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PCBN Tool Insert Wear Behavior Investigation and Optimization of Cutting Parameters When Hard Turning Hardened 42CrMo4 Steel.

[1]Musonda Emmanuel Kabaso and [2]Chen Yongjie

[1,2]Huazhong University of Science and Technology, School of Mechanical Science and Engineering, 1037 Luo Yu Road, Wuhan, Hubei 430074, P. R. China.

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ABSTRACT

Background: Better usage of polycrystalline cubic boron nitride (PCBN) turning tools can effectively be realized with a detailed understanding of PCBN tool wear patterns and models. Individual cutting parameter influences on the general tool wear patterns were quantitatively evaluated on the basis of appropriate physical and mathematical modeling approaches. Optimal turning parameters (cutting speed and feed rate) based on the Taguchi method to minimize surface roughness, cutting force and tool wear and to maximize tool life were selected. **Objective:** The goal of this experimental analysis was to observe the behavior of a PCBN tool during hard turning of Chromium-Molybdenum Alloy Steel (42CrMo4) to add empirical experimental data in this field to advance the use of PCBN cutting tools in industry. This is because in most cases the practicality of hard turning using a PCBN tool for a specific hard turning application requires experimental evidence for it to gain industrial application. **Results:** The outcomes indicated that PCBN tool suggests good wear resistance regardless of the aggressiveness of the $42CrMo_4$ at 62HRC. Even when the tool wear *VB* reached 0.3 mm, the majority of the recorded R_a values did not exceed 1 micrometer at the various speeds tested. ANOVA results indicated that feed rate had more effect than the cutting speed on the tool life, tool wear and surface roughness. **Conclusion:** The correlation of tool wear *VB* and surface roughness R_a established allows obtaining experimental empirical data on the cutting tool wear from measured surface roughness for practical use in industry. In addition, using appropriate combinations of speed and feed rate allows successful use of PCBN tools to machine hard materials with satisfactory results comparable to grinding and to economically prolong tool life.

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INTRODUCTION

Despite the obvious benefits of hard turning, further application of hard turning has been hindered mainly due to limited understanding of tool wear and tool failure. Furthermore, lack of suitable cutting conditions in the use of PCBN tools currently present a huge gap for the process to be effectively used in industry. Moreover, in order to minimize or eradicate the possibility of scrapping an expensive part, the most appropriate cutting conditions before a part is put into production must be determined. Therefore, this study hoped to add empirical experimental data in this field to advance the use of PCBN cutting tools in industry.

Currently hard turning application is further enhanced by the use of new materials such as Polycrystalline cubic boron nitride (PCBN) for making cutting tools (Dawson & Kurfess, 2006). However, the machining of these materials is becoming difficult due to the quality and precision requirements in most industries. Nevertheless, many difficult-to-machine, highly abrasive materials are becoming ideal for the application of PCBN tools. This is because these tools are able to achieve high quality and economic efficiency comparable to that of grinding. The possibility of high speed, long tool life, highest surface quality, optimal process reliability and repeatability has made PCBN cutting tools gain even more importance in the mechanical manufacture of new and harder materials. In addition, dry cutting presents ecological benefits for manufacturing enterprises by reducing overhead costs and protecting the environment because of the possibility of excluding cutting coolants (Haron *et al*., 2007).

The application of hard turning technology can further be improved by utilizing advanced optimization algorithms, which in turn helps manufacturers make informed decisions under multiple objectives that need to be satisfied (Tonshoff *et al*., 1996; Koning, 1984).

Corresponding Author: Musonda Emmanuel Kabaso, Huazhong University of Science and Technology, School of Mechanical Science and Engineering, 1037 Luo Yu Road, Wuhan, Hubei 430074, P. R. China.

In the past few decades, the applications of stainless steel materials have immensely increased in various engineering fields. The combination of good corrosion resistance, high wear resistance, wide range of strength levels, high surface finish, good formability and aesthetically pleasing appearance have made stainless steels as a good choice for a wide range of applications. But, their machinability is more difficult compared to other alloy steels due to low thermal conductivity, high built-up edge (BUE) formation tendency and high deformation hardening.

Tool Wear and Tool Life:

Since hardened parts are processed in hard turning, the tool wear is an important issue as cutting tools is subjected to high pressures and temperatures. In order to resist tool wear in these harsh cutting conditions tools should have high hardness, high thermal conductivity, high strength, chemical stability, and low thermal expansion coefficients. Many authors advocate that, the failure of the cutting tool is as a result of premature failure of the tool (ie, tool breakage) and progressive wear of the tool (Roy S., 2010). Generally, the wear of the cutting tool depends on the tool material and tool geometry, workpiece materials, cutting parameters (feed rate, cutting speed and depth of cut etc.), coolants and machine characteristics.

