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Evaluation of surface Roughness and hardness of PVD coated AISI D2 Steel by taguchi analysis

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Abstract **–** The enhancement of AISI D2 tool steel's surface properties through the application of Titanium Nitride (TiN) coating using the Physical Vapor Deposition (PVD) process. AISI D2 steel, widely used in the die and tool manufacturing industries, is known for its exceptional wear resistance and high hardenability. However, to further improve its hardness and reduce surface roughness, PVD TiN coating was applied. The study utilized Taguchi analysis to systematically investigate the effects of key process parameters—temperature, pressure, and time—on the hardness and surface roughness of the coated material. Rectangular AISI D2 steel plates were ground and polished before coating, with variable levels of temperature (275°C, 280°C, 285°C), pressure (0.0001 Pa, 0.001 Pa, 0.01 Pa), and time (6 min, 8 min, 10 min) used during the coating process. The results indicated that temperature had the most significant effect on both hardness and surface roughness, followed by time and pressure. The optimal conditions for achieving maximum hardness (174 HV) and minimum surface roughness (2.177 µm) were found at a temperature of 285°C, pressure of 0.001 Pa, and coating time of 10 minutes. Regression analysis and ANOVA confirmed the substantial influence of temperature and time on coating quality, with pressure playing a comparatively minor role. The findings demonstrate the critical importance of precise control over PVD parameters to optimize the performance of coated AISI D2 steel, providing valuable insights for industrial applications where enhanced tool performance and longevity are essential.

Keywords – Physical Vapor Deposition, Die D2 Steel, Titanium Nitride, Taguchi Analysis, Coating Parameters, Hardness, Surface Roughness.

I. INTRODUCTION

Physical Vapor Deposition (PVD) is extensively used for applying thin films to meet a variety of needs, such as enhancing tribological properties, improving optical performance, upgrading appearance, and more. This technology is highly adaptable, enabling continuous variation in coating characteristics throughout the film. PVD also allows for the deposition of alloy compounds, multilayer structures, and specialized configurations.

In PVD, the material to be deposited, referred to as the target, is converted into atomic particles through a thermal physical collision process. These particles are then directed toward the substrates in a vacuum or low-pressure gaseous plasma environment, where they condense to form a physical coating. [1]
AISI D2 tool steel is a renowned die steel, extensively utilized in the die and tool manufacturing industries due to its exceptional wear resistance, good hardenability, and high resistance to softening. Recently, the automotive industry's demand for this type of steel has increased due to its high strength-to-weight ratio compared to other materials. The microstructure of AISI D2 plays a crucial role in determining its wear properties.
TiN coating applied by the PVD process is widely recognized and has gained significant attention in engineering applications [2].This is due to its combination of high hardness, excellent wear resistance, chemical inertness, and low coefficient of friction. The study focuses on providing suitable solution to the mentioned issues by utilizing Taguchi analysis[3].

II. MATERIALS AND METHOD

The workpiece material chosen for this application is AISI D2 Die steel, which is widely utilized in the mould and die industries due to its common usage and favourable properties. The workpiece itself takes the form of a rectangular plate measuring 140mm by 50mm with a thickness of 10mm. (30)The chemical composition of AISI D2 Die steel is given Table 1 below

Table 1 chemical compositon

Material	C	Si	Mn	Mo	V	Cr	S	P
Composition in (wt%)	1.5	0.3	0.3	0.3	0.27	0.12	0.03	0.03

To enhance the surface properties and mitigate any porosities, a Physical Vapor Deposition (PVD) TiN coating was administered onto the fabricated components. This coating process aims to decrease surface roughness and also increase hardness of a material [4].
Initially I take AISI D2 Die Steel plates 80.29mm *48.59mm whose thickness is 22.64mm as shown in Fig. 1 below

Fig. 1 Die D2 Steel plate

The coating is applied on smooth surface but the material is so rough which is observed by biological microscope as shown in *Fig. 2* below

