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Experimental Evaluation in Dry Machining of Inconel 718 Using Coated Carbides

M. M. Reddy[1*], N. S. Reddy[2] and J. N. Evan[1]

[1]Department of Mechanical Engineering, Faculty of Engineering and Science,
Curtin University, Malaysia.
[2]Department of Metallic and Materials Engineering, Gyeongsang National University,
Jinju, South Korea.

Authors' contributions

This work was carried out in collaboration among all authors. Author MMR developed the manuscript and submitted for publication. Author NSR involved about some technical discussion and conclusion. Author JNE collected experiment results. All authors read and approved the final manuscript.

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ABSTRACT

Past two decades, the usage of ceramic tools has increased especially in milling and turning process. These advanced ceramic tools have good characteristics that are capable in maintaining high hardness in temperatures and also wears much slower when compared to carbide tools. With limited data available on the tool itself, research is to be done on these advance ceramic tools. The main purpose of this research project is to determine the cutting parameters affecting the cutting temperature and cutting force. The cutting parameters are cutting speed, depth of cut and feed rate. Silicon Nitride is chosen as the tool and Steel AISI4140 is chosen as the work piece. Analysis is conducted through Box-Behnken method with 3 levels, 3 factors and 2 responses. The regression model for cutting temperature and cutting force responses are identified. Analysis of Variance (ANOVA) is done to determine the effect of the cutting parameters and their contribution towards the cutting temperature and cutting force response. It is found that feed rate has the most influence on cutting temperature and force. The optimal cutting parameters that produce the lowest cutting temperature and lowest cutting force are also obtained.

**Corresponding author: Email: mohan.m@curtin.edu.my;*

Keywords: Ceramic tools; cutting force; response surface methodology.

1. INTRODUCTION

Machining is an important aspect of the modern industry as it is the basis of all goods and service being manufactured. Turning operation is a machining process that brings exact shape of rounded parts. This is done through rotating the work piece and moving it towards the tool. Turning operation is also one of the oldest and amongst the popular method of cutting metal. The surface quality produced from turning operation is good enough to replace grinding in several applications [1].

Within the past two decades, the usage of ceramic tools has increased especially in milling and turning of cast iron, hardened steels and nickel based super alloys. These advanced ceramic tools include alumina based and silicon nitride based which has a material removal rate 3-4 times greater compared to carbide tools. Both types of ceramic tools are also capable in maintaining high hardness in temperatures between 600^{o} C -1000^{o} C. The wear of these tools are also much slower when compared to carbide tools. Lower wear rates and higher material removal is basically an increase in efficiency for production[2]. Although there are tools which are stronger such as PCD and CBD tools, advance ceramic tools are able to serve as a cheaper alternative for the machining of certain materials whilst under the correct cutting parameters. Thus with the emergence that exhibit general characteristics of excellent hardness, toughness and thermal resistivity along with improvements of advance ceramic tools throughout the years turning operation on harder materials are much more possible

Productivity is defined as the rate of output against the rate of input. The common problem when trying to increase machining productivity is due to the decrease of quality of the final products and effective tool life. To increase production, tool life should have to increase. Tool life and machinability can improve by optimizing the cutting parameters such as cutting speed, feed rate and depth of cut. However to remove large amount of material we need to use higher depth of cut and higher feed rate. This in turn would cause the increase cutting temperature and cutting force which then decreases the effective tool life. This would also affect the quality of the final products such as accuracy and surface roughness. Thus there is no concluded or best way in reducing production cost while increasing production rate due to the number of complexities involved for machining [3]. Thus more research is to be done to balance quality and productivity to prevent the unnecessary increment in the cost of production. This paper mainly concerns in the temperature and cutting forces generated during turning as these factors affect the quality of the machined product and the tool life. The investigation will be done through a set of parameters which are cutting speed, feed rate and depth of cut. Optimization of these parameters will be done to obtain the lowest resulting temperature and cutting force to have a better understanding the effect of cutting parameters. Optimizing also helps in balancing productivity and quality to an acceptable degree.

