Journal of Materials and Manufacturing (2023) 1: 31-43

Journal of Materials and Manufacturing

Experimental and statistical investigation of the effect of coating type on surface roughness, cutting temperature, vibration and noise in turning of mold steel

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Abstract

In this study, machining experiments were performed by metal cutting in different cutting parameters with CVD - Chemical Vapor Deposition (MT-TiCN + TiC +Al_2O_3 + TiN) and PVD - Physical Vapor Deposition (TiAIN) coated carbide tools NIMAX plastic mold steel in a universal lathe. Changes in surface roughness, cutting temperature, vibration, and noise that occurred during machining were examined. The test specimens were machined with 18 different parameters using three different cutting speeds (120, 160, 200 m/min) at three different feed rates (0.1, 0.15, and 0.2 mm/rev) and a constant depth of cut (0.5 mm). As a result of the experiments performed, surface roughness, cutting temperature, vibration, and noise values were examined, and the best performance was obtained with PVD-coated cutting tool. Taguchi optimization was also applied to the experimental results of the study. The turning parameters giving the lowest Ra value were determined. The most effective turning parameters and effect ratios on Ra were determined by ANOVA analysis.

Keywords: CVD, Noise, Nimax, PVD, Cutting temperature, Vibration, Surface roughness, Taguchi analyses.

1. Introduction

The most critical factors for machining workpieces in machining are cutting speed, feed rate, depth of cut, and selection of the appropriate cutting tool type. When the workpieces are processed at low cutting speeds, the processing time will increase, and the time loss will increase. When machining is carried out at high cutting speeds, the cutting tool wears out quickly, and the tool life ends more quickly. For this reason, removing the cutting tool and installing the new insert causes a loss of time and increases machining costs. For all these reasons, all of these parameters, including the type of cutting tool, cutting speed, feed rate, and depth of cut, even in the heat treatment applied to the material to be processed, must be taken into account [1].

Nimax is a pre-hardened plastic mold steel with excellent machinability, very good polishability, pure and homogeneous microstructure, homogeneous hardness, high toughness, erosion compatibility and non-whitening capabilities. It is the steel type with the highest machinability in the material group with the same hardness value. It solves problems such as collapse, crushing and abrasion because of its high strength values; It also extends the service life of the mold thanks to its high toughness. Nimax, used in delivery hardness, eliminates the need for irrigation, saving mold cost and time. Nimax removes the need for nitration with wear resistance due to high hardness in most applications; however, it is possible to increase the surface hardness by nitriding

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DOI: 10.5281/zenodo.8020553
Received: 26 April 2023 / Accepted: 08 June 2023
ISSN: 2822-6054

if needed, thus further increasing the wear, adhesion, and erosion resistance in the mold. But the nitriding temperature is particular. A maximum of 2 hours of stress relief at 480 °C is required [2].

"Physical vapor condensation" (PVD) or "chemical vapor condensation" (CVD) techniques are needed for coating hard materials on the surfaces of other materials. In the physical vapor condensation process, the high-temperature vapor phase obtained is physically forced to condense when it hits the cold substrate surface. The driving force for condensation here is the rapid reduction of the steam to solid temperature on the cold substrate surface. The process of condensing the coating material onto the substrate surface by evaporating or splashing into the environment has emerged mainly with the developments in vacuum technology and has made its use widespread. Hard materials or their components often have a high melting point, and even melting them at ambient pressure is challenging. However, at low pressures, the melting temperatures of the substances decrease, and the evaporation temperature is lowered. In addition to easy evaporation, a low-density environment is needed to transfer the obtained steam to the substrate surface to be coated. Otherwise, the evaporating particles will collide with the gas particles in the atmosphere and condense in the environment. Therefore, low pressure or high vacuum is a necessity for such techniques. In chemical vapor condensation techniques, when some of the gas components in the environment hit the substrate surface, they undergo a chemical reaction, and the reaction product condenses on the substrate surface. In short, the driving force for condensation is chemical energy. Therefore, a high degree of vacuum is unnecessary in chemical condensation processes. Roughly, it can be said that chemical condensation processes develop in thermodynamic equilibrium conditions, whereas physical condensation processes develop in non-equilibrium conditions. Regarding historical development, CVD techniques were first developed, and then PVD methods were developed. Considering the application's advantages and disadvantages in hard coating production, both techniques can be used today [3-4].

Experimental studies require a certain amount of time and cost. Especially in experimental designs with many processing parameters, it takes a lot of time and cost to perform all the experiments. Determining the most suitable processing conditions and minimizing the number of experiments reduces this cost and time to very economical levels. Because of these positive results, optimization techniques such as Taguchi, Regression, Artificial Neural Networks, Response Surface Method, Ant Colony are applied to experimental data. One of these techniques is Taguchi optimization, developed by Genichi Taguchi. Thanks to the Taguchi method, time and time savings are achieved by making much fewer experiments [5-6].