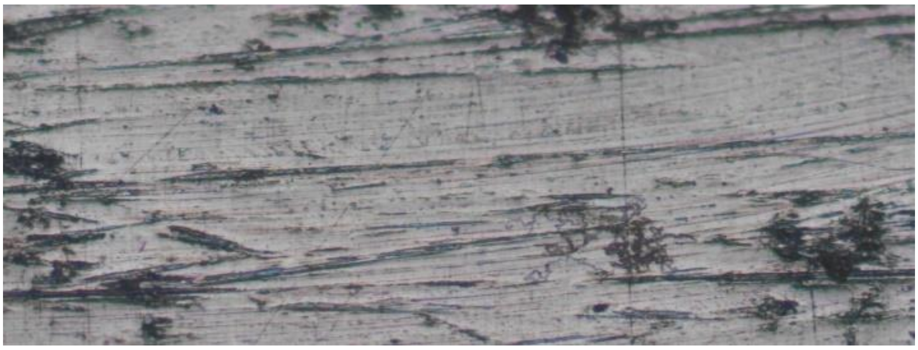

Fig. 2 Micro structure of Die D2 Steel

For good surface finish I used grinding machine then I grind the surface of plates after grinding I used different ampere P1000, P12000, P15000, P2000,P2500 for proper smooth surface then I used water paper for better surface finish these ampere paper are used to remove any Roughness of material after surface finish my material is ready for coating as shown in figure.

A. Variable Selection

In order to attain optimal coating quality, it's imperative to regulate all pertinent performance metrics or output variables. This can only be accomplished by managing the primary factors or input variables that exert the greatest influence on performance. Thus, the focus will be on identifying the most influential variables for the current study or research.

Table 2 Levels and Input parameters

Input Parameter	Level 1	Level 2	Level 3
Temperature(C)	275	280	285
Pressure (Pa)	0.0001	0.001	0.01
Time (min)	6	8	10

B. Experimentation

After preparing the steel surface to ensure proper adhesion. The plates are then placed in a vacuum chamber, where titanium and nickel are vaporized and deposited onto the steel surface. The deposition occurs at controlled temperatures to ensure a uniform and adherent coating. Finally, the coated plates are cooled and removed from the chamber for analysis. The coated plates of Die D2 is Shown in Fig. 3 below.

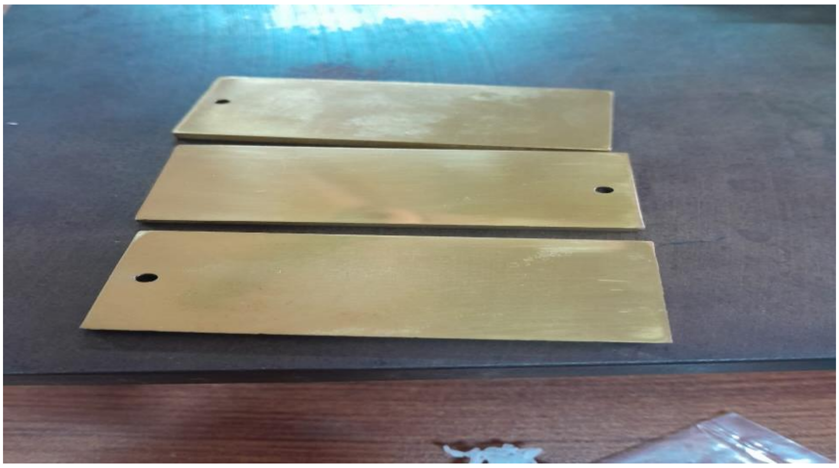

Fig. 3 coated Die D2 Steel plates

After coating, the hardness of the material is measured by using the Vickers hardness test. It took three readings for each part and then calculated the average hardness for each part. The results of the Vickers hardness test are shown in the Fig. 4 below.

Fig. 4 Vicker for Hardness test

After measuring the hardness, then measured the surface roughness of the material using the Mitutoyo device test. It also took three readings for each part and then calculated the average surface roughness for each part. The results of the Vickers hardness test are shown in the Fig. 5 below.

Fig. 5 Mitutoyo surface Roughness

Then an experimental design was devised to examine the hardness and surface finish of coated materials by varying parameter levels. Utilizing a Taguchi experimental design with an L9 array, the investigation focused on analyzing the output parameters: hardness and surface finish.