2. EXPERIMENTAL DETAILS

The objective of this research project is to obtain the lowest temperature and lowest cutting force of the silicon nitride ceramic tool in turning process by choosing right combinations of cutting parameters. The effects of cutting parameters on cutting force and cutting temperature will also be analysed. Silicon Nitride is chosen as the advanced ceramic tool for this research project

2.1 Work Piece Material

The work piece chosen is Steel AISI 4140. It is low alloy carbon steel that contains chromium, molybdenum, manganese carbon, silicon sulphur

Table 1. Chemical composition of steel AISI4140

Element	Content %
Chromium, Cr	0.80-1.10
Manganese, Mn	0.75-1.0
Carbon, C	0.380-0.430
Silicon, Si	0.15-0.30
Molybdenum, Mo	0.15-0.25
Sulphur, S	0.040
Phosphorus, P	0.035

Table 2. Properties of steel AISI4140

Properties	Metric
Density	7.85 g/cm^3
Melting Point	1416^o C
Tensile Strength	655 MPa
Yield Strength	415 MPa
Bulk Modulus (typical for steel)	140 GPa
Shear Modulus (typical for steel)	80 GPa
Elastic Modulus	190-210 GPa
Poisson's Ratio	0.27-0.30
Elongation at break (in 50mm)	25.70%
Hardness, Brinell	197

Table 3. Cutting parameters

Parameters	-1	0	+1
Cutting Speed (m/min)	600	700	800
Depth of Cut (mm)	0.5	0.6	0.7
Feed Rate (mm/rev)	0.3	0.4	0.5

Table 4. Results obtained from simulation work

Runs	Cutting speed (m/mm)	Depth of cut (mm)	Feed Rate (mm/rev)	Cutting Temperature (^{o}C)	Cutting Force (N)
1	800	0.6	0.3	1104.33	380.7518
2	800	0.6	0.5	1180.07	576.5475
3	600	0.5	0.4	1082.62	397.7710
4	700	0.6	0.4	1118.47	476.0382
5	700	0.5	0.3	1081.14	317.6142
6	700	0.6	0.4	1118.47	476.0382
7	700	0.7	0.3	1081.14	444.6599
8	600	0.6	0.5	1130.90	576.8278
9	600	0.6	0.3	1042.93	383.9617
10	700	0.6	0.4	1118.47	476.0382
11	600	0.7	0.4	1082.62	556.8793
12	700	0.5	0.5	1168.63	478.2703
13	700	0.7	0.5	1168.63	669.5783
14	700	0.6	0.4	1118.47	476.0382
15	800	0.7	0.4	1149.51	551.1906
16	700	0.6	0.4	1118.47	476.0382
17	800	0.5	0.4	1149.51	393.7075

and phosphorus. The material is chosen as the work piece because it is a type of hard steel and hardened steel are suitable to be machine by ceramic tools [4]. The table below shows the chemical composition and properties of the alloyed steel are shown in Table 1 and Table 2.

2.2 Design of Experiment

Box-Behnken design (BBD) method is used for the simulation design. The advantage that BBD has over other methods is that the design can avoid undesirable conditions due to combinations of all factors at the highest and lowest are avoided [5]. BBD also required 3 levels which are level -1, 0 and 1. A total of 17 runs are conducted. Table 3 shows the cutting parameters with their levels and Table 4 the simulation results.

3. RESULTS AND DISCUSSION

3.1 Regression Equation

From the results tabulated in Table 4, the model equation for cutting temperature and cutting force are shown in Equation1 and Equation 2.

$$Cutting\ Temperature = 1118.47 + 30.54V_c + 42.34f - 3.06V_c f - 6.37{V_c}^2 + 3.96d^2 + 2.45f^2 \quad (1)$$

$$Cutting\ Force = 623.22 - 8.56V_c + 105.23d + 132.11f - 1.80V_c d + 10.08V_c f + 22.30df + 5.82{V_c}^2 + 0.3806d^2 + 9.76f^2 \quad (2)$$

Where $V_c = cutting\ speed$, $d = depth\ of\ cut$, $f = feed\ rate$

3.2 Analysis of Variance (ANOVA)

With the software Design Expert, the results tabulated in Table 4 is analysed with ANOVA. The influences of the cutting parameters on cutting temperature and cutting force are determined. Terms with P-value less than 0.05 are considered to have significant contribution towards the responses. The sums of squares are to show the influence of each term on the responses. Table 5 shows ANOVA for cutting temperature responses and Table 6 shows ANOVA for cutting force response.