This study conducted machining experiments by machining Nimax plastic mold steel with CVD (MT-TiCN + TiC + Al_2O_3 + TiN) and PVD (TiAIN) coated carbide tools at different cutting parameters. The changes in cutting temperature, vibration, noise and surface roughness values during the metal cutting were investigated experimentally. It is aimed to investigate how the changes in cutting temperature, vibration, sound, and surface roughness values that occur during the metal cutting change according to the coating method.

2. Material and Method

In this study, chip removal experiments were carried out by machining Nimax plastic mold steel with CVD (MT-TiCN + TiC + Al_2O_3 + TiN) and PVD (TiAIN) coated carbide tools at different cutting parameters on a universal lathe. The changes in cutting temperature, vibration, noise, and surface roughness values during the process were investigated experimentally. Plastic mold steel was processed with a total of 18 different parameters at 120, 160, and 200 m/min cutting speed, 0.10, 0.15, 0.20 mm/rev feed rates, and 0.5 mm depth of cut. In the experiments, cylindrical Nimax plastic mold steel material with dimensions of Ø77x250 mm was used. Nimax plastic mold steel is generally used to manufacture elements subject to breakage, such as molds, punches, scissor blades, and deburring dies. The chemical composition of the test sample is given in Table 1.

Table 1. The chemical composition of Nimax steel

C	Si	Mn	Cr	Mo	Ni
0.10	0.30	2.50	3.00	0.30	1.00

Hard turning experiments were performed with three different cutting speeds (120, 160, 200 m/min), three different feed rates (0.10, 0.15, 0.20 mm/rev), and a fixed depth of cut (0.50 mm). Made with 18 different embroidery combinations. The 18 different machining parameters mentioned above were tested under dry cutting conditions of Nimax plastic mold steel with CVD and PVD-coated cutting tools. A total of 72 experiments were carried out by experimenting with each combination. The experimental setup is given in Figure 1.

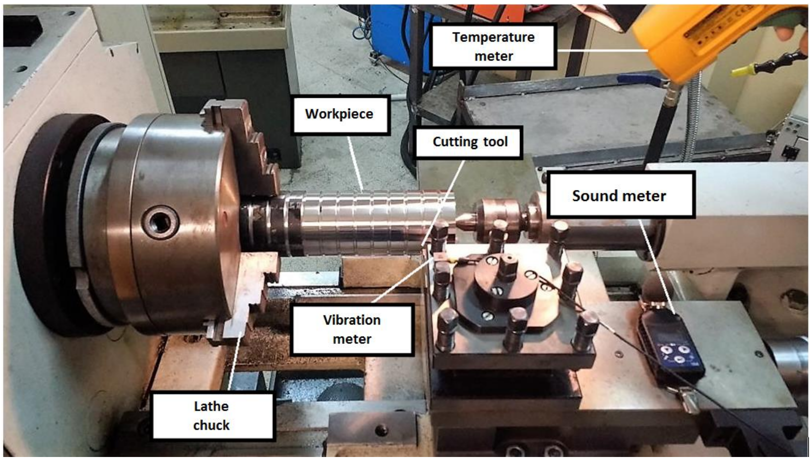

Fig. 1. Experimental setup

It is essential to measure and evaluate the surface roughness in machinability studies. For the surface roughness measurements of the machined surfaces, 'Taylor Hobson Surtronic 25' brand surface roughness measuring device was used. Surface roughness measurements were made three times from the machined surfaces, and the average surface roughness (Ra) values were determined by taking the average of these. The 'Fluke 572-2 IR Thermometer' brand high temperature measuring device was used for cutting temperature measurements. The four-channel, portable 'VIBROTEST 80' model vibration measuring device was used for vibrations occurring in the machine and cutting tools during the process. The device has Brüel & Kjaer software and hardware system. Vibration signals up to 5 kHz were received for 60 seconds for each test. Measurements were taken in the Hanning window at 6400 resolution. The total amplitude values of the vibration signals were determined by taking the root mean square (RMS). The vibration amplitude is on the g scale. Vibration signals were taken with a three-axis (x, y, z) piezoelectric accelerometer model Brüel & Kjaer 4527. The accelerometer is attached to the cutting tool holder. The lateral (CH1), axial (CH2), and vertical (CH3) axes of the accelerometer are indicated by x, y, and z, respectively. A noise measuring device (dosimeter) model 'SVANTEK SV 104' was used for sound measurements.

3. Experimental Results

3.1. Variation of surface roughness

After the hard turning tests of Nimax plastic mold steel with CVD and PVD-coated cutting tools, the changes in the surface roughness depending on the cutting parameters and cutting conditions are given in Figure 2. In general, surface roughness (Ra) values were found to vary between 0.773 µm and 1.18 µm for CVD-coated cutting tools and between 0.58 µm and 1.086 µm for PVD-coated cutting tools. For all cutting parameter values, Ra values tended to decrease with increasing cutting speed in both cutting tools. The increased cutting speed reduces friction by reducing the tool-chip contact area, allowing for better surface quality [7].

