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RESEARCH ARTICLE

Optimization of Cutting parameters when Hard Turning Hardened 42CrMo4 steel using the Taguchi Method

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Abstract

The general objective of this research study was to advance a science-based predictable understanding of a polycrystalline cubic boron nitride (PCBN) tool during hard turning of chromium - molybdenum alloy steel ($42CrMo_4$) and establish optimal machining parameters to enhance tool performance. Three different cutting speeds namely 105, 140 and 170 m/min with three different feed rates (0.15, 0.2 and 0.3 mm/rev) at a constant depth of cut (0.5 mm) were used to carry out the experiments. The Taguchi method, statistical methods of signal to noise ratio (SNR) and the analysis of variance (ANOVA) were applied to investigate the effects of cutting speed and feed rate on Tool life, surface roughness, cutting force and tool wear. From the ANOVA analysis it was concluded that the effect of feed rate had more influence than cutting speed, which entails that for improved tool life, slower cutting speeds should generally be selected in combination with suitable feed rates.

Introduction

During the past 30 years or so, many investigations that involve machining of hardened steels with PCBN tools have been reported. These include research on the mechanics of the chip removal process, tool materials, tool wear or life, determination of optimal tool geometry, cutting forces, cutting temperatures, surface roughness or integrity, machine tools, dimensional or form accuracy, residual stresses and work piece microstructure. Furthermore, engineers continue to desire materials that are capable of longer service lives, and processes for shaping those materials into finished products that are capable of maintaining tighter and consistence geometric tolerances and improved surface finish (Choudhury & El-Baradie, 1997). Additionally, 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.

Currently, the research linked to wear of cutting tools in hard turning has been focused on two major aspects. One aspect has been to find out the capability of certain cutting tools to undergo hard turning processes within a reasonable tool life. The other aspect has been to examine tool wear evolution and the behavior of the cutting conditions such that tool life is increased. The deductions of wear studies so far are sometimes contradictory and insufficient. However, a strong influence of cutting speed and the workpiece material has been reported by most authors.

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. Deliberation about optimization of machining parameter commenced as early as 1907 when (Taylor, 1907) recognized the presence of an optimum cutting speed for material removal rate maximizing in single pass cutting operations. Since the 1950's, research on optimization of machining parameter has increased. Unfortunately, the situation is very much valid even nowadays, even after a half century. Nonetheless, the efforts to model cutting process are still ongoing because understanding machining process parameter has great influence on the economics of cutting. To bridge the gap between practice and theory reliable predictive models for numerous technological performance measures must continuously be developed. The prediction of tool life, cutting force and surface roughness in machining is necessary for proper optimization despite it being a challenging task.

The latest techniques for optimization such as Scatter Search technique, Fuzzy Logic, Ant Colony technique, Taguchi technique, Response Surface Methodology, Genetic Algorithm and many others are being applied effectively for selecting optimal process parameters in the area of machining (Shirpurkar et al., 2012). Taguchi Method among these (Taguchi et al., 1989) is widely being used in industries for selecting optimal machining parameters.

For instance(Aslan et al., 2007) conducted an optimization study by machining hardened AISI 4140 grade (63 HRC) using the Taguchi method. For performance evaluation, flank wear (VB) and surface roughness were chosen. The results obtained were analyzed by utilizing variance analysis (ANOVA). It was seen that the VB value decreased as the cutting speed and the depth of cut increased; though, it initially decreased and afterwards increased with the increase of the feed rate. The surface roughness decreased with increasing cutting speed. In contrast, surface roughness increased when the feed rate increased.

(Yang & Tarng, 1998) likewise used the Taguchi method for defining the optimum cutting parameters during hard turning. Cutting speed, feed rate and depth of cut were chosen as cutting parameters. Taguchi signal to noise ratio and variance analysis were used to conclude the effect of the cutting parameters on tool life and surface roughness.

By employing Taguchi techniques (Bhattacharya et al., 2009) similarly examined the effects of cutting parameters on surface finish and power consumption. Their results indicated a significant effect of cutting speed on the surface roughness and power consumption, while the other parameters did not considerably affect the responses.

