Experimental and theoretical analysis of tool life between plasma enhanced CVD and PVD multilayer nanocoated cutting tools

Y Carlin Calaph\textsuperscript{1,3}✉, K Manikanda Subramanian\textsuperscript{1}, P Michael Joseph Stalin\textsuperscript{2} and N Sadanandam\textsuperscript{1}

\textsuperscript{1}Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Tamil Nadu, India
\textsuperscript{2}Department of Mechanical Engineering, Audisankara College of Engineering and Technology, Nellore, India
\textsuperscript{3}Author to whom any correspondence should be addressed.

E-mail: collinntech@gmail.com

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Abstract

Tool life of the traditional cutting tools is comparatively lesser on machining the martensitic stainless steel AISI 416 which is one of the hardest materials. In order to increase the tool life, wear-resistant nanocoatings on the cutting tools have been explored. This study enunciates a comparison of tool life between PECVD (plasma-enhanced CVD multilayer nanocoated) and PVDMNC (PVD multilayer nanocoated) cutting tools on turning a martensitic stainless steel AISI 416 by experimental and theoretical investigations in addition to exploration of the machinability studies of cutting tool flank wear, tool hardness and surface roughness of work material. An orthogonal design, signal-to-noise ratio and Analysis of Variance (ANOVA) methods were employed to confirm the parameters like cutting speed, tool hardness and feed rate that are involved in the study to estimate the cutting tool life. The investigations confirmed that cutting speed was the most dominant factor in determining tool life while comparing with other parameters. It was observed from the ANOVA results that the cutting speed, tool hardness, and feed rate have contributed 41.44%, 33.79%, and 24.35% respectively in determining the tool life of PECVD cutting tools whereas the contributions of the same parameters were found to be 40.01%, 32.90%, and 26.63% respectively for PVDMNC cutting tool. It is evident from the results that the cutting performance of the PECVD cutting tool is superior in terms of cutting speed and hardness which were enhanced by 1.43% and 0.89% respectively in addition to lesser wear rate when compared to the performance of PVDMNC cutting tools.

Nomenclature

\begin{tabular}{ll}
ANOVA & Analysis of variance \\
F & Feed rate (mm/min) \\
CVD & Chemical Vapor Deposition Process \\
V & Cutting speed (m/min) \\
PVD & Physical Vapor Deposition Process \\
S/N ratio & Signal-to-noise ratio \\
PE & Plasma Enhanced \\
MS & Means of squares \\
DOC & Depth of cut \\
DF & Degree of freedom \\
Fva & The value of variance \\
T & Tool life \\
HV & Hardness value by Vickers
\end{tabular}
1. Introduction