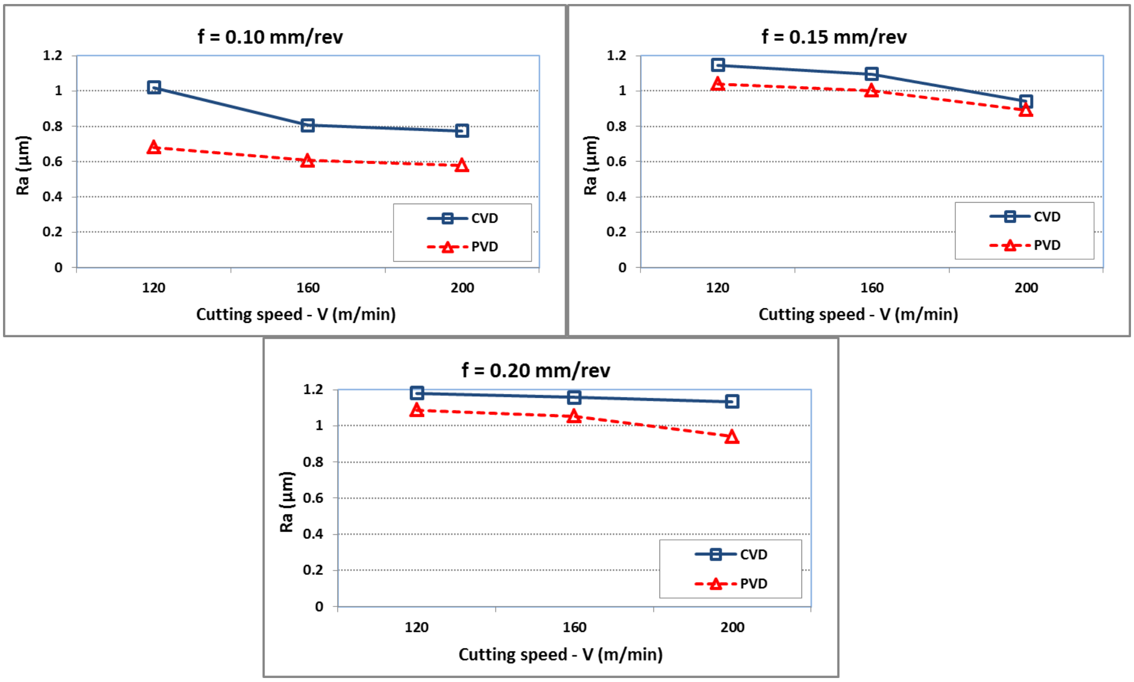

Fig. 2. Variation of surface roughness depending on cutting parameters

With CVD-coated cutting tools, after a 68% increase in cutting speed, improvements in surface roughness values of up to 25% at low feed rates of 0.10 mm/rev, improvements of 18% at feed rates of 0.15 mm/rev, and at 0.20 mm/rev values of feed It showed an improvement of 4%. The increased cutting speed reduces friction by reducing the tool-chip contact area, allowing for better surface quality. However, increasing the feed rate causes an increase in the temperature at the cutting tool-chip-workpiece interface [8-9]. The temperature increase at the interface also causes tool wear. Therefore, despite the increased cutting speed, the improvements in surface roughness were less with the increase in feed. With PVD-coated cutting tools, after a 68% increase in cutting speed, improvements in surface roughness values up to 15% at low feed rates of 0.10 mm/rev, 15% improvements in feed rates of 0.15 mm/rev, and 0.20 mm/rev of feed rate values improved by 14%.

3.2. Variation of cutting temperatures

During hard turning experiments of Nimax plastic mold steel with CVD and PVD-coated cutting tools, changes in cutting temperatures depending on cutting speed and feed rates were investigated. Temperature measurement was made from the tool-chip interface during turning. The graphs in Figure 3 were created to interpret the measured cutting temperature. In general, it has been observed that the cutting temperature varies between 55.3 °C and 83.1 °C for CVD-coated tools and 72.9 °C to 150.6 °C for PVD-coated cutting tools.