(Kopac et al., 2002) in their study also considered cutting speed, cutting tool materials, feed rate and depth of cut as input cutting parameters in turning C15 E4 steel. The Taguchi method determined that the cutting speed had the highest effect on surface roughness and better surface roughness values were obtained at higher cutting speeds.

In the meantime, (Sahin, 2009) using the Taguchi method compared the tool life of CBN and ceramic inserts in turning hard steels. The outcome of cutting parameters on tool life were determined by using orthogonal array, signal to noise ratio and variance analysis. It was concluded that the effects of cutting speed, tool hardness and feed rate on tool life were 41.63%, 32.68% and 25.22%, respectively.

(Thamizhmanii et al., 2007) used the Taguchi method for finding out the optimal value of surface roughness under optimum cutting condition in turning SCM 440 alloy steel. They discovered that the causes of poor surface finish were machine tool vibrations and tool chattering whose effects were ignored for analysis. The authors concluded that depth of cut was the only substantial factor which contributed to the surface roughness.

(Kilickap, 2010) explored the use of the Taguchi method and the Response Surface Methodologies (RSM) to minimizing the burr height and the surface roughness in drilling Al-7075. The optimization results revealed that the blend of low cutting speed, low feed rate and high point angle were essential to minimize burr height. The finest outcomes of the surface roughness were found at lower cutting speed and feed rates and at higher point angles.

In addition, (Wang & Lan, 2008) considered four parameters of cutting speed, depth of cut, feed rate and tool nose radius in conjunction with orthogonal array of Taguchi method together with the Grey Relational Analysis (GRA) in their optimization analysis. They contributed a satisfactory technique for improving the multiple machining performances in precision CNC turning with profound insight.

(Shetty et al., 2009) similarly studied the use of Taguchi and Response Surface Methodologies for minimizing the surface roughness. While, (ILhan & Harun, 2011) focused on optimizing turning parameters based on the Taguchi method to minimize surface roughness (R_a and R_z). The statistical methods of signal to noise ratio and the analysis of variance (ANOVA) were applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. Results indicated that the feed rate had the most significant effect on R_a and R_z.

In another work, (Mandal et al., 2011) applied Taguchi method and regression analysis and their results reported that the main contributing factors for the tool flank wear were depth of cut and the cutting speed. The feed rate had less influence on the flank wear.

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 ($42CrMo_4$). Hence, an attempt has been made in this work to optimize the cutting parameters to minimize the surface roughness, cutting force and tool wear during hard turning operations of chromium-molybdenum alloy steel ($42CrMo_4$).This study also focused on optimizing turning parameters based on the Taguchi method to maximize tool life.

1.1. Taguchi method Design of experiments: Orthogonal arrays

The most adverse effect of non-scientific practices of relying on the skill and experience of shop floor machine tool operators for optimal selection of cutting conditions and cutting tools results in decreased productivity due to sub optimal use of machining capabilities. To avoid such shortcomings many researchers have used Taguchi methods to optimize the various machining operations like turning, end milling, drilling, etc. of various alloys. By applying the Taguchi method,(Roy K. , 2001) described how to fulfill the practical potential of Design of Experiments (DOE) with a powerful, 16-step approach. The Taguchi design procedure can essentially be divided into three steps: (i) system design, (ii) parameter design and (iii) tolerance design (Byrne & Taguchi, 1987; Zhang et al., 2007). The parameter design stage among the three stages is considered to be the most significant stage.

1.2. Signal-to-Noise Ratio (SNR) and its Significance

For optimization of static problems, three Signal-to-Noise ratios are of common interest (Asilturk & Akkus, 2011) and are described below.

i. **Nominal-the-best characteristic:** This situation occurs when a definite value is most anticipated, meaning that neither a larger nor a smaller value is desirable. The computation of the SN ratio for the first test is displayed in equation (1) for the specific target value situation of performance characteristic.

$$SN_i = 10\log\frac{\overline{y_i^2}}{S_i^2} \tag{1}$$

Where S_i is the variance and y_i is the mean value. For a given experiment, y_i is the value of the performance characteristic.

ii. **Smaller-the-better characteristic** : In the case of performance characteristic minimization, the definition of the SN value should be calculated as folows:

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

iii. **Larger-the-better characteristic** : This situation is converted by taking the reciprocals of measured data and then taking the SN ratio as in the smaller-the-better case. For maximizing performance characteristic case , the SN ratio should be calculated according to the following definition :

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

Once the optimal level of the design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the design parameters. 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.