Martensitic stainless steel AISI 416 is a hard material that is generally used for manufacturing rotor shafts, turbine blades, pneumatic pistons, etc. Due to its superior thermal properties of martensitic material, it is mainly used in high-temperature environment applications such as nuclear and thermal power plants [1]. A lot of heat is generated while turning of martensitic material with a conventional cutting tool [2]. When the martensitic stainless steel AISI 416 is machined with the conventional cutting tool, the rate of wear of cutting tool is higher. Hence high resistance nanocoatings are being explored on the cutting tool to withstand high wear rate. The cutting tool requires properties such as resistance to wear, hot hardness, resistance to oxidation and thermal shock resistance [3, 4]. In the current scenario, more research work is going on utilizing PVD and CVD nanocoatings on the cutting tools in order to improve their performance [5]. The CVD coatings have high chemical stability that needs a high temperature of around 1000 °C for the process whereas PVD coatings require ionized vaporization deposition at around 500 °C [6]. The CVD method of coatings on the cutting tools is widely applied for improving the cutting performance [7]. Hybrid PVD–PECVD process of titanium sputtering process is used to prepare metal-carbon nanocomposites [8]. In the PVD method of TiAlN coated cutting tools, it is seen that they have less wear resistance than uncoated cutting tools [9]. In the process of the PECVD method of coatings with the material SiCN, the nano hardness and elastic modulus in the intermediate temperature between 300 °C and 700 °C are 30 GPa and 219 GPa respectively when compared to the PVD, CVD coatings which have the values of 13 GPa and 116 GPa respectively. At intermediate temperature, the SiCN coatings have strong bonds comparing to PVD and CVD coatings [10]. Abedi et al [11] revealed that PECVD coatings of TiSiCN and TiCN have shown very good tribological properties along with superior wear resistance. Zhang et al [12] have indicated that PECVD coatings of Al2O3 with a high deposition rate in which alumina acted as a thermal barrier. Muthuraja et al [13] conducted experiments on PECVD—Chromium diamonds like carbon (Cr-DLC) coated nozzle needle surface and revealed that it is to wear protective. Baba et al [14] investigated the PECVD–PVD hybrid nanocoatings of TiO2 on the cutting tool and revealed that the deposition of surface coating is suitable for only self-cleaning surfaces. Asha et al [15] explain that when HCHCr alloy steel machined by multilayer coated carbide inserts the tool life is increased. A comparative study of PVD TiAlN and CVD TiCN/Al2O3 coatings is carried out on turning AISI 4340 steel and found that they have superior wear behavior [16]. Kumar et al [17] explained the wear behavior and surface finish of TiAlN coated carbide cutting tools. Kondo et al [18] reveal the surface roughness, wear of TiAlSiN PVD coated cutting tools and concluded that it has a good surface and wear properties. Sui et al [19] evaluated the performance properties of TiAlN/TiAlSiN composite coated cutting tools. Ma et al [20] exposed the effect of TiAlSiN nanocomposite coated cutting tools on the voltage bias environment. Abedi et al [21] investigated the PECVD and PVD-CVD coatings of TiSiCN and concluded that PECVD coating is better than PVD-CVD coatings.

Previously, many researchers have performed theoretical studies relevant to PECVD and PVD coatings. Only limited literature is presented about the simultaneous experimental analysis of both PECVD and PVD coating processes. Therefore, the present study is undertaken for analyzing the tool life, tool hardness, flank wear and surface roughness of the coatings fabricated using PECVD and PVD processes. This research focuses on the comparison of experimental and theoretical results obtained during the turning of AISI 416 stainless steel using tungsten carbide nanocoated cutting tools.

The study of the important parameters such as tool life, flank wear and surface roughness pertaining to the PECVD and the PVD/MNC coated cutting tools is also included in the scope of this research. A model is developed to predict the tool life with the help of important parameters like cutting speed, feed rate, and tool hardness. The developed model of tool life is confirmed through the Taguchi method and then compared with that of experimental results.

2. PVD and PECVD nanocoating processes

Physical Vapor Deposition (PVD) is one of the vacuum deposition methods in which thin films and coating can be produced for industrial applications. In this process, a very high vacuum is created with the help of a high vacuum pump for converting the material from a condensed phase to a vapor phase before obtaining a thin film
condensed phase using a suitable power supply. Sputtering and evaporation are the most common PVD processes employed in industries. In this experimental study, two numbers of cutting tools have been nanocoated with TiAlN by the PVD method. Figures 1(a) and (b) show the coating principle of PVD and PECVD methods respectively.

In the case of the Plasma Enhanced Chemical Vapor Deposition (PECVD) process, a thin film of nanocoating is deposited on a material with the help of the high vacuum chamber in which chemical reaction is involved. The chemical reaction is involved due to the presence of plasma reacting gases. Two numbers of cutting tools have been nanocoated with TiAlSiN by the PECVD method for the purpose of the experimental study.

3. Experimental procedure

The following experimental procedure has been employed for the purpose of conducting an experimental study on cutting tools:

- Step 1: Selection of cutting tool inserts.
- Step 2: To carry out the experimental study through a suitable experimental setup.
- Step 3: To perform the SEM analysis for the purpose of studying microstructure.
- Step 4: To perform EDX analysis in order to find out the chemical composition in the cutting tool.
- Step 5: To evaluate the hardness of cutting tool after performing work on work material.
- Step 6: Taguchi Optimization Process.

3.1. Selection of cutting tool inserts

Four numbers of triangle-shaped Tungsten carbide uncoated cutting tools (inserts) were selected for the experiment as they are preferred for multiple applications in turning operations. The specifications of the cutting tools are given in table 1.