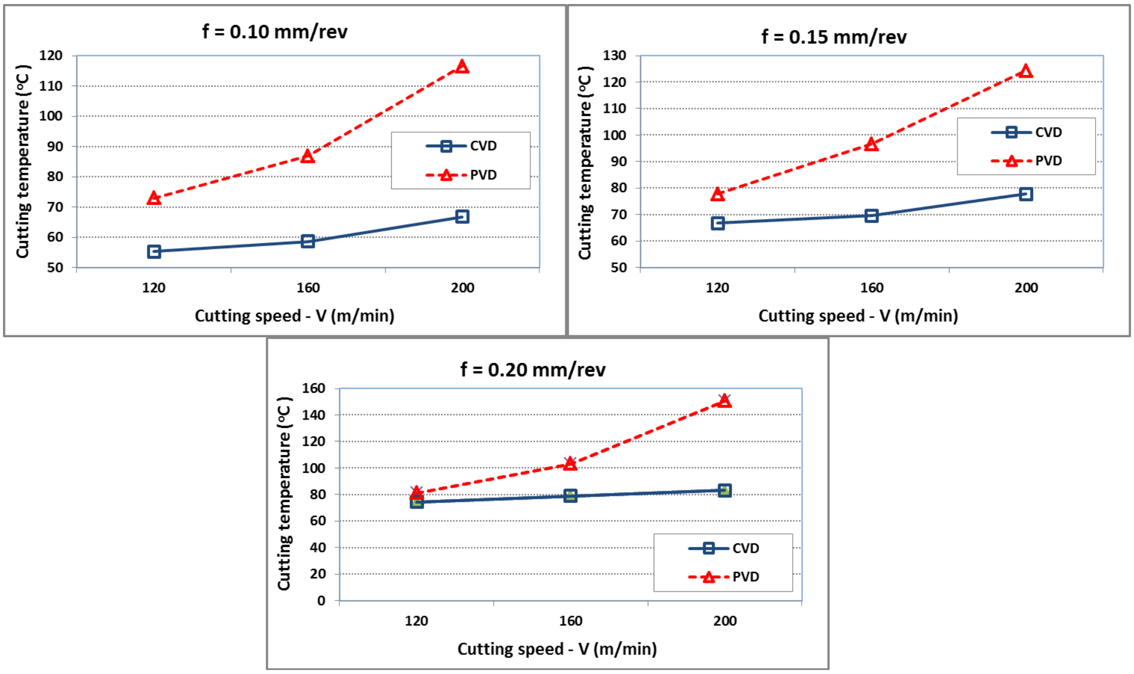

Fig. 3. Variation of cutting temperatures depending on cutting parameters

Considering the effect of feed rate on cutting temperature, it was seen that increasing feed rates in cutting speeds was an important factor in increasing the cutting temperature values. It is seen in Figure 3 that the cutting temperatures measured at all cutting speeds increase with the increase in the feed rate.

The literature shows that the cutting speed and the temperature change are directly proportional, and the temperature increases with the increase of the cutting speed [4, 8-9]. Increasing cutting speed directly affects the deformation rate in the shear plane and indirectly causes an increase in the heat released during cutting. As a result, the temperature formed along the tool-chip contact (second deformation zone) increases. Because, depending on the increasing cutting speed, the deformation rate in the first deformation region also increases, and the high strain rate causes high heat generation during chip removal, and therefore the temperature increases [10]. As the feed rate and cutting speed increase, the cutting temperatures also increase. When the values of the combinations at all cutting speeds and feed rates in turning operations with cutters coated with the PVD method were examined, it was observed that higher cutting temperatures occurred compared to the tools coated with the CVD-coated method.

3.3. Variation of vibration

During the hard turning experiments of Nimax plastic mold steel with CVD-coated and PVD-coated cutting tools, the variation of vibration values depending on the cutting speed and feed rates were experimentally investigated. Experiments were done with a universal lathe. Time domain vibration signals were taken at the specified sampling frequency for a recording time of 2.59 seconds. 16384 data were taken for each measurement. To comparatively examine the vibration amplitude values in hard turning experiments performed with CVD-coated and PVD-coated cutting tools at different cutting speeds and feed rates, the root mean square (RMS) of the data taken from each axis was calculated according to Equation 1 [11-12].

$$a_{RMS} = \sqrt{1/_N \sum_{k=1}^{N} a_k^2} \quad (1)$$

Here;
aRMS: Root mean square of acceleration signals (g),
ak: The kth acceleration value for time domain signals,

The RMS acceleration values obtained according to Equation 1 in the lateral (x), axial (y), and vertical (z) axes during the hard turning of Nimax plastic mold steel with CVD-coated and PVD-coated cutting tools are given in Table 2. RMS values for CVD and PVD-coated cutting tools give results in direct proportion to the surface roughness for all axes depending on the cutting speed and feed rate. Maximum vibration values are always at maximum feed rate and minimum cutting speed.

