




## Optimizing PVD Coating Parameters for Ti6Al4V Alloy

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### ABSTRACT

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Among the materials used most often in engineering are titanium alloys, especially Ti6Al4V. This is because Ti6Al4V has more advantageous characteristics. Due to diminished wear properties, Ti6Al4V's applications have been severely constrained. More focus is being paid to strategies including the creation of novel coatings, the advancement of wear resistance materials and the utilization of nanomaterials to enhance wear resistance. In this study, we aim to simulate the phenomenon of contact that occurs between the tool and workpiece during machining process. The main focus of attention of this simulation is to evaluate the COF (coefficient of friction), wear rate for 5 speed and loading conditions. The experiments were conducted on a PVD coated titanium alloy as TiN, TiAlN, TiN+TiAlN for duration of 5 minutes with loads varying from 15 to 25 kg in 1 step increment with disk speeds from 400-900 rpm as Taguchi analysis. After the Ti6Al4V substrate had its surface treated, an X-ray fluorescence test technique was used to integrate a thin layer of nickel coating measured between 40 and 42 micrometres. The coating was applied using thin film PVD magnetron sputtering nitride coatings, and the process was carried out in accordance with ASTM standards.

## 1. INTRODUCTION

Advanced materials that are used in engineering, including metallic alloys, ceramics, and composites, are commonly used in demanding operating conditions, leading to issues such as wear, corrosion, and fatigue. The current scarcity of raw materials and energy resources necessitates proactive measures to mitigate material failures. Titanium (Ti) and its alloys are highly sought-after engineering materials because of their remarkable properties, including a strength-to-weight high ratio, elastic modulus low, anti-magnetic characteristics, excellent compatibility with living organisms, and acceptable resistance to corrosion. Among alloys of titanium, Ti6Al4V has emerged as the most advantageous option since its debut in the early 1950s. Presently, Ti6Al4V alloy finds extensive utilization in industries such as automotive, aerospace, chemical, marine, and biomedical, contributing to nearly 50% of global titanium production.

Despite its favorable qualities, Ti6Al4V (Grade 5) titanium alloy exhibits suboptimal tribological properties characterized by inadequate resistance to wear, reduced hardness and an elevated coefficient of friction. Hence, there is a pressing need to enhance these properties in order to boost the performance of engineering parts and components to prolong their operational lifespan, thereby reducing unexpected failures. In this section provides a thorough comprehensive literature review of titanium alloy and its potential applications in engineering components. Additionally, we delve into Surface Modification Techniques, encompassing coatings like Titanium Aluminum Nitride (TiAlN) coating, Aluminum Chromium Nitride (AlCrN) coating, the use of a Chromium

interlayer to enhance bonding strength and the application of Molybdenum disulphide (MoS<sub>2</sub>) coating. This segment also examines various tribological testing methodologies, including the scratch test, pin-on-disc test, and reciprocating tribometer test.

The Titanium Grade 5 alloy known as Ti6Al4V is mostly used because of its excellent mechanical properties used in joint replacement [1] including those conferred by the surface such as resistance to corrosion and bioactivity it is utilized in dental implants and orthopaedics [2] due to its resistance to corrosion used in marine applications [3] light weight/low density and high strength used for air craft, missile, artillery and dental implants [4] used in medical domain due to its biocompatibility [5]. Titanium alloys which falls into the category of a two phase ( $\alpha$ - $\beta$ ) group contributes 45% to 60% of total titanium products are used in aerospace industry [6]. due to its poor formability and unalienable quality of this titanium alloy forming and machining of these alloys are most important problems in industries today [7]. As Vanadium is an isomorphous and  $\beta$  stabilizer because of this presence in Ti6Al4V it is high thermal stability [8]. As titanium grade 5 alloy is also known that it possesses poor tribological properties [9] which cause in elevated wear rates, a high coefficient of friction and diminished shear resistance.

Ti6Al4V earned its reputation as a premier titanium alloy due to its exceptional properties, distinguishing it from most other existing titanium alloys for various applications have indeed been developed through optimization and enhancements based on Ti6Al4V. As of now, Ti6Al4V continues to be the most widely and successfully utilized titanium alloy, representing roughly 50% of the global

population wide manufacturing titanium alloys [10]. However, it has certain drawbacks, comprising reduced surface hardness, a pronounced coefficient of friction, and limited resistance to abrasive wear. These limitations make it unsuitable for certain engineering conditions, particularly those related to tribology. Consequently, these shortcomings have significantly restricted or even excluded the broader applications of Ti6Al4V in various industries [11]. To date, various surface treatment techniques methods have been employed to enhance the resistance wear of titanium alloys, including ion implantation [12], thermal spraying [13], physical vapor deposition (PVD) [14], and chemical vapor deposition (CVD) [15].

In many researches a variety types of PVD (Physical Vapour Deposition) coatings are employed to curtail wear of titanium grade 5 alloy [16] along with nitride coatings [17] etc. Physical Vapour deposition method is coating vapourisation technique that transforms coating material to the gaseous state by heating electron beam to deposit on the substrate's surface [18]. Physical Vapour Deposition coatings are categorised into two important families traditional resistant to wear coatings the carbides and nitrides include TiN, TiCN, TiAlN, CrN among others which are worthy to increase resistance to coefficient of friction and wear [19]. Because of high hardness nitride and carbide coatings are hard which they play an important role in surface engineering parts for two decades [20]. Wear resistant coatings are Titanium Nitride [21]. Developed in early 1970 [22]. Coating which has high hardness are mostly used for anti-wear applications [23]. Excellent wear resistance and hardness the TiN film coating has also been used for orthopedic prosthesis and cardiac valves [24]. Yoneyama et al [25] demonstrated that an improved corrosion resistance and a consistent corrosion potential could be achieved by TiN and DLC coatings Wang et al. [26] showed a relationship exists between hardness and wear rate. When hardness increases wear decreases. Navinšek et al. [27] showed comparison of PVD process and galvanic that can produce ceramic coatings and metallic. To decrease wear two showed positive results to decrease wear. Fernández-Abia et al. [28] evaluated the effectiveness of the Physical Vapour Deposition (PVD) coated advanced tools for operating turning of difficulty to machine machines.

