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Enhancing Sustainability in Titanium Machining: Simulated and Experimental Insights into PVD & CVD Carbide Inserts Applications

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Abstract. In this article we proposed, an extensive investigation of environmentally friendly methods for machining titanium alloy (Ti–6AL–4V), a vital component of the aerospace and biomedical sectors, is presented. The novelty of the proposed work is to improve sustainability by applying various technologies, particularly carbide inserts made by Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD). These components are essential for increasing machining productivity and reducing environmental impact. Moreover, to optimise the entire process, the experimental inquiry entails a methodical analysis of machining parameters, such as cutting speed, feed rate, and depth of cut. Apart from these we have also provides the superior machining performance with lower energy use and good surface roughness is the novelty of the work. Moreover, this work emphasizes the importance of feed rate, cutting speed, and depth of cut in obtaining greater energy efficiency during titanium alloy machining. PVD and CVD carbide inserts provide consistent performance across a wide range of tools, increasing their dependability and making them attractive options for energy-efficient and environmentally friendly machining methods. Furthermore, compared to CVD-coated inserts, which achieve an optimal surface roughness of 0.232 μm under cutting parameters of 75 mm/min feed rate, 0.035 mm/rev feed, and a 0.5 mm depth of cut, PVD-coated inserts exhibit an optimal surface roughness of 0.258 μm under similar conditions. The consistent performance of both PVD and CVD carbide inserts across a range of tools enhances their reliability and usefulness in green manufacturing applications. The research takes into account the environmental effects of PVD and CVD carbide inserts, in line with the ideas of green manufacturing.

Keywords: metamaterial, directivity, gain, split ring

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Повышение устойчивости обработки титана: моделирование и экспериментальное изучение применения твердосплавных пластин с PVD- и CVD-покрытием

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Реферат. В данной статье представлено обширное исследование экологически безопасных методов обработки титанового сплава (Ti–6AL–4V), являющегося важнейшим материалом аэрокосмической и биомедицинской отраслей. Новизна предлагаемой работы заключается в повышении устойчивости путем применения различных технологий, в частности твердосплавных вставок, изготовленных методами физического осаждения из паровой фазы (PVD) и химического осаждения из паровой фазы (CVD). Эти компоненты необходимы для повышения производительности обработки и снижения воздействия на окружающую среду. Более того, для оптимизации всего процесса эксперимен-

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тальное исследование включает в себя методический анализ параметров обработки, таких как скорость резания, скорость подачи и глубина резания. Помимо этого, обеспечивается превосходная производительность обработки при меньшем потреблении энергии и хорошая шероховатость поверхности, что является новизной. Кроме того, в работе подчеркивается важность скорости подачи, скорости резания и глубины резания для повышения энергоэффективности при обработке титановых сплавов. Твердосплавные пластины с покрытием PVD и CVD обеспечивают стабильную производительность для широкого спектра инструментов, повышая их надежность и делая их привлекательными вариантами для энергоэффективных и экологически чистых методов обработки. По сравнению с пластинами с покрытием CVD, которые обеспечивают оптимальную шероховатость поверхности 0,232 мкм при скорости подачи 75 мм/мин, скорости резания 0,035 мм/об и глубине резания 0,5 мм, пластины с покрытием PVD имеют оптимальную шероховатость поверхности 0,258 мкм при аналогичных условиях. Стабильная производительность твердосплавных пластин с покрытием PVD и CVD при использовании различных инструментов повышает их надежность и эффективность в экологически чистых производственных условиях. В исследовании учитывается воздействие твердосплавных пластин с покрытием, нанесенным методом PVD и CVD, на окружающую среду в соответствии с требованиями экологичного производства.

Ключевые слова: метаматериал, направленность, прирост, разрезное кольцо

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Introduction

Now a days, in the automobile and others industries work on the titanium alloy (Ti–6AL–4V). Furthermore, because of its remarkable strength-to-weight ratio, resistance to corrosion, and biocompatibility, titanium alloy (Ti–6AL–4V) is a key component in fields including aerospace and biomedical engineering [1–6]. But machining titanium alloys can be quite difficult, necessitating the use of cutting-edge tools and techniques to maximise productivity and minimise environmental damage. This research explores how to improve sustainability in titanium alloy machining by applying experimental insights into the application of Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) carbide inserts [4]. This research is in response to the growing emphasis on sustainable manufacturing practices.

