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Mechanical and Tribological Properties of Cr_3C_2-NiCr Coated Ti6Al4V Implant Alloy

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Abstract

Ti6Al4V alloys are widely used in medical and aerospace applications due to their superior mechanical properties. But, Ti6Al4V alloys are poor in tribological properties such as wear. Poor wear resistance consequences in the formation of wear debris in human implants and leads to inflammation and pain. In this work, Cr_3C_2-NiCr coatings were applied to improve the mechanical properties such as tensile strength, hardness and tribological properties such as wear resistance. Cr_3C_2-NiCr coatings are deposited on the substrate with 100 µm, 200 µm, 300 µm, 400 µm thickness using detonation spray (DS). Implants are generally placed inside the human body; hence, wear behavior was studied in the simulated body environment using Hank's solution. Tensile tests are carried out with ASTM E-8 standard specimens and improvement was observed. Pin on disc wear tests have been carried out with ASTM G-99 standard specimens. Wear and surface roughness were studied using Taguchi design of experiments. Grey relational analysis was done and obtained the combined optimal factors for wear and surface roughness. Improvement was observed in hardness, surface roughness and wear resistance for the Cr_3C_2-NiCr coated Ti6Al4V alloy.

Keywords: *Detonation sray, Ti6Al4V, surface coatings, wear, Taguchi's orthogonal array, ANOVA*

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INTRODUCTION

Mechanical properties and bio-chemical compatibility makes Ti6Al4V alloy suitable for orthopedic implant applications [1]. Life of the implants materials depends on the wear resistance. Generally, wear property can be defined as source of damage to a solid surface by progressive loss of material, due to relative motion between contacting surfaces [2]. Poor wear resistance generates micro fragments, when the artificial implant is in contact with the healthy and natural joint, the accumulated micro fragments causes swelling, pain, loosening of the joint and life decreases [3].

Thermal barrier coatings are often deposited on metals to improve mechanical and tribological properties. Detonation spray (DS) is a thermal barrier coating technology in which melted or semi-melted state powder by the heat due to combustion of fuel in presence of oxygen was expel on the surface of work piece at a high speed [4,5]. This technique has been extensively used in aviation, space flight, petroleum, metallurgy and other machinery industries. D-gun thermal barrier coating gives an extremely good adhesive strength, low porosity and coating surfaces with compressive residual stresses.

The present research is carried out with the aim of determining the mechanical and tribological properties of Cr_3C_2-NiCr coated [6–10] Ti6Al4V implant alloy. Detonation spray technique is used to deposit the coating and thickness is varied as 100 µm, 200 µm, 300 µm, 400 µm to study the effect of coating thickness on tensile strength, hardness and wear resistance. Tensile tests were carried out with ASTM E-8 standard specimens of both substrate and coated material. Hardness was found by Rockwell hardness tester for both substrates and coated specimens. Wear tests were performed for different loads, speeds, sliding distances and coating thickness using pin-on-disc apparatus [11–13]. Surface roughness was measured using Talysurf surface tester [14].

Taguchi technique for design of experiments (DOE) has been successfully used by researchers [15, 16]. The design of experiments process consists of three main phases i.e. the planning phase, the conducting phase, and the analysis phase. Major step in the design of experiments process is the determination of the combination of factors and levels which will provide the desired information. Analysis of the experimental results uses the signal to noise ratio to obtain the best process designs. Taguchi creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiment. The experimental results are analyzed using analysis of means and variance to study the influence of parameters. The major aim of the present investigation is to analyse the influence of parameters like load, sliding speed, sliding distance and coating thickness on sliding wear and surface roughness of Ti6Al4V coated with Cr3C2-NiCr. Grey relational analysis [17, 18] was done to determine the optimum levels for wear and surface roughness. Non linear regression modal was developed using response surface method [19, 20].

SELECTION OF ORTHOGONAL ARRAY

A major step in the design of experiments process is the selection of orthogonal array based on number of factors and number of levels for each of the factor. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters [21]. In the present work, four factors and four levels were considered. Therefore, the degrees of freedom were calculated as shown below.

i) Number of factors =4
ii) Numbers of levels = 4
iii) Degrees of freedom of each factor = 4-1=3
iv) Total degrees of freedom = Sum of the degrees of freedoms of all factors.
= 3+3+3+3=12
v) Minimum numbers of experiments to be conducted = 12+1= 13.

Based on the required minimum number of experiments the nearest orthogonal array fulfilling the condition is L_{16}.

ANALYSIS OF THE SIGNAL-TO-NOISE RATIO

Analysis of the experimental results uses a signal to noise ratio to aid in the determination of the best process designs. The Taguchi technique is a powerful design of experiment tool for acquiring the data in a controlled way and to analyze the influence of process variable over some specific variable which is unknown function of these process variables and for the design of high quality systems. Taguchi creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiment. The experimental results are analyzed using analysis of variance to study the influence of parameters. Signal-to-noise ratio for smaller is the better characteristics given by Taguchi which can be calculated as logarithmic transformation of the loss function, is given as:

$$S/N = -10 \times log\left(\frac{\sum(Y^2)}{n}\right)$$

Where y is the observed data and n is the number of observations.

The present work includes the following:

- Study of effect of experimental parameters such as load, speed, distance and thickness to minimize the sliding wear behavior and surface roughness of Cr_3C_2-NiCr coated Ti6Al4V in dry and simulated body environment using Taguchi L_{16} orthogonal array.
- Simultaneous optimization of wear and surface roughness using grey relational analysis.
- Development of mathematical model for responses response surface nonlinear regression analysis.

