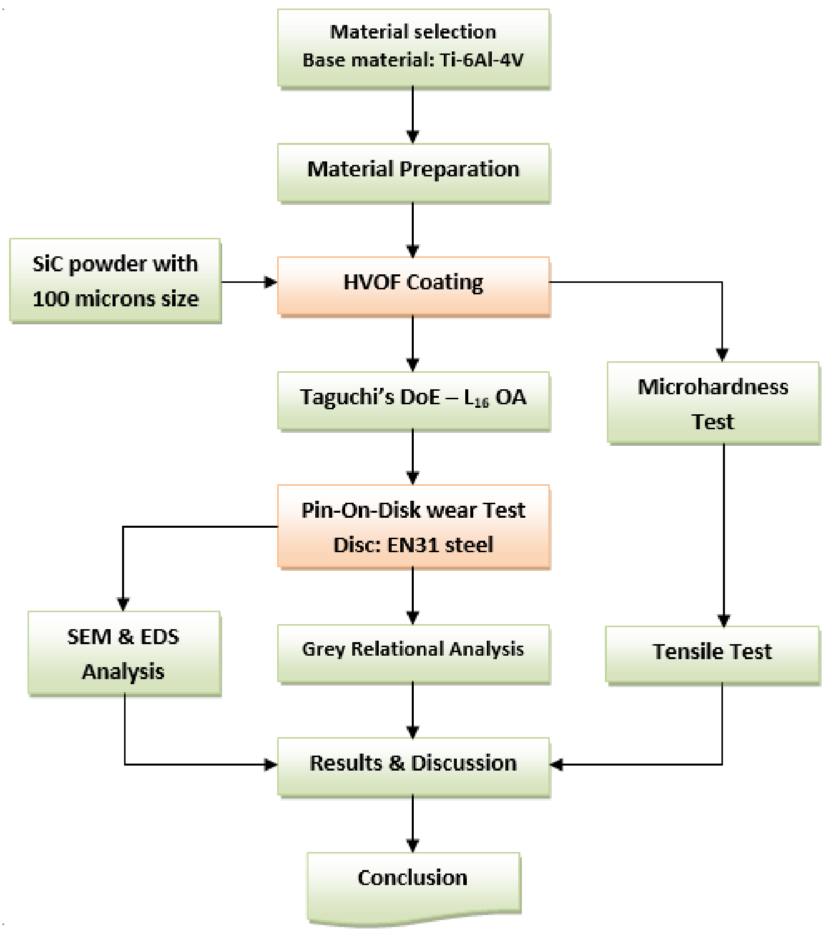
In this research work, Ti-6Al-4V alloy is selected as workpiece material and according to the ASTM G99 standards; the chosen material is prepared as pins having a diameter of 10 mm and a length of 20 mm. The chemical composition of the base material is listed in Table 1.

The tensile strength of Ti-6Al-4V alloy is about 860–965 MPa and the elastic modulus is 110 GPa (Niinom, 1998). The pins were tested for dry sliding wear properties against a counter surface material made of EN31 steel of 165 mm diameter, 8 mm thickness disc to perform the wear studies.

Table 1 Chemical composition of Ti-6Al-4V alloy

Elements in %	*Ti*	*Al*	*V*	*C*	*Fe*
Ti-6Al-4V alloy	90.120	5.750	3.680	0.056	0.065

Figure 1 Methodology flow chart (see online version for colours)



2.2 *HVOF thermal spray coating*

In HVOF thermal spray procedure, the stream of hot gas and powder is directed and was striking towards the coating surface (Mostaghimi et al., 2003). The coating powder melts partly in the stream and deposits upon the substrate material, resulting in coating, which has low porosity and higher bond strength. The coating quality increases with increasing particle velocities (Oksa et al., 2011). The plasma or thermal sprayed ceramic coatings like Al_2O_3, TiO_2, ZrO_2, Cr_2O_3 and SiC cermets are commonly used to improve the wear and surface properties (Torres et al., 2010). Ceramic coatings offer good wear resistance to the titanium material due to its unique microstructure and mechanical properties like high hardness and high fracture toughness (Mubarok and Espallargas, 2015). The Ti-6Al-4V pins were prepared as per the required dimensions and SiC is coated on the Ti-6Al-4V pin surface with powder size of 15 µm having a density of 3.2 g/cm^3 (Oh and Lee, 2004; Das et al., 2011).

The specification of HVOF setup used in this present work is: nozzle and gun type is DJ2600, oxygen flow rate of 30 litres per minute (lpm), hydrogen flow rate of 60 lpm, powder feed rate of 85 g/min and nozzle distance of 9 inches, the specimen is coated up to 100 µm thickness. The experimental setup of HVOF thermal spray coating setup is shown in Figure 2.

Figure 2 HVOF thermal spray coating setup (see online version for colours)

2.3 *Taguchi's design of experiments*

Optimisation is the act of obtaining the best result under given circumstances. A statistical method used to understand many parameters effectively and economically is design of experiments (DoEs) (Krishnaiah and Shahabudeen, 2012). The best parameter combination for optimised output can be obtained by studying the individual factors effect (Taguchi, 1986). Among many various styles available, Taguchi methodology is a well-organised problem solving tool, which might improve the performance of the product, process, design and system with a significant slash in experimental time and cost through a least the number of trials. Further, the foremost important parameters in the overall performance are determined by using this technique. If the process parameter increases the number of experiments increases (Nalbant et al., 2007). To solve this complication, the Taguchi methodology uses a special orthogonal array design to review the complete input process parameter with a small variety of experiments (Yang and Tarng, 1998). Before going to select a particular orthogonal array to be used as a matrix for the experiments, the subsequent two points must be considered:

1 the interactions of interest and number of parameters

2 the number of parameter levels of interest.