Endrino et al. [29] discussed the impact of AlCrNbN, AlCrN, AlTiN, TiAlN coating on wear characteristics and lifespan of finishing carbide tools. Ensinger et al. [30] observed the wear and corrosion behavior of PVD coated on Al and stainless steel by sputtering coating with ion beam. Hoche et al. [31] conducted a study into the chemical, structural, and electrochemical properties of TiMgAlN based PVD coating materials were investigated. These coatings were examined for their ability to provide corrosion protection and wear resistance to magnesium alloys. The study revealed that as the magnesium (Mg) content in the coatings was increased there was an enhancement in both mechanical and electrochemical properties. This improvement in properties indicates that TiMgAlN based coatings could be beneficial for applications requiring corrosion protection and wear. Bayón et al. [32] analysed the corrosion and wear behaviour of PVD process of Cr/CrN coatings with various thickness of individual layer deposited on substrates namely steel F1272 and silicon. The deposition was accomplished using the cathode arc methods part of the of PVD (Physical Vapour Deposition) process. It was summarized from the results that the coating of longer bilayer period became the most safety surface under wear- corrosion conditions. Oskouei and

Ibrahim [33] considered the fatigue properties of TiN coated on aluminum alloy 7075-T6 by using Physical Vapour deposition (PVD). From the fatigue test and tensile test, it was found that the coated Al alloy substrate exhibit more reductions in the yield and tensile strength. Gali et al [34] observed several types of Physical Vapour Deposition coatings (TiN, TiCN, TiAlN, CrN, Cr and DLC) were applied to M2 steel rolls and their performances compared with an uncoated roll. Conclusion of results were that, during hot rolling TiAlN coating had lowest Coefficient of Friction, the DLC coating had most minimal COF during cold rolling and highest during hot rolling. Costa et al. [35] observed that Titanium Nitride coating reduced the axial fatigue strength of Ti6Al4V alloy. The effect of Titanium nitride deposited by PVD on the fatigue strength of Ti6Al4V alloy are found.

To improve TiN coatings properties Al is added to give better performance in corrosion and wear [36]. For high-speed machining TiAlN coatings have more resistance to oxidation when compared to TiN [35]. Many studies reported that the best wear resistance is due to the formation of film which is stable Al<sub>2</sub>O<sub>3</sub> on TiAlN coatings [36]. Li et al. [37] suggested that the wear resistance of TiAlN coatings is four times more than that of TiN coatings. During high temperature film of Al<sub>2</sub>O<sub>3</sub> is formed by Al diffusing atoms at the surface preventing further oxidation [38]. Recently many multi layered coatings have been describe to be a promising method for optimizing and enhance performance as well as coating properties [39]. By multilayer coating Tribological properties can be improved [40]. Jensen et al. [41] had shown an example of deposition of multilayered coating of TiN/AlN which in fact improved properties of single layered TiAlN. TiN monolayer deposition by Physical Vapour Deposition has lesser wear properties and mechanical compared to TiN/Ti or TiN/TiCN multilayer [42]. Monolayers exhibit greater brittleness compared to multilayer coatings [43].

According to the literature review, it is found that titanium alloys have great potential for use in engineering mechanisms, techniques for surface modification, and in addition, they demonstrate exceptional corrosion resistance despite their low density. However, the tribological characteristics of titanium alloys made from Ti grade 5 are poor due to their poor resistance to wear, diminished hardness, and elevated coefficient of friction. In order to raise the ensure the longevity of the engineering elements and provide extended service life without any unexpected failures, these attributes must be improved. In order to calculate the COF (coefficient of friction) and wear rate, it was chosen to mimic the contact phenomena between the workpiece and the tool during milling using TiN, TiAlN, and TiN+TiAlN thin film coatings.

## 2. EXPERIMENTAL WORK

### 2.1 Test method

Pin-on-disk was used with standard test procedure to measure wear and CoF. The system's wear rate will depend on factors including the load applied, operating speed, environment circumstances, sliding distance, and material properties need to be considered both with and without coating.

However, it's important to note that the pin-on-disk test method is unable to reproduce all the conditions encountered during actual service. This includes factors such as lubrication, contact pressure, the geometry of contact surfaces, removal of

wear debris, and existence of corrosive environments.

## 2.2 Coating deposition and characterization

The cylindrical pin substrates were cleaned in ultrasonic bath using acetone prior to the TiN, TiAlN, TiN+TiAlN deposition. Before PVD nitride coatings were applied to Ti6Al4V alloy rods, they were chopped into 10-millimeter diameter and 30-millimeter length sections. Before coating, surface treatments should be made in order to sustain coating. While wear test is being conducted i.e., surface roughness should be Ra should be less than 0.08 microns in coatings company (Orelikon blazers ltd). When using blasting alone, surface roughness was not up to the mark when we tested for wear with 20N load. Hence, the coatings did not sustain. In this work, the substrate undergone process such as grinding, polishing with diamond paste, and polishing with papers to attain surface roughness 0.08 microns. Hence, the coating will be sustained more effectively.

## 2.3 Experimental setup

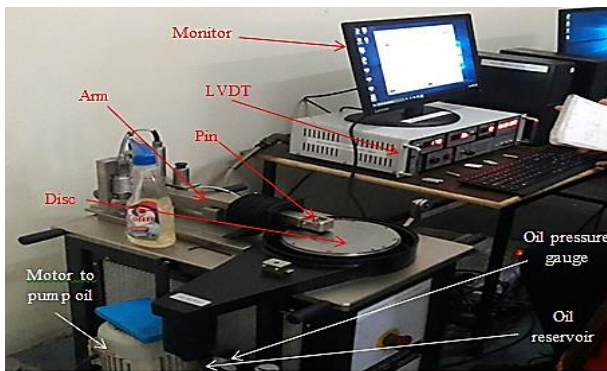


Figure 1. Experimental setup

The revolving disk and pin are the two essential components of the pin on disk machine (Figure 1). To measure the wear and frictional force, a load cell and LVDT are attached pin-on-disk. In order to prevent shaking from affecting the test, a motor was utilized to rotate the disc at various speeds. The holder for the specimen is linked to a lever arm that features a pivot point. In the testing process cylindrical pin samples were utilized. In this setup, the disk material is EN-31, and the pin undergoes wear as it is pressed against the rotating disk through the application of a dead-weight load. The system is equipped with a controller, data acquisition system, and WINDUCOM 2010 software. Tribological characteristics are assessed using pin on disk apparatus to assess different gear materials while subjecting to varying loading conditions. The force of friction generated between the pin and disk is measured using a load cell.