EXPERIMENTAL WORK

Detonation Spray

Specifically, calculated quantity of the combustion mixture consisting of oxygen and acetylene is fed through a tubular barrel closed at one end. In order to prevent the possibility back firing a blanket of nitrogen gas is allowed to cover the gas inlets. At the same time, a predetermined quantity of the coating powder is fed into the combustion chamber. The gas mixture inside the chamber is ignited by a spark plug. The combustion of the gas mixture creates high pressure detonation wave, which then propagate through the gas flow. Depending upon the ratio of the combustion gases, the temperature of the hot gas stream can go up to 4000°C and the velocity of the shock wave can reach up to 3500 m/sec. The hot gases generated in the detonation chamber travel down the barrel at a high velocity and in the process heat the particles to a plasticizing stage and also accelerate the particles to a velocity of 1200 m/sec. These particles then come out of the barrel and impact the component to form a coating. The high kinetic energy of the hot powder particles on impact with the substrate result in a buildup of a very dense and strong coating [10, 11].

Materials and Coating Deposition

Ti6Al4V was used as substrate and its chemical composition is given in Table 1. Cr_3C_2-NiCr was used as coating material whose chemical composition is given in Table 2. In the present work, coatings are performed by 100 µm, 200 µm, 300 µm, 400 µm thick using detonation spray technique. Prior to coating, Substrate was blasted with Al_2O_3 grits. Optimum surface roughness was obtained through grid blasting for the best adhesion between coating and substrate. Figures 1 and 2 shows the detonation spray and grid blasting equipment used in the present work. The spraying process parameters for DS are listed in Table 3.

Table 1: *Chemical Composition (Weight %) of Ti6Al4V.*

Ti	Al	V	Fe	Cr	Mo
89.5	6.53	3.85	0.08	0.01	0.03

Table 2: *Chemical Composition (Weight %) of Cr3C2-NiCr.*

Cr_3C_2	NiCr
75	25

Table 3: *DS Parameters for Cr_3C_2-NiCr Deposition.*

Oxygen Flow Rate (slph)	850
Acetylene Fuel (slph)	2440
Nitrogen Flow Rate (slph)	12
Spray Distance	120 mm
Gun Speed	10 mm/sec

Fig. 1: *Detonation Spray Process.*

Fig. 2: *Grid Blasting.*

Hank Solution

Simulated body fluid environment was created using Hank's solution. It was prepared using high purity reagents; their chemical composition is given in Table 4.

Table 4: *Hank Solution Chemical Composition.*

Component	NaCl	KCL	$NaHCO_3$	$CaCl_2$	$MgCl^2.6H_2O$
(g/L)	8	0.4	0.35	0.14	0.1
Component	Na2HPO42H2O	KH2PO4	MgSO4.7H2O	Glucose	pH
(g/L)	0.06	0.06	0.06	1	6.8

Surface Roughness Measurements

Coating material surface roughness before and after the wear test was measured by using Talysurf instrument shown in Figure 3. An average of five readings is reported for all experiments.

Fig. 3: *Talysurf Surface Roughness Instrument.*

Fig. 4: *Cr_3C_2 NiCr Coated Ti6Al4V Specimens.*

Hardness

Hardness of substrate and coated material were found by IS 1586 test procedure as per BIS standards using Rockwell hardness tester. An average of five readings is reported.

Wear Testing

Sliding wear behavior was studied by conducting experiments on a pin-on-disc wear testing machine according to the ASTM G99 standards. Ti6Al4V cylindrical pins of 6 mm diameter and 30 mm length with Cr_3C_2 - NiCr coating were used as test material. En-32 steel was used as counter face material. Rockwell hardness (HRC) values for implant material and counter face material were found as 53.33 and 60 respectively. En-32 steel disc was suitable for pin on disc wear test as its hardness value was greater than implant material. Loads acting on human joints vary significantly from joint to joint. For a particular joint, it varies with time during the loading cycle and with loading rate (Dumbleton, 1981; Park, 1984). It has been reported that the stresses in the living joints are of the order of 1 MPa (Dumbleton, 1981).

Considering the stresses induced in human joints levels for load, speed and distance were decided as shown in Table 5. Specimens are prepared as per ASTM G-99 standards as shown in Figure 4. Mass of each specimen was measured with an accuracy of ±0.0001g and the average of three readings was recorded. Pin on disc experimental set up was shown in Figure 5. Experiments were carried out as per Taguchi's design in the simulated body environment created using Hank's solution. Mass loss of the specimens was measured by using a balance with an accuracy of ±0.0001 g to study the wear behavior.

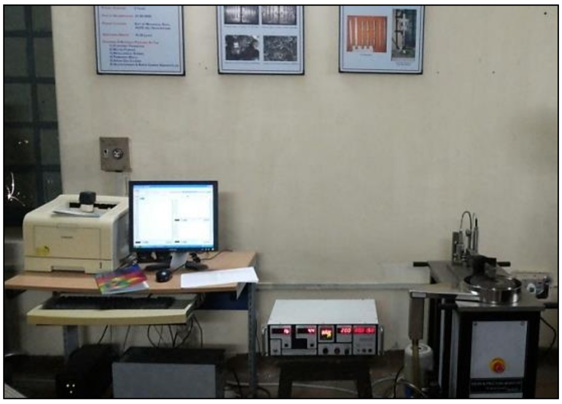

Fig. 5: *Pin on Disc Wear Testing Machine.*

The wear test were carried out by taking the Taguchi design of experiments by considering the load, speed, distance and coating thickness as factors and each factor is taken to three levels as shown in Tables 5 and 6. Weight loss of the specimens was measured by using a balance with an accuracy of ±0.0001 g.

Table 5: *Parameters Taken for Wear Test.*

Factors	Levels			
	1	**2**	**3**	**4**
Load in N	10	30	40	50
Speed in m/s	0.6	0.9	1.2	1.5
Distance in Km	0.25	0.5	0.75	1
Coating Thickness in μm	100	200	300	400

RESULTS AND DISCUSSIONS

In present work mechanical properties such as tensile stress and hardness were studied to report the effect of Cr_3C_2-NiCr coating thickness on the Ti_6Al_4V substrate.

Tensile Stress and Hardness

Tensile tests were carried out using ASTM E-8 standard specimens; Ultimate tensile stress and elongation were determined for substrate and coated materials as listed in Table 7. A rockwell hardness (HRC) value for substrate and coated material were found by IS 1586 test procedure as per BIS standards and average of three readings is reported in Table 6. Significant improvement in Ultimate tensile stress and hardness was achieved through coating.

