Journal of Advances in Mechanical Engineering and Science, Vol. 4(1) 2018, pp.19-29

RESEARCH ARTICLE

Analysis of Cutting Force Components in Hard Turning of AISI4340 Steel with Coated Carbide Tool: Regression Model and Cutting Conditions Optimization

***D Rajeev[1], N Austin[2], G Franklin[3]**

[1]Associate Professor, Department of Mechanical Engineering, MarEphraem College of Engineering and Technology, Tamil Nadu, India.

[2]Professor, Department of Mechanical Engineering, MarEphraem College of Engineering and Technology, Tamil Nadu, India.

[3]Assistant Professor, Department of Mechanical Engineering, MarEphraem College of Engineering and Technology, Tamil Nadu, India.

Received- 1 February 2018, Revised- 28 February 2018, Accepted- 1 March 2018, Published- 2 March 2018

ABSTRACT

Recently, hard turning has become an emerging technology in manufacturing replacing traditional grinding process. In this work, an experimental study on the influence of process parameters (cutting speed, feed rate and depth of cut) on cutting force components in the hard turning process is carried out. Hardened AISI 4340 steel (47 HRC (Rockwell hardness)) is machined using CVD coated Ti(C,N) + Al_2O_3 carbide tool. Experiments are carried out with response surface design using Box-Behnken approach. The process parameters are taken as factors and considered for experimentation in three-levels. The cutting forces measured from dynamometer are taken as response. Analysis of Variance (ANOVA) is carried out to determine the most influencing parameters. Regression equations are formulated using experimental data. The response surface analysis is carried out to determine the influence of interaction of process parameters on the responses. Optimal cutting conditions range is found out for minimizing the cutting forces. Results indicate that both depth of cut and feed has statistical significance on the cutting force components.

Keywords: Hard turning, RSM, Coated carbide, ANOVA, Cutting force, Tool Wear.

1. INTRODUCTION

Hard turning is carried out with materials in the hardness range of 45-70HRC and is basically a finishing process. Hard turning eliminates the series of operations required in the traditional procedures of machining hardened material, consequently reducing the cycle time and improving the productivity. Even though it is more advantageous in terms of cost, time, environment and productivity, its application is limited in industries due to uncertainty in surface integrity, tool wear and life. Hence a detailed review in machinability aspects during hard turning is conducted [1-8]. [9] has found out the optimal cutting conditions for reducing tool wear and surface roughness during the turning process of hardened AISI 4140 steel (63HRC) with Al_2O_3 +TiCN mixed ceramic tools using Taguchi method. [10] has experimentally investigated the tool performance and wear mechanisms of TiAlN PVD coated inserts. The material used is hardened AISI4140 steel. The result has showed a premature failure of inserts above speed of 410m/min. [11] has conducted experimental investigation of HiPIMS coated inserts during hardened AISI4340 steel (55 HRC) machining. The result has showed that HiPIMS coated inserts produced better tool life

*Corresponding author. Tel.: +919444895594
Email address: d_rajeev@yahoo.com (D.Rajeev)
Double blind peer review under responsibility of DJ Publications
https://dx.doi.org/10.18831/james.in/2018011002