Table 5 shows that feed rate has the highest sum of squares then followed by cutting speed. This means that feed rate has the highest influence towards cutting temperature among all three cutting parameters. Cutting speed comes after while depth of cut has no influence on cutting temperature. Cutting temperature model has an

Table 5. ANOVA for cutting temperature response

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	22088.59	9	2454.29	206.45	< 0.0001
A-Cutting Speed	7463.37	1	7463.37	627.82	< 0.0001
B-Depth of Cut	0.0000	1	0.0000	0.0000	1.0000
C-Feed Rate	14338.86	1	14338.86	1206.18	< 0.0001
AB	0.0000	1	0.0000	0.0000	1.0000
AC	37.39	1	37.39	3.15	0.1194
BC	0.0000	1	0.0000	0.0000	1.0000
A²	170.65	1	170.65	14.35	0.0068
B²	66.07	1	66.07	5.56	0.0505
C²	25.35	1	25.35	2.13	0.1876
Residual	83.21	7	11.89		
Lack of Fit	83.21	3	27.74		
Pure Error	0.0000	4	0.0000		
Cor Total	22171.80	16			
Standard Deviation = 3.45		$R^2 = 0.9962$	$R^2 adjusted = 0.9914$		

Table 6. ANOVA for cutting force response

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	1.264E+05	9	14047.86	15171.68	< 0.0001
A-Cutting Speed	21.92	1	21.92	23.67	0.0018
B-Depth of Cut	50394.43	1	50394.43	54425.95	< 0.0001
C-Feed Rate	74930.22	1	74930.22	80924.59	< 0.0001
AB	0.6604	1	0.6604	0.7132	0.4263
AC	2.15	1	2.15	2.32	0.1718
BC	1032.41	1	1032.41	1115.00	< 0.0001
A²	0.7435	1	0.7435	0.8030	0.4000
B²	10.40	1	10.40	11.23	0.0122
C²	39.52	1	39.52	42.69	0.0003
Residual	6.48	7	0.9259		
Lack of Fit	6.48	3	2.16		
Pure Error	0.0000	4	0.0000		
Cor Total	1.264E+05	16			
Standard Deviation = 0.9623	$R^2 = 0.9999$		$R^2 adjusted = 0.9999$		

F-value of 206.45. A large F-value indicates that the model is significant because it has a small chance of being influence by noise. This is also indicated by the P-value as there is only a 0.01% chance that the large F-value can occur due to noise. This also applies for both feed rate and cutting speed as both shows large F-values and small P-values. The model terms A, C and A² are significant model terms.

Table 6 shows also shows that feed rate has the highest sum of squares among all the cutting parameters. However, this is followed by depth of cut then cutting speed. This means that feed rate has the highest influence followed by depth of cut then cutting speed. The cutting force model has a F-value of 15171.68. A large F-value indicates that the model is significant because it has a small chance of being influence by noise. This is also indicated by the P-value as there is only a 0.01% chance that the large F-value can occur due to noise. This also applies for all three cutting parameters as they exhibit large F-values and small P-values. The model terms, A, B, C, BC, B², and C² are significant model terms.

3.3 Residual Analysis

Residual analysis is used to check the adequacy of the response model. It is a useful class of technique that can evaluate a fitted model. Linear regression models usually require a specified regression to function. Their errors also should be distributed consistently [6]. Plots to verify the validity of the response model through residual analysis are shown below.