Table 2. Average RMS values

Exp. No	Cutting tools	Cutting speed (V)	Feed rate (f)	Lateral (x) CH1	Axial (y) CH2	Vertical (z) CH3	Average Vibration Values
1	CVD	120	0.10	1.385	1.575	9.04	9.280
2		120	0.15	1.567	1.751	11.19	11.434
3		120	0.20	1.787	1.915	13.46	13.712
4		160	0.10	0.882	1.032	4.71	4.901
5		160	0.15	1.105	1.312	7.199	7.400
6		160	0.20	1.431	1.646	10.421	10.646
7		200	0.10	0.635	0.817	2.238	2.465
8		200	0.15	0.976	1.161	5.663	5.862
9		200	0.20	1.265	1.466	8.141	8.368
10	PVD	120	0.10	0.558	0.74	1.09	1.430
11		120	0.15	0.716	0.912	3.178	3.382
12		120	0.20	0.9	1.114	5.818	5.991
13		160	0.10	0.066	0.25	0.646	0.695
14		160	0.15	0.383	0.525	0.907	1.115
15		160	0.20	0.662	0.863	2.476	2.704
16		200	0.10	0.027	0.067	0.456	0.461
17		200	0.15	0.187	0.271	0.953	1.008
18		200	0.20	0.445	0.635	1.388	1.589

The average vibration value (a_t) in all axes (x, y, z) was calculated according to Equation 2 [11-12].

$$at = \sqrt{avertical^2(z) + alateral^2(x) + aaxial^2(y)} \qquad (2)$$

a_t: Average vibration value,
a vertical (z): RMS value in the vertical direction,
a lateral (x): RMS value in the lateral direction,
a axial (y): RMS value in the axial direction.

Considering the effect of feed rate on vibration, it has been seen that increasing feed rates in terms of cutting speeds are an essential factor in increasing vibration values. It is seen in Figure 4 that the vibration values measured at all cutting speeds increase with the increase in the feed rate.

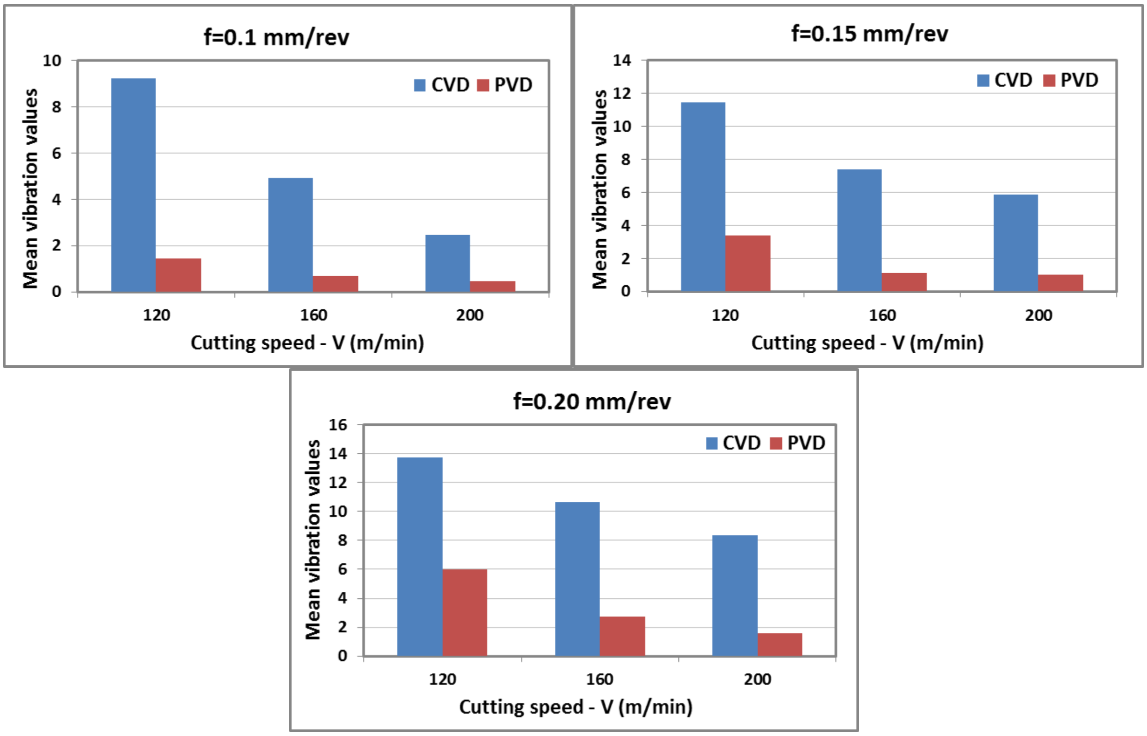

Fig. 4. Variation of mean vibration values depending on cutting parameters

As can be seen in the graphs in general, higher average vibration values were achieved in the turning operations performed with the inserts coated with the CVD coating method than those coated with the PVD coating method.

3.4. Variation of noise

Depending on the cutting speed and feed rate, the change in noise values in turning of Nimax plastic mold steel with CVD-coated and PVD-coated cutting tools was experimentally investigated. The variation of noise values depending on cutting speed and feed rate is given in Figure 5. In general, noise values were observed to vary between 93.2 dBA and 105.21 dBA.