Meanwhile, Tool life in many studies has been found to be very sensitive to feed rate and cutting speed (Arsecularante *et al*. 1998). In addition, workpiece microstructure and hardness has shown to have had a profound effect on the tool life of the PCBN tools (Barry & Byrne, 2001;Tonshoff *et al*., 1996;Matsumoto *et al*. 1987;Thiele & Melkote, 1999).

The Taylor tool- life equation (1) enables the evaluation of tool life data and can be used to predict tool life as well dispersion and confidence intervals.

$$V_c \; x \; T_c^{-1/k} = C \qquad (1)$$

Experimental Modeling and Optimization of Cutting Conditions in Hard Turning:

Modeling and optimization of cutting processes has concerned a number of scholars in view of its important impact to the overall product cost (Merchant, 1998). The optimized machining parameters are vital especially to reduce cost and maximize production rate. The efforts to model cutting process are still ongoing because understanding machining process parameter has great influence on the economics of cutting. Taguchi Method among the latest techniques for optimization (Taguchi *et al*., 1989) is widely being used in industries for making selecting optimal machining parameter. Several researchers have used the Taguchi method in their experimental studies to select optimization machining parameters with successful results (Aslan *et al*., 2007;Yang & Tarng, 1998;Zhang & Chen, 2009;Bhattacharya *et al*., 2009;Sahin, 2009).

In summary, the cited literatures confirmed that Taguchi method in combination with other techniques can be very useful in determining optimal cutting parameters for a given cutting operation. It further reviewed that limited investigations have been carried out on the machining characteristics of chromium-molybdenum alloy steel (42CrMo$_4$).

Taguchi method Design of experiments: Orthogonal arrays:

(Roy K., 2001) described how to fulfill the practical potential of Design of Experiments (DOE) with a powerful, 16-step approach for applying the Taguchi method. Taguchi design procedure can essentially be divided into three steps: (i) system design, (ii) parameter design and (iii) tolerance design (Byrne & Taguchi, 1987). The parameter design stage among the three stages is considered to be the most significant stage.

Signal-to-Noise Ratio (SNR) and its Significance:

The signal-to-noise ratio needs to be computed for each test conducted in order to determine the influence of each variable on the output. (Asilturk & Akkus, 2011)

In the case of performance characteristic minimization(smaller-the-better case), the definition of the *SN* value should be calculated as folows:

$$SN_i = -10 \log \left(\sum_{u=1}^{N_i} \frac{y_u^2}{N_i} \right) \qquad (2)$$

In the case of maximizing the performance characteristic, the *SN* ratio should be calculated according to the following definition :

$$SN_i = -10 \log \left[\frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{y_u^2} \right] \qquad (3)$$

To predict and confirm the quality characteristic at the optimal level the estimated SNR ($\hat{\eta}$) was used. The expected SNR $\hat{\eta}$ at the optimal level of the design parameters can be computed by the following equation (Yang & Tarng, 1998).

$$\hat{\eta} = \eta_N + \sum_{i=1}^{o} (\bar{\eta}_i - \eta_N) \tag{4}$$

η_i is the mean SNR at the optimal level, η_N is the total mean SNR ratio, and 'o' is the number of the main design parameters that influence the quality characteristic.

Analysis of Variance (ANOVA):

The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the quality characteristic. This is accomplished by separating the total variability of the SNR, which is measured by the sum of the squared deviations from the total mean SNR, into contributions by each of the design parameters and the error. To identify the design parameters that significantly affect the response the ANOVA analysis is carried out. The total sum of the squared deviations (SS_T) is computed using the following equation.

$$SS_T = \sum_{i=1}^{n} [\eta_i - \eta_N]^2 \tag{5}$$

The number of experiments is n, η_i is the mean SNR for the i^{th} test and η_N is the total mean SN ratio. The two sources of the SS_T are the sum of the squared deviations (SS_d) due to each design parameter and the sum of the squared error (SS_e). Statistically, the F test named after Fisher (Lin *et al*., 2001) is used to calculate which design parameters have a significant effect on the quality characteristic. The F value for each design parameter is the ratio of the mean of squared deviations (SS_m) to the mean of squared error. Normally, when $F>4$, it means that the change of the design parameter has a significant effect on the quality characteristic (Yang & Tarng, 1998; Lin *et al*., 2001).

MATERIALS AND METHODS

Cutting Tool Material:

In this study, a PCBN cutting tool insert of the standard designation CNGA120408S01030AWH was used for hard turning $42CrMo_4$ steel.

Workpiece Material:

The selected work piece material for investigation was chromium-molybdenum alloy steel ($42CrMo_4$) HRC 62 with the compositions as depicted in Table 1. The material's mechanical properties are outlined in Table 2. The length and diameter of the parts used in the tests were 450 mm and 148 mm, respectively.

Table 1: Chemical composition of chromium-molybdenum alloy steel ($42CrMo_4$).

C	Cr	Mn	Mo	P	Si	S	Fe
0.405	0.95	0.875	0.2	≤ 0.035	0.225	≤ 0.040	97.278 Bal.