Cutting Temperature

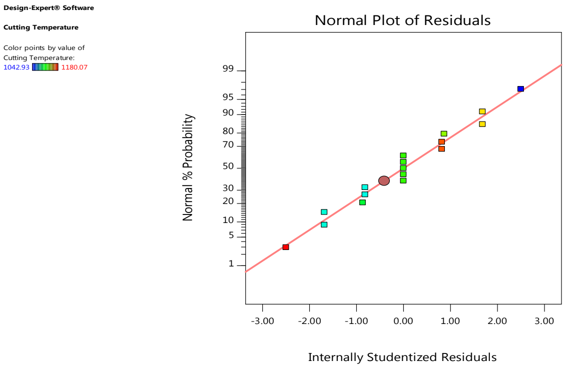

Fig. 1 Normal Plots for Cutting Temperature Response

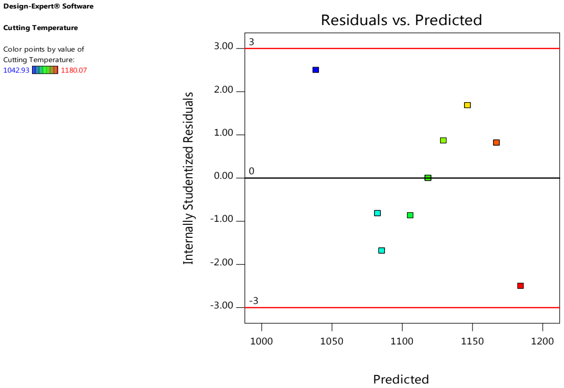

Fig. 2 Residual vs Predicted Plot for Cutting Temperature Response

Cutting Force

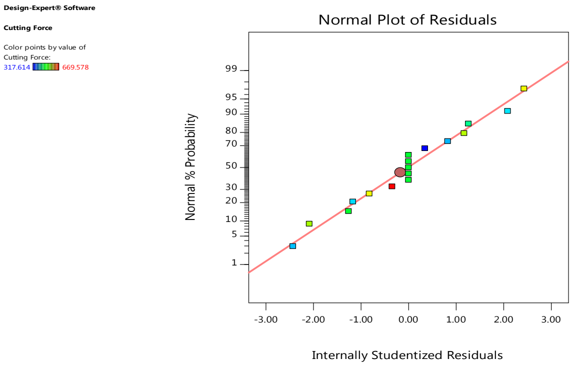

Fig. 4 Normal Plots for Cutting Force Response

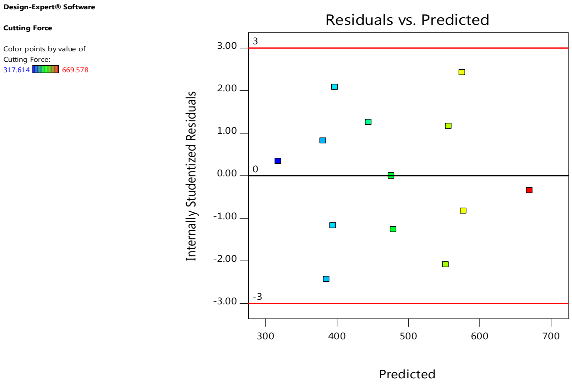

Fig. 5 Residual vs Predicted Plot for Cutting Force Response

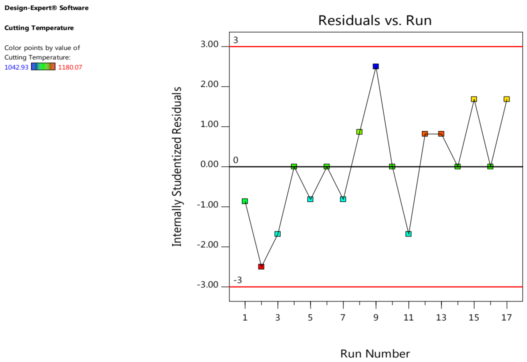

Fig. 3 Residuals vs run plot for cutting temperature response

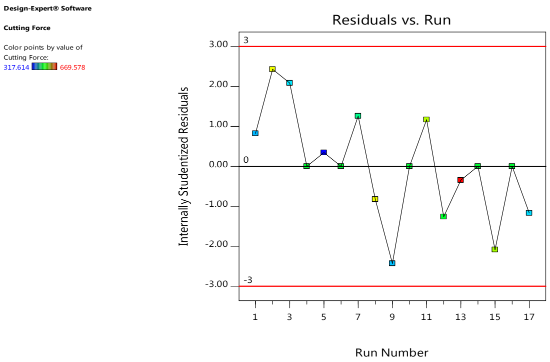

Fig. 6 Residuals vs run plot for cutting force response

Fig. 1 and Fig. 4 shows that the errors are distributed normally along the best fit. Fig. 2 and Fig. 5 shows the residuals versus predicted value plot. The residual plots are scattered randomly and equally for the positive and negative sides. Fig. 3 and Fig. 6 shows the residual plots versus the run of experiments. The plots are also scattered randomly with equal plots on the positive and negative sides. All figures do not show any obvious patterns since the figures exhibits random and unusual structures. Thus it can be said that residual analysis does not reveal and inadequacy from the cutting temperature and cutting force response model.