1.3. Analysis of Variance (ANOVA)

(Yang & Tarng, 1998) stated that the purpose of ANOVA was to investigate which design parameters significantly affect the quality characteristic of the process. 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 (Yang & Tarng, 1998). 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.

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

The number of experiments is n, η_i is the mean SNR for the ith 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).

2. EXPERIMENTAL PROCEDURE

2.1. Cutting Tool Material

In this study, a PCBN cutting insert of the standard designation CNGA120408S01030AWH was used to perform moderate range hard turning operations on 42CrMo4 steel.

2.2. 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.

2.3. Experimental Plan

Computation of optimal turning parameters (cutting speed and feed rate) was 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 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 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. Machining was also stopped when the notch wear depth was more than 1.00 mm and when the tool was severely broken (catastrophic failure). For purposes of achieving finish machining results applicable in industry, an additional tool life criterion was set such that the machined surface roughness was no more than 1.6μm. The tool wear was observed using Wanhao image measuring instrument VMS-1510G.The layout of the equipment for force measurement and tool wear measurement is depicted in Fig. 1.

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 %

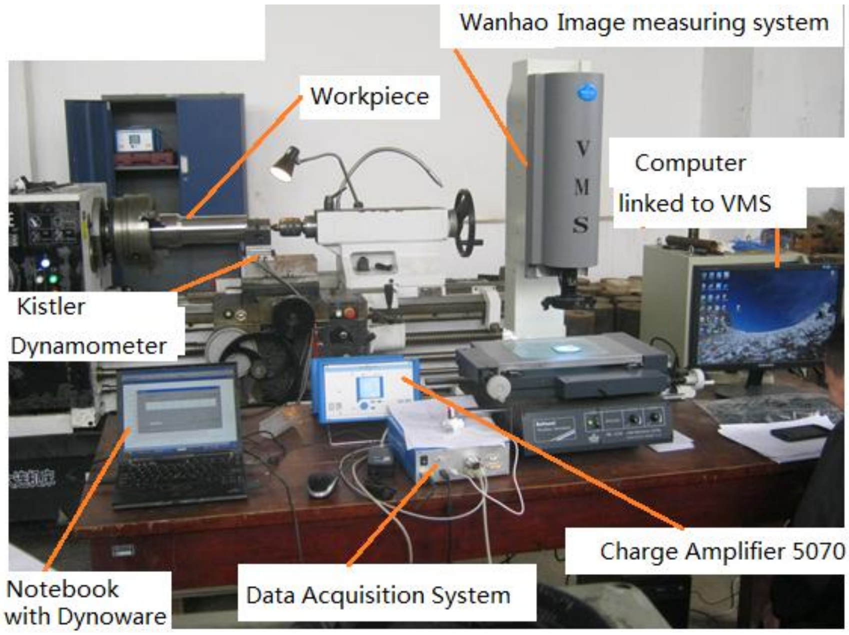


Figure 1: Layout of the Equipment for Force Measurement and Tool Wear Measurement

3. OPTIMIZATION OF CUTTING PARAMETERS

In this study, the cutting speed and feed rate were selected as the main cutting parameters. The depth of cut was taken constant as 0.5 mm being the value that yielded minimum vibrations on the machine and based on the investigation reported by Thakur et al. (2009). To obtain data for process optimization flank wear, cutting force and average surface roughness values were recorded at the two (2) minute machining interval. This was done in order to accommodate small tool life values at combinations of high speed and feed rate values. However, flank wear, cutting force and average surface roughness values were recorded throughout the test period until the tool failure criterion was attained. In the current research work cutting parameters and their levels used are presented in Table 3 while Table 4 shows the L_9 Orthogonal Array (OA) used for the test layout.

Table 3: 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 4: 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

3.2. Signal to Noise Ratio (SNR) and ANOVA Results

In this experimental analysis Tool life was defined as the cutting time that elapsed when the average flank wear land VB of the cutting tool was equal to 0.3 mm. 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 5.