Table 2: Mechanical properties of chromium-molybdenum alloy steel $42CrMo_4$).

Hardness, Brinell BHN	Hardness, Rockwell HRB	Tensile Strength, Ultimate	Tensile Strength, Yield	Elongation (in 50 mm)	Reduction of Area
197(105)	62	655 MPa	415 MPa	25.7 %	56.9 %

Experimental Procedure and Experimental Plan:

To understand both the wear behavior and tool life, two parts of long term experimental tests according to ISO 3685 standard were performed to make use of the well-known Taylor life model (ISO3685, 1993).The first part of this experimental analysis was to observe the behavior of the PCBN tool insert during hard turning of chromium - molybdenum alloy steel (42CrMo4). Tool wear was examined under the following hard turning cutting parameters: cutting speed (V_c) ranging from 105 to 200 m/min, feed rate (f_n) of 0.15 mm/rev and cutting depth (a_p) of 0.5 mm. A permissible flank wear value [VB] of 0.3 mm was adopted for the PCBN tool life. However, wear values were acquired beyond this limit to observe the inclusive PCBN tool wear behavior, under severe conditions.

The second part involved computation of optimal turning parameters (cutting speed and feed rate) based on the Taguchi method to minimize surface roughness, cutting force and tool wear and to maximize tool life. To achieve the computation of optimal cutting parameters, three different cutting speeds (105, 140 and 170) m/min) with three different feed rates (0.15, 0.2 and 0.3 mm/rev) and a constant depth of cut (0.5 mm) were used to carry out the tests. The statistical methods of signal to noise ratio (SNR) and the analysis of variance (ANOVA) were applied to see which process parameters were statistically significant.

The Semi-Automatic DMTG - CW6163E horizontal turning lathe with a variable spindle speed between 7.5 and 1000 rpm and a power rating of 11 kW was used to conduct the turning experiments. A PCBN cutting insert of the standard designation CNGA120408S01030AWH was mounted on a PCLNR2525M12 turning Tool-Holder 95° right hand cutting 25x25mm of 32mm shank width and 150mm long. The surface roughness was measured using a Mitutoyo 178-561-02A Surftest SJ-210 surface roughness tester. Cutting force was measured by interfacing Kistler dynamometer (9129AA) and charge amplifier (5070A) with a data acquisition system type 5697A (DAQ) in three components according to the directions X, Y and Z. A permissible flank wear value [VB] of 0.3 mm was adopted for the PCBN tool life. The layout of the equipment for force measurement and tool wear measurement is depicted in Fig. 1.

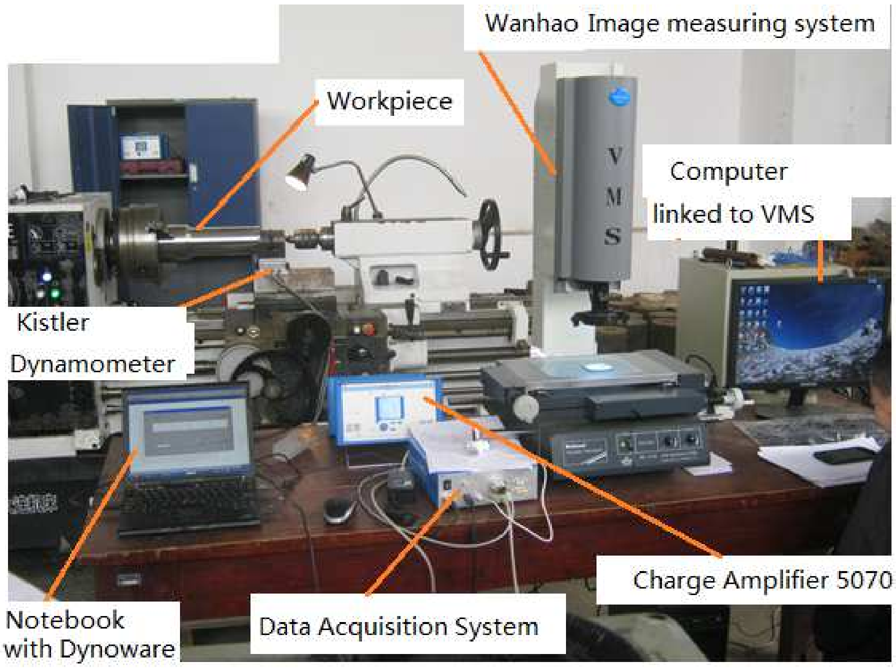

Fig. 1: layout of the equipment for force measurement and tool wear measurement.

Results and Discussions of Tool-Life Data Evaluation:

By fitting a straight line through several observations a more accurate linear regression analysis mathematical method was used to get a measure of the dispersion together with the significance confidence interval limits. The method of least squares was used to fit the line which entailed that the sum of the squares of the deviations between the observation points and the line was minimized. The procedure and calculation are presented in Table 3.