The investigation of environmentally friendly solutions has been prompted by the high energy consumption, significant material waste, and tool wear associated with traditional machining procedures. PVD and CVD carbide inserts are attractive options for sustainable titanium alloy machining since they are state-of-the-art materials with superior hardness and wear resistance [5, 7–9]. The objective of this research is to methodically examine how the performance of PVD and CVD carbide inserts is affected by machining factors such as feed rate, depth of cut, and cutting speed [10, 11].

This research aims to reconcile the goals of high machining efficiency with green production practices by assessing tool wear, surface polish, and environmental effects [12–16]. It is anticipated that the study's conclusions will offer insightful information about how to best machine titanium alloys, adding to the growing body of knowledge about environmentally conscious manufacturing practices and meeting the changing demands of sectors that place a high priority on environmenttal responsibility [17, 18]. Moreover, Author Bhvnesh Bharwdwaj et al. in [19], presented a refined surface roughness prediction model for EN 353 end milling using Box-Cox transformation integrated with response surface methodology (RSM). This analysis was conducted in two phases. Initially, a quadratic model was formulated using response surface methodology (RSM) based on a central composite rotatable design (CCRD), considering feed rate, cutting speed, depth of cut, and nose radius as input parameters [19]. Further, in [20], authors discussed in this study, experimental investigations were carried out to examine the influence of tool geometry (radial rake angle and nose radius) and cutting conditions (cutting speed and feed rate) on machining performance during dry milling using four-fluted solid carbide end mill cutters coated with TiAlN. Moreover, Experimental Modeling of Surface Finish and Material Removal Rate in CNC Milling Processes reported in [21]. This study explores how various process parameters influence the material removal rate and surface roughness during the milling of SAE52100 tool steel [21].

Table 1 illustrates the Chemical composition of Ti–6Al–4V. In table 1 we mention the materails and its percentage values. However, Table 2 provides the Mechanical Properties of Ti–6Al–4V materials. In Table 2 we gives the various mechanical propertits and its values of theses Ti–6Al–4V materials.

Table 1

Chemical composition of Ti–6Al–4V (Ezugwu and Wang, 1997)

Element	%	Element	%
C	<0.08	V	3.5-4.5
Al	5.5-6.75	N	<0.05
Fe	<0.4	H	<0.01
O	<0.2		
Ti	Balances		

Table 2

Mechanical Properties of Ti–6Al–4V (Machado and Wallbank, 1990)

Work piece material	Tensile strength (MPa)	Yield strength (MPa)	Elongation %	Modulus of Elasticity (GPa)	Hardness (HRC)
Ti-6Al-4V	993	830	14	114	36

Table 3 illustrates the Thermal Properties of Ti–6Al–4V composite materials. Table 3 gives the properties and its values. Methodology and Experimental Setup.

Table 3

Thermal Properties of Ti–6Al–4V (Ezugwu and Wang, 1997)

Properties	Values
Specific heat capacit	0.5263 J/g °C
Thermal conductivity	6.7 W/mk
Annealing temperature	700–785 °C
Melting point	1604–1660 °C
Solidus	1604 °C
Liquidus	1660 °C
Beta transus	980 °C

Figure 1 depicts the Methodology for execution of experimentation.

Find and collect specimens of Titanium Alloy Ti–6AL–4V for testing, making sure that the material's characteristics are constant. Obtain carbide inserts made for titanium machining, such as PVD and CVD. Make sure the inserts fulfil the necessary standards by conducting pre-testing evaluations. Make use of a CNC machining centre that has the right fixtures and cutting tools. Create a controlled atmosphere to reduce outside influences on the results of machining. To establish a matrix of test situations, systematically alter cutting parameters such as depth of cut, feed rate, and cutting speed. Use a factorial design to thoroughly investigate the ways in which the parameters interact.