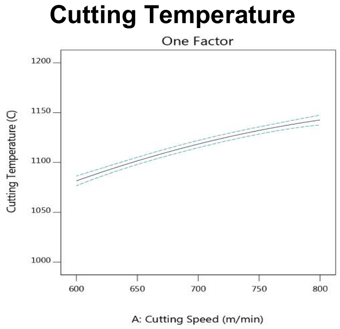

Fig. 7 Plot of cutting speed against cutting temperature

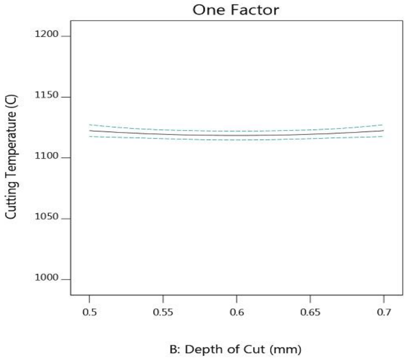

Fig. 8. Plot of depth of cut against cutting temperature

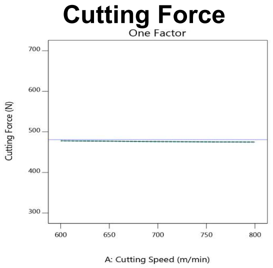

Fig. 10. Plot of cutting speed against cutting force

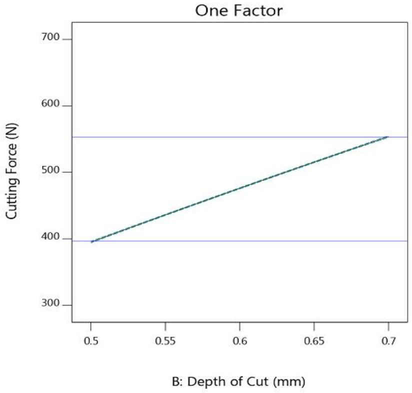

Fig. 11. Plot of depth of cut against cutting force

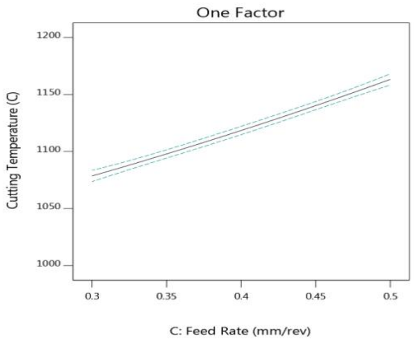

Fig. 9. Plot of feed rate against cutting temperature

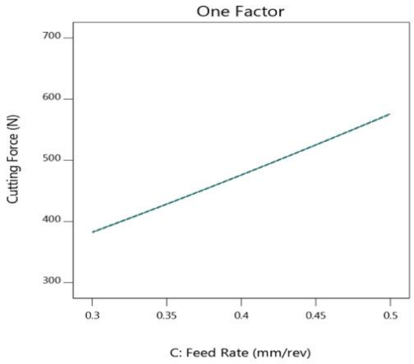

Fig. 12. Plot of feed rate against cutting force

3.4 Influence of Cutting Parameters on Responses

Fig. 7 to Fig. 12 have cutting parameters set at level 0, cutting speed 700m/min, depth of cut 0.6mm and feed rate 0.4mm/rev. Each figure shows the influence of one individual parameter on the response with the other two parameters set at level 0.For the cutting temperature response, Fig. 9 shows the highest gradient among all three parameters indicating that feed rate has the most significant effect in increasing the cutting temperature. This is followed by cutting speed as shown in Fig. 7. Fig. 8 shows the effect of depth of cut on cutting temperature. The line shows a minor curve when approaching 0.6mm depth of cut. Thus indicating the cutting temperature decreases as depth of cut approaches level 0. However, the overall gradient is not enough to show any significant change in cutting temperature.

For cutting force response, Fig. 12 shows the highest gradient among all three parameters indicating that feed rate has the most significant effect in increasing the cutting force. This is followed by depth of cut as shown in Fig. 11. Fig. 10 shows the effect of cutting speed on cutting force. Higher cutting speed slightly decreases cutting force. The gradient is quite small when compared to the other two parameters thus showing that cutting speed has the least effect on cutting force.