Table 3: Computation Schedule for Calculation of Regression Line $y = a + k(x - \bar{x})$.

1	2	3	4	5	6	7	8
Obsn. No.	Vc, m/min	T_C min	$x = \log Vc$	$y = \log Tc$	xy	x^2	y^2
1	105	203	2.021	2.307	4.664	4.085	5.325
2	105	223	2.021	2.348	4.746	4.085	5.515
3	105	44	2.021	1.643	3.322	4.085	2.701
4	140	102	2.146	2.009	4.311	4.606	4.034
5	140	60	2.146	1.778	3.816	4.606	3.162
6	140	3	2.146	0.477	1.024	4.606	0.228
7	170	68	2.230	1.833	4.087	4.975	3.358
8	170	35	2.230	1.544	3.444	4.975	2.384
9	170	2	2.230	0.301	0.671	4.975	0.091
10	200	48	2.301	1.681	3.869	5.295	2.827
11	200	6	2.301	0.778	1.791	5.295	0.606
12	200	0.5	2.301	-0.301	-0.693	5.295	0.091

The calculated constants k and C in the Taylor tool-life equation for the observations were -4.688 and 292,536 m/min respectively. The parameter C is the cutting speed corresponding to a one-minute tool life on the log-log plot of the tool life data. Equation (1) of the Taylor tool -life equation for the investigated data was therefore;

$$292.536 = V_C T_C^{-1/-4.688} \text{ or } 292.536 = V_C T_C^{0.213} \text{ or } T_c = e^{7.181} V^{-4.688} \quad (6)$$

The computed s_R^2/S_r^2 ratio of 5.681was greater than the *F*-value (4.96) in the *F*-table showing that the observed relationship should not be considered as a result of chance.

Confidence interval limits for the complete line were computed by using quantities obtained from Table 4 and 5. The 95% level of confidence was chosen and the two-sided *t*-value read from the Student's *t*-table for the number of degrees of freedom equal to $n - 2$ was 2.228.

The maximum and minimum constants for *k* were -9.075 and -0.302 respectively. While the maximum and minimum values for the constant *C* were 188.327 and 347.536 respectively. Having computed the cutting speed ranges in which the tool cutting parameter can be determined using the established equations we next examine the cutting speed influence on wear of the cutting tool.

Effect of Cutting Speed on Tool Wear:

Outcomes on PCBN tool wear progression (flank) as a function of cutting time for cutting speeds of 105, 140, 170 and 200 m/min, are depicted in Fig. 4.

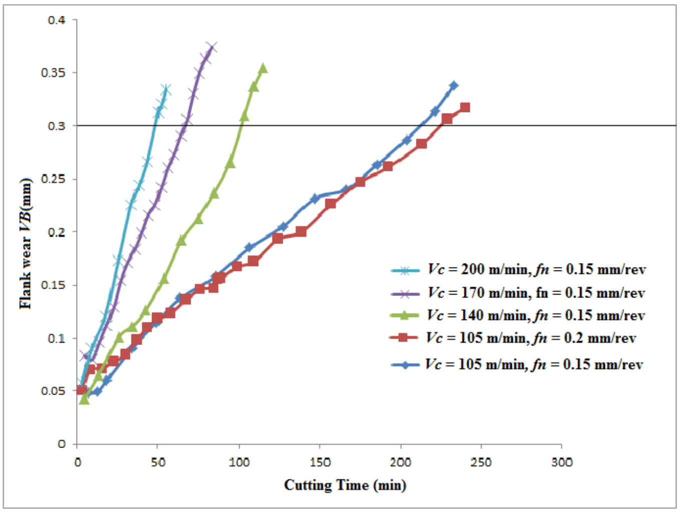

Fig. 2: Progression of Flank Wear (*VB*) as a Function of Cutting Time (Minutes).

As observed from the Fig.4 the increase in cutting speed had great influence on the tool wear behavior as swift rise of the wear commenced from the cutting speed of 140 m/min.

Effect of Wear on Roughness:

Outcomes of Flank wear *VB* on surface roughness are depicted in Fig.3 and Fig. 4, for cutting speeds of 105 and 170 m/min.