Two numbers of cutting tools were nanocoated with TiAlSiN by a plasma-enhanced CVD multilayer technique whereas the remaining two cutting tools with TiAlN by PVD multilayer technique. Figures 2(a)–(c) shows the image of an uncoated cutting tool, the TiAlN-PVDMNC cutting tool, and TiAlSiN-PECVD cutting tool respectively.

3.2. Experimental setup

The experiments were conducted using the Kirloskar EP -1675 centre lathe using 50 mm diameter and 1000 mm length martensitic stainless steel AISI 416 as a specimen for the purpose of the study. The specimen is having a hardness of about 45 HRC and composition of C (0.15%), Si (1%), Mn (1.25%), Cr (14%), Mo (0.6%), P (0.06%), S (0.15%) and Fe. The experimental set up of the investigation is shown in figure 3.

The experimental work was carried out on the lathe using the PVDMNC and PECVD cutting tools with the initial cutting speed, feed and depth of cut as mentioned in table 2 to machine the work material. The experimental readings were tabulated as given in table 2 after every turning operation by observing the disappearance of the nanocoating color and the wear on the nose of the cutting tools by the naked eye. The tool lives of the cutting tools were calculated by measuring the time using a stopwatch.
Table 1. Specifications of the cutting tools.

| Type of cutting tool | Tool designation | Edge length | Nose radius | Vickers Hardness Value (HV) | Coating Methods                                      |
|----------------------|------------------|-------------|-------------|-----------------------------|-------------------------------------------------------|
| WT6230               | WNMG 080408      | 0.34        | 0.06        | 1600                        | TiAlSiN - Plasma enhanced CVD multilayer nanocoating (PECVD) |
| WT6230               | WNMG 080408      | 0.34        | 0.06        | 1600                        | TiAIN- PVD multilayer Nanocoating (PVDMNC)             |
The exponential model for mean Tool life ($T_{\text{mean}}$) with variables $V$, $F$ and $TH$ are given in the equation (1).

$$T_{\text{mean}} = CV^pF^mTH^n$$

where $V$ is the cutting speed, $f$ is the feed rate and $TH$ is the hardness of cutting tool. According to Sahin et al [22], a logarithmic transformation can be used to convert the non-linear form of an equation into the linear form of an equation. It is represented in equation (2).

$$\ln T_{\text{mean}} = \ln C + n \ln V + m \ln F + p \ln TH$$

In this experiment, cutting speed ($V$) in m/min, feed ($F$) in mm/rev and Tool hardness ($TH$) in HV (Vickers hardness number) have been taken as control factors which play a vital role in determining the tool lives of the cutting tools. The parameters cutting speed ($V$), feed rate ($F$) values can be taken by the experiment. The hardness value was calculated by the Vickers hardness testing machine which is described in the following section.
3.3. Evaluation of hardness

The hardness of the cutting tool inserts was measured by the Micro Vickers hardness testing machine. The TiAlN and TiAlSiN nanocoated cutting tools inserts were cleaned by pure distilled water and removed moisture by a dry cloth. A square base pyramid diamond intender of 136° was mounted on the testing machine. At first, keeping the TiAlN nanocoated insert specimen on the support table and correcting the position. The table was adjusted vertically to the intender point by column handwheel. The load applied to the specimen through pyramid diamond intender the readings were noted. The experiment is repeated for TiAlSiN nanocoated inserts. The measured hardness value is in the range of 1910 HV-2360 HV.

3.4. SEM analysis

The SEM images of nanocoated TiAlN- PVDMNC and TiAlSiN- PECVD cutting tools are shown in figure 4. From the SEM images, it is seen that the multilayer nanocoating on the tungsten carbide substrate is having a thickness of approximately 4 μm. Also, it was found that the Vickers hardness values of TiAlN- PVDMNC and TiAlSiN- PECVD were in the range of 1910 HV-1990 HV and 2280 HV-2360 HV respectively. It is seen that the Vickers hardness value of TiAlSiN- PECVD is higher than that of TiAlN- PVDMNC which indicates the density of plasma-enhanced CVD nanocoating is better than PVD nanocoatings.