Following the measurement of hardness and surface finish, the results were documented. Table 3 presents the experimental design along with the recorded measurements of the output parameters

Table 3 Design of Experiment

Experiment	Temperature	Pressure	Time	Hardness	Surface Roughness
1	275	0.0001	6	147	2.177
2	275	0.001	8	151	2.201
3	270	0.01	10	154	2.260
4	280	0.0001	8	159	2.307
5	280	0.001	10	161	2.312
6	280	0.01	8	155	2.150
7	285	0.0001	10	174	2.481
8	285	0.001	6	155	2.291
9	285	0.01	8	163	2.315

III. RESULTS AND DISCUSSION

A. Regression Analysis: Surface Roughness versus Temperature, Pressure, Time

To reflect the lower surface roughness indicating better tribological properties of a material, a "larger is better" signal-to-noise (S/N) ratio was used for surface roughness to determine the optimal input process parameter levels for physical vapor deposition (PVD)[5]. The responses in terms of means and S/N ratios are presented in Table 4 alt and Table 5. The ranking of input factors highlights their impact on surface roughness. Delta values, representing the differences between the minimum and maximum average values for each factor, along with the ranks, indicate that temperature has the most significant effect on surface roughness, followed by temperature, time and pressure.

Table 4 Response Table for Signal to Noise Ratios for surface roughness

Level	Temperature	Pressure	Time
1	-6.897	-7.304	-6.869
2	-7.063	-7.111	-7.135
3	-7.461	-7.007	-7.418
Delta	0.564	0.296	0.549
Rank	1	2	3

Table 5 Response Table for Means for surface roughness

Level	Temperature	Pressure	Time
1	2.213	2.332	2.206
2	2.256	2.268	2.274
3	2.396	2.242	2.351
Delta	0.150	0.080	0.145
Rank	1	3	2

Figures 2 and 3 display the main effect plots for means and S/N ratios. These plots indicate that as the temperature increases from 275°C to 285°C, the pressure increases from 0.0001 Pascal to 0.001 Pascal, and the coating time increases from 6 minutes to 10 minutes, the surface roughness decreases. Additionally, the plots demonstrate that surface roughness reaches its lowest when the temperature is set to 285°C, the pressure is at its highest, and the coating time is maximized.

