Jurnal Mekanikal
June 2008, No. 25, 92 - 105

HARD TURNING OF COLD WORK TOOL STEEL USING WIPER CERAMIC TOOL

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ABSTRACT

While advanced cutting tools used in hard turning applications come with expensive unit price, coated ceramic offers cheaper alternative especially for mid range of hard turning. Wiper geometry featured in coated ceramic tools enabled an increase in productivity or an improved in surface finish despite limited report on this cutting edge modification. In this study, the performance of wiper coated ceramic tool (TiN coating with mixed Al_2O_3/TiCN substrate) when turning hardened cold work tool steel (54-55 HRC) is evaluated by varying the cutting speed and feed in terms of tool life and surface roughness. The results were compared with those of its conventional geometry counterpart. The wiper tool results in slightly shorter tool life but with much finer surface finish than the conventional one. Design of experiment was used to quantify the effect of cutting parameters on tool life and surface roughness and to determine the optimum cutting parameters that generate the preferred machining results.

Keywords: *Hard machining, ceramic, wiper geometry, cold work tool steel, tool life, surface roughness*

1.0 INTRODUCTION

Hardened steels are widely used when producing tools and dies, automotive parts, as well as various mechanical and tribological components. This is due to their high strength and wear resistance properties. Their hardness results in low machinability where grinding is the only feasible finish machining operation. The introduction of polycrystalline cubic boron nitride (CBN) tool has enabled the use of single-point turning as a finishing operation [1]. Continuous works in the field of hard turning have shown the potential advantages of hard turning over grinding. At proper condition, hard turning can produce good accuracy and surface finish comparable to grinding [2]. Additionally, hard turning is commonly conducted dry [3,4] which is in line with sustainable manufacture.

However, for some hard turning applications, the use of CBN tools is not economical due to their high cost. Ceramic tools have long been used for their high hardness and are attractive low cost alternatives for hard turning. As a finish

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machining operation, hard turning is characterized by low feed to achieve the strict targeted dimensional accuracy. This results in the low volume of excess material being removed from the workpiece. One improvement regarding this matter has been provided by tool manufacturers through the use of tools with wiper geometry. This involves modifying a conventional insert by introducing an additional radius adjacent to the nose radius of the cutting tool. This modification to the tool geometry enables the use of a higher feed than that used with a non wiper or conventional cutting tool while still obtaining a surface finish value obtained when using a non wiper or conventional cutting tool at lower feed. Alternatively, the same feed can be used and this will result in better surface finish [5].

Apart from the abovementioned positive properties, ceramic materials exhibit low toughness and low thermal conductivity. Therefore, they are prone to brittle fractures induced by mechanical and/or thermal stresses. As a consequence, for industrial implementation purpose, the suitability of ceramic tools for cutting cold work tool steel must be evaluated further.

In this study, the effect of cutting speed and feed on tool life and surface finish is investigated and analyzed using design of experiments technique. Previous work has shown that the developed empirical models using statistical techniques such as the response surface methodology (RSM) were adequate to represent the performance of a coated carbide tool [6].

2.0 EXPERIMENTAL DETAILS

The experiments were conducted on a 2-axis CNC lathe by longitudinal turning process without using coolant. The workpiece material was a high carbon, high chromium AISI D2 tool steel alloyed with molybdenum and vanadium with through hardness of 55 HRC. Typical composition of this special alloy steel is 1.55 % C, 0.4 % Mn, 11.6 % Cr, 0.8 % Mo, 0.9 % V, 0.3% Si with the balance consisting of Fe. It is the recommended material for tools requiring high wear resistance combined with moderate toughness.

The cutting tool is a commercially available coated ceramic (TiN coating over Al_2O_3 + TiCN substrate). The coated ceramic tool has an ISO designation of CNMG 120408 with multi radii (wiper) geometry adjacent to the designated 0.8 mm nose radius. As a comparison, a ceramic tool with regular (here addressed as conventional) 0.8 mm nose radius with the same ISO designation was also used. Both tools were mounted on a holder with an ISO designation of MCLNL 1616-H12. This combination gives a -5^0 rake angle, 5^0 relief angle, and -5^0 side cutting edge angle.

Tool wear was measured according to ANSI B94.55M-1985 standard in terms of the maximum flank wear width (VBmax) within the nose radius of the tool (zone C). The tool life criteria were set at maximum flank wear width of 0.2 mm or when the tool was severely broken and, for the purpose of achieving finish machining results, with surface roughness value of 1.6 µm. The surface roughness was measured using a portable surface profilometer. Scanning electron microscope (SEM) was used for image capturing and element identification with its energy dispersive x-ray spectrometer (EDS).