and it can be considered for hard turning. [12] has used Response Surface Methodology (RSM) to investigate the effects of cutting parameters and hardness on the roughness and cutting force components during turning of X38CrMoV5-1(50HRC) using Cubic Boron Nitride (CBN) inserts. [13] has studied the effects of insert shapes during machining of hardened AISI 4140 steel. The triangular insert is found to be superior to square and round inserts for minimal surface roughness. [14] A mathematical model is developed for surface roughness using ANN, fuzzy logic and regression methods. The fuzzy model provides better results. [15] has used Taguchi method to compare the tool life between CBN and ceramics cutting tools during hard turning of bearing steels. The result shows that velocity has significant impact on tool life [16, 17]. The CBN cutting tool outperforms ceramic based cutting tool in performance. [18] has studied the performance of coated and uncoated carbide inserts. Surface roughness, flank wear, cutting forces and chip morphology are taken as responses during hard turning of AISI 4340 steel (47 HRC). It is found that the performance of multilayer coated carbide inserts is better than uncoated carbide inserts. In hard turning of ASI H11 steel, the influence of velocity, feed, work piece hardness and depth of cut on cutting force components and surface roughness using CBN tools is studied. RSM based regression models are generated for the responses. [19] has optimized the cutting parameters using Taguchi and ANOVA. [20] has investigated the multilayer CVD coated $TiN/TiCN/Al_2O_3$ cemented carbide inserts performance while machining of hardened AISI 4340 steel (48 HRC). It is concluded that the combination of high cutting speed, low depth of cut and low feed rate resulted in minimal cutting force and surface roughness. Based on the literature on hard turning, it is observed that most of the works are limited to the expensive CBN or ceramic tools and definitely, there is a need for least expensive tool which can perform hard turning. In such context, the proposed alternative is coated carbide insert which are cheaper than CBN or ceramic tools, only a few works are reported on the ability of coated carbide tool during hard turning of alloy steel in the hardness range (46-48 HRC), which has high industrial applications.

In this work a comprehensive experimental investigation of cutting parameters is carried out based on RSM. AISI 4340 hardened steel is machined using coated carbide tools. The influencing parameters are found out using ANOVA. The optimal cutting conditions for reducing the cutting force are also analysed.

1.1. Nomenclature

d	Depth of cut
df	Degree of freedom
f	Feed rate
Fx	Feed (axial) force
Fy	Thrust (radial) force
Fz	Cutting (tTangential) force
MS	Mean square
R2	Determination coefficient
SS	Sum of squares
V	Cutting speed (velocity)

2. EXPERIMENTAL PROCEDURES

2.1. Materials and methods

AISI4340 hardened to 47 HRC and of 80mm diameter is used as the work piece material. Table 1 indicates the chemical composition of the work-piece material. A 6.6 KW spindle power Kirloskar lathe is used for carrying out the experiments under dry conditions. The chosen cutting tool is CVD coated $Ti(C,N) + Al_2O_3$ durotomic carbide tool designated as TH1500 grade (manufactured by SECO). The nose radius is 0.8mm. ISO designation of the cutting insert is CNMG120408. The tool holder is codified as PCLNR2525 M12 of the following specifications: major cutting edge angle = 95^0, back rack angle= -6^0 and negative cutting edge inclination angle= -6^0. The experiments are carried out for fixed length of 200mm.

Table 1.AISI 4340 steel-chemical composition

Composition	(Wt %)
C	0.42
Cr	0.8
Ni	1.7
Mo	0.25
Mn	0.7
P	0.035
S	0.04
Si	0.20
Fe	95.85

Table 2.Factors and levels

Level	V(m/min)	f(mm/rev)	d(mm)
1	70	0.08	0.3
2	120	0.1	0.45
3	170	0.12	0.6

2.2. Cutting force measurement

The measurement of cutting forces is done using dynamometer of Kistler make (9257B). The details are shown in figure 1. The cutting forces measured includes thrust force along feed direction (F_x), thrust force along radial direction (F_y) and cutting force (F_z) along the z direction. A tool wear microscope is used to measure the flank wear (V_b).

Figure 1.Experimental setup with dynamometer

2.3. Experiments design

The experiments are carried out based on RSM (Box-Behnken). The relation between input parameters and responses is obtained systematically through RSM. The steps involved in RSM include:

1) Definition of input factors and the levels
2) Design and conduction of experiments as per the plan.
3) Determination of influential parameter for the responses using ANOVA.
4) Development of response model in the form of regression equation.
5) Analysing the effect of interaction of input parameters on response surfaces using response surfaces.
6) Optimization of input condition for the minimization of responses.