Table 5: 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 6.

Table 6: 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

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

Table 7: Signal to Noise 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

As indicated the larger the SN ratio, the lesser is the change of tool life around the (the-higher-the-better) desired value. It was found that feed rate and cutting speed are the significant cutting parameters affecting tool life. Therefore, 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 was 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).

In the orthogonal experiments conducted ANOVA was used to appraise the response magnitude of each parameter to identify and quantify the origins of different test results from various trial runs. Table 8indicates the ANOVA analysis results for tool life, surface roughness, cutting force and tool wear of 42CrMo4.

Table 8: 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

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.

3.3. Predicted and Experimental Results Comparison at Optimal Cutting Conditions

Once the design parameters optimal level has been chosen, the last step is to predict and confirm the improvement of the quality characteristic by using the optimal level of the design parameters. Using the expected signal to noise ratio equation deliberated by (Yang & Tarng, 1998), the results at optimum cutting condition were computed. Table 9 compared the predicted and experimental tool life, surface roughness, cutting force and tool wear of 42CrMo4 using the optimal cutting parameters.

Table 9: 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

V1f1 for tool life in Table 9 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 %. Overall, the experimental results are nearer to the predicted values within 12% deviations except for tool life. This means that the experimental results validate the prior design and process analysis for cutting parameters optimization. Surface roughness and Tool life in hard turning operations are significantly improved through the approach.

3.4. Cutting Speed and Feed Rate Effect of on Tool Life

Figure 2 depicts the influence of cutting speed and feed rate on tool life.