3.5. EDX analysis

The EDX and surface morphology reports of TiAlN-PVDMNC and TiAlSiN-PECVD cutting tools are shown in figure 5. It is seen that both the images have multiple peaks which clearly indicate cutting tools are having multilayer coatings. The surface morphology reveals that Titanium nanoparticles are combined with other elements. In TiAlSiN- PECVD cutting tools scattered silicon particles with bulk, nano-range gives high hardness, high indentation and high dense.

In the PECVD cutting tools silicon is dispersed as quantum well, wire and bulk nanoparticles. The silicon nanoparticles of quantum well, wire and bulk are more along the surface boundary of TiAlSiN nanocoatings. This gives high density and hardness to TiAlSiN PECVD coatings comparing PVDMNC coatings. The atoms molecules of TiAlSiN have a Si-N bond that gives high bonding strength [23, 24].

3.6. Taguchi optimization process

Among many optimization tools, Taguchi method is one of a powerful statistical tool that is widely applied for improving the performance of the machining process with an extensive reduction in time for conducting experiments [25, 26]. A signal-to-noise (S/N) ratio was used to determine the difference between the observed value and predicted value. In this experiment, the Taguchi method is used to optimize the control factors. The control factors are cutting speed (V), Feed rate (F), Tool hardness (TH) and tool life (TL) for the optimization process. The response variation in signal to noise ratio is used to confirm the parameter optimization.

4. Results and discussion

The experimental works were carried out with PVDMNC and PECVD cutting tools on machining AISI 416 material. The theoretical analysis was carried by the Taguchi method form the observed experimental values. An
ANOVA, orthogonal design and signal-to-noise ratio were employed to estimate the parameters. For the theoretical analysis, Minitab17 software is generally used to perform the analysis based on Design of experiments, ANOVA, Regression, etc. In this experiment, the software has been used to convert the experimentally measured values of tool lives ($T_{\text{mean}}$) into theoretical values in terms of Signal to Noise ratio (S/N ratio) using Taguchi method. The corresponding S/N ratio values of the cutting tools PVDMNC and PECVD have been tabulated in table 2. Kondo et al.\cite{18} have also analyzed the S/N ratio values of the PVDMNC cutting tool in an experimental study and the results are agreed with the values mentioned in table 2. The results related to the PECVD cutting tool validated the results obtained by Muthuraja et al.\cite{13}.

4.1. Influence of control factors
In table 2, theoretical values of S/N corresponding to PVDMNC and PECVD cutting tools have been tabulated. Table 3 depicts the S/N response values of tool lives of cutting tools in turning for the control factors which were
derived from table 2. The evaluation was done to find out the difference between the maximum and minimum S/N ratio with level 1, level 2 and level 3 of the Taguchi method. The highly influenced control factor is decided based on the maximum difference in control factors. It is seen from table 3 that the cutting speed (V) is the most dominant factor with a difference of 5.32 dB and 5.02 dB for the PVDMNC and PECVD cutting tools respectively when compared to their tool hardness which has the difference of 4.58 dB and 4.34 dB respectively. Similar results have also been arrived by Sahin [22] in one of the experimental and theoretical analyses of the cutting tools.

4.2. Effects of tool life
The effect of tool life can be found by repeated experiments with the help of optimized results. From table 2, it is observed that the cutting speed (V₁) and feed (F₁) mentioned in the first row have the highest S/N value for both the cutting tools whereas tool hardness (TH₉) in the ninth row has the highest S/N value. These values which are given in table 4 have been taken as optimal controlling factors for second time repeated experiments in order to validate. From the experiment, it is observed that the tool life of PVDMNC cutting tools was 224.45 min and its S/N value was 47.12 dB₁. In the case of PECVD cutting tools the tool life was 287.53 min and its S/N value was 49.173 dB₂ as the optimization method was similar to the one followed by Sahin [22]. Hence it can be concluded that the PECVD cutting tool has an increased tool life than that of the PVDMNC cutting tool.