In this work, the relationship between the input parameters (V, f and d) and the responses (F_x, F_y and F_z) is obtained. Mathematically, the output is given in (2.1),

$$Y = \theta\,(V, f, d) \qquad (2.1)$$

where θ= Response function

The approximation model known as regression equation is formulated as in (2.2).

$$Y = a0 + \sum_{I=1}^{K} A_I\, XI + \sum_{I,J}^{K} A_{IJ}\, XiX\,j + \sum_{I=1}^{K} BA_{II}\, X_i^2 \qquad (2.2)$$

where a_0 is the constant coefficient, a_1, a_2, . . .,a_k are the linear coefficients, a_{11}, a_{22}, . . .a_{kk} are the quadratic terms and a_{12}, a_{13}, a_{23}…… are the interacting terms.

The data for computation of the above equation is based on Box–Behnken Designs (BBDs) where the numeric factors are varied by three levels represented as -1; 0; and+1. The factors selected and levels assigned are shown in table 2. The desired statistical properties are created using the above design. Another important aspect is only less number of experimental runs are required. 17 experiments are required for an input of 3 factors.

3. RESULTS AND DISCUSSION

The experimental results for tool wear as well as the cutting forces are depicted in table A1. The range obtained for the thrust force (F_x), thrust force (F_y) and the tangential force (F_z) are (12–158.4) N, (42.3–365) N and (37.14–335.1) N, respectively.

3.1. ANOVA for cutting forces

The results of ANOVA, for cutting forces (F_x, F_y and F_z) are depicted in tables A2-A4. The p-value <.005 indicates all the models are statistically significant. Table A2 shows analysis for F_x. Depth of cut succeeded by feed rate and velocity are significant and the interactions do not have much impact on the feed force (F_x). The reason is that as the depth of cut increases, the cutting edge length also increases owing to the increase in principal cutting edge angle. Redistribution of force takes place along the axial direction and hence the variation is more along the feed direction. Table A3 depicts the ANOVA for the cutting force along the radial direction (F_y). The highest influencing factor is depth of cut succeeded by feed and velocity is having the least influence. Table A4 shows the ANOVA results for cutting force along the tangential direction (F_z). It can be seen that the feed (f) is the highest influencing factor affecting F_z succeeded by depth of cut and cutting speed. It is found that the interaction of depth of cut and feed also influences F_z.

3.2. Regression equations

Regression equation formulated by the approximation of a nonlinear quadratic polynomial is given below. It gives the relation between the input parameters and responses. The regression models for various responses are given below.

3.2.1. Cutting forces

The regression model for the thrust force in feed direction (F_x) is given in (3.1). The prediction coefficient (R^2) is 98.05%.

$$F_X = -207.77655 - 0.096345 \times V + 2226.55000 \times f + 227.90167 \times d + 1.33500 \times V \times f - 0.35300 \times V \times d - 808.33333 \times f \times d - 2.69500 \times 10^{-4} \times V^2 - 2515.62500 \times f^2 + 227.61111 \times d^2 \quad (3.1)$$

The regression model for the cutting force in the radial direction (F_y) is shown in (3.2) and the R^2 value for the above model is 91.76%.

$$F_y = -96.21100 - 0.28140 \times V + 2965.75000 \times f - 731.33333 \times d - 6.22500 \times V \times f - 0.61667 \times V \times d + 12008.33333 \times f \times d + 3.78500 \times 10^{-3} \times V^2 - 21093.75000 \times f^2 + 278.33333 \times d^2 \quad (3.2)$$

The regression model for cutting force in the tangential direction (Fz) is shown in (3.3). The prediction coefficient (R^2) is 77.79%. (3.3) is validated by input drawn from random cutting conditions. The measured and predicted values calculated from the regression equations for the validation data are compared and is depicted in table A5 and figures 2-4.

$$Fz = +776.95990 + 0.19031 \times V - 11284.37500 \times f - 1579.74667 \times d - 3.92500 \times V \times f - 0.52267 \times V \times d + 12570.00000 \times f \times d + 1.41000 \times 10^{-4} \times V^2 + 47106.25000 \times f^2 + 914.11111 \times d^2 \quad (3.3)$$