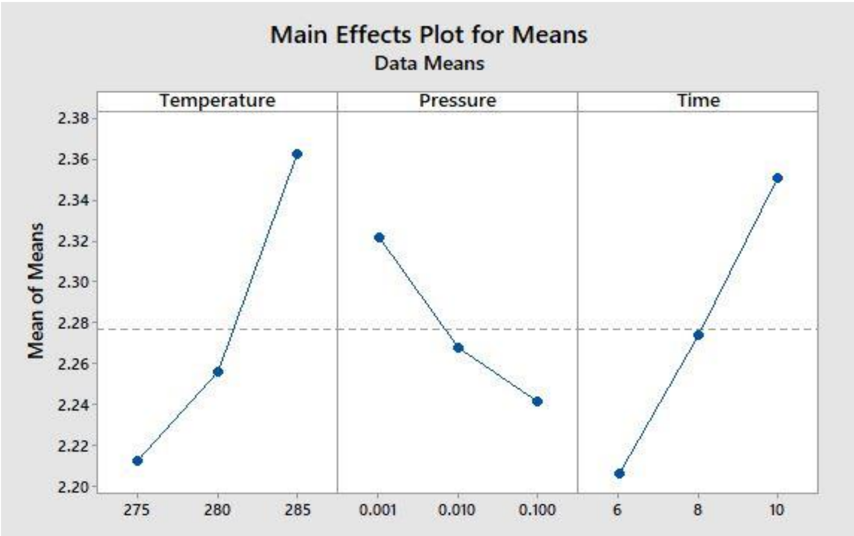

Fig. 6 Mean effect plot for means

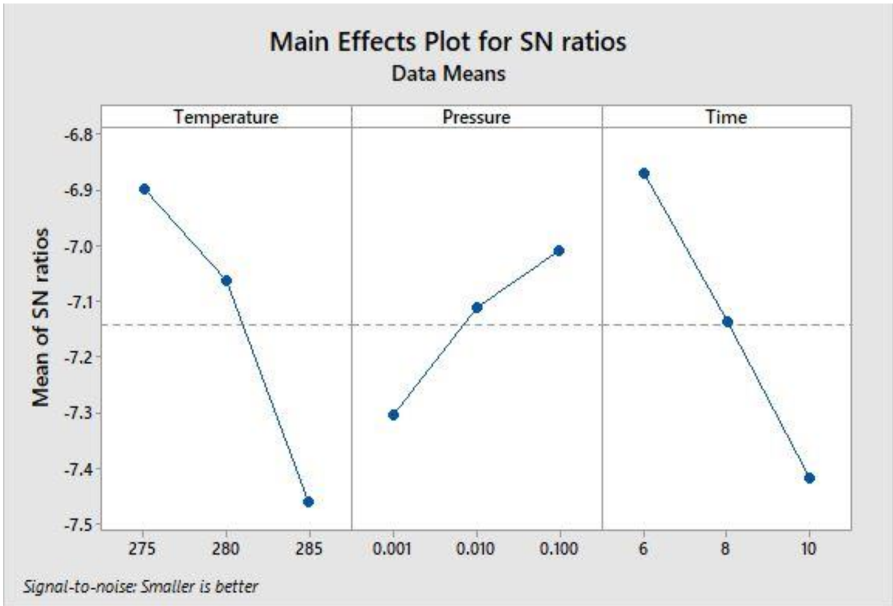

Fig. 7 Mean effect plot for S/N ratio

B. Regression Equation for surface roughness

A best fit line, made up of input parameters weighted by their respective contributions to the output parameter in the form of regression coefficients, was created to model the output parameter. The regression equation for prediction of Surface roughness is presented below.

Surface Roughness = -2.181 + 0.01497 Temperature - 0.599 Pressure + 0.03625 Time

C. ANOVA for Surface roughness

ANOVA has also been used to determine the percentage contributions for each of the many input components separately and to categorize the statistically significant input factors.P-value was used to assess the relevance of process parameter values. If the process's P-value parameters is less than 0.05, a 95% confidence level indicates that the component has a significant impact[6].

The P-value of temperature (0.003) is less than 0.05. So, it has significant effects on the surface roughness. Time has a P-value of 0.004, which is less than 0.05 is also significant input parameter whereas pressure P-value is 0.068 is greater than 0.05 so that is comparative insignificant input parameter.

Table 6 ANOVA for surface roughness

Source	DF	AdjSS	AdjMS	F-Value	P-Value
Regression	3	0.071592	0.023864	19.94	0.003
Temperature	1	0.033600	0.033600	28.08	0.003
Pressure	1	0.006454	0.006454	5.39	0.068
Time	1	0.031537	0.031537	26.36	0.004
Error	5	0.005983	0.001197		
Total	8	0.077575			
Model Summary					
S		R-Seq		R-Seq (adj)	R-prediction
0.0345923		92.29%		87.66%	72.99%

D. REGRESSION ANALYSIS: HARDNESS VERSUS TEMPERATURE, PRESSURE, TIME

To reflect the increase in hardness indicating better tribological properties of a material, a "larger is better" signal-to-noise (S/N) ratio was used for surface roughness to determine the optimal input process parameter levels for physical vapor deposition (PVD). The responses in terms of means and S/N ratios are presented the ranking of input factors highlights their impact on surface roughness[7]. Delta values, representing the differences between the minimum and maximum average values for each factor, along with the ranks, indicate that temperature has the most significant effect on surface roughness, followed by temperature, time and pressure.

Table 7 Response Table for Signal to Noise Ratios for hardness

Level	Temperature	Pressure	Time
1	43.56	44.06	43.65
2	43.99	43.84	43.95
3	44.29	43.93	44.23
Delta	0.73	0.22	0.58
Rank	1	3	2

Table 8 Response Table for Means

Level	Temperature	Pressure	Time
1	150.7	160.0	152.3
2	158.3	155.7	157.7
3	164.0	157.3	163.0
Delta	13.3	4.3	10.7
Rank	1	3	2

Figures 2 and 3 display the main effect plots for means and S/N ratios. These plots indicate that as the temperature increases from 275°C to 285°C, the pressure increases from 0.0001 Pascal to 0.001 Pascal, and the coating time increases from 6 minutes to 10 minutes, the surface roughness decreases. Additionally, the plots demonstrate that surface roughness reaches its lowest when the temperature is set to 285°C, the pressure is at its highest, and the coating time is maximizing