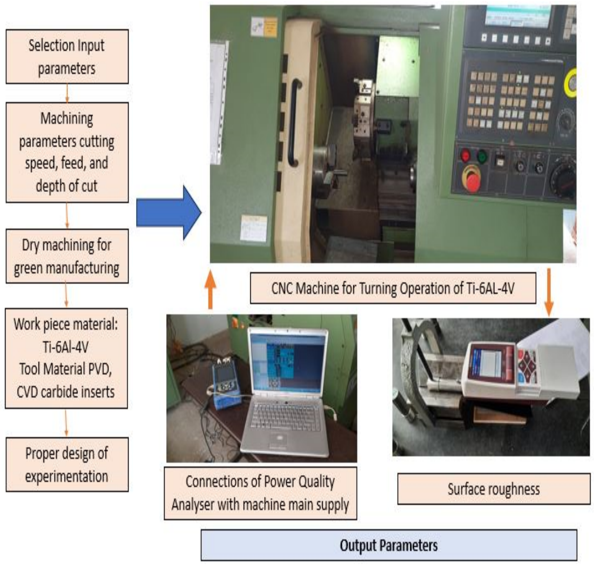

Fig. 1. Methodology for execution of experimentation

Measurements of surface roughness and profilometry are used to assess surface finish properties. Connect the machining settings to the surface finish. Keep systematic records of surface finish, and other pertinent metrics for every experimental run. Repeatedly measure and record data to ensure accuracy and dependability. Examine how machining techniques affect the environment by taking waste production and energy usage into account. Examine and contrast the effects of PVD and CVD carbide inserts on the environment. Utilise statistical techniques, such as analysis of variance (ANOVA), to pinpoint important variables and their interactions. Establish the ideal machining parameters to produce effective and lasting results. Keep detailed records of all experimental setups, outcomes, and observations. Write a thorough report including the results, conclusions, and suggestions. By considering both performance indicators and environmental effect, this methodology seeks to offer a methodical and rigorous way to investigating the sustainability of titanium alloy machining utilising PVD and CVD carbide inserts.

From the various literature review the researchers used different sizes of titanium alloy grade 5 i.e. Ti–6Al–4V for their experimental work so in this study 20 mm diameter and 75 mm length of material selected and PVD and CVD carbide inserts with cutting speed of 50, 75, 100 m/min, feed rate of 0.035, 0.046, 0.069 mm/rev. and the depth of cut of 0.50, 0.75, 1.00 mm the machining parameters are used for the experimentation. The experiments were conducted on CNC machine Smart turn/Smart Jr (FANUC Oi MATE TD) Fanuc Simulation Controller, having the specification of max turning diameter 250 mm, max turning length 250 mm, spindle size 165 mm, capacity: swing over bed 480 mm, chuck diameter: 165 mm, machine size: front side 2275×1640 mm and machine weight: 2300 Kg with the power supply of voltage: Ac 415 ± 10 %, 3 Phase, frequency: 50 ± 1 and power of 15 kVA.

In the Taguchi L18 orthogonal array, the selection of machining parameters and their levels for the turning operation of a 20 mm diameter and 75 mm length using PVD and CVD carbide inserts done as follows.

Table 4 illustrates the input response of the various parameters. In this table we explore the various parameters such as, cutting speed, feed, depth of cut, and cutting tools.

Table 4

Input response parameters

Parameters	Level 1 Low	Level 2 Medium	Level 3 High
Cutting Speed	50 m/min	75 m/min	100 m/min
Feed	0.035 mm/rev.	0.046 mm/rev.	0.069 mm/rev.
Depth of Cut	0.5 mm	0.75 mm	1.00 mm
Cutting Tools	PVD Carbide Inserts	CVD Carbide Inserts	

With the Taguchi L18 orthogonal array, studies can be carried out with a small number of trials and the effects of various parameter combinations can still be recorded. Effectively investigate the effects of many parameters on the turning operation and determine the ideal parameter settings for better performance, such as reduced tool enhanced surface finish and energy efficiency (EE), by employing this design of experiments (DOE) approach.

In the Taguchi L18 array, every trial is a distinct set of parameter levels. Determine the primary impacts and interactions of the factors by carrying out the tests and evaluating the outcomes. This will enable you to optimise the turning process for the specified workpiece dimensions and carbide insert selection for PVD and CVD. It was discovered that a combination of greater feed, lower spindle speed, and deep cut depth proved effective in lowering the energy consumption during turning. Elevated feed rates combined with moderate speeds and deep cutting depth were ideal for optimising energy efficiency. The optimal combination for power factor was high speed, feed, and depth of cut.

Table 5 shows the experimental results and S/N ratio values for Surface Roughness (Ra) with various parameters such as cutting speed, feed, depth of cut, SNRA and MEAN.