Figure 2.Measured v/s predicted values comparison for F_x

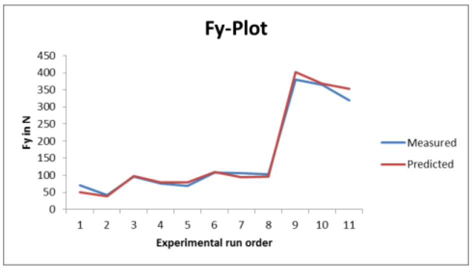

Figure 3.Measured v/s predicted values comparison for Fy

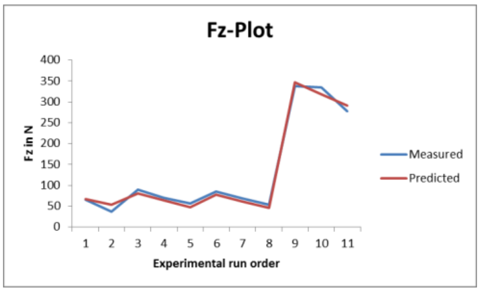

Figure 4.Measured v/s predicted values comparison for F_z

3.3. Response surface analysis

The response surface analysis results are given in figures 5-13.

3.3.1. Response surfaces-cutting forces

Figure 5 shows the variations of axial force F_x with cutting speed (V) and feed rate (f). The ANOVA results indicate that for axial force, the interaction of feed and cutting speed are not statistically significant; it is evident from figure 5 that a low axial force occurs for a lower feed and higher cutting speed.

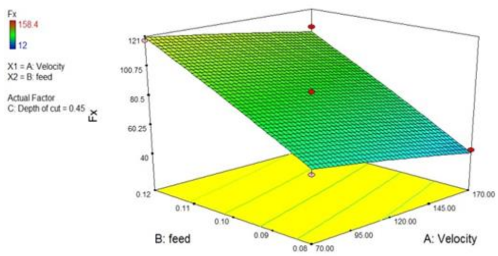

Figure 5.Interaction (V x f) on F_x

Figure 6 shows the variations of axial force F_x with cutting speed (V) and depth of cut (d). The ANOVA results indicate that for axial force, the interaction of depth of cut and cutting speed are not statistically significant; it is evident from figure 6 that a low radial force occurs for a lower depth of cut and higher cutting speed.

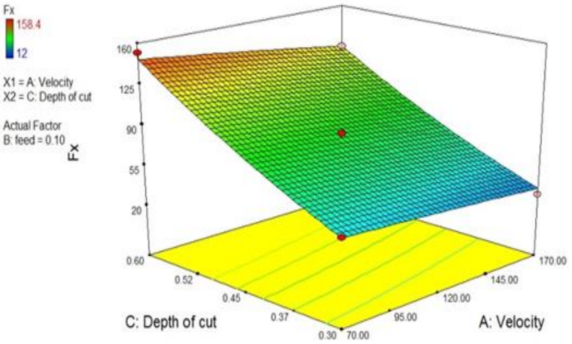

Figure 6.Interaction (V x d) on F_x

Figure 7 shows the variations of axial force F_x with feed (f) and depth of cut (d). The ANOVA results indicate that for axial force the interaction of depth of cut and feed are not statistically significant; It is evident from figure 7 that a low radial force occurs for a lower depth of cut and feed.

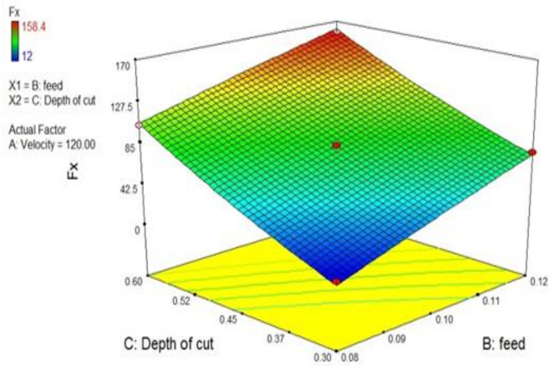

Figure 7.Interaction (f x d) on F_x

Figure 8 shows the variations of radial force F_y with cutting speed (V) and depth of cut (d). The ANOVA results indicate that for radial force, the interaction of depth of cut and cutting speed are not statistically significant; It is evident from figure 8 that a low radial force occurs for a lower depth of cut and higher cutting speed.