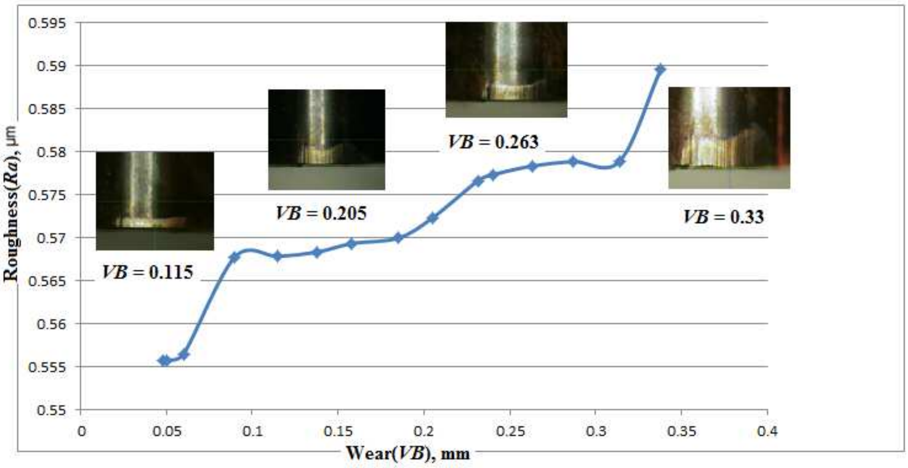

Fig. 3: Influence of Wear on Roughness at V_c = 105 m/min; f_n =0.15m/rev; a_p = 0.5 mm.

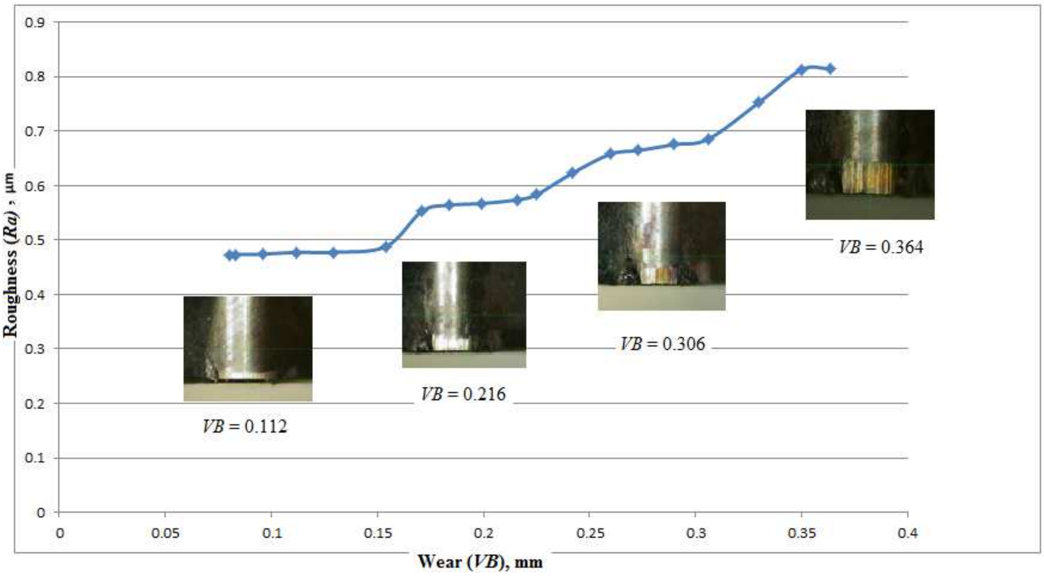

Fig. 4: Influence of Wear on Roughness at $V_c = 170$ m/min; f_n =0.15m/rev; a_p = 0.5 mm.

During the cutting process there was no significant stable or uniform roughness value for surface roughness *(R_a)*, but sudden roughness increments as a function of machining time were noted. The uneven surface attained on the faces and cutting edges of the active tool part led to the degradation of roughness of the machined material. However, during a large portion of the machining time the curves indicated that PCBN ensured decent surface roughness quality. At 105 m/min even after 200 minutes of cutting the surface roughness R_a did not go beyond 1 µm. In fact for all the higher speeds of 140, 170 and 200 m/min the roughness R_a remained lower than 1µm within the flank wear of 0 to 0.3 mm. Microscopic observations of the tool nose Fig. 4 explains the change in the surface roughness behavior as the function of *VB* wear. The R_a values above 0.8 towards the end of machining could be attributed to the large width of flank wear and significant notch wear. Nevertheless, the surface roughness quality had similar pattern of very minimal variations even for speeds of 140 and 200 m/min.

Mathematical models for Tool Life:

Outcomes attained from Fig. 2 permits the establishment of tool life models according to least square analysis for *VB* = 0.3 mm limit wear standards explained by the equations in Table 4.

Table 4: Tool life Mathematical Models as a Function of Cutting speed for f_n = 0.15, 0.2, 0.3mm/rev.

V_c, m/min	f_n, mm/rev	Mathematical Models	R^2
105 140 170 200	0.15	$T_c = e^{5.221}V^{-2.232}$	0.999
105 140 170 200	0.2	$T_c = e^{7.554}V^{-5.223}$	0.934
105 140 170 200	0.3	$T_c = e^{8.108}V^{-6.608}$	0.956

The coefficients R^2 determined for the recommended models are close to unit especially at f_n = 0.15, giving a decent correlation with the experimental outcomes. The coefficients R^2 varied from 0.934 to 0.999 in the cases above with highest at f_n = 0.15 mm/rev. Consequently, the established models can assist in the construction of Taylor straight line drawn on a bi-logarithmic scale in Fig.5 for the wear criteria [*VB*] =0.3 mm.