The range of cutting parameters was within those of finish machining values provided by the tool's manufacturer. Also, the values of the feed were selected such that, theoretically, the resulting surface roughness would fall below 1.6 µm.

The cutting force measurement system used consists of a three-component dynamometer comprising of a basic unit (Kistler, Type 9265 B) and a screwed-on working adapter in a form of tool holder for turning (Kistler, Type 9441 B), a multi channel charge amplifier (Kistler, Type 5019 A), and a data acquisition system consisting of a personal computer equipped with an A/D board and Dyno Ware software (Kistler, type 2825 D1-2, version 2.31)

In order to determine if there was a relationship between the input (cutting parameters) and the response (tool life and surface roughness) variables, the data collected was analyzed using regression. A regression was performed whereby an observed, empirical variable (response) is approximated based on a functional relationship between the estimated variable, y_{est}, and one or more input variables, x_1 and x_2. In the case where a non-linear relationship existed between a particular response and two input variables, a quadratic equation,

$$y_{est} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2 + b_4 x_1^2 + b_5 x_2^2 + error \tag{1}$$

may be used to describe this functional relationship. The least square technique was used to fit a model equation containing the said regressors or input variables by minimizing the residual error measured by the sum of square deviations between the actual and the estimated responses. This involved the calculation of estimates for the regression coefficients, i.e. the coefficients of the model variables including the intercept or constant term, for statistical significance test.

Table 1: Design layout of the experiment

Std.	Cutting Speed (m/min)	Feed (mm/rev)	Coded form x_1	x_2
1	115	0.1	-1	-1
2	145	0.1	0	-1
3	183	0.1	1	-1
4	115	0.125	-1	0
5	145	0.125	0	0
6	183	0.125	1	0
7	115	0.16	-1	1
8	145	0.16	0	1
9	183	0.16	1	1
10	145	0.125	0	0
11	145	0.125	0	0

The lower and upper limit values of the input variables have been selected according to recommendation by the tool manufacturer for turning steels and irons with hardness of 48-65 HRC. Considering that the coated ceramic tool was designed for finish machining and that the depth of cut was 0.4 mm, the selected lower and upper limit values for feed were 0.1 and 0.16 mm/rev, respectively, and for cutting speed, they were 115 and 183 m/min, respectively. The values selected for the middle limit were 145 m/min for cutting speed and 0.125 mm/rev for feed.

The face-centered (α=1) central composite design was selected with two factors as the input, repeated three times at the center point resulting in a total of 11 runs (Table 1). A commercial statistical analysis software was used for the convenience of designing the experiments and analyzing the results.

3.0 RESULTS AND DISCUSSION

3.1 Tool Life

From the experiments conducted, at most cutting parameters, the coated ceramic tools lasted for more than ten minutes. Tool life was affected by cutting speed and feed, as can be seen in Figure 1. A trend can be observed where the tool life decreases with increasing cutting speed and feed. The longest life time of the tools was achieved at low cutting speed and low feed where the tool lasted for eighteen minutes. The long tool life is a good indication of its suitability for performing hard turning from the view of machine shops.

The ratios of the maximum tool life to the minimum one was 5.14 and 5.83 for conventional and wiper tool, respectively. Ratio of more than 3 indicates that power transformation may be required to improve the empirical model. One way to define which power transformation was appropriate was by diagnosing the box-cox plot of the tool life data. The lowest points of the plot that result in the minimum residual sum of square in the transformed model (λ value) were 0.93 for conventional and 0.45 for wiper tool. Therefore, no power transformation (λ=1) was required.

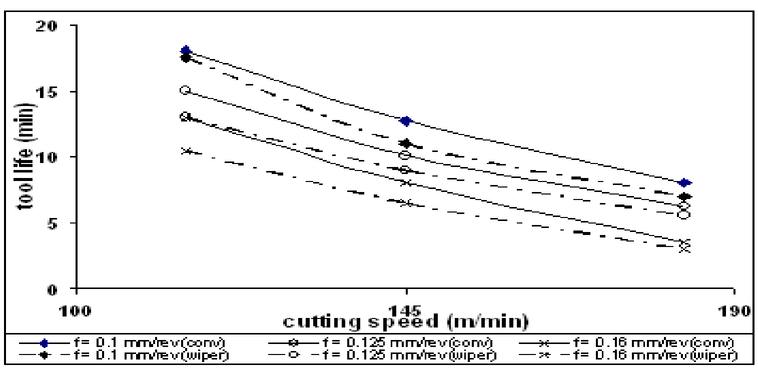


Figure 1: Tool life at various cutting speed and feed

Fit summary output to determine the most suitable regression model was then evaluated. Having the least probabilistic value, *Prob>F*, and the most insignificant lack of fit, the quadratic model was selected to represent the tool life data of both tools.