4.3. Surface plots of tool lives
Based on the experimental results and data collected as in table 2, a three-dimensional surface plots diagram has been drawn between mean tool life (Tmean) and turning variables (Cutting speed, feed rate, and tool hardness) in order to analyze their interaction effects with tool life.

Figures 6 (a) and (b) represent surface plots diagrams showing the relationship among mean tool life, cutting speed and feed rate for the PVDMNC and PECVD cutting tools. At lower cutting speed, the increment in feed rate does not affect the tools life. Whereas at medium cutting speeds, the increment of feed rate affects the cutting tools life. This leads to a decrement in cutting tools life. It is observed that both PVDMNC and PECVD cutting tools perform well at lower cutting speeds and feed rates. Similar results have been reported in one of the studies conducted by Kondo et al [18].

It is seen from figures 6(a) and (b) that the tool life of the PECVD cutting tool is greater than that of the PVDMNC cutting tool while maintaining the cutting speed and feed rate as constant. This is due to the reason that high-density deposition of nanocoating by plasma-enhanced CVD. A similar investigation regarding the PECVD process concerning the speed and feed rates was also reported by Abedi et al [11].

Figures 7(a) and (b) represent surface plots diagrams showing the relationship among mean tool life, cutting speed and tool hardness for the PVDMNC and PECVD cutting tools. At increased cutting speed and feed rate, the PECVD cutting tools have performed better than PVDMNC cutting tools because of its hardness, fracture toughness and resistance to high temperature. The PECVD-TiAlSiN coatings have 83.87% of titanium and 4.55% of Silicon which higher than PVDMNC-TiAlN coatings. Porada et al [10] detail the identical chemical
stability of Si and N bondings. The PECVD-TiAlSiN coatings atomic percentage of Nitrate, titanium, and silicon are higher compared to TiAlN coatings. According to the EDX composition of PECVD-TiAlSiN coatings from figure 5 the Ti, Si, N was producing more continuum intensity than PVDNMC- TiAlN. Wang et al [27] investigated TiAlSiN coatings and bonding characteristics of Ti, Si, N in an experimental study and revealed that Si-N bonding has a superior hardness. It is seen from figures 7(a) and (b) that the tool life of the PECVD cutting tool is greater than that of the PVDNMC cutting tool while maintaining the constant cutting speed and variable tool hardness.

Figures 8(a) and (b) represent surface plots diagrams showing the relationship among mean tool life, feed rate and tool hardness for the PVDNMC and PECVD cutting tools. It is observed from the surface plots that the tool life of the PECVD cutting tool shows more consistency at increased feed and tool hardness when compared to that of the PVDNMC cutting tool in addition to higher tool life. Correa et al [2] justified that feed rate and tool hardness are important parameters for improving tool life.

4.4. Comparison of S/N ratios of cutting tools

Figure 9 depicts the comparison of S/N ratios (dB) versus velocity and feed rate of the cutting tools under investigation. It is observed that the S/N ratio of the PECVD cutting tool is greater than that of the PVDNMC cutting tool at a lower cutting speed of turning operation. At moderate speeds (velocity at 62.83 m min^{-1}), S/N ratios of both the cutting tools are almost equal having the value of 41.6 dB [22]. When the cutting speed is increased above 94.24 m min^{-1}, the S/N ratio of PECVD is slightly higher than that of the PVDNMC cutting tool with a difference of 0.426 dB. When cutting speed is further increased above 102.10 m min^{-1}, the difference between the S/N ratios of both the cutting tools is increased which shows better tool life of the PECVD cutting
tool due to its high dense nanocoating. Sui et al.\cite{19} also reported that the tool life of TiAlN/TiAlSiN cutting tools is better and normal at higher cutting speeds.

### 4.5. Flank wear measurement

The specification of the Profile Projector (PP-200) which was used to measure the flank wear is given in table 5.

Figure 10 shows a schematic view of the profile projector through which flank wear is measured. It consists of a light source that produces a beam of light all the way through the projection lens and condenser lens. A shadow reflection image of the specimen is created for which the magnification is up to 5 to 100.