Wear Analysis

Wear test was carried out for the Ti6Al4V substrate using pin-on disc wear testing machine and wear resistance was studied by taking mass loss. The experiments were conducted as per L^{16} orthogonal array, mass loss and surface roughness in both dry and wet (Hank's solution) conditions were listed in Table 8.

Table 6: *Taguchi Design of Experiments for Wear Test.*

Experiment No.	Load N	Speed m/sec	Distance Km	Thickness µm
1	10	0.6	0.25	100
2	10	0.9	0.5	200
3	10	1.2	0.75	300
4	10	1.5	1	400
5	30	0.6	0.5	300
6	30	0.9	0.25	400
7	30	1.2	1	100
8	30	1.5	0.75	200
9	40	0.6	0.75	400
10	40	0.9	1	300
11	40	1.2	0.25	200
12	40	1.5	0.5	100
13	50	0.6	1	200
14	50	0.9	0.75	100
15	50	1.2	0.5	400
16	50	1.5	0.25	300

Table 7: *Rockwell Hardness, Ultimate Tensile Stress and Elongation.*

Material	Rockwell Hardness (HRC)	Ultimate Tensile Stress N/mm^2	% Elongation
Ti6Al4V	25.67	890.940	17.440
Cr_3C_2 - NiCr 100 µm Coated Ti6Al4V	35.33	967.343	19.640
Cr_3C_2 - NiCr 200 µm Coated Ti6Al4V	41.33	990.320	19.320
Cr_3C_2 - NiCr 300 µm Coated Ti6Al4V	49.67	1036.082	18.880
Cr_3C_2 - NiCr 400 µm Coated Ti6Al4V	53.33	1066.667	19.040

Table 8: *Mass Loss, Surface Roughness in Dry and Wet Conditions.*

Expt No.	Load N	Speed m/sec	Distance Km	Thickness µm	Dry Condition		Wet Condition (Hank's Solution)	
					Mass Loss gm	Ra µm	Mass Loss Gm	Ra Micron
1	10	0.6	0.25	100	0.00039	4.16	0.00034	4.23
2	10	0.9	0.5	200	0.00068	4.77	0.00089	4.87
3	10	1.2	0.75	300	0.00055	4.24	0.00071	4.46
4	10	1.5	1	400	0.00116	4.02	0.00027	3.98
5	30	0.6	0.5	300	0.00151	3.82	0.00204	4.03
6	30	0.9	0.25	400	0.00088	4.08	0.00011	4.24
7	30	1.2	1	100	0.00096	2.52	0.00083	3.75
8	30	1.5	0.75	200	0.00096	4.03	0.00053	3.57
9	40	0.6	0.75	400	0.00656	3.75	0.00114	4.18
10	40	0.9	1	300	0.01252	2.77	0.00048	4.29
11	40	1.2	0.25	200	0.00363	3.32	0.00043	4.01
12	40	1.5	0.5	100	0.00072	3.6	0.00092	4.36
13	50	0.6	1	200	0.00183	3.36	0.00187	3.86
14	50	0.9	0.75	100	0.00075	4.38	0.00121	4.51
15	50	1.2	0.5	400	0.00055	3.92	0.00075	4.43
16	50	1.5	0.25	300	0.00089	4.26	0.00135	4.72

Grey Relational Analysis

The experimental results of mass loss and surface roughness were listed in Table 9. The first step in grey relational analysis is normalization of experimental data in the range of zero to one. Mass loss and surface roughness were normalized for dry and wet conditions based on the smaller-the-best characteristic and values are listed in Table 9.

$$Smaller - the - better = \frac{Maxy_i[I] - y_i}{Maxy_i[I] - Miny_i[I]} \quad (1)$$

Where Min yi [I] is the least value of yi [I] and Max yi [I] is the highest value of I^{th} response where I=1,2,3,4 for various responses considered in a sequence.

The second step is evaluating the absolute difference of $x_o(k)$ and $x_i(k)$ for each of the responses. It is denoted by Δ_{oi} and values are listed in Table 10.

Table 9: *Normalization of Experimental Mass Loss and Surface Roughness.*

Experiment No.	Dry Condition		Wet Condition (Hank's Solution)	
	Mass Loss (Smaller-the-better)	Ra (Smaller-the-better)	Mass Loss (Smaller-the-better)	Ra (Smaller-the-better)
1	1	0.2711	0.8808	0.4923
2	0.9761	0	0.5959	0
3	0.9868	0.2356	0.6891	0.3154
4	0.9365	0.3333	0.9171	0.6846
5	0.9077	0.4222	0	0.6462
6	0.9596	0.3067	1	0.4846
7	0.953	1	0.6269	0.8615
8	0.953	0.3289	0.7824	1
9	0.4913	0.4533	0.4663	0.5308
10	0	0.8889	0.8083	0.4462
11	0.7329	0.6444	0.8342	0.6615
12	0.9728	0.52	0.5803	0.3923
13	0.8813	0.6267	0.0881	0.7769
14	0.9703	0.1733	0.4301	0.2769
15	0.9868	0.3778	0.6684	0.3385
16	0.9588	0.2267	0.3575	0.1154

Table 10: *Loss Function (Δ_{oi}).*

Experiment No.	Dry Condition		Wet Condition (Hank's Solution)	
	Mass Loss (Smaller-the-better)	Ra (Smaller-the-better)	Mass Loss (Smaller-the-better)	Ra (Smaller-the-better)
1	0	0.7289	0.1192	0.5077
2	0.0239	1	0.4041	1
3	0.0132	0.7644	0.3109	0.6846
4	0.0635	0.6667	0.0829	0.3154
5	0.0923	0.5778	1	0.3538
6	0.0404	0.6933	0	0.5154
7	0.047	0	0.3731	0.1385
8	0.047	0.6711	0.2176	0
9	0.5087	0.5467	0.5337	0.4692
10	1	0.1111	0.1917	0.5538
11	0.2671	0.3556	0.1658	0.3385
12	0.0272	0.48	0.4197	0.6077
13	0.1187	0.3733	0.9119	0.2231
14	0.0297	0.8267	0.5699	0.7231
15	0.0132	0.6222	0.3316	0.6615
16	0.0412	0.7733	0.6425	0.8846