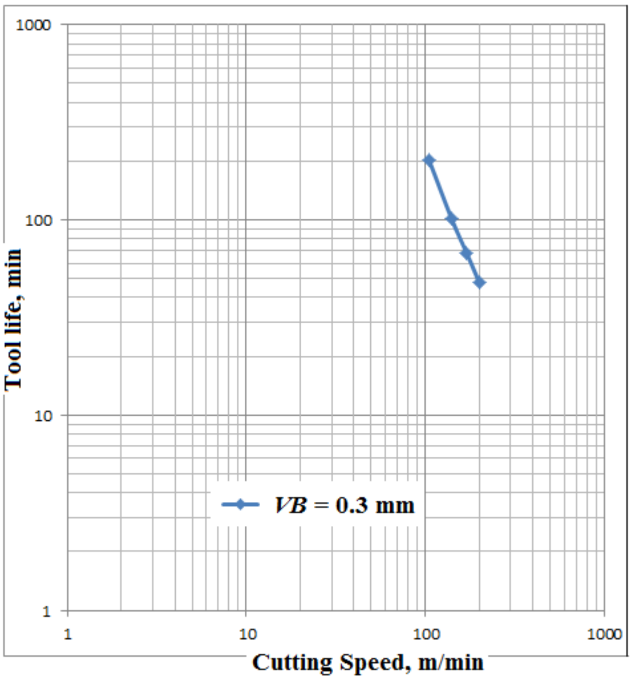

Fig. 5: Effect of Cutting Speed on Tool Life Using Taylor Straight Lines at V_c = 105 m/min; f_n =0.15m/rev; a_p = 0.5 mm.

The line allows us determine economically the PCBN tool life when machining AISI 4140 steel hardened to 62 HRC, at any designated cutting speed ranging from 105 to 200 m/min.

Surface Roughness Mathematical Models:

To appreciate the interaction between tool wear and workpiece roughness, it is prudent to propose a relation linking Roughness (R_a) to wear (VB). Even though VB and R_a are correlated to different parts, it is acknowledged that each one jointly influences the other and must conform to an independent relationship. Data scrutiny from the roughness-wear (VB) curves (Fig. 3-4 allowed the development of general mathematical model in the equation:

$$R_a = K \exp [\alpha (VB)] \tag{7}$$

The numerical values of the constants K and α are presented in Table 5. The method suggests the possibility of regulating VB making use of values of roughness measured from the workpiece and simultaneously calculating the remaining tool lifetime.

Table 5: Roughness Mathematical Models as the Function of Wear VB for f_n = 0.15 mm/rev

Cutting Material	Vc, m/min	Mathematical Models	R^2
PCBN CNGA120408S01030AWH	105	$R_a = 0.554\ e^{0.167VB}$	0.915
	140	$R_a = 0.334\ e^{5.272VB}$	0.967
	170	$R_a = 0.384\ e^{2.006VB}$	0.970
	200	$R_a = 0.576\ e^{1.395VB}$	0.858

The recommended models can be utilized to estimate roughness (R_a) as a function of wear VB or the other way around. The coefficients R^2 varied from 0.858 to 0.97 in the cases above with highest at V_c = 170.

Optimization of Cutting Parameters:

In the current research work cutting parameters and their levels used for optimization are presented in Table 6 while Table 7 shows the L_9 Orthogonal Array (OA) used for the test layout.

Table 6: Cutting Parameters and Their Levels

Symbol	Cutting Parameter	Level 1	Level 2	Level 3
V_c	Cutting Speed (m/min)	105	140	170
f_n	Feed Rate (mm/rev)	0.15	0.2	0.3

Table 7: Coded Experimental Layout Using L_9 Orthogonal Array

Experiment Number	Cutting Parameter Level	
	Cutting Speed (A)	Feed Rate (B)
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

Signal to Noise Ratio (SNR) and ANOVA Results:

In this research work The-higher-the-better quality characteristic for tool life was taken in order to obtain optimal cutting performance. The experimental results for tool life and the corresponding S/N ratio are shown in Table 8.

Table 8: Experimental Results for Tool Life and S/N Ratio

Experiment No.	Cutting speed (m min−1)	Feed rate (mm rev−1)	Tool life (min)	S/N ratio (dB)
1	105	0.15	203	46.150
2	105	0.2	223	46.966
3	105	0.3	44	32.869
4	140	0.15	102	40.172
5	140	0.2	60	35.563
6	140	0.3	3	9.542
7	170	0.15	68	36.650
8	170	0.2	35	30.881
9	170	0.3	2	6.021

On the other hand, the-lower-the-better quality characteristic for surface roughness, cutting force and tool wear were taken in order to get optimal cutting performance. Surface roughness, cutting force and tool wear with their corresponding SNR experimental results are shown in Table 9.

Table 9: Experimental Results for Surface Roughness, Cutting Force and Tool Wear with Their Respective SNR.