Table 5

Experimental results and S/N ratio values for Surface Roughness (Ra)

Experiment No	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut. (mm)	Ra	SNRA	MEAN
1	PVD	50	0.069	0.5	0.422	7.493751	0.422
2	PVD	50	0.046	0.75	0.327	9.719676	0.3266
3	PVD	50	0.035	1	0.274	11.24499	0.274
4	PVD	75	0.069	0.5	0.414	7.659993	0.414
5	PVD	75	0.046	0.75	0.337	9.444825	0.3371
6	PVD	75	0.035	1	0.258	11.77603	0.25775
7	PVD	100	0.069	0.75	0.534	5.453242	0.53375
8	PVD	100	0.046	1	0.433	7.270242	0.433
9	PVD	100	0.035	0.5	0.296	10.56683	0.29625
10	CVD	50	0.069	1	0.560	5.036239	0.56
11	CVD	50	0.046	0.5	0.356	8.977102	0.35575
12	CVD	50	0.035	0.75	0.320	9.897	0.32
13	CVD	75	0.069	0.75	0.499	6.037989	0.499
14	CVD	75	0.046	1	0.430	7.340737	0.4295
15	CVD	75	0.035	0.5	0.232	12.70898	0.2315
16	CVD	100	0.069	1	0.635	3.94179	0.6352
17	CVD	100	0.046	0.5	0.356	8.964903	0.35625
18	CVD	100	0.035	0.75	0.328	9.695774	0.3275

Experimental results for S/N ratio

Rank 1 (Δ: 5.044): Feed rate has the most significant impact on the S/N ratio. Level 1 has the highest S/N ratio among the feed rates. Rank 2 (Δ: 1.627): Depth of cut has a moderate impact on the S/N ratio. Level 2 has the highest S/N ratio among the depths of cut. Rank 3 (Δ: 1.513): Cutting speed has a notable impact on the S/N ratio. Level 3 has the highest S/N ratio, suggesting that a specific cutting speed is associated with a better surface finish (lower Ra). Rank 4 (Δ: 0.892): There is little difference in the S/N ratio for different types of tools. All tools have similar S/N ratios. Table 6 illustrates the response for S/N ratio of surface roughness (Ra). While Table 7 discusses the response for means of surface roughness (Ra).

Taguchi Analysis: Ra versus Type of Tool, Cutting Speed (m/min), Feed (mm/rev.), Depth of Cut (mm).

Table 6

Response table for S/N ratio of Surface Roughness (Ra)

Level	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut (mm)
1	8.959	8.728	10.982	9.395
2	8.067	9.161	8.620	8.375
3		7.649	5.937	7.768
Δ	0.892	1.513	5.044	1.627
Rank	4	3	1	2

Table 7

Response Table for Means of Surface Roughness (Ra)

Level	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut. (mm)
1	0.3660	0.3764	0.2845	0.3460
2	0.4127	0.3615	0.3730	0.3907
3		0.4303	0.5107	0.4316
Δ	0.0467	0.0689	0.2262	0.0856
Rank	4	3	1	2

Rank 1 (Δ: 0.2262): Feed rate has the most significant impact on the means. Level 3 has the highest mean among the feed rates. Rank 2 (Δ: 0.0856): Depth of cut has a moderate impact on the means. Level 2 has the highest mean among the depths of cut. Rank 3 (Δ: 0.0689): Cutting speed has a minor impact on the means. Level 3 has the highest mean, indicating that a specific cutting speed is associated with a slightly better surface finish. Rank 4 (Δ: 0.0467): Similar to the S/N ratio table, there is little difference in the means for different types of tools. All tools have similar means. Figure 2 shows the plot of mean of S/N ratio vs Main Effects plot for S/N ratio of Surface Roughness (Ra).

Feed rate appears to be the most critical factor, affecting both S/N ratios and means significantly (Tab. 8). Level 1 of feed rate is associated with the highest S/N ratio and mean for achieving a better surface finish (lower Ra). Cutting speed and depth of cut also have noticeable impacts on the S/N ratios, with specific levels associated with better surface finish. Type of tool has little impact on both S/N ratios and means in this context. Figure 3 illustrates the mean of means vs Main Effects plot for Means of Surface Roughness (Ra).

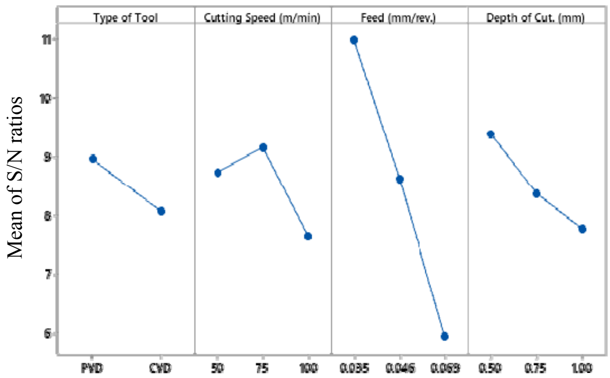

Fig. 2. Main Effects plot for S/N ratio of Surface Roughness (Ra)