Third step is the calculation of grey relational coefficients ξ_i (K) using the Equation 2 given below.

$$\xi_i(k) = \frac{\Delta_{min}+\psi\Delta_{max}}{\Delta_{oi}(k)+\psi\Delta_{max}} \quad (2)$$

Where, $\|x_0(K) - x_i(K)\|$ the difference of the absolute values between x_0(K) and x_i(K). Δ_{min} and Δ_{max} are the minimum and maximum values of the absolute differences of Δ_{oi}. Ψ is the distinguishing coefficient $0 \leq \psi \leq 1$. Process parameters are equally weighted and Ψ value is taken as 0.5. Fourth step is calculation of grey relational grade γ_i using the Equation-(3).

$$\gamma_i = \frac{1}{n}\sum_{K=1}^{n} \xi_i(K) \quad (3)$$

Where n is representing the number of process responses. Grey relational coefficients, grade, S/N Ratio's and Ranks for wear in dry and wet conditions are listed in Tables 11 and 12 respectively. The multi response problem was converted into equivalent single response problem i.e. grey relational grade. Then, Taguchi analysis was done to obtain the optimum parameters for both dry and wet sliding wear conditions. From the main effects plots shown in Figures 6 and 7 optimum parameters are listed in Table 13.

Table 11: *GRC, GRG, S/N Ratio of GRG and Rank for Dry Sliding Wear.*

Experiment No.	Grey Coefficients		Grey Relational Grade	S/N Ratio of GRG	Rank
	Mass Loss	Ra			
1	1	0.4069	0.70345	-3.05533532	4
2	0.9544	0.3333	0.64385	-3.824306	13
3	0.9743	0.3535	0.6639	-3.55794663	8
4	0.8873	0.4286	0.65795	-3.63614217	11
5	0.8442	0.4639	0.65405	-3.687781	12
6	0.9252	0.419	0.6721	-3.45132209	6
7	0.9141	1	0.95705	-0.38130745	1
8	0.9141	0.4269	0.6705	-3.47202436	7
9	0.4957	0.4777	0.4867	-6.25477308	16
10	0.3333	0.8182	0.57575	-4.79532107	15
11	0.6518	0.5844	0.6181	-4.17882513	14
12	0.9484	0.5102	0.7293	-2.74187573	2
13	0.8081	0.5725	0.6903	-3.21924253	5
14	0.9439	0.3769	0.6604	-3.60385871	9
15	0.9743	0.4456	0.70995	-2.97544473	3
16	0.9239	0.3927	0.6583	-3.6315229	10

Table 12: *GRC, GRG, S/N Ratio of GRG and Rank for Sliding Wear in Hank's Solution.*

Experiment No.	Grey Coefficients		Grey relational grade	S/N ratio of GRG	Rank
	Mass Loss	Ra			
1	0.8075	0.4962	0.65185	-3.7170466	6
2	0.553	0.3333	0.44315	-7.06898493	14
3	0.6166	0.3746	0.4956	-6.09737405	12
4	0.8578	0.6132	0.7355	-2.66834646	3
5	0.3333	0.5856	0.45945	-6.75523488	13
6	1	0.4924	0.7462	-2.54289511	2
7	0.5727	0.7831	0.6779	-3.37668732	4
8	0.6968	1	0.8484	-1.4279868	1
9	0.4837	0.5159	0.4998	-6.02407496	10

10	0.7229	0.4745	0.5987	-4.45581484	7
11	0.751	0.5963	0.67365	-3.43131372	5
12	0.5437	0.4514	0.49755	-6.06326539	11
13	0.3541	0.6915	0.5228	-5.63328842	8
14	0.4673	0.4088	0.43805	-7.16952631	15
15	0.6013	0.4305	0.5159	-5.74868944	9
16	0.4376	0.3611	0.39935	-7.97292622	16