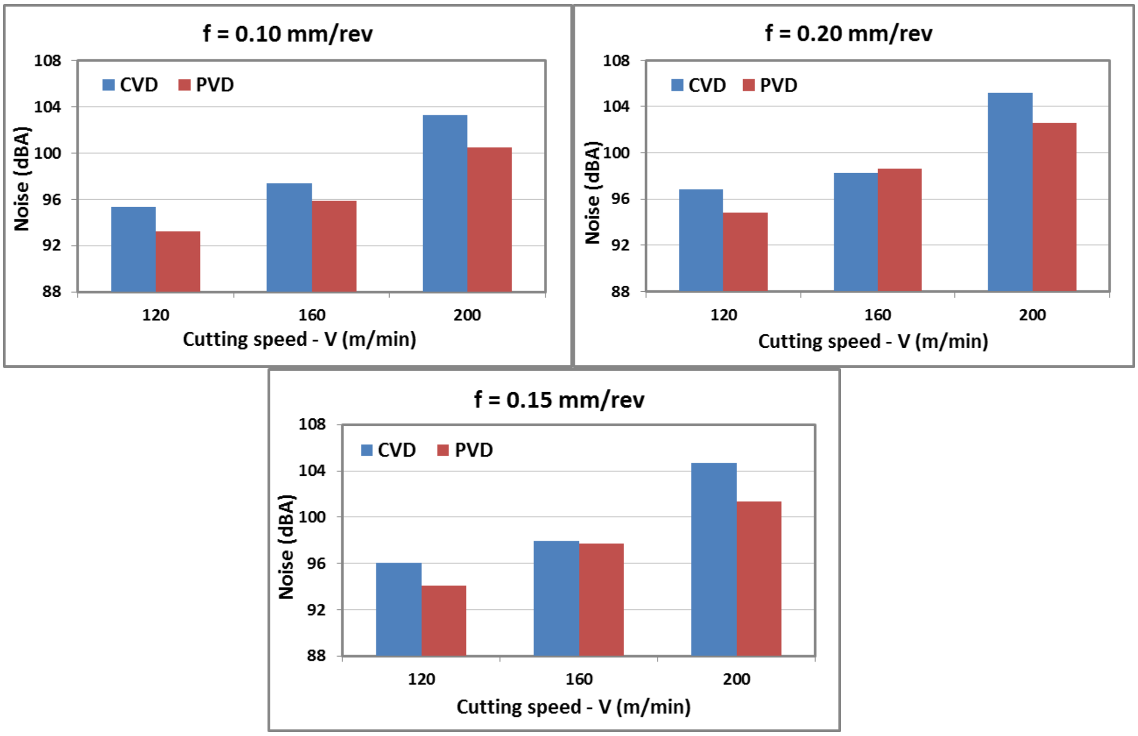

Fig. 5. Variation of noise values depending on cutting parameters

When Figure 5 is examined, it is seen that the noise values increase with the increase in cutting speed at a feed rate of 0.10 mm/rev. Noise values in the CVD-coated cutting tool were measured as 95.35 dBA at 120 m/min cutting speed, 97.36 dBA at 160 m/min cutting speed, and 103.26 dBA at 200 m/min cutting speed. Noise values in the PVD-coated cutting tool were measured as 93.2 dBA at 120 m/min cutting speed, 95.91 dBA at 160 m/min cutting speed, and 100.45 dBA at 200 m/min cutting speed. It is observed that the noise values increase with the increase in cutting speed at a feed rate of 0.15 mm/rev. Noise values in the CVD-coated cutting tool were measured as 96.02 dBA at 120 m/min cutting speed, 97.96 dBA at 160 m/min cutting speed, and 104.66 dBA at 200 m/min cutting speed. Noise values in the PVD-coated cutting tool were measured as 94.1 dBA at 120 m/min cutting speed, 97.7 dBA at 160 m/min cutting speed, and 101.39 dBA at 200 m/min cutting speed. It is seen that the noise values increase with the increase of cutting speed at 0.20 mm/rev feed rate. The CVD-coated cutting tool's noise values were 96.82 dBA at 120 m/min cutting speed, 98.28 dBA at 160 m/min cutting speed, and 105.21 dBA at 200 m/min cutting speed. Noise values in the PVD-coated cutting tool were measured as 94.8 dBA at 120 m/min cutting speed, 98.6 dBA at 160 m/min cutting speed, and 102.56 dBA at 200 m/min cutting speed. Considering the effect of cutting speed and feed on noise, it was seen that increasing cutting speed and feed was an important factor in increasing noise values. As can be seen in the graphs, higher noise values were determined in turning with CVD-coated inserts than in turning with PVD-coated inserts.

3.5. Optimization of experimental outputs (Surface roughness and Cutting temperature)

In this study, Taguchi optimization was carried out to determine the most suitable turning parameters: the lowest Ra value. Three different techniques are used in the Taguchi technique: the greatest best, nominal best, and smallest best [13-15]. Since the lowest values were requested for the outputs in this study, the smallest-best formula was applied to the experimental results. The formula corresponding to the principle of "the smallest best" is given in Equation 1.