The analysis of variance (ANOVA) was then performed to test the significance of the regression model and the individual coefficients of the quadratic model. The maximum probabilistic value of 5% was set for the model and its coefficients to be considered significant. The quadratic model had probabilistic value well below 0.05, but not all its coefficients did. For the conventional tool, the product of cutting speed and feed (*vf*) was considered not significant and was removed. For the wiper tool, the product of cutting speed and feed and the square of feed (f^2) were removed. The reduced quadratic models were then retested (Tables 2 and 3). The reduced models' values of coefficient of determination, R^2, were 0.996 and 0.911. These coefficients of determination were very close to unity, indicating the models have closely approximated the tool life data. The models' values of adequate precision ratio, which compared the range of the predicted values at the design points to the average prediction error, were well beyond the minimum adequacy limit of 4.

The tool life data of conventional tool model can be presented as:

$$T = 71.7185 - 0.4073v - 260.0358f + 0.0009v^2 + 697.3600f^2 \tag{2}$$

while for the wiper tool, the model of its tool life data is:

$$T = 80.5675 - 0.7178v - 83.5387f + 0.0020v^2 \tag{3}$$

where *v* was cutting speed (m/min) and *f* was feed (mm/rev).

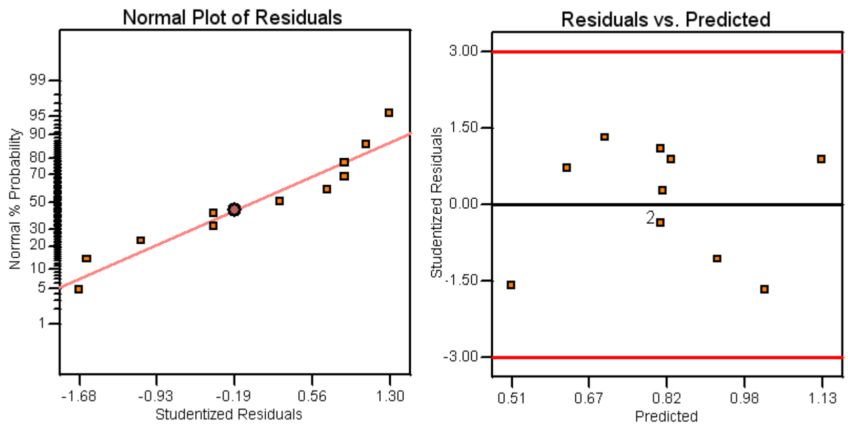
Table 2: ANOVA for response surface reduced quadratic model of conventional ceramic tool

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	168.018	4	42.005	351.303	< 0.0001	*significant*
X_1	133.670	1	133.670	1117.946	< 0.0001	
X_2	33.465	1	33.465	279.881	< 0.0001	
X_1^2	2.656	1	2.656	22.212	0.0033	
X_2^2	0.932	1	0.932	7.797	0.0315	
Residual	0.717	6	0.120			
Lack of Fit	0.446	4	0.111	0.820	0.6140	*not significant*
Pure Error	0.272	2	0.136			
Cor Total	168.736	10				

Table 3: ANOVA for response surface reduced quadratic models of wiper ceramic tool

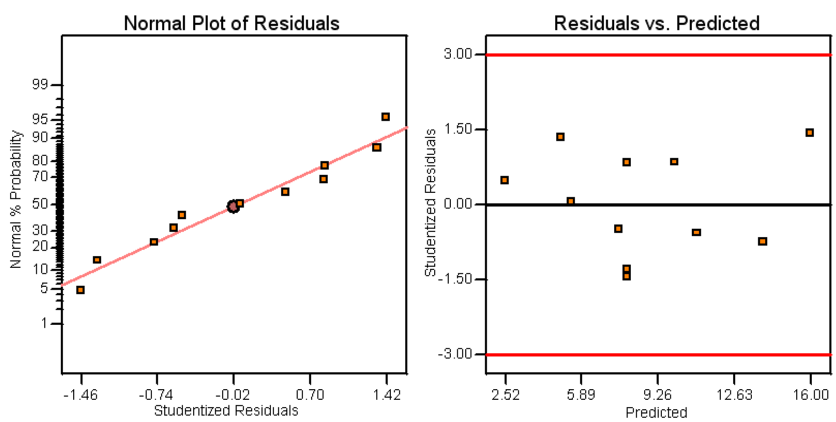
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	153.169	3	51.056	23.829	0.0005	*significant*
X_1	107.527	1	107.527	50.185	0.0002	
X_2	38.127	1	38.127	17.795	0.0039	
X_2^2	13.946	1	13.946	6.509	0.0380	
Residual	14.998	7	2.143			
Lack of Fit	9.372	5	1.874	0.666	0.6914	*not significant*
Pure Error	5.627	2	2.813			
Cor Total	168.167	10				

Inspection of some diagnostic plots of the model was done to test the statistical validity of the model. The residuals could be said to follow a straight line in normal plot of residuals implying that the errors were distributed normally and were randomly scattered within constant variance across the residuals versus predicted plot (Figures 2a and 2b for conventional tool and Figures 3a and 3b for wiper tool).