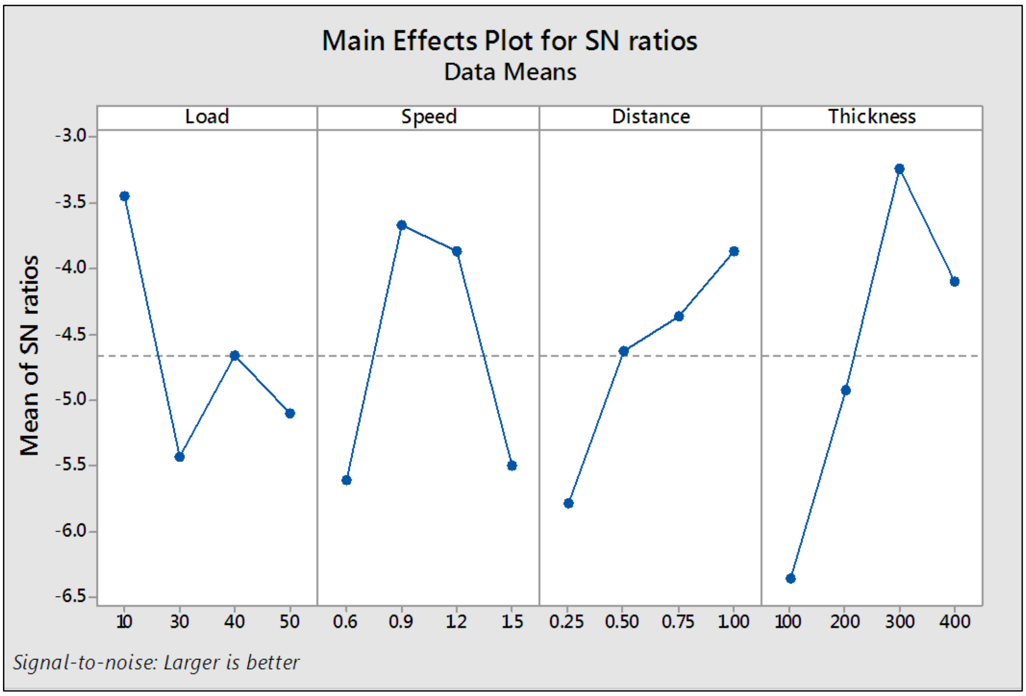

Fig. 6: *Main Effects Plot of GRG for Dry Sliding Wear.*

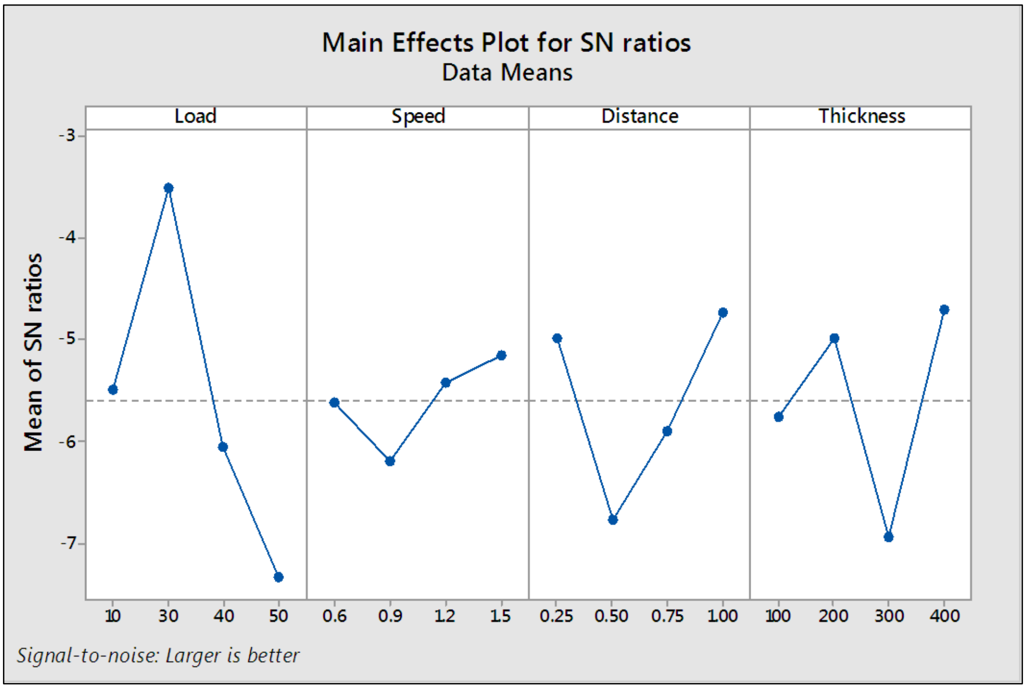

Fig. 7: *Main Effects Plot of GRG for Sliding Wear in Hank's Solution*

Table 13: *Optimum Parameters Obtained for Sliding Wear in Dry and Hank's Solution.*

S. No	Factors	Dry condition		Wet condition (Hank's solution)	
		Optimum Level	Optimum value	Optimum Level	Optimum value
1	Load in N	L1	10	L2	30
2	Speed in m/s	S2	0.9	S4	1.5
3	Distance in Km	D4	1	D4	1
4	Thickness in µm	T3	300	T4	400

Table 14: *Analysis of Variance for SN Ratios- GRG for Dry Sliding Wear.*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Load	3	6.2721	6.2721	2.0907	10.78	0.041	30.23
Speed	3	4.0956	4.0956	1.3652	7.04	0.072	19.72
Distance	3	3.2142	3.2142	1.0714	5.52	0.097	15.48
Thickness	3	6.5963	6.5963	2.1988	11.34	0.038	31.77
Residual Error	3	0.5819	0.5819	0.1940			
Total	15	20.7601					

Table 15: *Analysis of Variance for SN Ratios- GRG for Sliding Wear in Hank's Solution.*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Load	3	19.385	19.385	6.4617	1.87	0.310	34.29
Speed	3	2.840	2.840	0.9466	0.27	0.842	5.02
Distance	3	13.170	13.170	4.3899	1.27	0.424	23.30
Thickness	3	10.759	10.759	3.5863	1.04	0.488	19.03
Residual Error	3	10.368	10.368	3.4560			
Total	15	56.522					

ANOVA OF GREY RELATIONAL GRADE

ANOVA was used to determine the design parameters significantly influencing the mass loss and surface roughness (responses) combined through grey relational grade. Analysis of variance (ANOVA) results of GRG for wear in dry and wet conditions were shown in Tables 14 and 15 respectively. This analysis was evaluated for a confidence level of 95%, that is for significance level of α=0.05. The last column of Tables 14 and 15 shows the percentage of contribution of each parameter on the response, indicating the degree of influence on the result. Contribution for each source parameter is calculated as follows.

$$\%Contribution = \frac{SeqSSofeachparameter}{TotalofseqSSofallparameters} \times 100$$

It can be observed from the results obtained, load was the most significant parameter in both dry and wet sliding conditions based on the percentage of contribution.

REGRESSION ANALYSIS

Mathematical models for the mass loss and surface roughness have been developed using non linear regression analysis in response surface method.

Dry Sliding Wear

Non linear regression equations for mass loss and surface roughness were obtained for sliding wear behavior in dry condition were shown in Equations 1 and 2 respectively. Experimental values, Predicted values and %error of mass loss and surface roughness were listed in Tables 16 and 17 respectively. Comparison of experimental values with predicted values of mass loss and surface roughness were plotted in Figures 8 and 9 respectively.