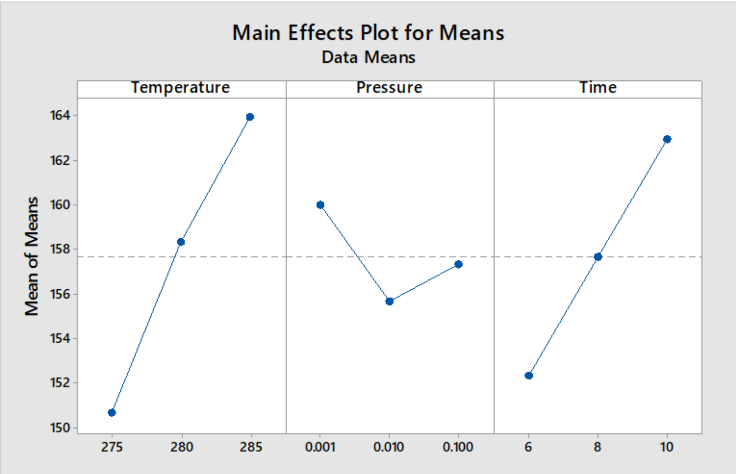

Fig. 8 Main Effects Plot for Means for hardness

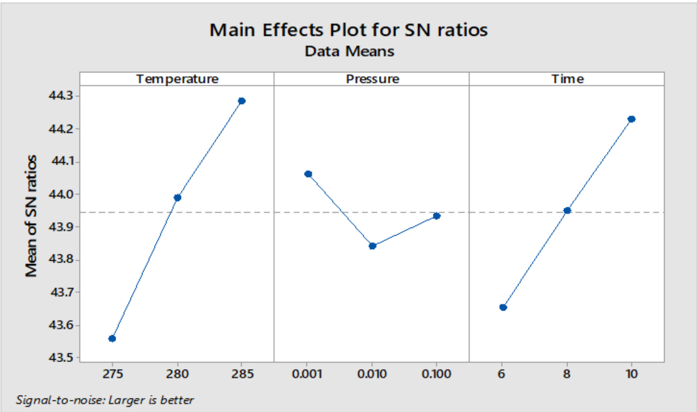

Fig. 9 Mean of SN ratios for hardness

E. Regression Equation for hardness

A best fit line, made up of input parameters weighted by their respective contributions to the output parameter in the form of regression coefficients, was created to model the output parameter. The regression equation for prediction of Surface roughness is presented below.

Hardness = -236.7 + 1.333 Temperature - 8.5 Pressure + 2.667 Time

F. ANOVA for Hardness

ANOVA has also been used to determine the percentage contributions for each of the many input components separately and to categorize the statistically significant input factors. P-value was used to assess the relevance of process parameter values. If the process's P-value parameters is less than 0.05, a 95% confidence level indicates that the component has a significant impact.
The P-value of temperature (0.004) is less than 0.05. So, it has significant effects on the hardness. Time also has a P-value of 0.011, which is less than 0.05 is also significant input parameter whereas pressure P-value is 0.746 so that is comparative insignificant input parameter.

Table 9 Anova for hardness

Source	DF	AdjSS	AdjMS	F-Value	P-Value
Regression	3	438.635	146.212	13.20	0.008
Temperature	1	266.667	266.667	24.08	0.004
Pressure	1	1.302	1.302	0.12	0.746
Time	1	170.667	170.667	15.41	0.011
Error	5	55.365	11.073		
Total	8	494.000			
Model Summary					
S		R-Seq		R-Seq (adj)	R-prediction
3.32761		88.79%		82.07%	54.28%

IV. CONCLUSION

In conclusion, the study demonstrates that the Physical Vapor Deposition (PVD) process significantly enhances the hardness and reduces the surface roughness of AISI D2 tool steel when coated with TiN. The Taguchi analysis identified temperature as the most influential parameter, followed by time and pressure. Optimal coating quality was achieved at a temperature of 285°C, pressure of 0.001 Pa, and a time duration of 10 minutes, resulting in the highest hardness and lowest surface roughness. The regression equations and ANOVA results corroborated these findings, emphasizing the substantial impact of temperature and time on the coating's performance, while pressure was comparatively less significant. These insights provide a valuable foundation for optimizing PVD processes in industrial applications, ensuring enhanced tool performance and longevity.

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