The pin under examination is securely positioned within a pin holder and brought into contact with disc, as illustrated in Figure 2. A fixed wear track of 50 mm is established simulate the application. The rotational speed of the disk is adjusted within the range of 500 to 700 rpm, with each trail lasting 5 minutes. The load applied to the pin is varied at 15 N, 20 N and 25 N, respectively. All the specimens, each having a diameter of 10 mm and length 30 mm, undergo testing on the pin on disk machine. The results are directly displayed on a digital readout.

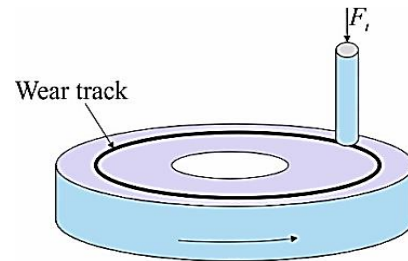


Figure 2. Diagram illustrating the pin-on-disk apparatus

## 3. TAGUCHI METHOD AND DOE

### 3.1 Taguchi method

Design of experiments (DOE) is a systematic structured approach for studying conditions responsible variable changes based on one or more independent parameters. This method involves considering multiple factors in the experimentation process, and it includes the following key aspects:

- Planning the test so that appropriate data can be analyzed.
- Set and establish the best or the optimum condition.
- Evaluate the influence of individual factors.

DOE and the statistical analysis aspects of any experimental problem are required to consider. In this study, it's crucial to identify the key factors that require special attention for the purpose of either controlling or optimizing the system's performance. The Taguchi's L9 orthogonal array is employed, featuring 3 parameters each with 3 levels. For each experiment, three quality characteristics are measured. The analysis of the experimental results to achieve the following objectives:

- The primary goal is to establish the optimal operating conditions through Signal to Noise Ratio (SNR) analysis.
- The study seeks to evaluate the impact of individual parameters to identify the most dominant ones. This assessment is carried out using Analysis of Variance (ANOVA).
- Linear regression analysis is applied to investigate the relationship between two characteristics across the three parameters.

These objectives are crucial for understanding and enhancing the performance of the system under investigation.

As per the orthogonal array the experiment is performed, and the outcomes for some combinations were obtained. The commercial software MINITAB 17, which is primarily used in DOE applications, was used to analyse the measured results. To gauge the qualities, the experimental numbers are converted into a S/N (Signal-to-Noise) ratio. S/N ratio responses has been used to analyse the impact of control factors such as load, sliding speed, and distance on wear rate. The response tables provide the ranking of process parameters using S/R ratios obtained from wear rate. Experimental observations were further transformed into S/N ratios, which were calculated as a logarithmic transformation of loss function.

For higher desirability:

$$S/N(\eta) = -10 \log_{10} \left[ \frac{1}{n} \sum y^2 \right] \quad (1)$$

For lower desirability:

$$S/N(\eta) = -10 \log_{10} \left[ \frac{1}{n} \sum y^2 \right] \quad (2)$$

where ‘n’ is the number of observations and ‘y’ is the observed data.

### 3.2 Process parameters levels

**Table 1.** Factors and their levels wear test

S. No.	Input Parameters	Levels		
1	Load (N)	15	20	25
2	Speed(rpm)	500	600	700
3	Time	5	5	5

**Table 2.** Taguchi’s L<sub>9</sub> orthogonal array design

Experiment No.	Parameters and Their Levels		
	Load	Speed	Time
1	15	500	5
2	15	600	5
3	15	700	5
4	20	500	5
5	20	600	5
6	20	700	5
7	25	500	5
8	25	600	5
9	25	700	5

DOE is performed using Taguchi analysis. Table 1 shows the considered parameters and their levels. Table 2 presents Taguchi orthogonal L<sub>9</sub> (3<sup>2</sup>) arrays for experimental designs with 9 experiments.

## 4. RESULTS AND DISCUSSIONS

The L<sub>9</sub> (3<sup>2</sup>) orthogonal array for wear rate, which is provided in Tables 1-2 was used as the basis for the analysis. Here, various load, sliding speed, and time characteristics are taken into account. The weight loss resulting due to pin wear

is noted by estimating the difference between the weight before and after test. To obtain the lowest wear rate, the experimental design aims to identify the dominating parameters and their interactions. The tests were created using an orthogonal array with the goal of establishing a relationship between the impacts of sliding speed (rpm) and load (N) for the wear test.

### 4.1 Influence on wear, speed and weight

The load is a major influencing parameter on the wear rate, tailed by sliding speed and load, and it has been observed that the control parameters are statistically significant in the S/N ratio. The graphical representation of how process parameters affect wear rate and coefficient of friction is shown in Figures 3 and 4. The optimal circumstances resulting in the minimal rate of wear and friction coefficient are determined by the analysis of these testing findings using S/N ratio.

### 4.2 Signal-to-Noise ratio analysis

The quadratic (quality) loss function is used to express the S/N ratios in a decibel scale. The Signal-to-Noise ratios are obtained for each experiment. Table 3 shows measured values of Signal-to-Noise ratios. The term “signal” represents the mean value, while “noise” represents the undesirable variance in the output response of the process. This technique aims to identify the factors that can be controllable to minimize the impact of uncontrollable (noise) factors on the response. The factors selected based on the highest Signal-to-Noise ratio are expected to deliver optimal quality with minimal variance. Tables 4-6 provide the S/N response table for Signal-to-Noise ratios, and the response table for means. Experiments were conducted following the specified orthogonal array (OA) in Table 2, and resulting output response values and Signal-to-Noise ratios are summarised in Table 3.