(a) (b)

Figure 2: Normal plot of residuals (a) and residual vs. predicted (b) graphs for tool life of conventional tool



(a) (b)

Figure 3: Normal plot of residuals (a) and residual vs. predicted (b) graphs for tool life of wiper tool

In order to verify the adequacy of the developed model, another set of trials were conducted considering 95% confidence interval as the adequacy limit of the model. Selecting cutting speed of 183 m/min and feed of 0.1 mm/rev for the conventional tool, the resulted tool life was 8.1 minutes. The predicted tool life for this cutting parameter combination was 8 minutes, very close to the actual one. While for the wiper tool, selecting combinations of cutting speed-feed of 145 m/min-0.1 mm/rev and 145 m/min-0.16 feed, the tool life values were 10.5 and 6 minutes, respectively. The predicted values for these cutting parameter combinations were 10 and 5 minutes, respectively, which were within the confidence intervals. These trial results verify that the models were sufficient to represent the tool life data for both conventional and wiper tool for this particular hard turning. One suggestion that comes from these findings is that the coated ceramic tools suffered gradual wear during cutting.

The obtained final equations for both tools can be represented by graphs of contours (Figures 4a and 4b). Both graphs showed that longer tool life was obtained when lower cutting speed and feed were selected. There are less cutting speed-feed combinations for wiper tool that results in more than 10 minutes of tool life compared to that of conventional tool. The wider tool-chip contact area of the wiper tool than that of conventional tool seems to influence the tool life.

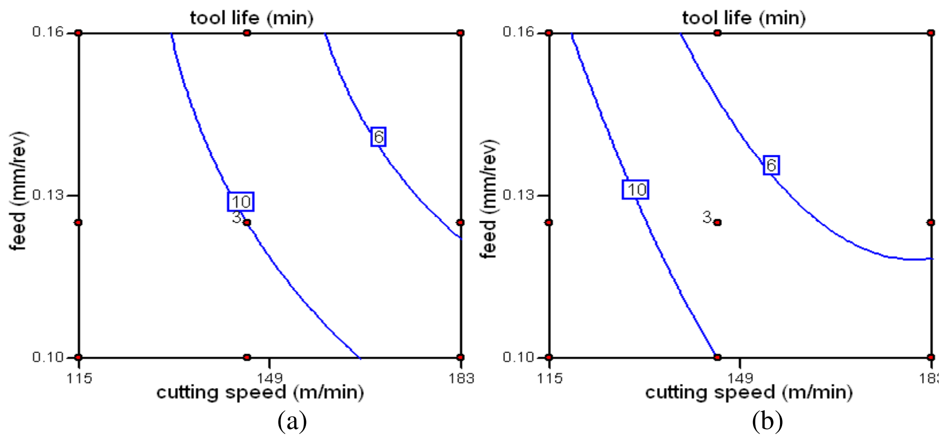
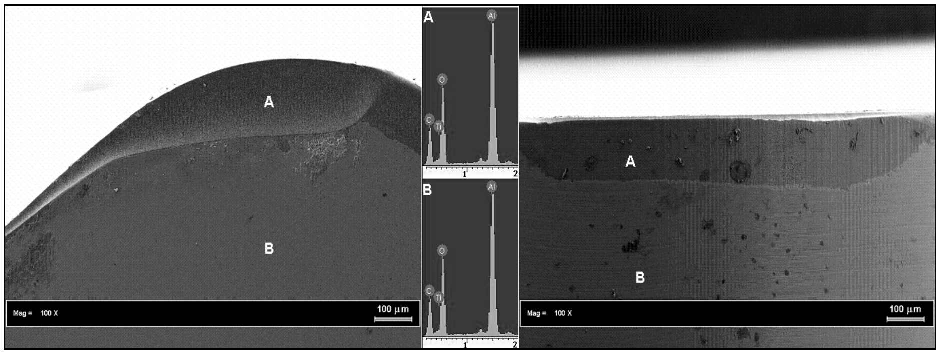


Figure 4: Response surface graphs of contours for tool life of (a) conventional and (b) wiper tools

These statistical analysis results supported the remark that longer tool life was obtained when lower cutting parameters were selected. Thus, in order to ensure that the cutting tool lasts long enough, it is suggested that hard turning of tool steel using coated ceramic tool should be limited to low cutting parameters.