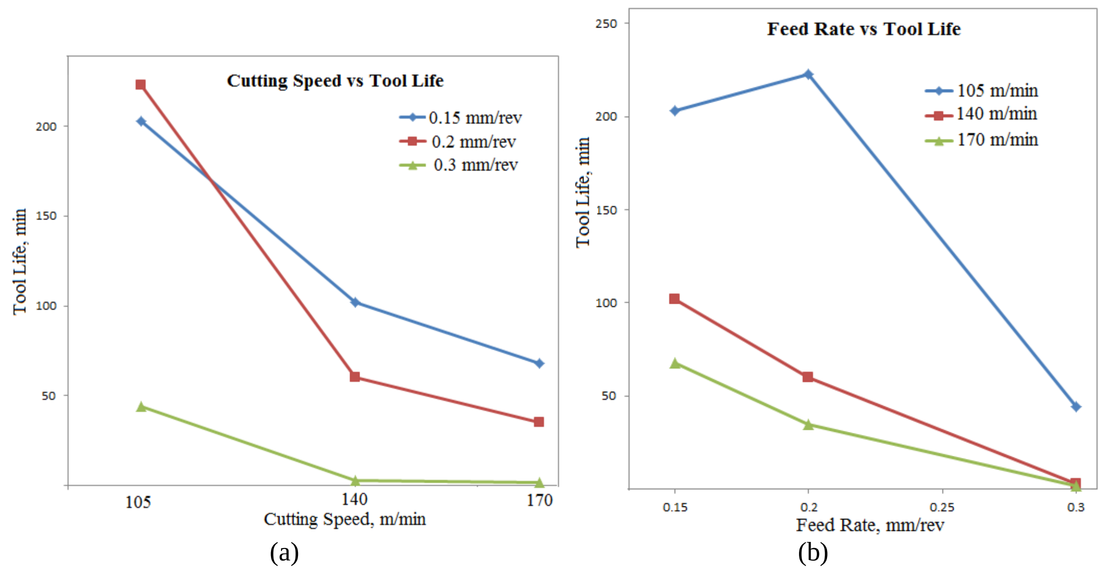


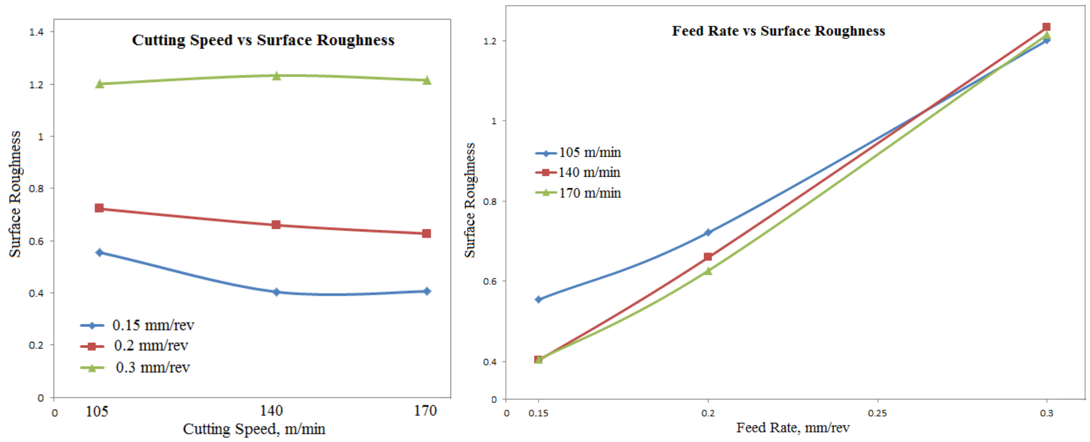
Figure 2: (a) Cutting Speed (b) FeedRate vs. Tool Life of PCBN Tool Inserts

It can be deduced from the Figure 2(a) above that the tool life value decreases when cutting speed increases for all the feed rate values tested. Similar research results by Lin et al. (2001) indicated that the cutting speed had a significant impact on tool life. Comparable trends were reported by (Ciftci, 2006)in turning austenitic stainless steels using CVD multilayered coated cemented carbide tools in which cutting speed was found to have a significant effect on the tool life. It was also noted that maximum tool life occurred with minimum speed for all feed rate values.It is clear that the tool life at105 m/min cutting speed increases until 0.2 feed rate then begins to decreases with increased feed rate. For the other cutting speeds (140, 170) the tool life decreased with increased feed rate. Also it was noted that maximum life happened with minimum feed rate for all cutting speed values apart from 105 m/min, were the maximum tool life was at 0.2 mm/rev. This clearly shows that the effect of increased feed is a more complicated phenomenon. It was also evident from Figure 2(b) that at 105 m/min before the 0.2mm/rev feed rate value, increased feed did not have negative (tool life increase) effect on tool life. The trend was reversed after the critical 0.2mm/rev feed rate value, where increased feed rate essentially reduced tool life by a slight amount (at lower speed level). Nevertheless, this occurrence can be credited to the fact that higher feed rate values reduced tool life in minutes, but actually increased the amount of material that could be removed by the tool.(Naife, 2010).

It was further found that the longest life of the cutting tool was at feed rate (0.2 mm / rev) and cutting speed (105 m/min), where the life of cutting tool was (223 min). The shortest life of cutting tool occurred at feed rate (0.3mm / rev) and (170m/min) cutting speed, where the value of the tool life was about (2 min). It was therefore noted that the feed rate and cutting speed had a direct impact on the longevity of the tool insert. This led to the conclusion that for improved tool life, slower cutting speeds (105 m/min) should normally be selected in combination with suitable feed rates (0.15, 0.2 mm/rev).

3.5. Cutting Speed and Feed Rate Effect of on Surface Roughness

Figure 3 shows the effect of cutting speed on surface roughness of 42CrMo4 for three different feed rates.



(a) (b)