Mass loss = 0.01440 - 0.001604 Load - 0.00335 Speed - 0.1260 Distance + 0.000321 Thickness
+ 0.000031 Load*Load + 0.000347 Speed*Speed + 0.04328 Distance*Distance
- 0.000000 Thickness*Thickness + 0.000017 Load*Speed - 0.000004 Load*Distance
- 0.000000 Load*Thickness+ 0.0695 Speed*Distance- 0.000168 Speed*Thickness Equation-1

The coefficient of determination (R^2) = 98.52%

Table 16: *Experimental, Predicted Values of Mass Loss and Percentage Error for Dry Sliding Wear.*

Experiment No.	Load N	Speed m/sec	Distance Km	Thickness µm	Mass loss gms	Predicted Mass loss gms	Error gms	% Error
1	10	0.6	0.25	100	0.00039	0.000452	-6.2E-05	-15.99318
2	10	0.9	0.5	200	0.00068	0.000507	0.000173	25.373852
3	10	1.2	0.75	300	0.00055	0.000723	-0.00017	-31.37131
4	10	1.5	1	400	0.00116	0.001098	6.24E-05	5.3770188
5	30	0.6	0.5	300	0.00151	0.001484	2.55E-05	1.6895102
6	30	0.9	0.25	400	0.00088	0.000884	-3.6E-06	-0.414149
7	30	1.2	1	100	0.00096	0.000956	3.64E-06	0.379637
8	30	1.5	0.75	200	0.00096	0.000986	-2.6E-05	-2.657459
9	40	0.6	0.75	400	0.00156	0.001589	-2.9E-05	-1.868982
10	40	0.9	1	300	0.00252	0.00252	-7.4E-18	-2.93E-13
11	40	1.2	0.25	200	0.00163	0.00163	-3.9E-18	-2.39E-13
12	40	1.5	0.5	100	0.00072	0.000691	2.92E-05	4.0494609
13	50	0.6	1	200	0.00183	0.001812	1.82E-05	0.9957691
14	50	0.9	0.75	100	0.00075	0.000776	-2.6E-05	-3.401547
15	50	1.2	0.5	400	0.00055	0.000524	2.55E-05	4.6384733
16	50	1.5	0.25	300	0.00089	0.000908	-1.8E-05	-2.04748

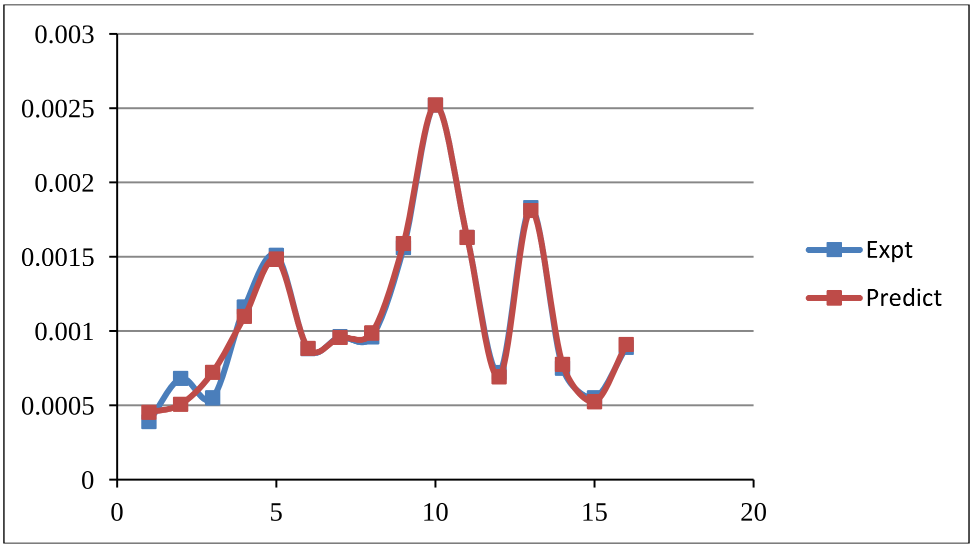

Fig. 8: *Comparison of Experimental and Predicted Values of Mass Loss.*

Ra = -2.03 + 0.726 Load - 1.50 Speed + 63.5 Distance - 0.146 Thickness - 0.0146 Load*Load
+ 0.69 Speed*Speed - 24.4 Distance*Distance + 0.000127 Thickness*Thickness
+ 0.0173 Load*Speed + 0.0571 Load*Distance - 0.000150 Load*Thickness
- 34.2 Speed*Distance + 0.0849 Speed*Thickness Equation-2

The coefficient of determination (R^2) = 90.21%

Table 17: *Experimental, Predicted Values of* ***Ra*** *and Percentage Error of* ***Ra*** *for Dry Sliding Wear.*

Experiment No.	Load N	Speed m/sec	Distance Km	Thickness µm	Ra µm	Predicted Ra µm	Error Ra µm	% Error Ra
1	10	0.6	0.25	100	4.16	4.193481	-0.03348	-0.804832
2	10	0.9	0.5	200	4.77	4.539494	0.230506	4.8324178
3	10	1.2	0.75	300	4.24	4.470506	-0.23051	-5.43647
4	10	1.5	1	400	4.02	3.986519	0.033481	0.832861
5	30	0.6	0.5	300	3.82	4.047611	-0.22761	-5.958397
6	30	0.9	0.25	400	4.08	4.047484	0.032516	0.7969564
7	30	1.2	1	100	2.52	2.552516	-0.03252	-1.29031
8	30	1.5	0.75	200	4.03	3.802389	0.227611	5.6479097
9	40	0.6	0.75	400	3.75	3.489873	0.260127	6.9367089
10	40	0.9	1	300	2.77	2.77	2.66E-15	9.619E-14
11	40	1.2	0.25	200	3.32	3.32	8.88E-16	2.675E-14
12	40	1.5	0.5	100	3.6	3.860127	-0.26013	-7.225738
13	50	0.6	1	200	3.36	3.522579	-0.16258	-4.838664
14	50	0.9	0.75	100	4.38	4.152389	0.227611	5.1965927
15	50	1.2	0.5	400	3.92	4.147611	-0.22761	-5.806397
16	50	1.5	0.25	300	4.26	4.097421	0.162579	3.8164111