At the end of its service life, the typical image of the rake face (Figure 5a) indicates the loss of coating material (TiN) and subsequently some of the substrate (Al_20_3 + TiCN). Similar elements were identified at the worn area and the initial coated region, yet the differences in morphology and depth where the A region is situated indicate that region A consists of the substrate elements. Flank face of the coated ceramic tool (as seen in Figure 5b) clearly showed smooth ridges and grooves, suggesting that abrasion took place during the cutting process. It was suggested that the hard and loose carbide particles contained in the workpiece were sliding against the tool and leaving such marks [7]. Again, element identification showed similar results between the fresh and worn regions.



(a) (b)

Figure 5: Micrographs of conventional tool's (a) rake and (b) flank faces and their corresponding EDAX spectra

3.2 Cutting Forces

Cutting forces are the criteria used for tool wear monitoring. High cutting forces produced during the cutting process will deteriorate tool life. If cutting force is too large, the tool will fracture. Increasing feed and decreasing cutting speed will increase cutting forces (Figure 6). Wiper tool has lower tool life and higher cutting force compared to conventional tool. This is due to the wiper tool having larger contact area with workpiece material resulting from wiper radii adjacent to the nose radius. These additional radii increase cutting force in between 5-10%. Higher cutting force causes faster tool wear and thus reduces the tool life. Zhou *et al*. [8] when turning 100Cr6 steel using CBN cutting tool (60-62 HRC) reported that there is a strong correlation between the radial force and the tool flank wear in the hard turning process. Although a good correlation was also found between the cutting force and the tool wear, the radial force exhibits a higher sensitivity to the tool wear among the three force components, which suggests the feasibility of tool wear monitoring by monitoring the radial force.

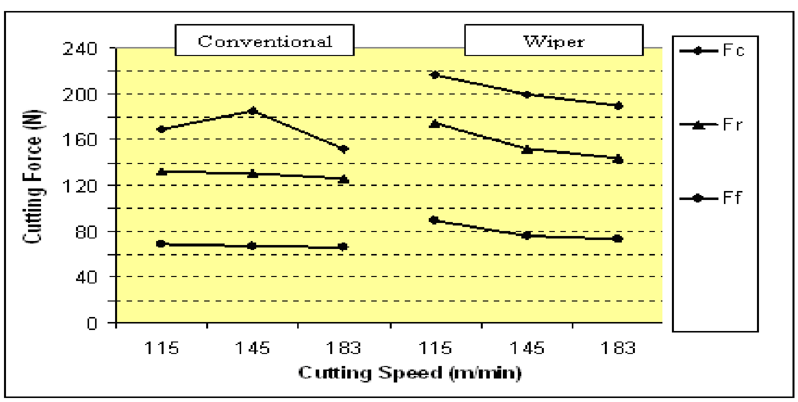


Figure 6: Tool life and cutting forces of conventional and wiper tools at various cutting speeds

3.3 Surface Finish

The generated surface roughness (*Ra*) values were less than 1.6 µm as expected (Figure 7). This meant that the coated ceramic tools could generate surface finish at tight tolerance range of finish machining as they were intended to. Some of the results were even one level better as being less than 0.8 µm in surface roughness. The decrease in feed improves the *Ra* values. Cutting speed was generally found to be inversely proportional to the *Ra* achieved.