With these objectives, Taguchi's DoE is applied considering four input parameters viz., load, speed, distance and track diameter (Roy, 2001; Santhi et al., 2013; Muthuramalingam and Mohan, 2014) and for each parameter four level values were chosen, as shown in Table 2. Four levels were chosen in order to have a higher range of input values, which will yield better results. For various combinations of control parameters and its levels, an L_{16} OA is formulated using Minitab 18 statistical package which is shown in Table 3.

Table 2 Input parameters and chosen level values

Parameters	*Levels*			
	1	*2*	*3*	*4*
Load (N)	20	25	30	35
Speed (rpm)	200	300	400	500
Distance (m)	200	300	400	500
Track diameter (mm)	50	60	70	80

Table 3 L_{16} – experimental design

Trial no.	*Input control parameters*			
	Load (N)	*Speed (rpm)*	*Distance (m)*	*Track diameter (mm)*
1	20	200	200	50
2	20	300	300	60
3	20	400	400	70
4	20	500	500	80
5	25	200	300	70
6	25	300	200	80
7	25	400	500	50
8	25	500	400	60
9	30	200	400	80
10	30	300	500	70
11	30	400	200	60
12	30	500	300	50
13	35	200	500	60
14	35	300	400	50
15	35	400	300	80
16	35	500	200	70

2.4 Pin-on-disc wear test setup

Wear is expounded to interactions among two surfaces and especially the removal and deformation of material on the surface as a result of mechanical action on the alternative surface. Wear is measured by using a tribometer, an instrument that measures tribological quantities, like coefficient-of-friction, frictional force and wear rate between two surfaces in contact (Sahoo et al., 2013; Gurrala and Regalla, 2017). Specifications of the DUCOM pin-on-disc tribometer used in this study are as follows; model: DUCOM, disc speed: 200 to 2,000 rpm, normal load: 5 N to 200 N, frictional force: 0 to 200 N, wear: ± 2 mm, temperature: max. 400ºC, wear track diameter: min. 10 mm to max. 100 mm, sliding speed: min. 0.5 m/s to max. 10 m/s, timer: max. 98 hrs. EN31 is used as disc material (Chawla et al., 2013) and the wear loss is calculated by weight loss method. The morphology of damage surfaces was determined by SEM, so as to spot the microstructural behaviour and governing wear mechanisms for both uncoated and SiC coated pins. Photographic view of the pin-on-disc wear test experimental setup is shown in Figure 3.

Figure 3 Pin-on-disc wear tester (see online version for colours)

2.5 Grey relational analysis

For optimisation of multi responses, GRA technique is employed to find the optimum conditions of the given input parameters. There are many causes of engineering problems in the workplace which pose a decision problem (Dhinakar et al., 2014; Srivastava et al., 2018). Some of them pick the best from among multiple existing alternatives. However, no single alternative works well for all performance attributes, so GRA for solving this kind of problems (Gupta and Kumar, 2013). GRA generally investigates the dynamic process of the system. It is used to find the optimum result over two or more outputs. The final dynamic optimum parameter is identified by GRA. The knowledge that is either incomplete or undetermined is termed as grey (Senthilkumar et al., 2015). The raw experimental information cannot be used in the GRA; it should to have been pre-processed into a quantitative index for subsequent analysis. The first step in the GRA is pre-processing of raw information on changing an original data sequence into a decimal sequence it lies between zero to one. Zero implies no data information and one implies data with full of information (Senthilkumar and Tamizharasan, 2014). Normalising the data for lower the better condition is given in equation (1).

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{1}$$

where $x_i^0(k)$ is the original sequence, $x_i^*(k)$ the sequence after the data pre-processing, $\max x_i^0(k)$ the largest value of $x_i^0(k)$, and $\min x_i^0(k)$ imply the smallest value of $x_i^0(k)$. Following this the second step is, data pre-processing in order to express the bond between the ideal and actual normalised results, a grey relational coefficient is calculated. The grey relational coefficient can be expressed in equation (2). The deviational sequence is determined by finding the maximum of the normalised results regardless of response variables, trails and replications (Senthilkumar et al., 2014).

$$\zeta_i(k) = \frac{\Delta_{\min} + \zeta \cdot \Delta_{\max}}{\Delta_{0i}(k) + \zeta \cdot \Delta_{\max}} \tag{2}$$

where $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence, which is given by:

$$\Delta_{0i}(k) = \left\| x_0^*(k) - x_i^*(k) \right\| \tag{3}$$

$$\begin{aligned} \Delta_{\max} &= \max_{\forall j \in i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|, \\ \Delta_{\min} &= \min_{\forall j \in i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \end{aligned} \tag{4}$$

ζ is distinguishing or identification coefficient: $\zeta \varepsilon$ [0, 1]. $\zeta = 0.5$ is generally used. After obtaining the grey relational coefficient, normally the average of the grey relational coefficient is taken as the grey relational grade. The grey relational grade is defined as:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} {}_i \zeta_i(k) \tag{5}$$

3 Results and discussion

After preparing the pins, which will be subjected to wear procedure, simultaneously mechanical properties were also characterised through determination of micro hardness and tensile test. Afterwards, wear studies were performed and statistical analysis were employed on the measured output responses for identifying the most influencing parameter and optimal set of input conditions for lower wear or for higher wear resistance.