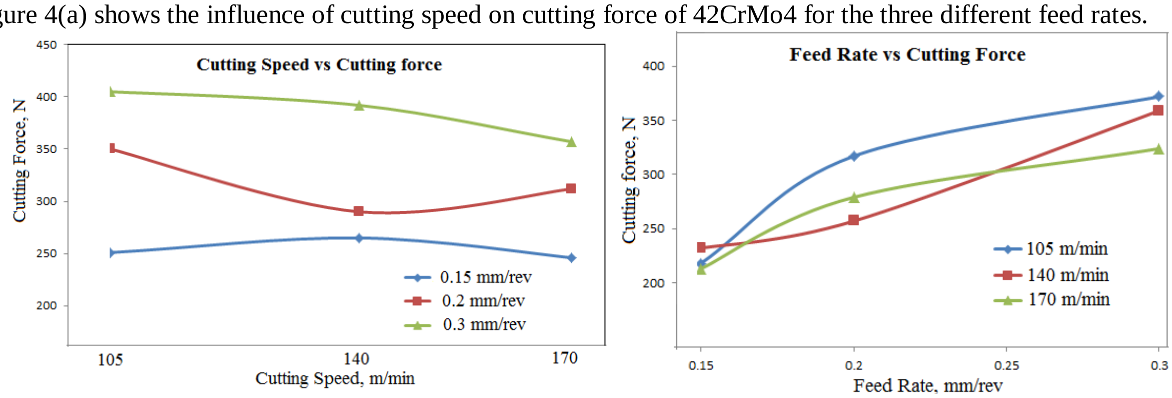
Figure 3: (a) Cutting Speed and (b) Feed Rate vs. Surface Roughness of 42CrMo4

It can be deduced from the Figure 3(a) above that generally the surface roughness value decreases when cutting speed increases for all the feed rate values tested. At 140 and 170 the Ra values are almost similar and the increase in cutting speed from 105 to 170 m/min reduces the surface roughness value due to the reduction in built up edge formation tendency. Similar research results by Lin et al. (2001) indicated that the cutting speed did not have a significant impact on surface roughness. Comparable trends were reported by (Ciftci, 2006) in which cutting speed was found to have a significant effect on the machined surface roughness values. The research further noted that with increasing cutting speed, surface roughness values decreased until a minimum value was reached, beyond which they increased. In addition, (Ciftci, 2006)attributed higher surface roughness values at lower cutting speeds to the high Built up Edge (BUE) formation tendency. Chipping of the cutting edges, were also found to be responsible for the high surface roughness values.

The feed rate influence on surface roughness is depicted in Figure 3(b) for the three different cutting speeds. Due to the increase in friction between work piece and tool interface and temperature increases in the cutting zone the increase in feed rate increases the surface roughness. Therefore, the shear strength of the material lessens and acts in a ductile fashion. Corresponding results by Lin et al. (2001) revealed that increasing feed rate increased the surface roughness value, while the cutting speed does not have a significant impact on surface roughness. 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.

3.5. Cutting Speed and Feed Rate Effect of on Cutting Force

Figure 4(a) shows the influence of cutting speed on cutting force of 42CrMo4 for the three different feed rates.



(a) (b)

Figure4: (a) Cutting Speed and (b) Feed Rate vs. Cutting Force of 42CrMo4

Increasing cutting speed from 105 m/min to 140 m/min indicated a slight decrease in the cutting forces. This is because higher cutting forces are required at lower cutting speed due to the higher coefficient of friction between the tool and work piece. The temperature generation rate at higher cutting speeds is higher resulting in a soft material at the cutting region, which assists in removing the material at lesser cutting forces. It was further noted that the chips get thinner and cutting forces reduce as the cutting speed increased. The decrease in cutting force can be attributed to the reduction in contact area and partly due to the fall in shear strength in the flow region as the temperature increases with increase in cutting speed. Similar results were attained by Thakur et al, (2009) in which decrease in both cutting force and feed force was due to decrease in contact area and partly due to a drop in shear strength in the flow zone as the temperature increases with increased speed. (Marusich, 2001)also advanced that the decrease in cutting force must come from the reduction in effective friction at the tool-chip interface evidenced by the thinning of the chip at higher cutting speeds. Meanwhile (Thamizhmanii et al., 2007) indicated that the BUE formation was very strong in low cutting speed than at high cutting speed. At high cutting speeds, the BUE weakened and disappeared. At 170 m/min cutting speed the cutting forces showed a slight increase but generally lower when compared to a lower cutting speed of 105 m/min. This could be attributed to the BUE which alters the rake angle and hence increases the contact area and in turn increases the cutting force at 170 m/min speed.