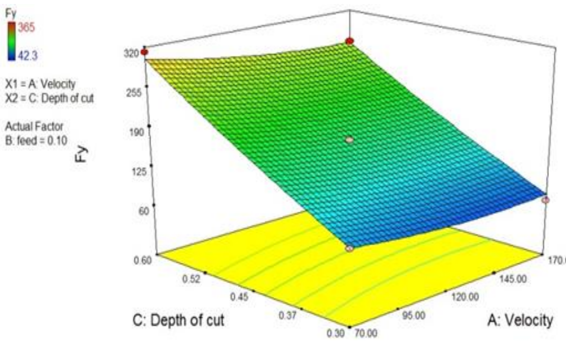

Figure 8.Interaction (V x d) on F_y

Figure 9 shows the variations of radial force F_y with feed (f) and depth of cut (d). ANOVA results indicate that for radial force the interaction of depth of cut and feed are statistically significant; It is evident from fig.9 that a low radial force occurs for a small feed and depth of cut.

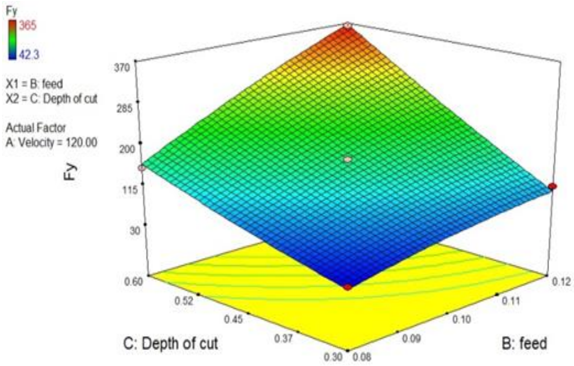

Figure 9.Interaction (f x d) on F_y

Figure 10 shows the variations of radial force F_y with feed (f) and cutting speed (V). ANOVA results indicate that for radial force, the interaction of cutting speed and feed are not statistically significant; It is evident from figure 10 that a low radial force occurs for a small feed and higher cutting speed.

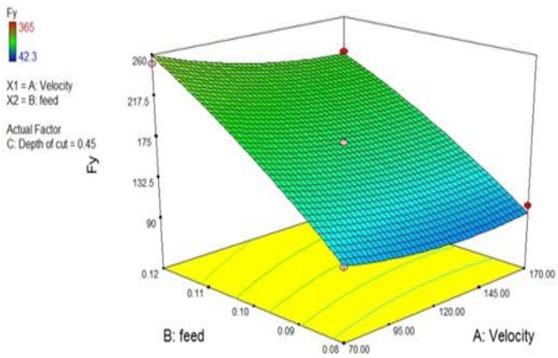

Figure 10.Interaction (V x f) on F_y

Figure 11 shows the variations of Tangential force F_z with depth of cut (d) and cutting speed (V). The ANOVA results indicate that for tangential force, the interaction of cutting speed and depth of cut are not statistically significant; It is evident from figure 11 that a low tangential force occurs for a small depth of cut and higher cutting speed.