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \tag{1}$$

In Equation 1, yi is the measured experimental output values, and n is the number of experiments performed. In this study, cutting parameters, cutting tool type (Ct), cutting speed (V), and feed rate (f) were selected. Control factors and levels used in the hard turning of Nimax plastic mold steel are given in Table 3. Analysis of Variance (ANOVA) was applied to the obtained output values with 95% confidence limits. The order and ratios of the effects of turning parameters on the outputs were determined by ANOVA analysis. Minitab 18 software was used for the optimization and ANOVA analysis.

Table 3. Turning parameters and levels

Symbol	Turning parameters	Level 1	Level 2	Level 3
A	Cutting tools (Ct)	CVD	PVD	
B	Cutting speed - V (m/min)	120	160	200
C	Feed rate - f (mm/rev)	0.1	0.15	0.2

The average Ra values obtained from the turning tests performed according to the Taguchi L18 experimental design for Nimax plastic mold steel and the S/N ratios calculated by the optimization of these values are given in Table 4.

Table 4. Experimental outputs and signal-to-noise ratios

Test no	(A) Cutting tool Ct	(B) Cutting speed V (m/min)	(C) Feed rate f (mm/rev)	Mean surface roughness Ra (µm)	Ra - S/N ratio (dB)
1	CVD	120	0.1	1.02	1.86612
2	CVD	120	0.15	1.14667	-0.80149
3	CVD	120	0.2	1.18	-1.26416
4	CVD	160	0.1	0.80667	2.23267
5	CVD	160	0.15	1.09667	0.53744
6	CVD	160	0.2	1.15667	-1.08715
7	CVD	200	0.1	0.77333	3.34982
8	CVD	200	0.15	0.94	-0.34067
9	CVD	200	0.2	1.13333	-0.72193
10	PVD	120	0.1	0.68	4.34100
11	PVD	120	0.15	1.04	-0.02890
12	PVD	120	0.2	1.08667	-0.45132
13	PVD	160	0.1	0.60667	4.73144
14	PVD	160	0.15	1.00333	0.97973
15	PVD	160	0.2	1.05333	0.53744
16	PVD	200	0.1	0.58	1.86612
17	PVD	200	0.15	0.89333	-0.80149
18	PVD	200	0.2	0.94	-1.26416

The S/N response table created by the Taguchi method determines the optimum levels of turning parameters and the most effective one among these parameters on the average surface roughness. The largest signal-to-noise values in this table show the optimum level for that processing parameter. The S/N response table showing the effect of each turning parameter on the mean Ra is given in Table 5.

Table 5. Signal-to-noise response table

Levels	Turning parameters		
	Ct	V	f
Level 1	-0.14611	-0.08519	**2.72484**
Level 2	**1.37740**	0.61021	-0.14044
Level 3		**1.32193**	-0.73746
Delta	1.52351	1.40712	3.46230
Range	2	3	1

When Table 5 is examined, the feed rate is the most effective influential parameter on Ra. The analysis of variance confirmed this result. However, the optimum Ra for turning Nimax plastic mold tool steel is; obtained at the second level of the cutting tool type, the third level of the cutting speed, and at the first level of the feed rate. The main effect graph showing the optimum values of the control factors, namely the hard turning parameters, is given in Figure 6. As in the S/N response table, the largest S/N values in the main effect graph show the optimum level of that parameter. Accordingly, optimum values for cutting tool type, cutting speed, and feed rate were determined as PVD-coated tool, 200 m/min and 0.1 mm/rev, respectively.

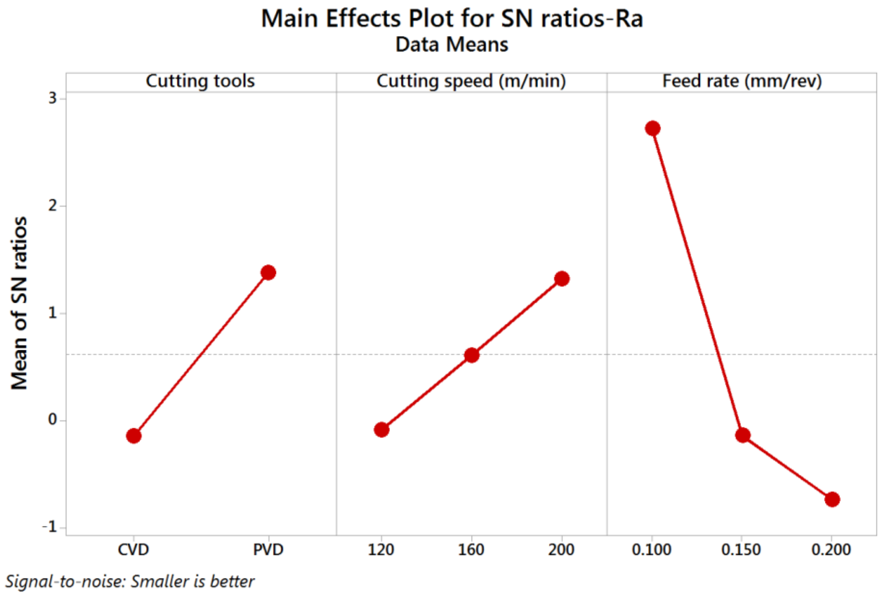

Fig. 6. Main effect plot for S/N ratios.