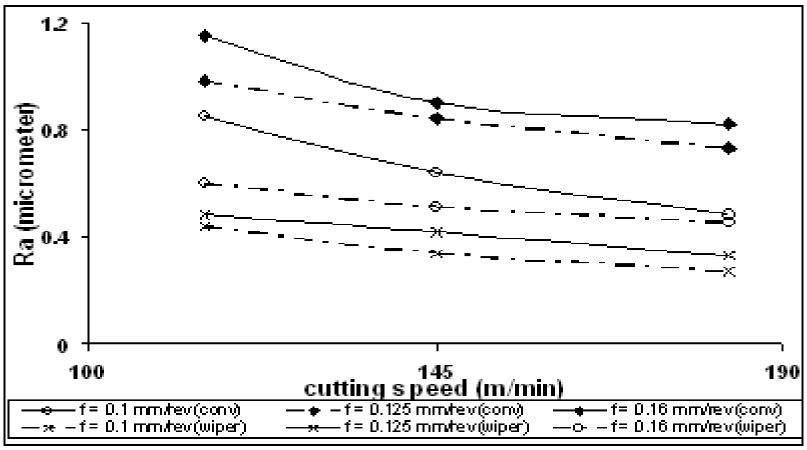


Figure 7: Surface roughness at various cutting speed and feed

It is interesting to note that the resulting surface roughness values show similar trend to the life time of the tool with regards to the cutting speed and feed. A minimum roughness of 0.48 µm for conventional tool and 0.27 µm for wiper tool on the hardened steel surface were achieved at low feed-high cutting speed combination. In order to achieve tighter tolerance, most of the selected cutting parameters resulted in surface roughness of below 0.8 µm for wiper tool whereas for conventional tool surface roughness of 0.8 µm or finer was generated with less number of combinations. These results are expected to be a valuable input in implementing hard turning techniques as finish machining operation in the manufacturing industry, especially in convincing the users of the machined component that the technique resulted in machined surface with very tight tolerance.

Using the similar steps used to develop and analyze the tool life model, the models of surface roughness data from the hard turning tests were developed and validated. Preliminary diagnosis to determine the appropriate power transformation was conducted. Having the maximum to minimum ratio of close to and less than 3, applying any power transformation would have little effect and thus, no power transformation was set (λ=1). The next step was to determine the suitable regression model. The probabilistic value, *Prob>F*, and lack of fit of each model were determined and the quadratic model for conventional tool and linear model for wiper tool were selected for having the least probabilistic value and the most insignificant lack of fit.

The analysis of variance was then performed to test the significance of each selected regression model and its coefficients. As before, the maximum probabilistic value of 5% was set for the model and its coefficients to be considered significant. For conventional tool, quadratic model is the most suitable, yet the product of cutting speed and feed (*vf*) should be removed as being not significant (Table 4). For wiper tool, the linear model and its coefficients were considered significant (Table 5).

Table 4: ANOVA for response surface of reduced quadratic model for conventional ceramic tool

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.293	4	0.073	71.881	< 0.0001	*significant*
X_1	0.150	1	0.150	147.654	< 0.0001	
X_2	0.135	1	0.135	132.520	< 0.0001	
X_1^2	0.011	1	0.011	11.202	0.0155	
X_2^2	0.009	1	0.009	9.241	0.0228	
Residual	0.006	6	0.001			
Lack of Fit	0.005	4	0.001	2.365	0.3186	*not significant*
Pure Error	0.001	2	0.001			
Cor Total	0.299	10				

Table 5: ANOVA for response surface of linear model for wiper ceramic tool

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.081	2	0.041	195.849	< 0.0001	*significant*
X_1	0.036	1	0.036	175.353	< 0.0001	
X_2	0.045	1	0.045	217.262	< 0.0001	
Residual	0.002	8	0.000			
Lack of Fit	0.001	6	0.000	1.735	0.4098	*not significant*
Pure Error	0.000	2	0.000			
Cor Total	0.083	10				

The final equation that represents the *Ra* generated by conventional tool is:

$$Ra = 0.98827 - 0.02225\,v + 23.21955\,f + 0.00006\,v^2 - 70.07519\,f^2 \tag{4}$$

Whereas for wiper tool, the *Ra* resulted can be represented as:

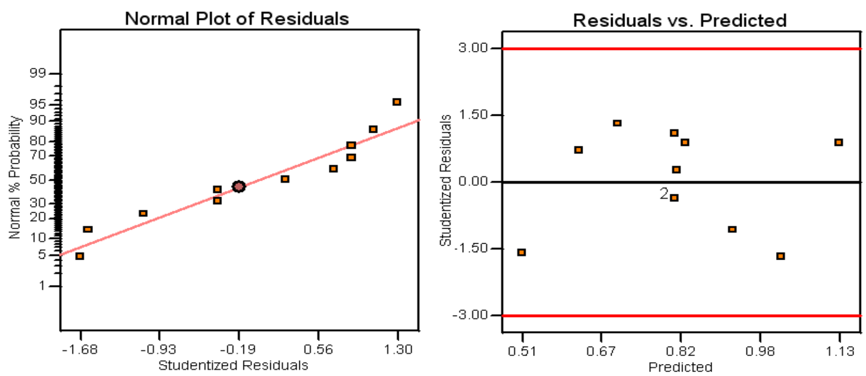
$$Ra = 0.39299 - 0.00228\,v + 2.866441\,f \tag{5}$$

where *v* was cutting speed (m/min) and *f* was feed (mm/rev).

The statistical validity of the model was evaluated by inspecting the residuals and residuals versus predicted plots. The residuals could be said to follow a straight line in normal plot of residuals and were randomly scattered within constant variance across the residuals versus predicted plot (Figures 8 and 9). The models have close to unity values for coefficient of determination, R^2, which is 0.98 for both conventional and wiper tools. Their values of adequate precision were also high, suggesting that the models were adequately representative.