The flank area of the cutting tool was positioned on the work table. The magnified silhouette of the flank wear (VB) of the cutting tool was projected upon the screen and the VB was measured. The worn flank area was captured through a zoom microscopic lens with a magnification up to 100x. The flank wear (VB) imperfections of the cutting tool are shown on the screen as a 2D space diagram. The average value of four readings is considered for the study and the wear is measured in terms of millimeters (mm). In figure 9 the wear versus cutting speed, the feed rate is plotted.

The wear rate of the TiAlN- PVDMNC and TiAlSiN- PECVD carbide cutting tools and surface roughness of the AISI 416 material are shown in table 6. From figure 11 it is observed that maximum flank wear occurred for both the cutting tools when the cutting speed is reduced less than 47.12 m min\(^{-1}\) because of high friction between flank and work surface\cite{13, 18}. It is also seen that the flank wear of the TiAlSiN- PECVD cutting tool is comparatively less than the TiAlN- PVDMNC cutting tool at medium (70.69 m min\(^{-1}\)) as well as higher...
The reason is that the TiAlSiN-PECVD cutting tool has been nanocoated with dense bonding in addition to silicon nitrate. For TiAlN-PVD cutting tools, flank wear is much higher due to the inability to withstand higher temperatures at higher cutting speeds. In the case of TiAlSiN-PECVD cutting tools, high lubrication of SiN reduces the heat generation. It is seen from SEM image as shown in figure 12 that the wear path of TiAlN cutting tools is much thicker leading to high wear on the flank nose area when it is operated at higher speeds and feed rates. In the case of TiAlSiN cutting tool, the wear path is comparatively thinner on the flank nose area due to less wear rate at higher speeds and feed rates which is observed from the SEM image as shown in figure 13.

As far as surface roughness concerned, it is observed from the figure 14 that the surface roughness of TiAlSiN-PECVD inserts are observed as 1.5 microns when compared to TiAlN-PVD cutting tools which give

| Table 5. Specifications of profile projector. |
|---------------------------------------------|
| **Profile Projector (PP-200)**              |
| **Focusing**                                |
| Through rack and pinion system              |
| **Focus screen**                            |
| Antiglare hard 200 mm diameter with the cross line, rotatable 360° |
| **Contact Nosepiece**                       |
| Single nose or Optionally provided quadrangle ball bearing |
| **Magnification**                           |
| 10x,20x,50x & 100x                         |
| **Work Stage**                              |
| 150 x150 mm with X-Y movement of 25x25 mm   |
| **Working distance**                        |
| 30 mm approx. under 10x magnification       |
| **Micrometer**                              |
| Zero adjustment, 25mm graduations with least count 0.005mm |
| **Illumination**                            |
| Counter illuminator of 12V–100 W & 2 surface lamps of 6V/20W |
| **Optical**                                 |
| Vinyl cover, duster & fuse 2 Nos            |
| **Accessories**                             |
| Objective 40x,80x Halogen Bulb, Digital Micrometers |

![Figure 10. Schematic view of profile projector.](image)

| Table 6. Experimental results for wear rate and surface roughness. |
|---------------------------------------------------------------|
| **Trial SNo** | **V (m/min)** | **F (mm/rev)** | **DOC** | **PVDMNC (VB1)** | **PECVD (VB2)** | **PVDMNC (μm)** | **PECVD (μm)** |
|--------------|---------------|----------------|--------|-----------------|----------------|----------------|----------------|
| 1            | 47.12         | 0.2            | 0.2    | 0.188           | 0.161          | 1.044          | 1.082          |
| 2            | 54.97         | 0.2            | 0.2    | 0.164           | 0.133          | 1.192          | 1.365          |
| 3            | 62.83         | 0.2            | 0.2    | 0.198           | 0.144          | 0.874          | 1.212          |
| 4            | 70.69         | 0.15           | 0.2    | 0.123           | 0.101          | 0.762          | 1.008          |
| 5            | 78.54         | 0.15           | 0.2    | 0.155           | 0.133          | 0.894          | 1.206          |
| 6            | 86.39         | 0.15           | 0.3    | 0.172           | 0.146          | 0.982          | 1.187          |
| 7            | 94.24         | 0.1            | 0.3    | 0.119           | 0.102          | 1.127          | 1.384          |
| 8            | 102.10        | 0.1            | 0.3    | 0.128           | 0.109          | 1.241          | 1.446          |
| 9            | 109.95        | 0.1            | 0.3    | 0.139           | 0.110          | 1.321          | 1.568          |

(102.10 m min$^{-1}$) cutting speeds [13]. The reason is that the TiAlSiN-PECVD cutting tool has been nanocoated with dense bonding in addition to silicon nitrate.