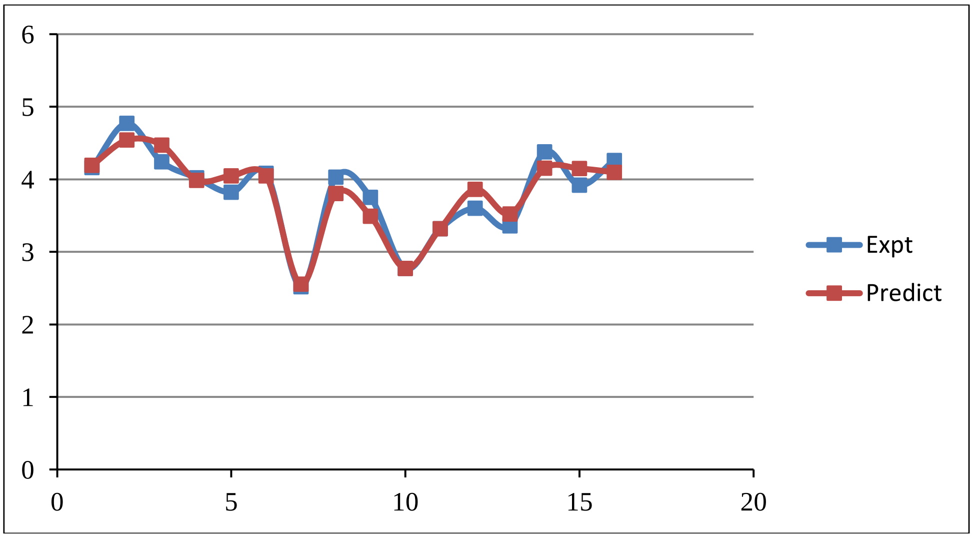

Fig. 9: *Comparison of Experimental and Predicted Values of Surface Roughness (Ra).*

Sliding Wear Behavior in Simulated Body Fluid (Hank's Solution)

Non linear regression equations for mass loss and surface roughness were obtained for sliding wear behavior in simulated body environment (Hank's solution) were shown in Equations 3 and 4 respectively. Experimental values, predicted values and % error of mass loss and surface roughness were listed in Tables 18 and 19 respectively. Comparison of experimental values with predicted values of mass loss and surface roughness were plotted in Figures 10 and 11 respectively.

Mass loss = -0.00382 + 0.000427 Load - 0.001310 Speed + 0.0399 Distance - 0.000082 Thickness
- 0.000008 Load*Load + 0.000799 Speed*Speed - 0.01205 Distance*Distance
+ 0.000000 Thickness*Thickness + 0.000031 Load*Speed - 0.000057 Load*Distance
- 0.000000 Load*Thickness - 0.02119 Speed*Distance + 0.000044 Speed*Thickness
Equation-3

The coefficient of determination (R2) = 99.39%

Table 18: *Experimental, Predicted Values of Mass Loss and Percentage Error for Sliding Wear in Hank's Solution.*

Experiment No.	Load N	Speed m/sec	Distance Km	Thickness µm	Mass loss Gms	Predicted Mass loss gms	Error gms	% Error
1	10	0.6	0.25	100	0.00034	0.000361	-2.1E-05	-6.031273
2	10	0.9	0.5	200	0.00089	0.000819	7.15E-05	8.0334708
3	10	1.2	0.75	300	0.00071	0.000781	-7.1E-05	-10.07013
4	10	1.5	1	400	0.00027	0.000249	2.05E-05	7.5949367
5	30	0.6	0.5	300	0.00094	0.000957	-1.7E-05	-1.857774
6	30	0.9	0.25	400	0.00011	0.000108	2.49E-06	2.2679325
7	30	1.2	1	100	0.00083	0.000832	-2.5E-06	-0.300569
8	30	1.5	0.75	200	0.00053	0.000513	1.75E-05	3.2949208
9	40	0.6	0.75	400	0.00114	0.00112	2E-05	1.7506847
10	40	0.9	1	300	0.00078	0.00078	2.17E-18	2.78E-13
11	40	1.2	0.25	200	0.00053	0.00053	1.08E-18	2.046E-13
12	40	1.5	0.5	100	0.00092	0.00094	-2E-05	-2.169327
13	50	0.6	1	200	0.00147	0.001482	-1.2E-05	-0.848546
14	50	0.9	0.75	100	0.00121	0.001193	1.75E-05	1.4432298
15	50	1.2	0.5	400	0.00075	0.000767	-1.7E-05	-2.328411
16	50	1.5	0.25	300	0.00135	0.001338	1.25E-05	0.9239725

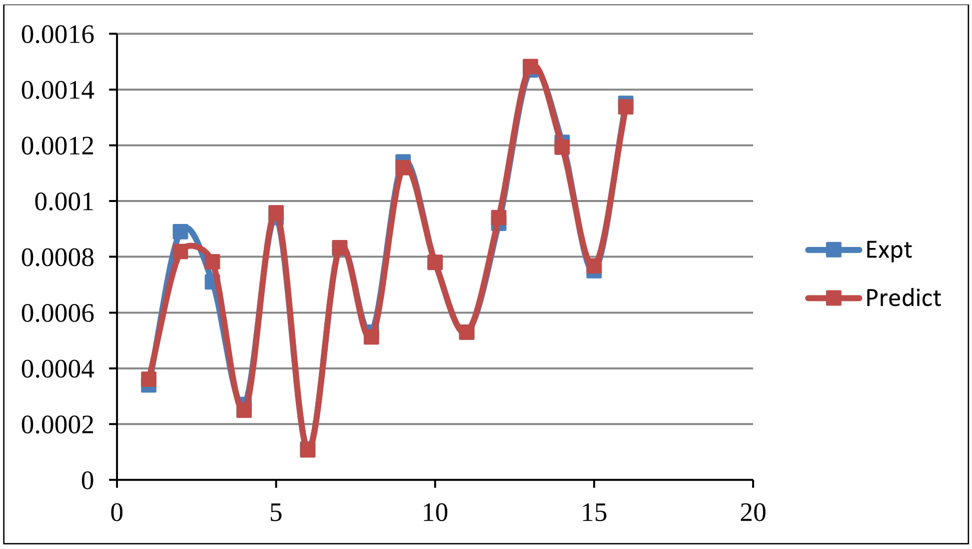

Fig. 10: *Comparison of Experimental and Predicted Values of Mass Loss for Sliding Wear in Hank's Solution.*