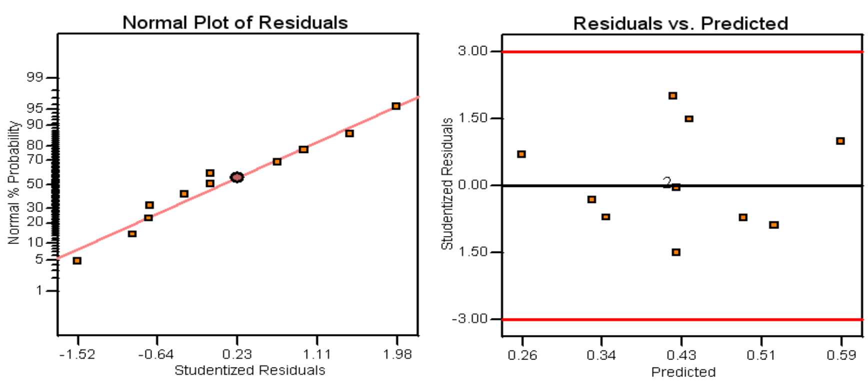
When tested at cutting speed of 183 m/min and feed of 0.125 mm/rev, the *Ra* generated by conventional tool was 0.5 µm, which was very close to the predicted *Ra* value at this cutting parameter combination of 0.51 µm and clearly within the range of 95% confidence interval. While for wiper tool, at combinations of cutting speed-feed of 145 m/min-0.1 mm/rev and 145 m/min-0.16 mm/rev, the *Ra* values were 0.35 and 0.51 µm. The predicted *Ra* values for these combinations are 0.35 and 0.52. These results verified the adequacy represented by the models.

The surface roughness models were represented by graphs of contours (Figure 10). Both graphs showed that lower surface roughness was obtained by selecting lower feed and higher cutting speed. Almost half of the combinations for conventional tool result finer than 0.8 µm *Ra* while the entire combinations for wiper tool do. It is also clear that almost all cutting parameters that result in 0.8 µm *Ra* for conventional tool result in 0.4 µm for wiper tool. This supports the manufacturer's claim that wiper geometry would result in finer surface finish at current feed.



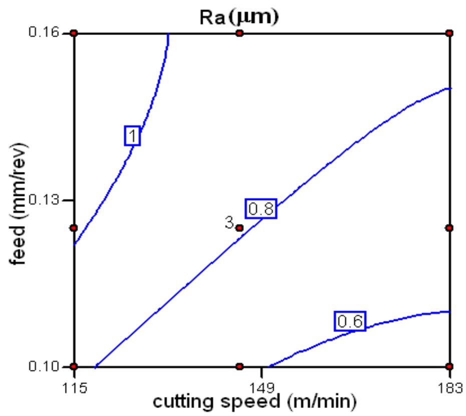
(a) (b)

Figure 8: Normal plot of residuals (a) and residual vs. predicted (b) graphs for *Ra* of conventional tool

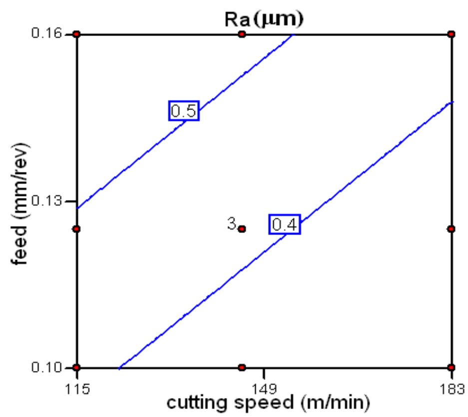


(a) (b)

Figure 9: Normal plot of residuals (a) and residual vs. predicted (b) graphs for *Ra* of wiper tool



(a)



(b)

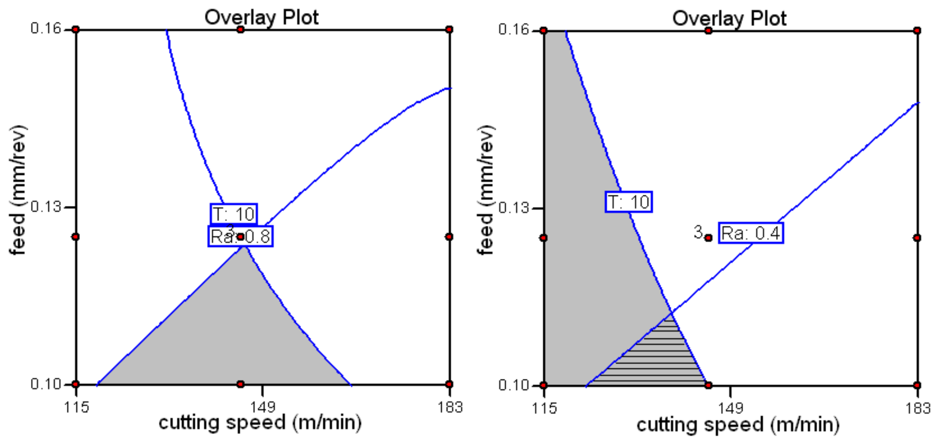
Figure 10: Response surface graphs of contours for *Ra* of (a) conventional and (b) wiper tools