Figure 4(b) shows the influence of feed rate on cutting force of 42CrMo4 for the three different cutting speeds. Increasing feed rate at all selected cutting speeds increased the cutting force. The result indicated that the amount of material in contact with the tool increased with increased feed rate. The value of cutting force also increased due to increased tool-work contact length. Furthermore, due to the higher amounts of material in contact with the tool the force resisting deflection is high which also contributed to an increase in the cutting forces. Similar conclusions by Lin et al. (2001) indicates that the cutting force tends to increase with an increased feed rate and in order to ensure an optimal surface roughness value and an optimal metal-removal rate measures should be taken to maximize the cutting speed and the depth of cut, yet minimize the feed rate. Lower cutting forces can be attained by using a combination of lower level feed rate (0.15 mm/rev) with high level cutting speed (170 m/min).

3.6. Cutting Speed and Feed Rate Effect of on Tool Wear

Figure 5(a) depicts the influence of cutting speed on tool wear of 42CrMo4 for the three different feed rates.

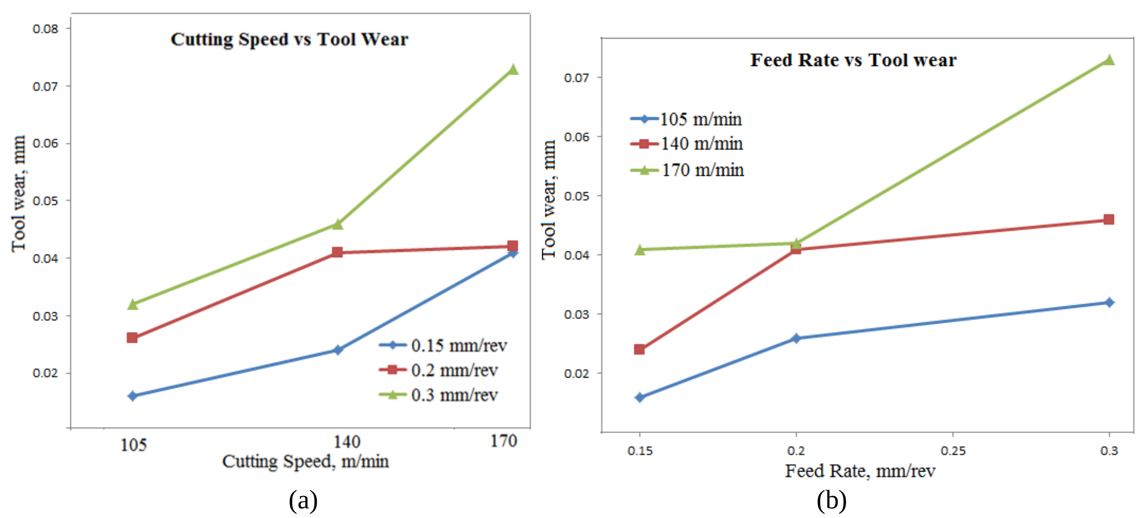


Figure 5: (a) Cutting Speed and (b) Feed Rate vs. Tool Wear of PCBN

Figure 5(a) shows that an increase in cutting speed increased the tool wear. The cutting temperature at the cutting edge of the tool increased as the cutting speed increased causing the tool to lose its strength and leading to plastic deformation. Consequently, cutting edge deformation and tool wear significantly increased due increased cutting speed. Thamizhmanii et al.(2007) in their research also concluded that the flank wear increased when the cutting speed and feed rate and depth of cut was increased which could be due to abrasive action between the tool cutting edge and work piece, and temperature generated between cutting edge and work piece. Figure 5(b) shows the influences of feed rate on tool wear of 42CrMo4 for the three different cutting speeds. Increase in feed rate increased the tool wear. The bigger the feed, the larger was the cutting force per unit area of work-tool contact on the flank face and chip-tool contact on the rake face. Correspondingly, Thamizhmanii et al. (2007) established that the flank wear increased with increased feed rate probably due to abrasive action between the tool cutting edge and work piece, and temperature generated between cutting edge and work piece. In this study the effect of feed rate on tool wear were quite significant when compared to proportionate changes in cutting speed. By employing a combination of lower feed rate (0.15 mm/rev) with a lower cutting speed (105 m/min) a minimum tool wear was achieved.

4. 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.

- 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. 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.
- Overall, the experimental results are nearer to the predicted values within 12% deviations except tool life which yielded 36, % deviation.

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