Exp. No.	Cutting Speed (m/min)	Feed Rate (mm/rev)	Surface Roughness R_a(μm)	Cutting Force F_c(N)	Tool wear VB(mm)	SNR Ratio (dB)R_a	SNR Ratio (dB)F_c	SNR Ratio (dB)VB
1	105	0.15	0.555	251	0.016	5.114	-47.993	35.918
2	105	0.2	0.722	350	0.026	2.829	-50.881	31.701
3	105	0.3	1.32	405	0.032	-2.411	-52.149	29.897
4	140	0.15	0.404	265	0.024	7.872	-48.465	32.396
5	140	0.2	0.66	290	0.041	3.609	-49.248	27.744
6	140	0.3	1.279	392	0.046	-2.137	-51.866	26.745
7	170	0.15	0.406	246	0.041	7.829	-47.819	27.744
8	170	0.2	0.64	312	0.042	3.876	-49.883	27.535
9	170	0.3	1.215	357	0.073	-1.691	-51.053	22.734

Table 10: SNR Response Table for Tool Life, Surface Roughness, Cutting Force and Tool Wear.

Cutting Parameters	Mean SNR Ratio (dB)			Max - Min
	Level 1	Level 2	Level 3	
Tool Life				
Cutting Speed	41.995	28.426	24.517	17.478
Feed Rate	40.991	37.803	16.144	24.847
Surface Roughness				
Cutting Speed	2.118	3.221	3.398	1.280
Feed Rate	6.939	3.498	-1.701	8.639
Cutting Force				
Cutting Speed	-50.341	-49.860	-49.585	0.756
Feed Rate	-48.092	-50.004	-51.689	3.597
Tool Wear				
Cutting Speed	32.505	28.962	26.004	6.501
Feed Rate	32.019	28.993	26.458	5.561

By averaging the SN ratios for the experiments 1 to 3 the mean SN ratio for cutting speed at level 1 was computed. By averaging the SN ratios for tests 1, 4 and 7 the mean SN ratio for feed rate at level 1 can be calculated. The mean SN ratio for cutting speed and feed rate at level 2 and 3 are computed in a similar manner.

Table 10 shows the SNR response table for Tool life, surface roughness, cutting force and tool wear of 42CrMo4.

Based on the SNR and ANOVA analyses, the optimal cutting parameters for tool life are the feed rate at level 1(0.15 mm/rev) and the cutting speed at level 1(105 m/min) The greater SN ratio for surface roughness of 42CrMo4 are attained at cutting speed level 3 and feed rate level 1. Hence, the optimal machining parameters for surface roughness of 42CrMo4 are the cutting speed at level 3(170 m/min) and the feed rate at level 1 (0.15 mm/rev). The higher SN ratio for the cutting force was obtained at cutting speed level 3(170m/min) and feed rate level 1(0.15mm/rev). Consequently, the optimum cutting parameters for cutting force were *V3f1*. *V1f1* yielded the higher SN ratio for tool wear. Therefore, the optimal cutting parameters for tool wear were the cutting speed at level 1 (105 m/min) and the feed rate at level 1 (0.15 mm/rev).

Table 11 indicates the ANOVA analysis results for tool life, surface roughness, cutting force and tool wear of 42CrMo4.

Table 11: Tool Life, Surface Roughness, Cutting Force and Tool Wear For 42CrMo4 ANOVA Results.

Cutting Parameters	Degree of freedom	Sum of squares	Mean of squares	F Ratio	Contribution (%)
Tool Life					
Cutting Speed	2	504.87	252.43	9.71	29.60
Feed Rate	2	1096.65	548.32	21.10	64.30
Error	4	103.94	25.99		6.09
Total	8	1705.46			100.00
Surface Roughness					
Cutting Speed	2	2.89	1.44	1.99	2.42
Feed rate	2	113.50	56.75	78.19	95.15
Error	4	2.90	0.73		2.43
Total	8	119.29			100.00
Cutting Force					
Cutting Speed	2	0.88	0.44	1.31	4.06
Feed rate	2	19.43	9.72	28.85	89.72
Error	4	1.35	0.34		6.22
Total	8	21.66			100.00
Tool Wear					
Cutting Speed	2	63.56	31.78	18.56	54.37
Feed rate	2	46.50	23.25	13.58	39.78
Error	4	6.85	1.71		5.86
Total	8	116.91			100.00

The percentage contribution indicates that the feed rate was the more prominent cutting parameter affecting tool life followed by a smaller contribution by the cutting speed. Feed rate and cutting speed had approximately 64.30 % and 29.60 %, respectively as percentage contribution in affecting the tool life of the PCBN tool insert. Likewise, the percentage contribution on surface roughness indicated that the feed rate had more effect on the surface roughness followed by a smaller contribution by the cutting speed. Feed rate and cutting speed had approximately 95.15 % and 2.42%, respectively as percentage contribution in affecting the surface roughness of 42CrMo4. The ANOVA results further indicated that feed rate had a larger effect of about 89.72 % on the cutting force as opposed to only 4.06 % from the cutting speed. In case of tool wear both cutting speed and feed rate had an effect with approximately 54.37 % and 39.78 % contribution respectively. The cutting speed was a more significant cutting parameter followed by feed rate for tool wear.