3.4 Optimum Cutting Parameters

Similar effect of cutting speed and feed to tool life yet opposite effect to surface roughness create two distinct options on which the response should be of higher priority. Practically, hard turning as a finishing operation should generate fine surface to meet customer's demand of accuracy of the machined component. On the other hand, machine shops will be more efficient when the cutting tool lasts long. Therefore, a compromised solution is in need to select the cutting parameters.

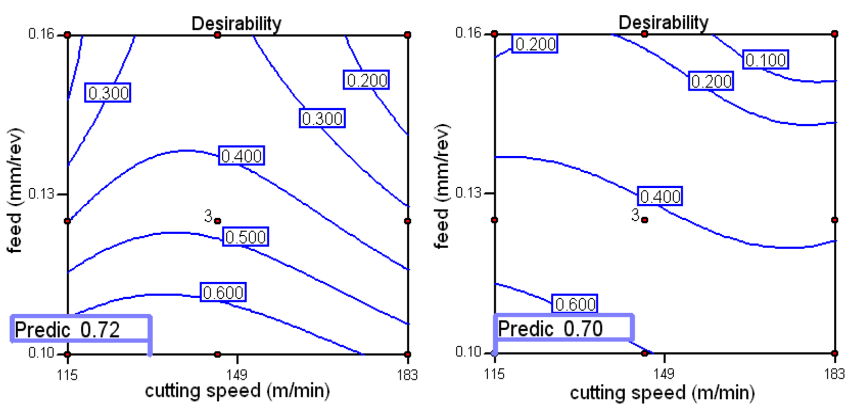
The developed models offer an optimizing option to select the range of cutting speed and feed that will result in satisfying predetermined criteria of tool life and surface roughness. It was suggested that a cutting tool should last at least ten minutes to be convenient to the machine shops and should generate surface roughness of 0.8 µm or finer to meet the costumer's strict tolerance. These criteria would be met when the cutting speed and feed combination is within the grey area of the overlay plots (Figure 11). The solution was the intersection between the solutions for the tool life criteria (area at the left of the tool life contour of ten minutes) and the solutions for surface roughness criteria (area below the *Ra* contour of 0.8 µm). For wiper tool, it is determined solely by tool life, since the *Ra* values were entirely less than 0.8 µm. The wiper tool enables tighter surface finish criteria, for example maximum *Ra* of 0.4 µm, as shown in Figure 11b.

The solution could even be more detail by setting sharp response criteria. By setting that the tool life should be maximum and that the surface roughness should be minimum, the desirability value for conventional tool (Figure 12a) was higher toward lower cutting speed and lower feed and being maximum at two combinations, i.e. the cutting speed-feed of 131.35 m/min-0.1 mm/rev and 131.70 m/min-0.1 mm/rev. These combinations will result in 15 minutes of tool life and 0.7 µm of *Ra*. For wiper tool (Figure 12b), the most desired combination is 115 m/min cutting speed and 0.1 mm/rev speed. This combination will result in 16 minutes of tool life and 0.42 µm of *Ra*.



(a) (b)

Figure 11: Overlay plot of the input factors for the predetermined response criteria of minimum 10 minutes of tool life and of maximum 0.8 μm of surface roughness for (a) conventional and (b) wiper tools



(a) (b)

Figure 12: Desirability plots of the input factors to obtain the maximum tool life and minimum surface roughness for (a) conventional and (b) wiper tools

4.0 CONCLUSIONS

From trials conducted, the coated ceramic tool performed reasonably when hard turning steel (55 HRC) in dry condition and at the cutting parameters selected. The empirical models for both conventional and wiper tools indicate that the tool life was proportional to cutting speed and feed. The measured cutting force reduced with increasing cutting speed and rose with increasing feed. The empirical surface roughness models show such that the obtained *Ra* was proportional to feed and inversely proportional to cutting speed. Considering both the tool life and the surface roughness, a combination of low cutting parameters is the optimum solution to make the coated ceramic tools last long enough and simultaneously generate fine surface finish.

ACKNOWLEDGEMENTS

Financial supports from the Ministry of Science, Technology, and Innovation, Malaysia is acknowledge with gratitude.

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