3.5 Interactions between Cutting Parameters

Cutting Temperature

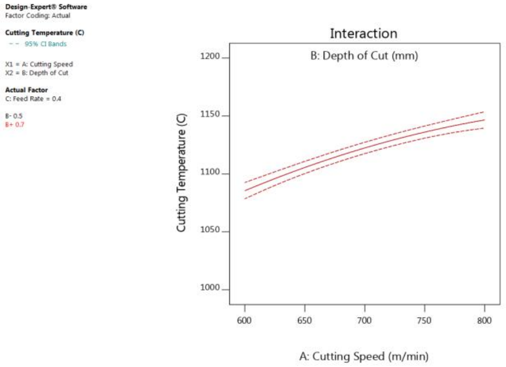

Fig. 13. Interaction of Cutting Speed and Depth of Cut against Cutting Temperature

Cutting Force

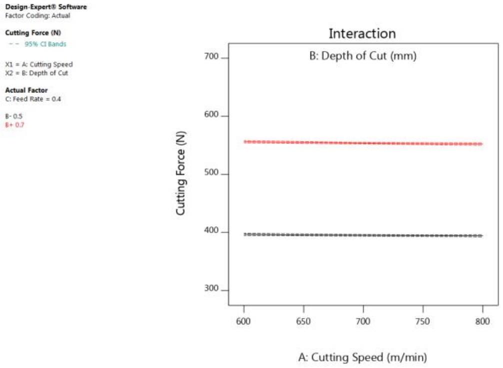

Fig. 16. Interaction of Cutting Speed and Depth of Cut against Cutting Force

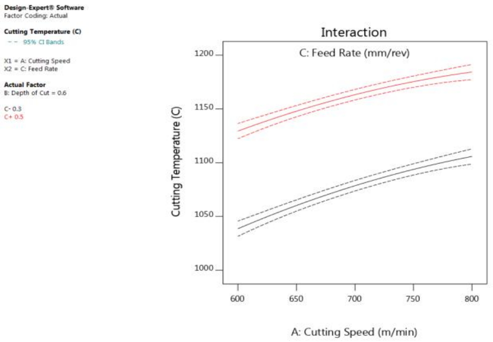

Fig. 14. Interaction cutting speed and feed rate against cutting temperature

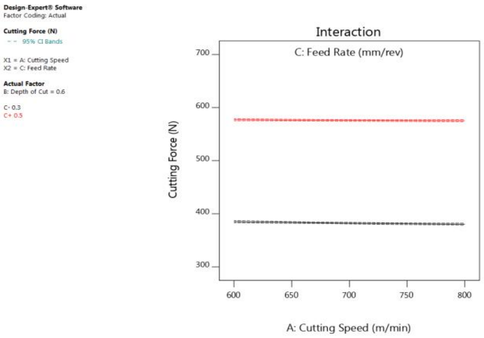

Fig. 17.Interaction cutting speed and feed rate against cutting force

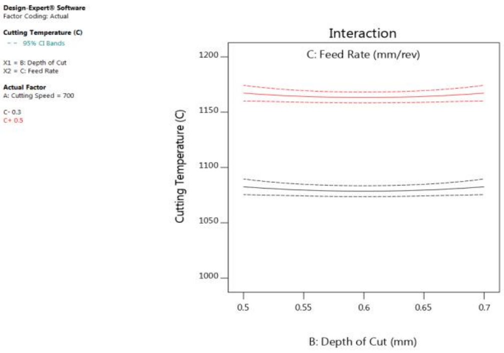

Fig. 15 Interaction of Depth of Cut and Feed Rate against Cutting Temperature

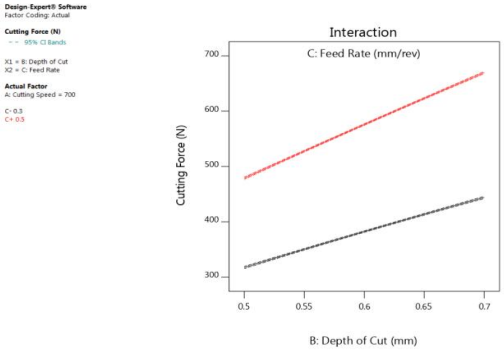

Fig. 18 Interaction of Depth of Cut and Feed Rate against Cutting Force

Fig. 13 to Fig. 15 shows the interaction between parameters on the cutting temperature response. There are no interactions between other combinations of parameters as the lines in each figure are shown to be parallel, it does not create any specific combined effect on the cutting temperature

Fig. 16 to Fig. 18 shows the interaction between parameters on the cutting force response. Fig. 16 and Fig. 17 shows that the lines are parallel. Thus the combinations of depth of cut and cutting speed have no unique interaction on the cutting force response. The same applies for feed rate and cutting speed as shown by the parallel lines in Fig. 17. In Fig. 18, the combination of feed rate and depth of cut does produce an interaction on the cutting force. The cutting force response is higher when both parameters of feed rate and depth of cut are higher. The red line in Fig. 18 shows that when feed rate is at 0.5mm/rev the gradient is much higher than the black line (feed rate at 0.3mm/rev).