Predicted and Experimental Results Comparison at Optimal Cutting Conditions:

Tables 12 compared the predicted and experimental tool life, surface roughness, cutting force and tool wear of 42CrMo4 using the optimal cutting parameters.

V1f1 for tool life in Table 12 denotes cutting speed at level 1(105m/min) and feed rate at level 1(0.15mm/rev). The experimental results for Tool life deviate from the predicted values by 36.85 %. On the other hand, the experimental results for surface roughness are near the predicted values with a mere deviation of 9.74%. The cutting force value for the predicted and experimental varied only by 0.540 %. Meanwhile the cutting tool wear predicted and experimental results varied by 11.76 %.

Table 12: Predicted and Experimental Results Comparison for Tool Life, Surface Roughness, Cutting Force and Tool Wear of 42CrMo4 at Optimum Cutting Conditions.

	Optimal Cutting Parameters	
	Predicted	Experimental
Tool Life	*V1f1*	*V1f1*
Level		
Tool Life(min)	368.963	233.000
SNR Ratio (dB)	51.340	47.347
Surface Roughness		
Level	*V3f1*	*V3f1*
Surface Roughness (μm)	0.493	0.445
SNR Ratio (dB)	6.144	7.033
Cutting Force		
Level	*V3f1*	*V3f1*
Cutting Force (N)	266.227	267.673
SNR Ratio (dB)	-48.505	-48.552
Tool Wear		
Level	*V1f1*	*V1f1*
Tool Wear (mm)	0.017	0.015
SNR Ratio (dB)	35.367	36.478

Conclusions:

This research hoped to add empirical experimental data in this field to advance the use of PCBN cutting tools in industry and made the following conclusions.

- The present study outcomes indicated that PCBN tool suggests a good wear resistance regardless of the aggressiveness of the 42CrMo4 at 62HRC. At 200 m/min, the machining system becomes uneven and results in significant sparks and vibrations just after a few minutes. This can be the highest cutting speed when low values of feed rates are used for PCBN tools utilization particularly when cutting hardened AISI 4140 (42CrMo4) steel. It was therefore recommended that to achieve improved tool life, slower cutting speeds (105 m/min) should generally be selected in combination with suitable feed rates (0.15, 0.2 mm/rev).
- It was clear that tool lifetime was sensitive to cutting speed variation. This could be due the presence of high temperatures produced around the tool nose by the cutting process supporting several wear mechanisms (abrasion and diffusion) and subsequently decreasing the cutting tool capacity.
- The coefficients R^2 determined for the quantitative relationships models between the cutting speed and Tool life at various feed rates are close to unit especially at f_n = 0.15, giving a decent correlation with the experimental outcomes.
- Furthermore, a VB and R_a relationship was suggested in the form $R_a = K \exp[\alpha (\mathrm{VB})]$. The parameters k and α, are coefficients that varied respectively from 0.334 to 0.576 and 0.167 to 5.272. By utilizing a combination of lower level feed rate (0.15mm/rev) with higher level cutting speeds (170 m/min) the surface roughness can be minimized. Even when the tool wear VB reached 0.3 mm, the majority of the recorded R_a values did not exceed 1μm at the various speeds tested. This indicates that the PCBN tool can successfully be used for machining hard materials with satisfactory results comparable to grinding.
- Based on the ANOVA analyses and SNR, the optimal cutting parameters for tool life were obtained at level 1 cutting speed (105 m/min) and feed rate at level 1(0.15 mm/rev). The lowest surface roughness for 42CrMo4 was attained at a cutting speed of 170 m/min and a feed rate of 0.15 mm/rev. A combination of 170 m/min cutting speed and 0.15 mm/rev feed rate yielded the lowest cutting force for 42CrMo4. While 105 m/min cutting speed and 0.15 mm/rev feed rate gave the lowest tool wear for 42CrMo4. These different combinations of speed and feed rate can be used to attain the required outcomes economically to prolong tool life.
- Feed rate and cutting speed had approximately 64.30 % and 29.60 %, respectively as percentage contribution in affecting the tool life of the PCBN tool insert. Feed rate and cutting speed had approximately 95.15 % and 2.42%, respectively as percentage contribution in affecting the surface roughness of 42CrMo4. Feed rate had a larger effect of about 89.72% on the cutting force as opposed to only 4.06% from the cutting speed. In case of tool wear both cutting speed and feed rate had an effect with approximately 54.37% and 39.78% contribution respectively.
- Overall, the experimental results are nearer to the predicted values within 12% deviations except tool life which yielded 36, % deviation.

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