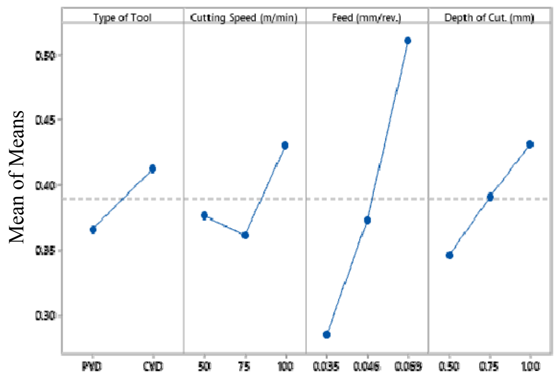

Fig. 3 Main Effects plot for Means of Surface Roughness (Ra)

Response Table for Signal to Noise Ratios EE versus Type of Tool, Cutting Speed (m/min), Feed (mm/rev.), Depth of Cut (mm) (Tab. 9).

Rank 1 (Δ: 5.03): Feed rate has the most significant impact on the S/N ratio. Level 1 has the highest S/N ratio among the feed rates. Rank 2 (Δ: 3.75): Cutting speed has a notable impact on the S/N ratio. Level 3 has the highest S/N ratio, suggesting that a specific cutting speed is associated with better energy efficiency. Rank 3 (Δ: 0.83): Depth of cut has a moderate impact on the S/N ratio. Level 2 has the highest S/N ratio among the depths of cut. Rank 4 (Δ: 0.24): There is little difference in the S/N ratio for different types of tools. All tools have similar S/N ratios.

Table 8

Experimental results and S/N ratio values for Energy Efficiency

Expt. No	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut. (mm)	EE	SNRA4	MEAN4
1	PVD	50	0.069	0.5	29.6716	–29.4468	29.6716
2	PVD	50	0.046	0.75	58.16422	–35.2931	58.16422
3	PVD	50	0.035	1	58.93	–35.4067	58.93
4	PVD	75	0.069	0.5	26.89199	–28.5925	26.89199
5	PVD	75	0.046	0.75	34.52036	–30.7615	34.52036
6	PVD	75	0.035	1	42.1406	–32.494	42.1406
7	PVD	100	0.069	0.75	22.581	–27.0749	22.581
8	PVD	100	0.046	1	27.40027	–28.7551	27.40027
9	PVD	100	0.035	0.5	30.97206	–29.8194	30.97206
10	CVD	50	0.069	1	26.60415	–28.499	26.60415
11	CVD	50	0.046	0.5	47.85885	–33.5992	47.85885
12	CVD	50	0.035	0.75	58.38051	–35.3254	58.38051
13	CVD	75	0.069	0.75	24.98615	–27.954	24.98615
14	CVD	75	0.046	1	36.40623	–31.2235	36.40623
15	CVD	75	0.035	0.5	48.8224	–33.7724	48.8224
16	CVD	100	0.069	1	22.89598	–27.1952	22.89598
17	CVD	100	0.046	0.5	31.92944	–30.0838	31.92944
18	CVD	100	0.035	0.75	40.36242	–32.1195	40.36242

Table 9

Signal to Noise Ratios for Energy Efficiency (EE)

Level	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut. (mm)
1	–30.85	–32.93	–33.16	–30.89
2	–31.09	–30.80	–31.62	–31.42
3		–29.17	–28.13	–30.60
Δ	0.24	3.75	5.03	0.83
Rank	4	2	1	3

Table 10

Response Table for Means for Energy Efficiency (EE)

Level	Type of Tool	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut. (mm)
1	36.81	46.60	46.60	36.02
2	37.58	35.63	39.38	39.83
3		29.36	25.61	35.73
Δ	0.77	17.24	21.00	4.10
Rank	4	2	1	3

Rank 1 (Δ: 21.00): Feed rate has the most significant impact on the means. Level 3 has the highest mean among the feed rates. Rank 2 (Δ: 17.24): Cutting speed has a substantial impact on the means. Level 1 has the highest mean, indicating that a specific cutting speed is associated with higher energy efficiency. Rank 3 (Δ: 4.10): Depth of cut has a moderate impact on the means. Level 1 has the highest mean among the depths of cut. Rank 4 (Δ: 0.77): Similar to the S/N ratio table, there is little difference in the means for different types of tools. All tools have similar means. Figure 4 discussed the mean of S/N ratio vs main effect plot for S/N ratio of Energy Efficiency (EE). However, Figure 5 shows the mean of means vs Main Effects plot for Means of Energy Efficiency (EE).