3.1 Mechanical characterisation of coated specimens

Hardness of uncoated and SiC coated of Ti-6Al-4V alloy is determined by micro Vickers hardness tester. The micro hardness testing is conducted as per the ASTM E384 standard. Hardness value for the applied load of 100 grams is noted and the average hardness results shown in Figure 4 for uncoated and coated specimens. From micro Vickers hardness test results it shows that, coated specimen had the higher hardness than uncoated specimen. Therefore, significantly wear rate decreases due to the coating on Ti-6Al-4V alloy. The comparison graph is plotted for hardness results of uncoated and coated were shown in Figure 4.

Tensile test is carried out for uncoated and coated Ti-6Al-4V alloy specimens, as per ASTM A370 standard, ultimate tensile strength (UTS) was determined from the test. The UTS was noted from a computerised universal testing machine (UTM). From the tensile test results, coated specimen had a higher ultimate strength compared to uncoated specimen. The comparison graph is plotted for tensile test results of uncoated and coated are shown in Figure 5.

Figure 4 Comparison of micro hardness test results for uncoated vs. coated specimens (see online version for colours)

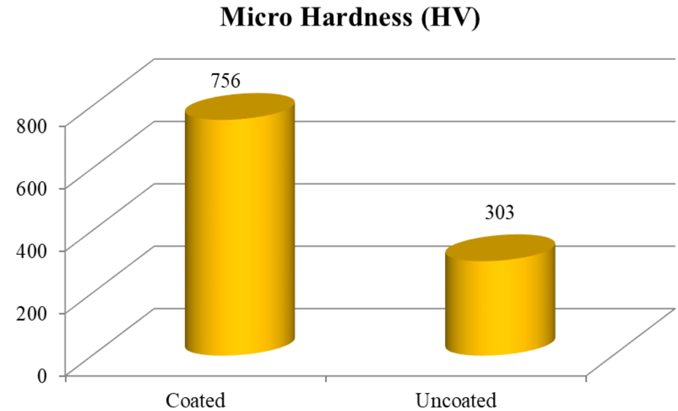
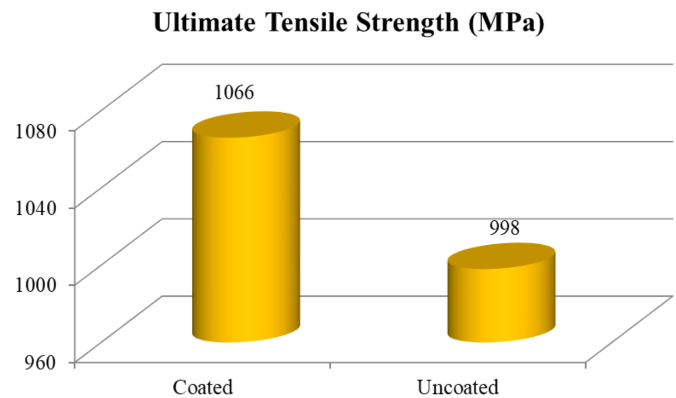


Figure 5 Comparison of tensile test results for uncoated vs. coated specimens (see online version for colours)



3.2 Dry sliding wear studies

As per the formulated Taguchi's orthogonal array of L_{16}, dry sliding wear studies were performed on pin-on-disc apparatus with respect to Taguchi's DoEs. Sixteen different work pieces are considered, for each level a separate pin was used during investigation. The measured outputs for uncoated and coated pins viz., wear loss, coefficient of friction and frictional force values were noted, which are shown in Table 4.

From Table 4, it is identified that the experiment number five produces the lowest wear loss and experiment number nine produces the maximum wear loss based on the raw output responses of pin-on-disc for both uncoated and coated specimens. The observations made from the output responses shows that, wear loss decreased by 71.43% for low wear loss specimen and for high wear loss specimen, wear loss decreased by 35.71% when comparing uncoated specimens with coated specimens. Similarly, coefficient of friction is increased by 98.85% for the low wear loss specimen, 98.07% for the high wear loss specimen. Frictional force was increased by 44.44% for the low wear loss specimen, 86.75% for the high wear loss specimen during comparison.

Table 4 Output responses of uncoated and coated pins

Trial no.	*Output responses of uncoated*			*Output responses of SiC coated*		
	Wear loss (g)	*Coefficient of friction*	*Frictional force (N)*	*Wear loss (g)*	*Coefficient of friction*	*Frictional force (N)*
1	0.023	0.110	2.250	0.004	0.610	17.900
2	0.029	0.035	3.900	0.008	0.530	10.500
3	0.008	0.020	1.500	0.006	0.530	10.300
4	0.012	0.120	4.100	0.004	0.450	9.000
5	0.007	0.070	1.300	0.002	0.610	17.200
6	0.015	0.090	2.300	0.006	0.370	9.150
7	0.018	0.070	1.980	0.010	0.640	15.800
8	0.008	0.110	3.800	0.005	0.330	8.200
9	0.028	0.100	2.000	0.018	0.520	15.100
10	0.015	0.100	2.550	0.012	0.530	15.600
11	0.023	0.110	3.070	0.005	0.540	16.100
12	0.008	0.250	8.400	0.007	0.430	12.800
13	0.009	0.210	4.200	0.006	0.680	23.400
14	0.012	0.150	3.650	0.008	0.510	24.200
15	0.015	0.100	2.830	0.006	0.500	14.800
16	0.016	0.100	2.750	0.004	0.300	10.100

3.2.1 Multi-objective optimisation

In GRA technique, the complex multiple response optimisation problems were simplified into single response grey relational grade. GRA gives the effective solution to multiple input and discrete data problems (Sankar et al., 2017). In this analysis, for analysing the data, smaller the better concept of normalising is selected while considering all the response from the pin-on-disc setup. Normalised data of responses after pre-processing by GRA is determined using equation (1). Normalising sequence results shown in Table 5.