For TiAlN-PVD cutting tools, flank wear is much higher due to the inability to withstand higher temperatures at higher cutting speeds. In the case of TiAlSiN-PECVD cutting tools, high lubrication of SiN reduces the heat generation [21]. It is seen from SEM image as shown in figure 12 that the wear path of TiAlN cutting tools is much thicker leading to high wear on the flank nose area when it is operated at higher speeds and feed rates. In the case of TiAlSiN cutting tool, the wear path is comparatively thinner on the flank nose area due to less wear rate at higher speeds and feed rates which is observed from the SEM image as shown in figure 13.
surface roughness less than 1.3 microns. Hence the surface roughness of TiAlN-PVDMNC is better than TiAlSiN-PECVD due to the deposition of nanoparticles on the sharp edge corners of the cutting tools. Kondo et al. [18] have observed a similar pattern of surface texture in a detailed manner. The quantum well, wire and bulk nanoparticles accumulated on the sharp edges of PVDMNC cutting tools that give smooth surface on turning. From the above results, it is concluded that the PECVD cutting tools can be used for rough surface finish with heavy loads and PVDMNC for high accuracy surface finish with light loads [28].

4.6. Analysis of uncertainty for the results of PVDMNC
Population distribution is normal $n < 30$, $\sigma$ not known, $t$-distribution used with an $n-1$ degree of freedom.

The population means

$$\mu = \bar{T} \pm \frac{t_{n-1/2}}{\sqrt{n}} S$$

In the equations (3), $1 - \alpha = 0.95$ and $\alpha/2 = 0.025$ at 95% confidence interval finding unknown mean population of tool life.

We know that $\pm t_{n-1/2} = 9$df from students ‘t’ distribution 0.05 -8df [22] the value 2.262

Figure 11. Wear versus Velocity, feed rate.

Figure 12. Wear path of TiAlN- PVDMNC carbide tool inserts.
Sample mean, $T$

$$T = \frac{\sum Ti}{n} = \frac{162.41 + 149.66 + 120.34 + 155.46 + 140.33 + 119.66 + 120.34 + 144.51 + 101.46 + 88.65}{9} = 127.73$$

Variance

$$\sigma^2 = \frac{(T_i - \bar{T})^2}{9} = 760.289$$

Population standard deviation $\sigma = 27.57$

Sample standard deviation (S) can be calculated from the following equation

$$S^2 = \frac{\sum (T_i - \bar{T})^2}{n - 1}$$

and $S = 29.45$

Estimated standard error, $\sigma_x = \frac{S}{\sqrt{n}}$, $\sigma_x = 9.743$
Estimation of population parameters $\mu$ can be obtained using equation (3)

$$\mu = 127.73 \pm 2.262 \times 9.743 = 127.73 \pm 22.039$$

$$\mu_{\text{upper}} = 127.73 + 22.039 = 149.77 \text{ min}$$

$$\mu_{\text{lower}} = 127.73 - 22.039 = 105.69 \text{ min}$$

### 4.7. Analysis of uncertainty for the results of PECVD

In this analysis, the mean tool life of cutting tool has been evaluated by using a normal distribution curve with population $n < 30$ and unknown standard deviation ($\sigma$) as well as t-distribution with $n−1$ degree of freedom.

The population mean is given by $\mu = \bar{T} \pm t_{\alpha/2,(n−1)} \frac{S}{\sqrt{n}}$ (7)

In equation (3), the value of $1− \alpha = 0.95$ and $\alpha/2 = 0.025$ at 95% confidence interval finding the unknown mean population of tool life.