Feed rate appears to be the most critical factor, affecting both S/N ratios and means significantly. Level 1 of feed rate is associated with the highest S/N ratio and mean for energy efficiency (Tab. 10). Cutting speed also has a notable impact, with Level 3 being associated with the highest S/N ratio and Level 1 being associated with the highest mean. Depth of cut has a moderate impact on both S/N ratios and means. Type of tool has little impact on both S/N ratios and means in this context.

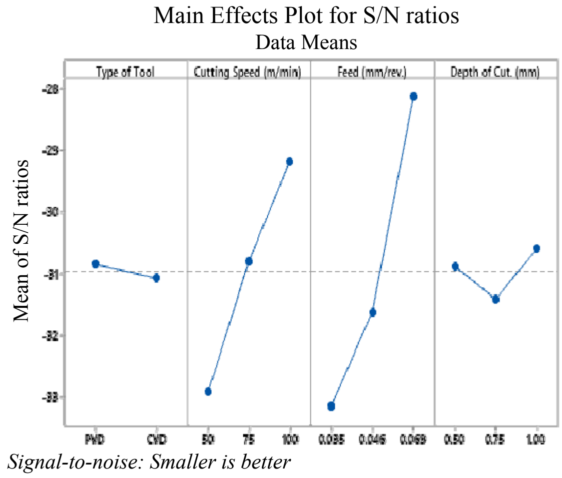

Fig. 4. Main Effects plot for S/N ratio of Energy Efficiency (EE)

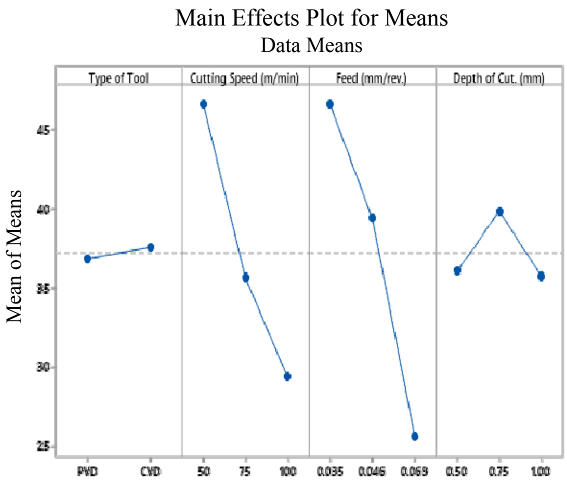

Fig. 5. Main Effects plot for Means of Energy Efficiency (EE)

CONCLUSION

In the work we proposed the significance of feed rate, depth of cut, and cutting speed in enhancing surface polish and sustainability in titanium alloy machining is underscored by the study. Surface roughness values for both cutting inserts varied in the experiment, and the CVD carbide insert has less value than the PVD carbide insert, according to the experimental data. In contrast to the CVD coated inserts, which have an optimal surface roughness of 0.232 when cutting parameters of 75 millimeter/minutes, feed 0.035 millimeter/rev, and depth of cut of 0.5 millimeter are observed, the PVD coated inserts have an optimal surface roughness of 0.258 when cutting parameters. The consistent performance of PVD and CVD carbide inserts across a range of tools further bolsters their dependability and utility in green production processes. In terms of energy efficiency (EE), once more, the feed rate for turning operations for the chosen material has the greatest influence on the S/N ratio. This is followed by the spindle's cutting speed, which has a noticeable influence on the S/N ratio and suggests that a particular cutting speed is associated with better energy efficiency. The depth of cut also has a moderate influence on the S/N ratio, and lastly, there is minimal variation in the S/N ratio for different types of tools. These findings support the development of environmentally friendly titanium alloy machining methods by offering vital information for improving tool selection and machining parameter selection. This investigation highlights the significance of feed rate, cutting speed, and depth of cut in achieving enhanced energy efficiency during titanium alloy machining. PVD and CVD carbide inserts provide uniform performance across a variety of tools, so augmenting their dependability and making them appealing alternatives for energy-conserving and ecologically sustainable machining procedures. These findings are consistent with green manufacturing concepts and aid in the development of energy-efficient titanium alloy machining methods. Additionally, they provide vital information for optimising machining parameter.

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