3.6 3-D Surface Plots

Cutting Temperature

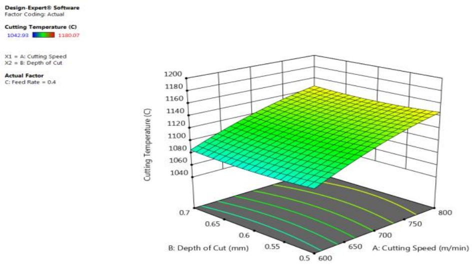

Fig. 19. 3D surface plot of cutting speed and depth of cut against cutting temperature

Cutting Force

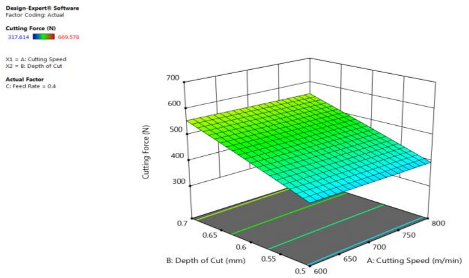

Fig. 22. 3D surface plot of cutting speed and depth of cut against cutting force

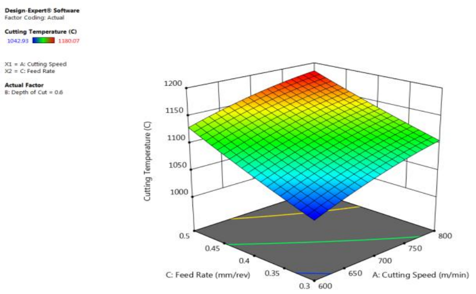

Fig. 20 3D surface plot of cutting speed and feed rate against cutting temperature

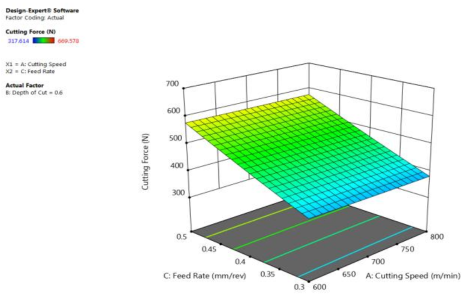

Fig. 23 3D surface plot of cutting speed and feed rate against cutting force

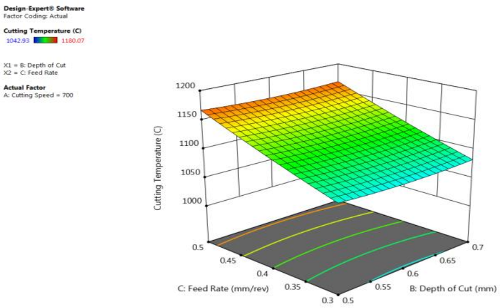

Fig. 21. 3D surface plot of depth of cut and feed rate against cutting temperature

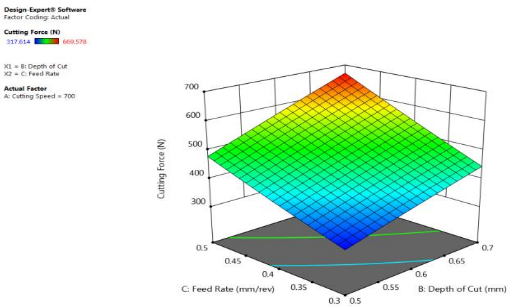

Fig. 24 3D surface plot of depth of cut and feed rate against cutting force

Table 7. Optimal cutting parameters for minimal cutting temperature

Cutting Speed (m/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Cutting Temperature (°C)	Cutting Force (N)	Desirability
600.28800	0.69933	0.300193	1042.74	447.057	1

Table 8. Optimal cutting parameters for minimal cutting force

Cutting Speed (m/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Cutting Temperature (°C)	Cutting Force(N)	Desirability
796.872	0.500676	0.300381	1108.26	316.709	1