The results of the analysis of variance performed to determine the percent contribution rates and order of influence of the turning parameters on Ra are given in Table 6. The table shows the F values and percentage effect ratios (Percentage Contribution Ratio-PCR), showing the importance level of each parameter. ANOVA analysis was performed with 95% confidence intervals and 5% significance levels. The influence of the hard-turning parameters is determined by comparing the F values. The parameter with the largest F value is the parameter that affects the result the most.

Table 6. ANOVA table

Source	Degree of freedom (DF)	The sum of squares (SS)	Mean square (MS)	F ratio	P	PCR (%)
Ct	1	0.10427	0.104272	28.89	0.000	16.89
V	2	0.06653	0.033267	9.22	0.004	10.78
f	2	0.40326	0.201630	55.86	0.000	65.32
Error	12	0.04331	0.003609			7.02
Total	17	0.61738				100.00

S = 0.0600788 R-Sq = % 92.98 R-Sq (adj) = % 90.06

According to the results of the analysis of variance, it was seen that the most critical parameter affecting the surface roughness was the feed rate, with a rate of 65.32%. Next comes the cutting tool type with a ratio of 16.89%, and finally, the cutting speed with a ratio of 10.78%.

4. Conclusion

In this study, chip removal experiments were carried out by machining Nimax plastic mold steel with CVD (MT-TiCN + TiC + Al_2O_3 + TiN) and PVD (TiAIN) coated carbide tools at different cutting parameters on a universal lathe. The changes in cutting temperature, vibration, noise, and surface roughness values during the machining were investigated experimentally. Plastic mold steel was processed with a total of 18 different parameters at 120, 160, and 200 m/min cutting speed, 0.10, 0.15, 0.20 mm/rev feed rates, and 0.5 mm depth of cut. The experiments were designed according to the Taguchi L_{18} orthogonal array, and Taguchi optimization was performed to determine the turning parameters giving the lowest Ra values. In addition, the effects of cutting parameters on the average surface roughness were determined by analysis of variance. As a result of the experimental study, the following results were obtained in general:

- In the hard turning experiments, when CVD-coated and PVD-coated cutting tools were evaluated and all cutting parameters were taken into account; generally better surface roughness (Ra) values of PVD-coated cutting tools were obtained than CVD-coated cutting tools.
- the The lowest Ra value for the tool with CVD-coated code was 0.773 μm at 200 m/min cutting speed, 0.1 mm/rev feed rate, and 0.5 mm depth of cut.
- Lowest Ra value for the tool with PVD-coated cutting tools; It was found to be 0.58 μm at 200 m/min cutting speed, 0.1 mm/rev feed rate, and 0.5 mm depth of cut.
- As the cutting speed increased, the surface roughness decreased.
- As the feed rate increased, the surface roughness increased.
- In hard turning experiments, when CVD-coated and PVD-coated cutting tools are evaluated, and all cutting parameters are taken into account, it has been observed that generally PVD-coated cutting tools have higher temperature (°C) values than CVD-coated cutting tools.
- As the cutting speed increased, the temperature increased. As the feed rate increased, the temperature increased.
- In hard turning experiments, when CVD-coated and PVD-coated cutting tools are evaluated, and all cutting parameters are taken into account, it has been observed that generally lower average vibration values of PVD-coated cutting tools than CVD-coated cutting tools.
- Vibration increased as the cutting speed increased. Vibration increased as the feed rate increased.

- In the hard turning experiments, when CVD-coated and PVD-coated cutting tools are evaluated, and all cutting parameters are taken into account, generally lower noise (dBA) values of PVD-coated cutting tools compared to CVD-coated cutting tools.
- As the cutting speed increased, the noise increased. The noise increased as the feed rate increased.
- As a result of Taguchi analysis, the lowest average Ra values were reached at the second level of the cutting tool type (PVD-coated tool), the third level of cutting speed 200 m/min, and the first level of feed speed 0.1 mm/rev for the average surface roughness.
- The Ra value for optimum levels was found to be 0.58 μm.
- According to the ANOVA results, the most influential parameter on Ra was the feed rate (65.32%), followed by the cutting tool type (16.89%) and the cutting speed (10.78%), respectively.

Author Contribution Statement

All authors have contributed equally.

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