Students ‘t’ distribution is given by $t = t_{\alpha/2,(n−1)}$ for $n−1 = 9df$ from 0.05 – 8df [22] and its value is 2.262

Sample mean, $\bar{T}$

$$\bar{T} = \frac{\sum T_i}{n} = \frac{196.55 + 165.46 + 121.21 + 168.77 + 146.81 + 128.74 + 151.77 + 141.88 + 110.25}{9}$$

$$= 147.94 \text{ min}$$ (8)

Variance, $\sigma^2$

$$\sigma^2 = \frac{(T_i - \bar{T})^2}{9} = 628.90$$ (9)

Population standard deviation $\sigma = 25.07$

Sample standard deviation (S) can be calculated from the following equation

$$S^2 = \frac{\sum (T_i - \bar{T})^2}{n−1} \text{ and } S = 26.60$$ (10)

Estimated standard error, $\sigma_x = \frac{S}{\sqrt{n−1}} \sigma_x = 8.866$

The estimation of population parameters $\mu$ can also be found using equation (7)

$$\mu = 147.94 \pm 2.262 \times 8.866 = 147.94 \pm 20.054$$

$$\mu_{\text{upper}} = 147.94 + 20.054 = 167.994 \text{ min}$$

$$\mu_{\text{lower}} = 147.94 - 20.054 = 127.886 \text{ min}$$

The uncertainty values for the both the cutting tools are shown in table 7.

### 4.8. Analysis of variance

The ANOVA was used to examine the design parameters which considerably influence the quality distinctiveness of the tool life for the turning process and to test the ability of the representation. The ANOVA software of Minitab 17 was used to find the tool lives of the cutting tools shown in table 8. In the turning operation, a mathematical model was developed and examined in order to find suitable optimized parameters. The value of variance ($F_{va}$), the degree of freedom, the sum of squares (SS), $F_{va}$—ratios, and percentage of each factor contribution (P)-values are interrelated with each other. The analysis was carried out at a 90% level of confidence to estimate the calculation. The $F_{va}$ value of each parameter was calculated separately. The cutting speed with high influence of $F_{va}$ —value for PVDMNC cutting tools was 131.25 whereas its value for PECVD
cutting tools was 155.93. The \( F_{v,a} \)—values of feed rate, TH value for PVDMNC cutting tools were found to be about 87.39 and 107.92 respectively and for PECVD cutting tools the \( F_{v,a} \)—values of those were about 91.68 and 127.18 respectively.

5. Conclusion

An experimental investigation was carried out to compare the tool life performance between PECVD (plasma-enhanced CVD multilayer nanocoated) and PVDMNC (PVD multilayer nanocoated) cutting tools on turning martensitic stainless steel AISI 416 hard material.

The following conclusions are drawn from the experimental as well as theoretical results:

- The tool lives of cutting tools with identification of the most and least dominant cutting parameters were determined.
- The S/N ratio results show that the value of the S/N ratio of the PECVD cutting tool is enhanced when the cutting speed is increased above moderate speeds which shows better tool life of the PECVD cutting tool due to its high dense nanocoating.
- The ANOVA results at 90% of the confidence level also indicated that the contribution of the cutting speed was more significant than other parameters.
- The cutting speed, tool hardness, and feed rate have contributed to the tune of 41.44%, 33.79%, and 24.35% respectively for PECVD cutting tools.
- The contributions of cutting speed and tool hardness were diminishing by 1.43% and 0.89% respectively in the case of PVDMNC cutting tools.
- The wear rate of PECVD cutting tools is comparatively lesser than PVDMNC cutting tools.
- The much-improved surface roughness of AISI 416 material was obtained when it is a machine with PVDMNC cutting tools.
- The performance of the PECVD cutting tools in terms of tool life is superior to that of the performance of PVDMNC cutting tools.
- The performance of the PVDMNC cutting tools in terms of surface roughness is superior to that of the performance of PECVD cutting tools.

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ORCID iDs

Y Carlin Calaph  https://orcid.org/0000-0002-3293-6976
P Michael Joseph Stalin  https://orcid.org/0000-0002-5532-1798
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