Table 9. Optimal cutting parameters for minimal combination of cutting temperature and cutting force

Cutting Speed (m/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Cutting Temperature (°C)	Cutting Force (N)	Desirability
614.754	0.500001	0.3	1042.93	319.83	0.997

From Fig. 19 to Fig. 21, feed rate shows the most significant impact on the cutting temperature. This is followed by cutting speed while depth of cut does not show much influence on cutting temperature. Fig. 20 shows temperature is highest when cutting speed and feed rate is at their highest (800m/min and 0.5 mm/rev). The temperature increase through cutting speed is probably due to the increase of friction [7]. The increment of feed rate also increases friction thus also increases cutting temperature. [8]

Fig. 22 to Fig. 24 also shows that feed rate has most significant impact on the cutting force. This is then followed by depth of cut then cutting speed. Fig. 24 shows that that cutting force is highest when depth of cut and feed rate is at their highest (0.7mm and 0.5mm/rev). Higher cutting speed is able to reduce cutting force might be due to temperature. Since temperature increases at higher speeds, it is then able to soften the material at the cutting zone [9]. Increasing depth of cut increases the effective area between tool and workpiece, thus more force is required for material removal [10] Cutting forces increases with feed rate might be due to the hardness of the workpiece [11].

3.7 Optimization of Cutting Parameters

Cutting temperature and cutting force influences tool wear and thus tool life. Optimizations of the cutting parameters are done to obtain low cutting temperature and cutting force. Table 7 and Table 8 show the optimal parameters to obtain the lowest value for cutting temperature and cutting force. Table 9 shows the optimal parameters to obtain the lowest combination of cutting force and cutting temperature.

4. CONCLUSION

This research project studies the effect of cutting parameters on cutting force and cutting temperature which may have a direct impact on tool wear and subsequently tool life. Through Box-Behnken Design and Response Surface Methodology, the effects and influence of each cutting parameter are analysed. The study results valid for the ranges of cutting speed 600-800m/min, depth of cut 0.5-0.7mm and feed rate 0.3-0.5mm/rev. The following conclusion can be drawn from this research

1. Feed rate is the most significant cutting parameter for both cutting temperature and cutting force.
2. Minimum cutting temperature is obtained with 600.288m/min cutting speed, 0.69933mm/rev feed rate and 0.300193mm depth of cut.
3. Minimum cutting force is obtained with 614.637m/min cutting speed, 0.300381mm/rev feed rate and 0.500676mm depth of cut.
4. The lowest combined temperature and force can be obtained at 614.754m/min cutting speed, 0.3mm/rev feed rate and 0.500001mm depth of cut.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Rao CJ, NR. Influence of cutting parameters on cutting force and surface finish in turning operation. *Pr*ocedia Engineering. 2013;64(2013):1405–1415.
2. Katz R. Advanced Ceramics: At the Cutting Edge. Retrieved 2017, from Ceramic Industry; 2000. Available:https://www.ceramicindustry.com/articles/82791-advanced-ceramics-at-the-cutting-edge
3. Sunil R. Andhale PT. Problems in Improving Production Rate in Turning Operation. International Journal of Engineering Research & Technology (IJERT). 2014;3(1):2177-2182.
4. Vitor Augsuto A. de Godoy AE. Turning of interrupted and continuous hardened steel surfaces using ceramic. Journal of Materials Processing Technology. 2011;1014-1026.
5. Behnken DW, GE. Some New Three Level Designs for the Study of Quantitative Variables. Technometrics. 1960;2(4):455-475.
6. Topp R, G. G. Residual analysis in linear regression models with annterval-censored covariate. Statistics in Medicine. 2004;3378-3391.
7. Abhang LB, M. Chip-Tool Interface Temperature. International Journal of Engineering Science and Technology. 2010;382-393.
8. Fnides B, M.Y. Hard turning of hot work steel AISI H11: Evaluation of cutting pressures, resulting force and temperature. Mechanika. 2008;59-63.
9. Philip Selvaraj D, P. C. Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method. Measurement. 2014;49:205-215.
10. Pathak BN, K. L. Effect of Machining Parameters on Cutting

Forces and Surface Roughness in Al-(1-2) Fe-1V-1Si Alloys. Materials and Manufacturing Processes. 2013;28:463-469.

11. Li Qian MR. Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts. Journal of Materials Processing Technology. 2007;191:274-278.

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