The next procedure in GRA is to determine the deviational sequence as provided in equation (3). The determined deviation sequences of GRA for both uncoated and coated specimens were tabulated in Table 6.

In multi response optimisation, which considers all the output responses simultaneously, the grey relational grade is derived by considering equal weightages to the grey relational coefficient of individual responses (Senthilkumar et al., 2016a). After determining the deviation sequence, grey relational coefficient and grey relational grade of each individual response was determined by equation (2) and in equation (5), which were tabulated in Table 7.

Based on the calculated grey relational grade, average grades were calculated for each response level value of uncoated and coated to formulate the response table, for identifying the optimal level values, as Table 8.

Table 5 Normalising sequence of GRA for uncoated and coated results

Trial no.	Normalising sequence for uncoated			Normalising sequence for SiC coated		
	Wear loss	*Coefficient of friction*	*Frictional force*	*Wear loss*	*Coefficient of friction*	*Frictional force*
1	0.273	0.609	0.866	0.875	0.184	0.394
2	0.000	0.935	0.634	0.625	0.395	0.856
3	0.955	1.000	0.972	0.750	0.395	0.869
4	0.773	0.565	0.606	0.875	0.605	0.950
5	1.000	0.783	1.000	1.000	0.184	0.438
6	0.636	0.696	0.859	0.750	0.816	0.941
7	0.500	0.783	0.904	0.500	0.105	0.525
8	0.955	0.609	0.648	0.813	0.921	1.000
9	0.045	0.652	0.901	0.000	0.421	0.569
10	0.636	0.652	0.824	0.375	0.395	0.538
11	0.273	0.609	0.751	0.813	0.368	0.506
12	0.955	0.000	0.000	0.688	0.658	0.713
13	0.909	0.174	0.592	0.750	0.000	0.050
14	0.773	0.435	0.669	0.625	0.447	0.000
15	0.636	0.652	0.785	0.750	0.474	0.588
16	0.591	0.652	0.796	0.875	1.000	0.881

Table 6 Deviation sequence of GRA for uncoated and coated results

Trial no.	Deviation sequence for uncoated			Deviation sequence for SiC coated		
	Wear loss	*Coefficient of friction*	*Frictional force*	*Wear loss*	*Coefficient of friction*	*Frictional force*
1	0.727	0.391	0.134	0.125	0.816	0.606
2	1.000	0.065	0.366	0.375	0.605	0.144
3	0.045	0.000	0.028	0.250	0.605	0.131
4	0.227	0.435	0.394	0.125	0.395	0.050
5	0.000	0.217	0.000	0.000	0.816	0.563
6	0.364	0.304	0.141	0.250	0.184	0.059
7	0.500	0.217	0.096	0.500	0.895	0.475
8	0.045	0.391	0.352	0.188	0.079	0.000
9	0.955	0.348	0.099	1.000	0.579	0.431
10	0.364	0.348	0.176	0.625	0.605	0.463
11	0.727	0.391	0.249	0.188	0.632	0.494
12	0.045	1.000	1.000	0.313	0.342	0.288
13	0.091	0.826	0.408	0.250	1.000	0.950
14	0.227	0.565	0.331	0.375	0.553	1.000
15	0.364	0.348	0.215	0.250	0.526	0.413
16	0.409	0.348	0.204	0.125	0.000	0.119

Table 7 Grey relational coefficient and grey relational grade of uncoated and coated results

Trial no.	For uncoated specimens				For SiC coated specimens			
	Grey relational coefficient			Grey relational grade	Grey relational coefficient			Grey relational grade
	Wear loss	Coefficient of friction	Frictional force		Wear loss	Coefficient of friction	Frictional force	
1	0.407	0.561	0.789	0.586	0.800	0.380	0.452	0.544
2	0.333	0.885	0.577	0.598	0.571	0.452	0.777	0.600
3	0.917	1.000	0.947	0.954	0.667	0.452	0.792	0.637
4	0.688	0.535	0.559	0.594	0.800	0.559	0.909	0.756
5	1.000	0.697	1.000	0.899	1.000	0.380	0.471	0.617
6	0.579	0.622	0.780	0.660	0.667	0.731	0.894	0.764
7	0.500	0.697	0.839	0.679	0.500	0.358	0.513	0.457
8	0.917	0.561	0.587	0.688	0.727	0.864	1.000	0.864
9	0.344	0.590	0.835	0.590	0.333	0.463	0.537	0.445
10	0.579	0.590	0.740	0.636	0.444	0.452	0.519	0.472
11	0.407	0.561	0.667	0.545	0.727	0.442	0.503	0.557
12	0.917	0.333	0.333	0.528	0.615	0.594	0.635	0.615
13	0.846	0.377	0.550	0.591	0.667	0.333	0.345	0.448
14	0.688	0.469	0.602	0.586	0.571	0.475	0.333	0.460
15	0.579	0.590	0.699	0.623	0.667	0.487	0.548	0.567
16	0.550	0.590	0.710	0.617	0.800	1.000	0.808	0.869

Table 8 Response table of grey relational grade for uncoated and coated results

Factors	Level 1		Level 2		Level 3		Level 4	
	Uncoated	SiC coated	Uncoated	SiC coated	Uncoated	SiC coated	Uncoated	SiC coated
Load	0.683	0.634	0.732	0.675	0.575	0.522	0.604	0.586
Speed	0.666	0.513	0.620	0.574	0.700	0.555	0.607	0.776
Distance	0.602	0.684	0.662	0.600	0.705	0.601	0.625	0.533
Track diameter	0.606	0.617	0.777	0.649	0.595	0.519	0.617	0.633

The main effect plot for the calculated grey relational grade is drawn as shown in Figure 6 and Figure 7 for uncoated and coated specimens respectively. From the calculations of response table and main effects plot, the optimum condition identified for uncoated specimens were, load of 25 N, speed of 400 rpm, a distance of 400 m and track diameter of 60 mm and similarly for coated specimens, the optimal condition is; load of 25 N, speed of 500 rpm, a distance of 200 m and the track diameter of 60 mm.