**Table 3.** Output response and S/N ratios

S.No.	TIN			TIAIN			TIN+ TIAIN		
	S/N RATIO	Predicted Value	Fitted Value	S/N RATIO	Predicted Value	Fitted Value	S/N RATIO	Predicted Value	Fitted Value
1	-17.26	24.19	21.5	-20.38	24.6229	15.5	-20.39	27.59	26.39
2	-17.21	27.3	24.66667	-20.47	26.0876	20.33333	-20.2	30.505	28.22
3	-17.44	28.68	27.83333	-20.46	31.5817	25.16667	-19.81	32.561	30.06
4	-17.54	29.44	28.5	-20.62	28.6233	28.5	-20.3	30.416	38.06
5	-17.57	32.56	31.66667	-20.43	30.0879	33.33333	-20.15	33.330	39.89
6	-17.31	33.94	34.83333	-20.22	35.5821	38.16667	-20.37	35.386	41.72
7	-17.2	26.14	35.5	-20.21	26.5071	41.5	-20.66	27.724	49.72
8	-17.4	29.25	38.66667	-20.21	27.9718	46.33333	-20.3	30.638	51.56
9	-17.61	30.63	41.83333		33.466	51.16667	-20.31	32.694	53.39

**Table 4.** Response to S/N ratios (difference in weight)

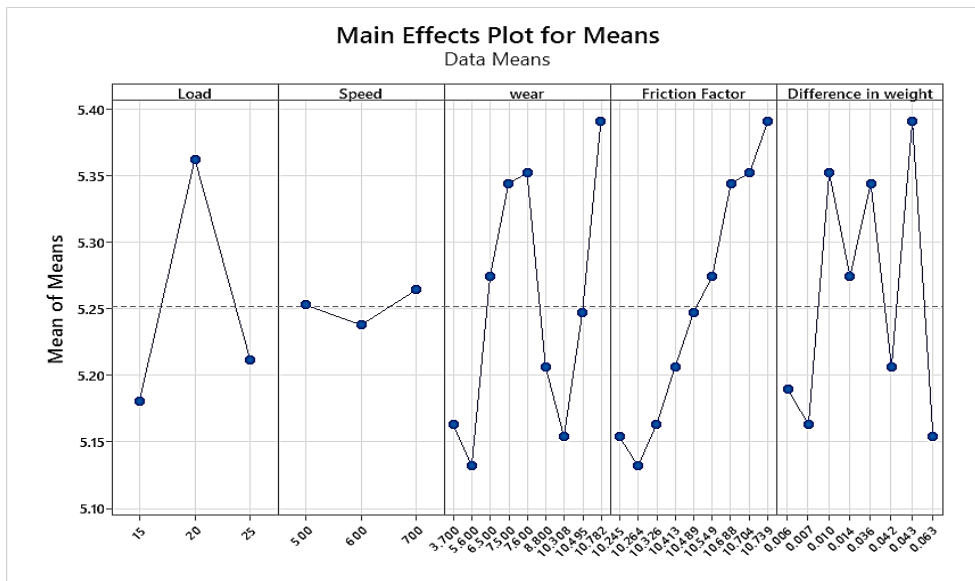
Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	-17.29	-17.41	-17.26	-17.20	-17.31
2	-17.57	-17.37	-17.21	-17.21	-17.26
3	-17.32	-17.40	-17.44	-17.26	-17.57
4			-17.54	-17.31	-17.44
5			-17.57	-17.40	-17.54
6			-17.31	-17.44	-17.31
7			-17.20	-17.54	-17.61
8			-17.40	-17.57	-17.20
9			-17.61	-17.61	
Delta	0.28	0.04	0.41	0.41	0.41
Rank	4	5	2	2	2

**Table 5.** Responses for means

Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	5.181	5.253	5.163	5.154	5.190
2	5.362	5.238	5.132	5.132	5.163
3	5.212	5.264	5.274	5.163	5.352
4			5.344	5.207	5.274
5			5.352	5.248	5.344
6			5.207	5.274	5.207
7			5.154	5.344	5.391
8			5.248	5.352	5.154
9			5.391	5.391	
Delta	0.181	0.026	0.259	0.259	0.237
Rank	4	5	1.5	1.5	3

**Table 6.** Responses for fitted value and residual value

S.No.	Load	Speed	Time	Wear	Friction Factor	Weight Before Wear	Weight After Wear	Difference in Weight	SNRA1	MEAN1	FITS	RESI
1	15	500	5	29	0.5	10.262	10.258	0.004	21.58362	29	21.5	7.5
2	20	500	5	34	1.8	10.065	10.06	0.005	28.94316	34	24.66667	9.333333
3	25	500	5	56	5.6	10.264	10.258	0.006	29.24796	56	27.83333	28.16666
4	15	600	5	40	7.6	10.704	10.694	0.01	30.62958	40	28.5	11.5
5	20	600	5	46	6.5	10.549	10.535	0.014	34.96376	46	31.66667	14.33333
6	25	600	5	62	0.7	10.456	10.532	-0.076	23.52183	62	34.83333	-27.16667
7	15	700	5	49	2.1	10.257	10.253	0.004	27.9588	49	35.5	13.5
8	20	700	5	74	3.7	10.326	10.319	0.007	32.0412	74	38.66667	35.33333
9	25	700	5	88	7.5	10.688	10.652	0.036	33.25516	88	41.83333	46.16666



**Figure 3.** Main effects for means

Table 3 presents the S/N ratio, predicted value and fitted value of TIN, TIAIN and TIN+TIAIN. From Table 3, it is observed that the predicted and fitted value of TIN+TIAIN shows a closed match and fitted value of TIN+TIAIN is optimized. Figure 3 displays the S/N ratios and reaction for each factor against each of its levels under the smaller-is-better condition for wear.

The results of the analysis led to the conclusion that when the levels of the parameters grow, the mean amount of material lost to abrasion and wear increases. When the load, speed, and time increased (A, B, and C), the wear loss rises practically linearly. Factors A, B, and C have a substantial impact on wear minimization; their combination, A1, B1, and C1, results in the least amount of wear.

### 4.3 TIN Coating

#### 4.3.1 Optimal combination of wear, speed and weight difference

For improving the tribological behaviour of grade5 titanium alloy coated with TiN coating the response is based on smaller is better. The optimization parameters criterion is based on the smaller is better S/N ratios from Figure 3 Optimal combinations for load 25N and speed 500rpm level 7. The ratio of frictional force to the normal load was improved based on smaller is better response. The optimization parameters criterion is based on better is small for S/N ratios from Figure 3 Optimal combinations at Load 15N and 500 rpm. Weight before wear and weight after wear was based on the smaller is better. The optimization parameters are based on smaller is better for S/N ratios from Figure 3 Optimal combinations are 20N and 700rpm.