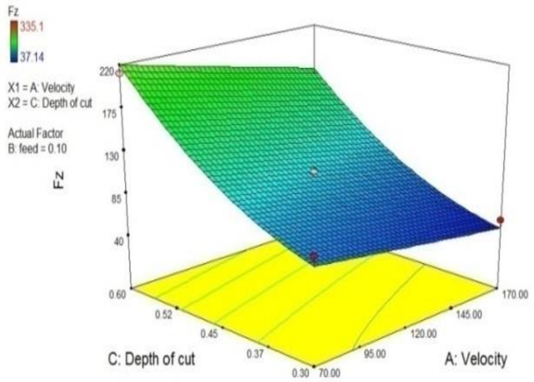

Figure 11.Interaction (V x d) on F_z

Figure 12 shows the variations of Tangential force F_z with feed (f) and cutting speed (V). The ANOVA results indicate that for tangential force, the interaction of cutting speed and feed are not statistically significant; It is evident from figure 12 that a low tangential force occurs for a small feed and higher cutting speed.

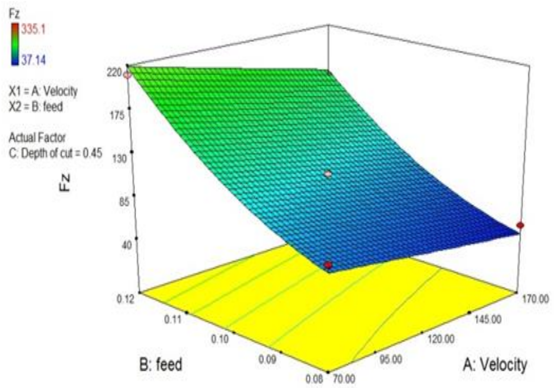

Figure 12.Interaction (V x f) on F_z

Figure 13 shows the variations of Tangential force F_z with feed (f) and depth of cut (d). ANOVA results indicate that for tangential force the interaction of depth of cut and feed are statistically significant; It is evident from figure 13 that a low tangential force occurs for a small feed and depth of cut.

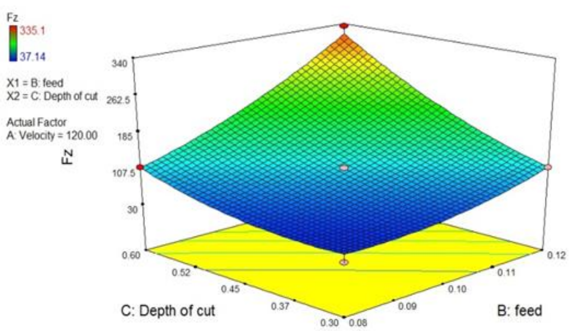

Figure 13.Interaction (d x f) on F_z

4. OPTIMIZATION OF CUTTING CONDITIONS

Based on the data available in table A1, optimal conditions for minimizing the cutting forces are found out. Table 3 shows the defined goals as well as their ranges considered for optimization. Optimal results obtained based on RSM are shown in table A6. These optimal levels can be considered in hard turning of AISI4340 steel.

Table 3.Optimization ranges and the goals

Variable	Goal	Lower bound	Upper bound
V	Within	70	170
f	Within	0.08	0.12
d	Within	0.3	0.6
F_x	Minimize	12	158.4
F_y	Minimize	42.3	365
F_z	Minimize	37.14	335.1

5. CONCLUSION

This paper presents a thorough experimental investigation on the impact of machining parameters on the cutting forces during hard turning of AISI4340 (47 HRC) steel. Coated carbide tool is used as the insert. An RSM (Box-Behnken) approach is used to formulate a regression equation for tool wear as well as cutting forces prediction. Optimal cutting conditions are derived for minimizing wear and force components.

The following conclusions are made.

1. With RSM, determining the most influencing factors affecting the cutting forces are possible.
2. ANOVA results show that the both feed and depth of cut influences the cutting forces while the cutting speed has the least influence.
3. The regression models of cutting forces are found significant.
4. Comparison of predicted values from regression equation and experimental values for the validation data drawn from random cutting conditions shows good correlation.
5. Effect of process parameter interactions on the cutting forces are found out from the surface analysis plot.