Interaction of the input parameters on the output results can be studied with the use of interaction plots as shown in Figure 8 and Figure 9 for uncoated and coated specimens through grey relational grade results respectively. From the interaction study, we can understand the behaviour of chosen input parameters individually and in accordance with the other chosen input parameters. If the interaction plotted lines are parallel it indicates that, the factors are said to be independent and small or no interaction is assumed to exist. If the interaction plotted lines are non-parallel lines, it indicates the presence of some interaction. Highly intersecting plotted lines indicates a strong interaction between the two factors (Senthilkumar et al., 2016b). In this present work from the interaction plot for uncoated specimens, interaction between track diameter and other input parameters were identified as significant and also a considerable interaction between speed and distance. In between other parameters a moderate relationship exists.

Figure 6 Main effects plot for grey relational grade of uncoated specimens (see online version for colours)

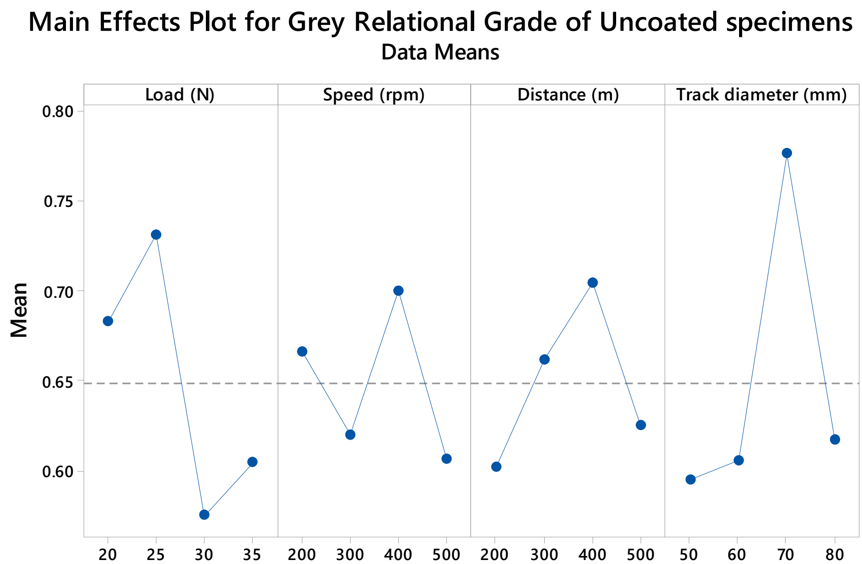


Figure 7 Main effects plot for grey relational grade of coated specimens (see online version for colours)

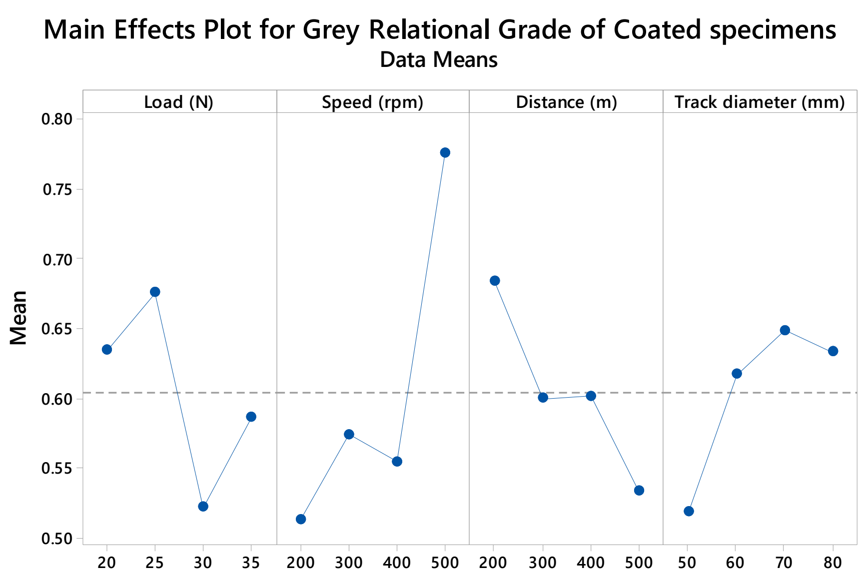


Figure 8 Interaction plot for grey relational grade of uncoated specimens (see online version for colours)