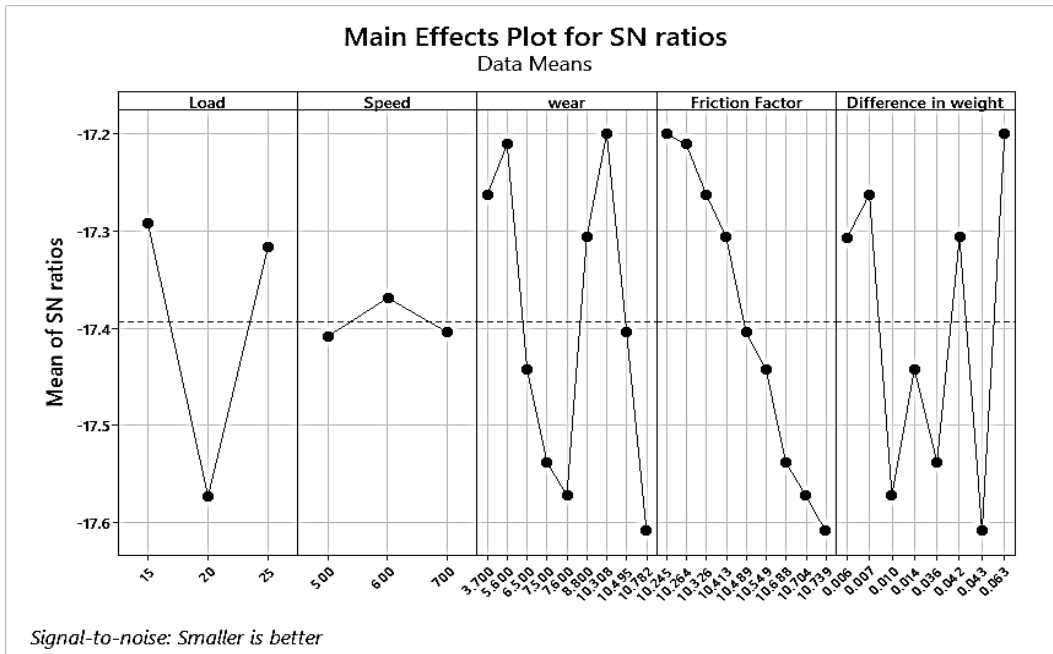


Figure 4. Main effects plot for S/N ratios

#### 4.3.2 Multiple linear regression models

Using the statistics programmer MINITAB 17, numerous linear regression models have been developed for two important: the rate of wear and the frictional coefficient. These models utilise linear equations to assess the relationship between and independent or predictor variable. By applying the model to the collected data, it becomes possible to determine the relationship among the significant factors pinpointed in the ANOVA analysis, specifically the applied load and sliding speed. This equation aids in understanding how these factors influence the wear rate and coefficient of friction.

$$\text{wear} = -7.84 + 0.194 \text{ Load} + 0.01981 \text{ Speed}$$

$$\text{Friction Factor} = 10.449 + 0.0043 \text{ Load} - 0.000073 \text{ Speed}$$

$$\text{Weight after wear} = -27.80 + 0.007 \text{ Load} + 0.0524 \text{ Speed}$$

The relationship between the rate of wear and the coefficient of friction concerning the load (L) is observed to be positive based on the regression equations. This suggests that as there is an increase in load and speed, the wear rate of the composite also increases. Additionally, sliding speed is negatively correlated with the equation, indicating that as speed increases, both the rate of wear and friction decrease. The coefficient of friction related to speed has been found to be negatively correlated with the equation, indicating that friction is increasing with decreasing speed. Wear rate and friction are directly inversely correlated with applied load, meaning that as the load increases, so do the wear rate and coefficient of friction. The wear rate and the coefficient of friction decrease with increasing sliding speed.

Table 7. Model summary (wear)

S	R-sq	R-sq (adj)	R-sq (pred)
1.71321	62.36%	49.81%	18.69%

Table 8. Model summary (coefficient of friction)

S	R-sq	R-sq (adj)	R-sq (pred)
0.220360	1.04%	0.00%	0.00%

Table 9. Model summary (weight after wear)

S	R-sq	R-sq (adj)	R-sq (pred)
13.01822	75.09%	66.79%	49.01%

Tables 7-9 indicate that weight after wear is dependent on load and speed. In analysis, wear is 75.09% dependent on speed and load. We analyse that weight after wear is most affected by load and speed in comparison to wear, and the coefficient of friction. Tables 7-9 indicate that wear and the coefficient of friction are dependent on load and speed. In analysis, wear is 62.36% dependent on speed and load, although the coefficient of friction is only 1.04% dependent on load and speed.

#### 4.3.3 Analysis of variance (ANOVA)

The load applied, speed of sliding, and wear, weight after wear parameters—which exert a notable influence on the performance measures—were examined using ANOVA to analyse the experimental data. ANOVA allows for the identification of the independent variable that predominates over the others as well as the percentage contribution of that particular independent variable. The ANOVA outcomes for wear rate and coefficient of friction involve assessing three components altered at three levels, as well as interactions of those factors, as displayed in Tables 10-11. The analysis is carried out with a 95% confidence level and a significance level of  $\alpha = 0.05$ . Sources were considered to have a significant impact on the performance metrics when their P-value was below 0.05.

Table 10. Analysis of variance (wear)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	29.174	14.587	4.97	0.053
Load	1	5.632	5.632	1.92	0.015
Speed	1	23.542	23.542	8.02	0.030
Error	6	17.611	2.935		
Total	8	46.785			

The results of the analysis of variance (ANOVA) indicate that load and speed have the most significant influence on

both coefficient of friction and wear rate. Therefore, throughout the wear process, load is a crucial control component to be taken into account, followed by sliding speed. However, the impact of relationships between load and sliding speed is quite limited. For wear rate and coefficient of friction, the pooled errors included in the ANOVA table were less than 5%. So there is a significant relationship between load and speed because its value (P value) is less than 0.05.

**Table 11.** Analysis of variance (Weight after wear)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	164.784	82.392	9.04	0.015
Load	1	0.007	0.007	0.00	0.049
Speed	1	164.777	164.777	18.09	0.005
Error	6	54.658	9.110		
Total	8	219.442			

#### 4.4 TiAlN coating

For DOE the parameters and levels are listed in Table 12.