Ra = 5.74 - 0.324 Load + 0.38 Speed - 9.8 Distance + 0.0385 Thickness + 0.00454 Load*Load
- 1.132 Speed*Speed + 3.35 Distance*Distance - 0.000021 Thickness*Thickness
+ 0.1008 Load*Speed + 0.0109 Load*Distance - 0.000171 Load*Thickness
+ 5.5 Speed*Distance - 0.0195 Speed*Thickness

Equation-4

The coefficient of determination (R2) = 97.13%

Table 19: *Experimental, Predicted Values of Surface Roughness **(Ra)** and Percentage of Error for Sliding Wear in Hank's Solution.*

Experiment No.	Load N	Speed m/sec	Distance Km	Thickness µm	Ra µm	Predicted Ra µm	Error Ra µm	% Error Ra
1	10	0.6	0.25	100	4.23	4.275348	-0.04535	-1.072059
2	10	0.9	0.5	200	4.87	4.721783	0.148217	3.0434764
3	10	1.2	0.75	300	4.46	4.608217	-0.14822	-3.323258
4	10	1.5	1	400	3.98	3.934652	0.045348	1.1393995
5	30	0.6	0.5	300	4.03	4.051303	-0.0213	-0.528604
6	30	0.9	0.25	400	4.24	4.236957	0.003043	0.0717747
7	30	1.2	1	100	3.75	3.753043	-0.00304	-0.081153
8	30	1.5	0.75	200	3.57	3.548697	0.021303	0.5967155
9	40	0.6	0.75	400	4.18	4.155654	0.024346	0.58244
10	40	0.9	1	300	4.29	4.29	-1.8E-15	-4.14E-14
11	40	1.2	0.25	200	4.01	4.01	0	0
12	40	1.5	0.5	100	4.36	4.384346	-0.02435	-0.558394
13	50	0.6	1	200	3.86	3.875216	-0.01522	-0.394203
14	50	0.9	0.75	100	4.51	4.488697	0.021303	0.4723446
15	50	1.2	0.5	400	4.43	4.451303	-0.0213	-0.480875
16	50	1.5	0.25	300	4.72	4.704784	0.015216	0.3223781

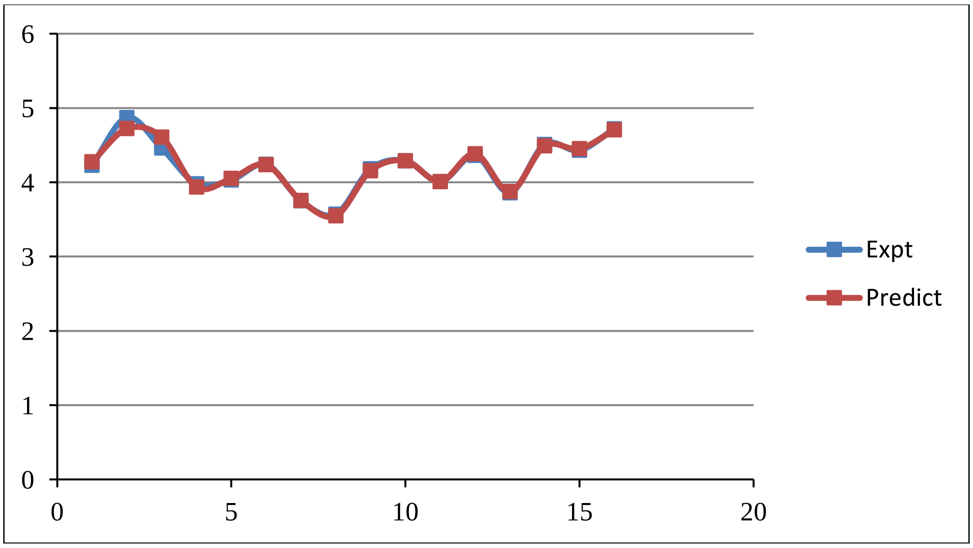

Fig. 11: *Comparison of Experimental and Predicted Values of Surface Roughness **(Ra)** for Sliding Wear in Hank's Solution.*

CONCLUSIONS

This paper has presented the mechanical properties of Ti6Al4V substrate and Cr_3C_2-NiCr coated Ti6Al4V and application of Taguchi method along with grey relational analysis for minimizing mass loss and surface roughness during pin on disc wear test. The following conclusions were drawn based on the experimental results.

- Cr_3C_2-NiCr coating on Ti6Al4V substrate was successfully employed using Detonation spray technique.
- Hardness improved from Ti6Al4V substrate to Cr_3C_2-NiCr coated Ti6Al4V was 25.67 HRC to 59 HRC respectively.
- Ultimate tensile strength improved from Ti6Al4V substrate to Cr_3C_2-NiCr coated Ti6Al4V was 890.940 MPa to 1066.667 MPa respectively.

- Optimum combination of parameters obtained for mass loss and surface roughness in dry sliding wear using grey relational analysis are:
  - **Load:** Level 1, 10 N
  - **Speed:** Level 2, 0.9 m/s
  - **Distance:** Level 4, 1 Km
  - **Thickness:** Level 3, 300 µm
- Optimum combination of parameters obtained for mass loss and surface roughness for sliding wear in Hank's solution using grey relational analysis are:
  - **Load:** Level 2, 30 N
  - **Speed:** Level 4, 1.5 m/s
  - **Distance:** Level 4, 1 Km
  - **Thickness:** Level 4, 400 µm
- ANOVA results highlighted major influencing experimental parameter in dry sliding wear was coating thickness followed by load, speed and distance.
- ANOVA results highlighted major influencing experimental parameter for sliding wear in simulated body environment (Hank's solution) was load followed by, distance, coating thickness and speed.
- Regression modal was developed for Mass loss and surface roughness in dry and wet conditions. Experimental values and predicted values are good in agreement.

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