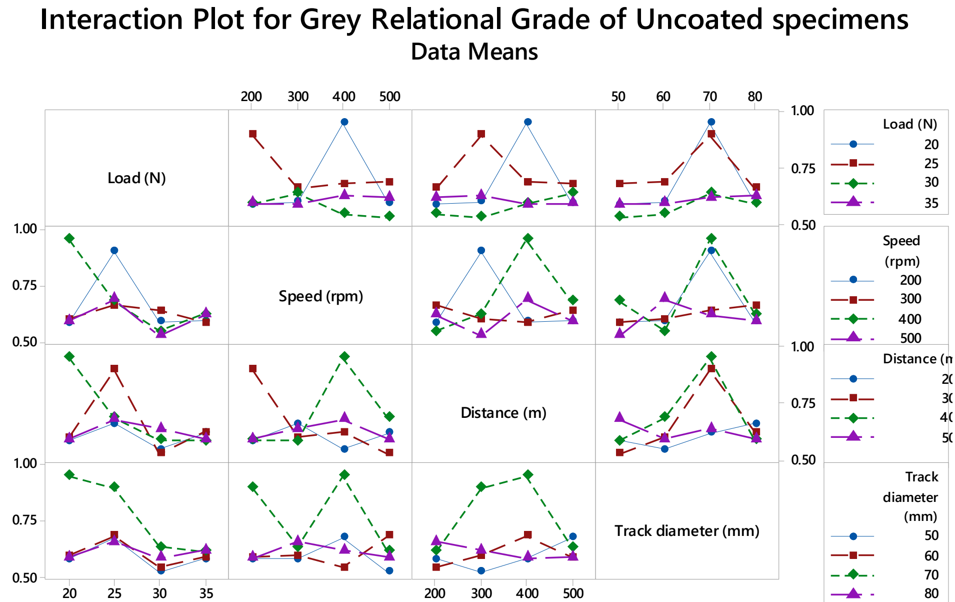
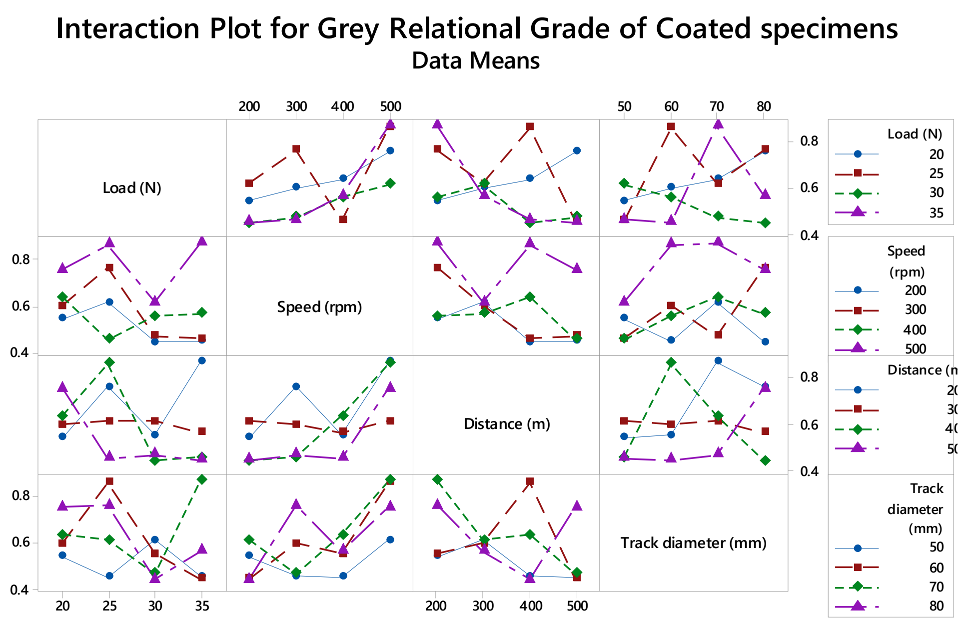


Figure 9 Interaction plot for grey relational grade of coated specimens (see online version for colours)



From the interaction plot shown in Figure 9 for coated specimens, interaction effects between speed and other input parameters are significant and also between load and track diameter. In between other parameters a moderate relationship exists.

3.2.2 Analysis of variance

A statistical approach, analysis of variance (ANOVA) was employed to investigate the significance of the pin-on-disc parameters towards the wear loss, which is critically important for the control of the wear loss. The ANOVA provides results of the sum of the squared deviations, mean squared deviation and the fisher's values (F) were calculated for each output response. Grey relational grade ANOVA table for uncoated and coated shown in Tables 9 and 10, respectively. From ANOVA Table 9, related to uncoated specimens, it was found that the most influential parameter is the track diameter that contributes for the output responses is 42.97%, while the load, distance and track diameter are the least contribution factors with the 30.10%, 11.73% and 10.77% respectively. The R^2 value obtained is 95.62%, which is good for an analysis model. The percentage contribution of input over the grey relational grade is given as pie chart in Figure 10 uncoated specimens.

Table 9 ANOVA table for grey relational grade of uncoated results

Factors	*DoF*	*SS*	*MS*	*F value*	*P value*	*% contribution*
Load	3	0.0620	0.0207	6.807	0.075	30.10%
Speed	3	0.0222	0.0074	2.436	0.242	10.77%
Distance	3	0.0242	0.0081	2.653	0.222	11.73%
Track diameter	3	0.0886	0.0295	9.717	0.047	42.97%
Error	3	0.0091	0.0030			4.42%
Total	15	0.2061	0.0137			100.00%

From ANOVA, Table 10 for coated specimens, it was found that the most influential parameter that contributes for the output responses is speed, which is the greatest influencer on the wear loss of the coatings with 54% contribution, while the load, distance and track diameter are the least contribution factors by 17.11%, 14.92% and 13.49% respectively. The R^2 value obtained during analysis is 99.51%, which is the ideal value. The percentage contribution of input over the grey relational grade is given as pie chart in Figure 11 for coated specimens.