##### 4.4.1 Optimal combination of wear, speed and weight difference

To improve the tribological behaviour of grade 5 titanium alloy coated with TiAlN coating the response are based on smaller is better. The optimization parameters criterion is based on the smaller is better S/N ratios in Tables 13-14. From Figures 5 and 6 optimal combinations for load 25N and speed 500rpm level 7 and also 25N 600rpm level 8. The ratio of frictional force to the normal load was improved based on smaller is better response. The optimization parameters criterion is based on better is small for S/N ratios from Figures 5 and 6 optimal combinations at load 25N ,500 rpm level 7 and 25N 700rpm level 9. Weight before wear and weight after wear was based on the smaller is better. The optimization parameters are based on smaller is better for S/N ratios from Figures 5 and 6 optimal combinations are 25N load, speed 500rpm level 7 and 25N load, speed 700rpm level 9.

The load has substantial impact on the wear rate, while sliding speed also holds a significant role. It's worth mentioning that the control parameters demonstrated statistical significance in the Signal-to-Noise ratio analysis. The graphic representation of how process parameters affect the coefficient of friction and wear rate is shown in Figures 5 and 6. The analysis of these results using the S/N ratio enables the identification of the optimal conditions where both minimal wear rate and coefficient of friction are achieved.

**Table 12.** Design of experiment

S. No.	Load	Speed	Wear	FrictionFactor	Weigh Before Wear	Weight After Wear	Difference in Weight	SNRA1	STDE1	MEAN1
1	15	500	30	5.7	10.455	10.441	0.014	-20.3807	0.009899	10.448
2	20	500	31	1.9	10.562	10.539	0.023	-20.4655	0.016263	10.5505
3	25	500	40	5.1	10.562	10.526	0.036	-20.4601	0.025456	10.544
4	15	600	48	2.5	10.743	10.727	0.016	-20.616	0.011314	10.735
5	20	600	64	4.3	10.448	10.427	0.021	-20.3719	0.014849	10.4375
6	25	600	95	6.5	10.265	10.23	0.035	-20.2124	0.024749	10.2475
7	15	700	75	4.1	10.257	10.248	0.009	-20.2166	0.006364	10.2525
8	20	700	64	7.4	10.575	10.56	0.015	-20.4794	0.010607	10.5675
9	25	700	76	7.8	10.264	10.223	0.041	-20.209	0.028991	10.2435

**Table 13.** Signal to noise ratios

Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	-20.40	-20.44	-20.38	-20.47	-20.22
2	-20.44	-20.40	-20.47	-20.62	-20.38
3	-20.29	-20.30	-20.46	-20.22	-20.48
4			-20.62	-20.37	-20.62
5			-20.43	-20.46	-20.37
6			-20.22	-20.38	-20.47
7			-20.21	-20.21	-20.21
8			-20.21	-20.48	-20.46
9				-20.21	-20.21
Delta	0.15	0.13	0.41	0.41	0.41
Rank	4	5	2	2	2

**Table 14.** Response table for means

Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	10.48	10.51	10.45	10.55	10.25
2	10.52	10.47	10.55	10.73	10.45
3	10.35	10.35	10.54	10.25	10.57
4			10.73	10.44	10.73
5			10.50	10.54	10.44
6			10.25	10.45	10.55
7			10.24	10.25	10.25
8			10.25	10.57	10.54
9				10.24	10.24
Delta	0.17	0.16	0.49	0.49	0.49
Rank	4	5	2	2	2