Table 10 ANOVA table for grey relational grade of coated results

Factors	*DoF*	*SS*	*MS*	*F value*	*P value*	*% contribution*
Load	3	0.0521	0.0174	35.292	0.008	17.11%
Speed	3	0.1644	0.0548	111.412	0.001	54.00%
Distance	3	0.0454	0.0151	30.792	0.009	14.92%
Track diameter	3	0.0410	0.0137	27.823	0.011	13.49%
Error	3	0.0015	0.0005			0.48%
Total	15	0.3044	0.0203			100.00%

Figure 10 % contribution of input parameter over grey relational grade of uncoated results (see online version for colours)

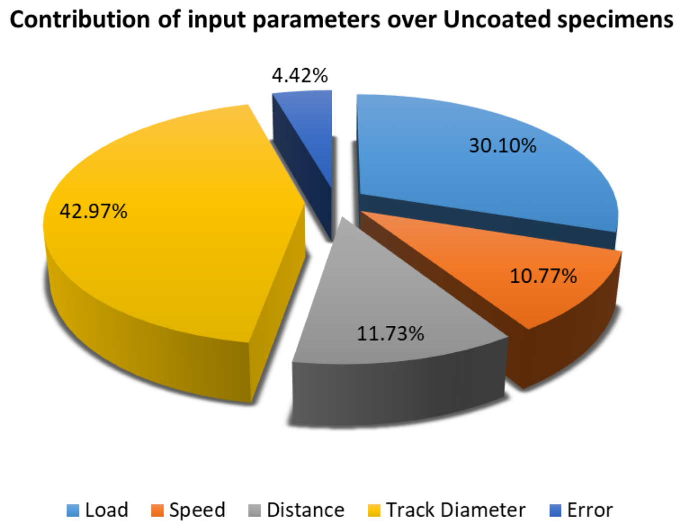
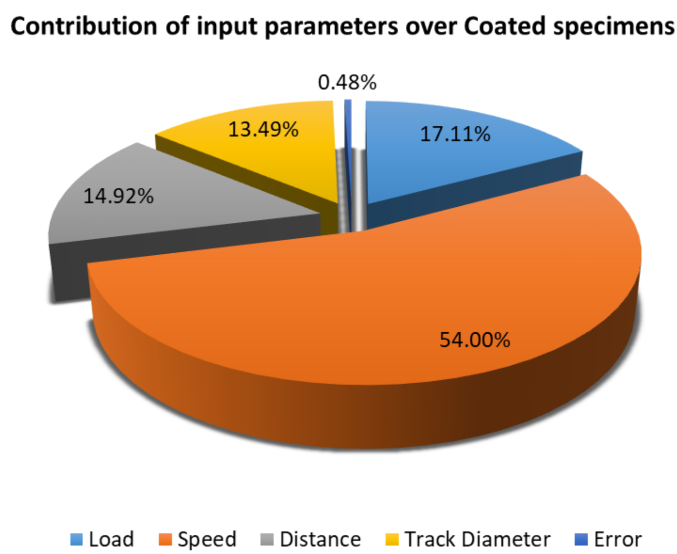


Figure 11 % contribution of input parameter over grey relational grade of coated results (see online version for colours)



3.2.3 Confirmation test

The identified optimum parameter level values of pin-on-disc wear test are to minimise the wear loss of Ti-6Al-4V alloy is verified, for which a confirmation test is conducted. After analysing the output responses determined from the experimental trials, two sets of experiments were conducted, one for uncoated and another for coated results for validating the results of grey technique and the results obtained were tabulated in Table 11.

Table 11 Confirmation experiment results and comparisons

Validation results	*Optimum values*		*Wear loss (g)*	
	Uncoated	*Coated*	*Uncoated*	*Coated*
Load (N)	25	25		
Speed (rpm)	400	500		
Distance (m)	400	200	0.017	0.009
Track diameter (mm)	60	60		
% improvement with average values			11.76%	22.92%
Validation results	*Coefficient of friction*		*Frictional force (N)*	
	Uncoated	*Coated*	*Uncoated*	*Coated*
Load (N)				
Speed (rpm)				
Distance (m)	0.120	0.580	3.540	17.200
Track diameter (mm)				
% improvement with average values	9.11%	12.93%	10.70%	16.37%

3.3 Scanning electron microscope

The SEM is used to identify the worn surface of the coated pins after wear test. From the experimental condition of load 25 N, speed 200 rpm, distance 300 m and track diameter 70 mm, it is observed that lower wear exists on dry sliding and for a load 30 N, speed 200 rpm, distance 400 m and track diameter 80 mm shows high wear loss on sliding. Worn surface morphologies of coated Ti-6Al-4V alloy were investigated using SEM. The changes in internal grain structure during the pin-on-disc wear tested of SiC coated pins are exhibited by the SEM micrographs. Figure 12(a) and 12(b) shows the SEM micrograph of the low worn surface and SEM micrograph of high worn surface at 500X magnification. Figure 12(a) shows wear track of material along the sliding direction and it does not produce much wear debris on the sliding surface and surface finish of worn surface was better conditioned against them. This indicates the lower temperature will be produced in an interface area and were dissipated properly, this occurs at lower time of running (Hong et al., 2014; Dolimont et al., 2015). The adding of SiC coating improves the hardness and tensile strength of the Ti-6Al-4V alloy as compared to uncoated alloy, which increases the wear resistance of the base material. Improved surface hardness of the material reduces the penetration by the abrasive particle, which leads to lower wear, higher temperature resistance, hardness and tensile strength increase by the increase of reinforcement substance (Das et al., 2008; Alidokht et al., 2011). Wear scratch is found to decrease among improved hardness, fracture toughness and stiffness similarly as decreased in grain size and contact load (Bonny et al., 2009).