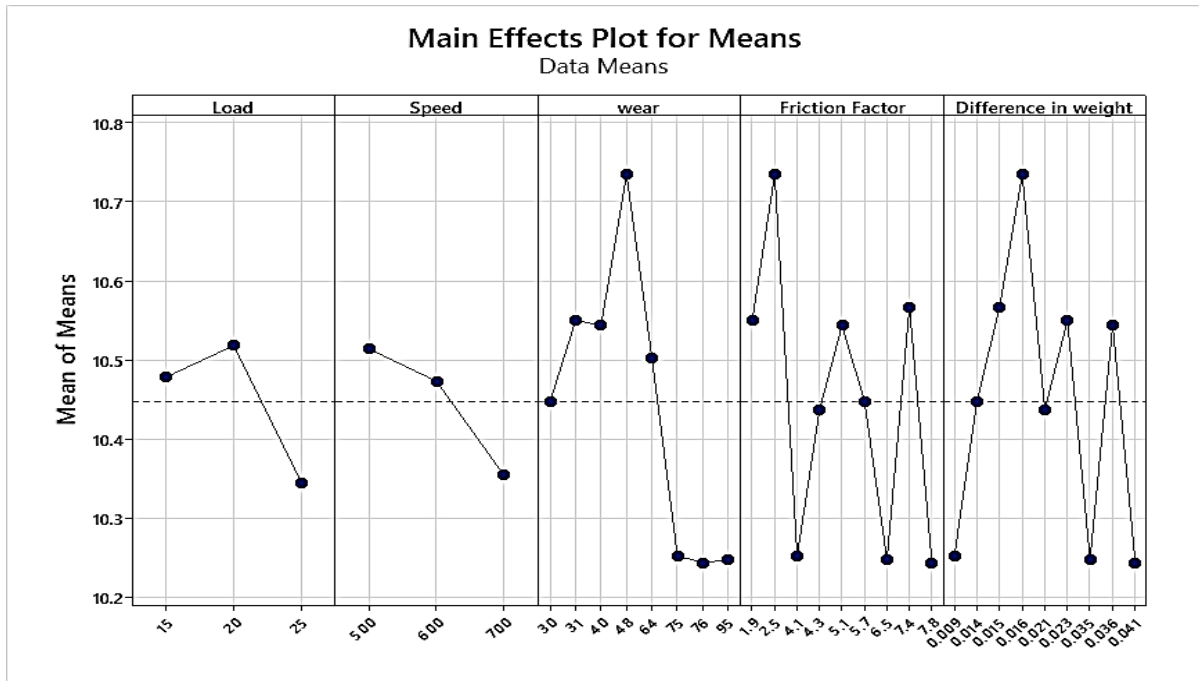


Figure 5. Main effects for means

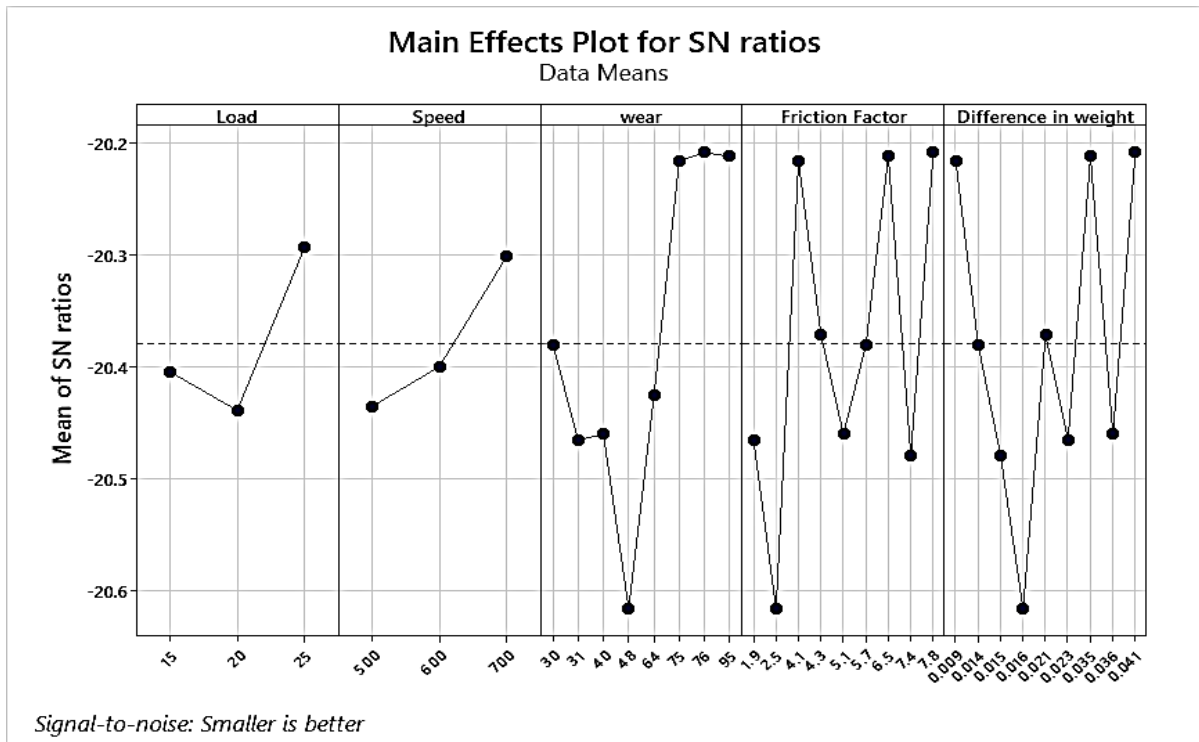


Figure 6. Main plot for S/N ratio

#### 4.5 Duplex TiN+TiAlN coating

##### 4.5.1 Parameters and their levels

For the design of experiments the parameter and levels are in Table 15.

##### 4.5.2 Optimal combination of wear, speed and weight difference

To improve the tribological behaviour of grade5 titanium alloy coated with TiN +TiAlN coating the response are based on smaller is better. The optimization parameters criterion is based on the smaller is better S/N ratios. Figures 7-8 and

Tables 16-17 show the main effects pots for means and S/N ratios for optimal combinations for load 15 N and speed 700 rpm level 3. The ratio of frictional force to the normal load was improved based on smaller is better response. The optimization parameters criterion is based on better is small for S/N ratios from. Figures 7-8 for optimal combinations at Load 15N, 700 rpm level 3. Weight before wear and weight after wear was based on the smaller is better. The optimization parameters are based on smaller is better for S/N ratios from Figures 7-8 Optimal combinations are 15Nload, speed 500rpm level 1.



Table 15. Parameters and their levels

S. No.	Load	Speed	Wear	Friction Factor	Weight Before Wear	Weight After Wear	Difference in Weight	SNRA1	STDE1	MEAN1
1	15	500	27	1.9	10.471	10.449	0.022	-20.3906	0.015556	10.46
2	20	500	32	3.8	10.251	10.226	0.025	-20.2047	0.017678	10.2385
3	25	500	54	8.6	10.806	10.78	0.026	-20.6628	0.018385	10.793
4	15	600	33	2.6	9.788	9.777	0.011	-19.809	0.007778	9.7825
5	20	600	44	0.4	10.182	10.161	0.021	-20.1477	0.014849	10.1715
6	25	600	56	6.7	10.364	10.343	0.021	-20.3017	0.014849	10.3535
7	15	700	35	3.2	10.363	10.33	0.033	-20.2959	0.023335	10.3465
8	20	700	48	5.3	10.468	10.413	0.055	-20.3745	0.038891	10.4405
9	25	700	58	6.9	10.394	10.325	0.069	-20.3068	0.04879	10.3595