Figure 12 SEM morphology (a) low wear loss and (b) high wear loss specimen

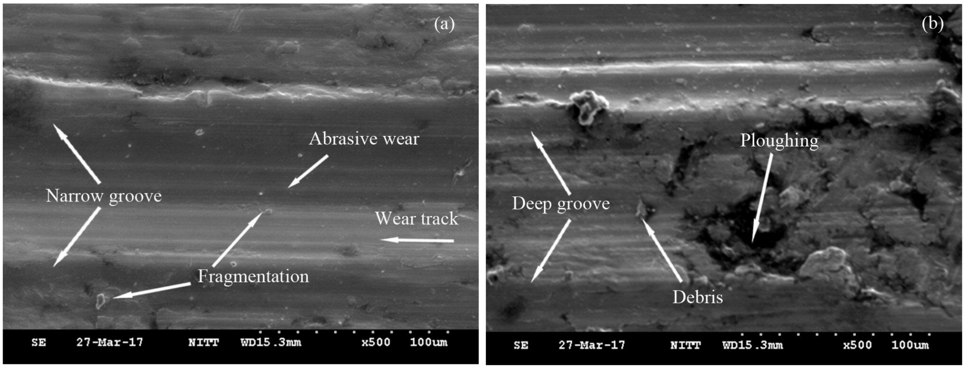


Figure 13 EDS analysis (a) low wear loss and (b) higher wear loss specimen (see online version for colours)

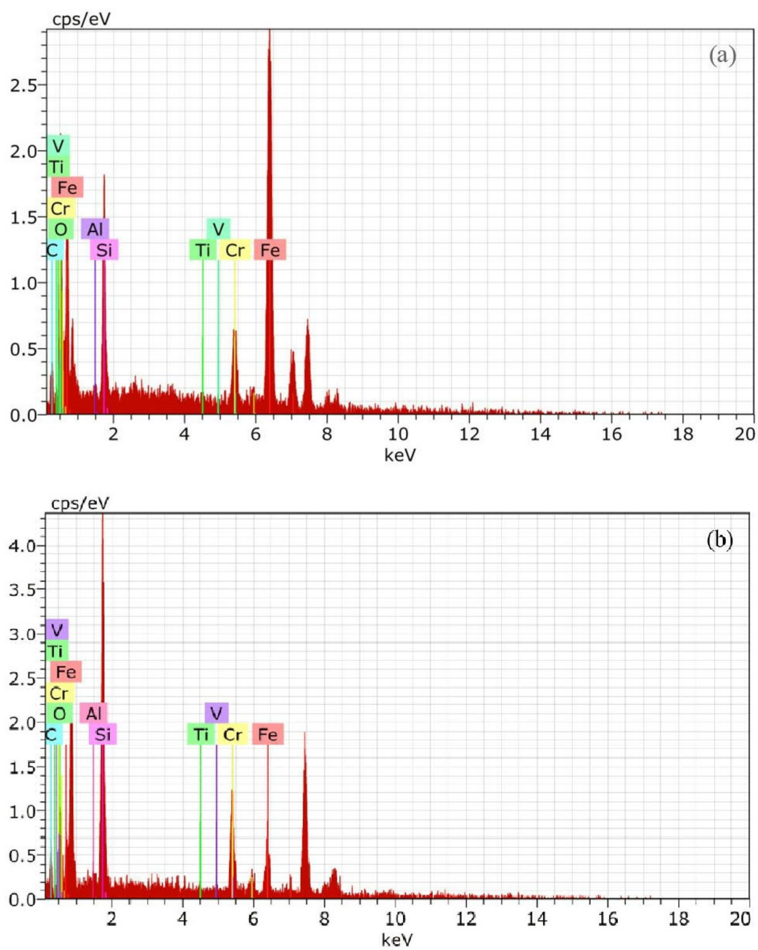


Figure 12(b) indicates the wear track in deep groove form, debris and ploughing also identified and marked. It shows that the material was removed by ploughing, wear debris was delaminated form entrapped wear particles. These particles increase the temperature of the interface area; thus it results in losing the material wear resistance. As a result of increase in contact surface temperature, given speed and the longer time of running additional heat generated between the contact surfaces results in softening of the coated surface, which leads to deep grooves and generation of higher amount of debris.

3.4 Energy dispersive spectrum analysis

To understand relation of asperity behaviour ply between the two contacting surfaces, energy dispersive spectrum (EDS) analysis is done on the worn surface of the low and high wear specimens of coated Ti-6Al-4V alloy as depicted in Figures 13(a) and 13(b) respectively. It can be seen that; some quantity of counter surface material is transferred to the pin. The elements of Cr, Si and O are present on the worn surface of the composite specimen.

4 Conclusions

To improved wear resistance of Ti-6Al-4V alloy, HVOF thermal spray coating was successfully employed by applied the SiC as a coating agent. By the information of results and discussion some useful conclusions are made.

1. Micro hardness was increased from 303 HV to 756 HV and the tensile test result shows increase in UTS from 998 MPa to 1066 MPa for uncoated to coated Ti-6Al-4V alloy. Since the wear resistance is the function of hardness; improved hardness minimises the wear loss of coated specimens.
2. For optimising dry sliding wear parameters, a L_{16} OA is designed as per Taguchi's design and a multi-objective approach of grey analysis technique is used. The optimum condition arrived for uncoated specimen is: load of 25 N, speed of 400 rpm, a distance of 400 m and the track diameter of 60 mm and for SiC coated specimen is: load of 2 5N, speed of 500 rpm, a distance of 200 m and the track diameter of 60 mm.
3. From ANOVA, for uncoated experiments, track diameter is the most influencing parameter; it contributes 42.97% of the output responses. For coated experiments, it is found that the most influential parameter is speed it contributes 54% of the output responses. Confirmation test was conducted for the optimum conditions, shows better output responses than the design of experimental values, with a reduction in wear loss, CoF and FF.
4. The changes in internal structure during the pin-on-disc wear tested pins were exhibited by the SEM micrographs, wear tracks were identified and the asperity behaviour between the two mating surfaces were well understood by EDS analysis carried out on the worn surface of the low and high worn specimens of coated Ti-6Al-4V alloy.

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