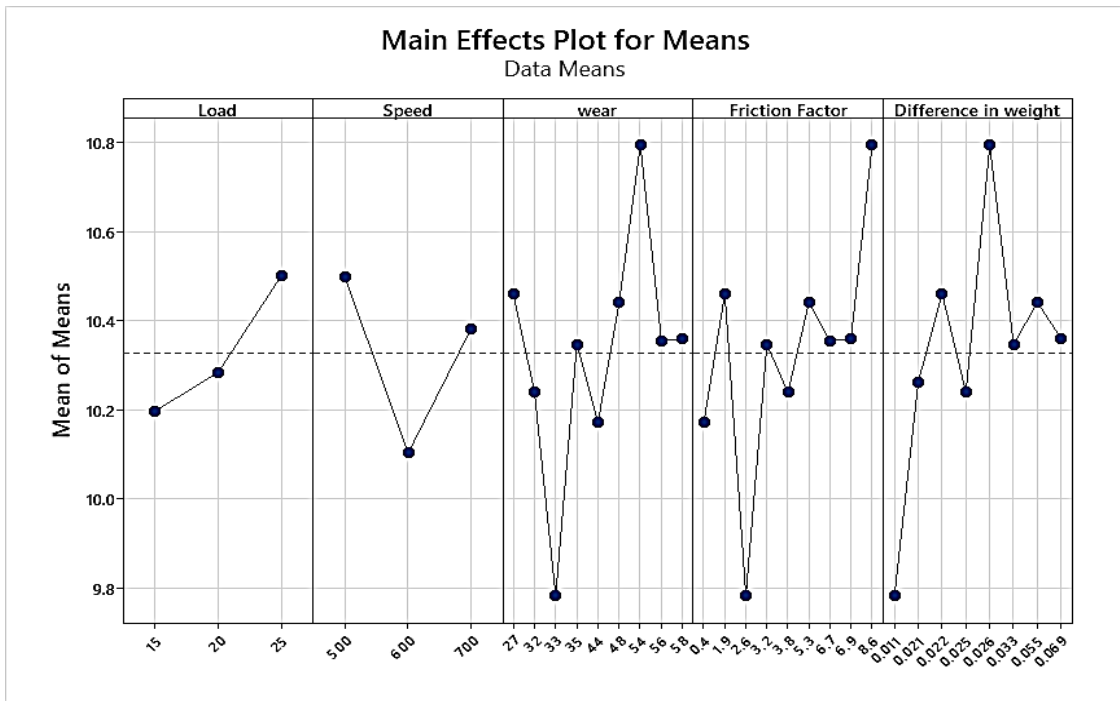


Figure 7. Main effects pots for means

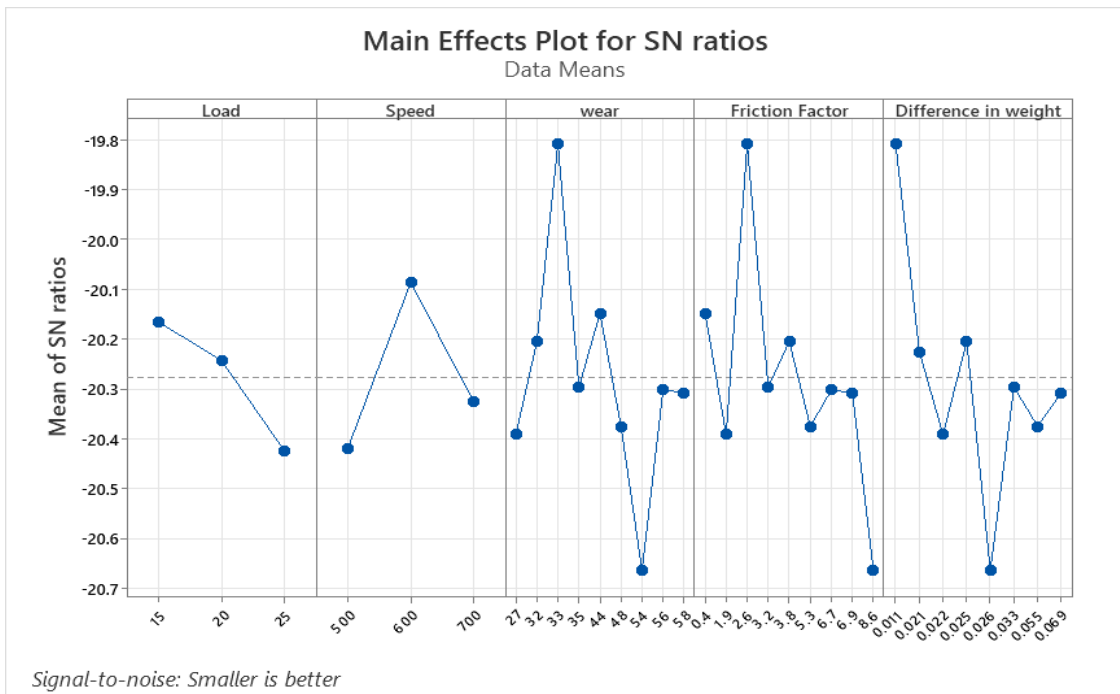


Figure 8. Graphical representation of main effects using S/N ratios

**Table 16.** Responses for signal to noise ratios

Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	-20.17	-20.42	-20.39	-20.15	-19.81
2	-20.24	-20.09	-20.20	-20.39	-20.22
3	-20.42	-20.33	-19.81	-19.81	-20.39
4			-20.30	-20.30	-20.20
5			-20.15	-20.20	-20.66
6			-20.37	-20.37	-20.30
7			-20.66	-20.30	-20.37
8			-20.30	-20.31	-20.31
9			-20.31	-20.66	
Delta	0.26	0.33	0.85	0.85	0.85
Rank	5	4	2	2	2

**Table 17.** Responses for means

Level	Load	Speed	Wear	Friction Factor	Difference in Weight
1	10.196	10.497	10.460	10.171	9.782
2	10.284	10.103	10.239	10.460	10.262
3	10.502	10.382	9.782	9.782	10.460
4			10.346	10.346	10.239
5			10.171	10.239	10.793
6			10.441	10.441	10.346
7			10.793	10.354	10.441
8			10.354	10.360	10.360
9			10.360	10.793	
Delta	0.306	0.395	1.011	1.011	1.011

The rate of wear is significantly impact by the load, followed by sliding speed and these control parameters have been observed to be statistical significance within the context of the Signal to Noise ratio analysis. Figures 7-8 illustrate the graphic representation of how process parameters impact wear rate and coefficient of friction. The optimal circumstances resulting in the most minimal wear rate and friction coefficient are determined by the analyzing the test results outcomes through the analysis of the Signal-to-Noise (S/N) ratio.

## 5. CONCLUSION

In order to calculate the coefficient of friction (COF) and wear rate were evaluated across different speed and loading conditions, the primary objective of the study aimed to explore and examine the contact phenomena between the work piece and tool utilized during machining. the goal was attained with the aid of thorough experimental and statistical analysis. Following observations are obtained from experimental and statistical analyses.

- Taguchi method's parameter design offers a straightforward, organized, and effective process for improving wear test parameters.
- The particular wear rate is significantly influenced by the material type, sliding speed and load.
- It was possible to calculate the estimated S/N ratio for particular wear rate using the best testing parameters, and with a confidence level of 99%, a strong correlation was observed between the predicted and real specific wear rates.
- Thus, it can be seen that the load and the sliding speed are the most important aspect in the case of the wear. TiN +TiAlN content was the maximum important material among all the others.

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