REFERENCES

[1] Khaider Bouacha, Mohamed Athmane Yallese, Tarek Mabrouki, and Jean-Francois Rigal, Statistical Analysis of Surface Roughness and Cutting Forces using Response Surface Methodology in Hard Turning of AISI 52100 Bearing Steel with CBN tool, International Journal of Refractory Metals and Hard Materials, Vol. 28, No. 3, 2010, pp. 349–361, https://doi.org/10.1016/j.ijrmhm.2009.11.011.

[2] H.M.Lin, Y.S.Liao and C.C.Wei, Wear Behavior in turning High Hardness Alloy Steel by CBN Tool, Wear, Vol. 264, No. 7-8, 2008, pp. 679–684, https://doi.org/10.1016/j.wear.2007.06.006.

[3] C.H.Muralimohan, S.Haribabu, Y.Hariprasada Reddy, V.Muthupandi and K.Sivaprasad, Joining of AISI 1040 Steel to 6082-T6 Aluminium Alloy by Friction Welding, Journal of Advances in Mechanical Engineering and Science, Vol. 1, No. 1, 2015, pp. 57-64, http://doi.org/10.18831/james.in/2015011006.

[4] Mohamed Athmane Yallese, KamelChaoui, Nassereddine Zeghib, Lakhdar Boulanouar and Jean-François Rigal, HardMachining of Hardened Bearing Steel using Cubic Boron Nitride Tool, Journal of Materials Processing Technology, Vol. 209, No. 2, 2009, pp. 1092–1094, https://doi.org/10.1016/j.jmatprotec.2008.03.014.

[5] U.Caydas, Machinability Evaluation in Hard Turning of AISI 4340 Steel with Different Cutting Tools using Statistical Techniques, Journal of Engineering Manufacture Vol. 224, No. 7, 2009, pp. 1043–1055, http://doi.org/10.1243/09544054JEM1822.

[6] M.Ganesan, S.Johny James and P.Santhamoorthy, Design to Replace Steel Drive Shaft in Automobiles with Hybrid Aluminium Metal Matrix Composite, Journal of Advances in Mechanical Engineering and Science, Vol. 1, No. 3, 2015, pp. 41-48, http://doi.org/10.18831/james.in/2015031005.

[7] Ashok Kumar Sahoo and Bidyadhar Sahoo, Performance Studies of Multilayer Hard Surface Coatings ($TiN/TiCN/Al_2O_3/TiN$) of Indexable Carbide Inserts in Hard Machining:Part-II (RSM, grey relational and techno economical approach), Measurement, Vol. 46, No. 8, 2013, pp. 2868–2884, https://doi.org/10.1016/j.measurement.2012.09.023.

[8] R.Sri Siva and B.Balachithra, Optimization of Machining Parameters using Scatter Search Algorithm, Journal of Advances in Mechanical Engineering and Science, Vol. 2, No. 4, 2016, pp. 11-18, http://doi.org/10.18831/james.in/2016041002.

[9] Ersan Aslan, Necip Camuscu and Burak Birgoren, Design Optimization of Cutting Parameters when Turning Hardened AISI 4140 Steel (63 HRC) with Al_2O_3 + TiCN Mixed Ceramic Tool, Materials and Design, Vol. 28, No. 5, 2007, pp. 1618–1622, https://doi.org/10.1016/j.matdes.2006.02.006.

[10] Samir K.Khrais and Y.J.Lin, Wear Mechanisms and Tool Performance of TiAlN PVD Coated Inserts during Machining of AISI 4140 Steel, Wear, Vol. 262, No. 1-2, 2007, pp. 64–69, https://doi.org/10.1016/j.wear.2006.03.052.

[11] Satish Chinchanikar and S.K.Choudhury, Hard Turning using HiPIMS-Coated Carbide Tools: Wear Behaviour under Dry and Minimum Quantity Lubrication (MQL), Measurement, Vol. 55, 2014, pp. 536–548, https://doi.org/10.1016/j.measurement.2014.06.002.

[12] H.Aouici, M.A.Yallese, A.Belbahm, F.Ameur and M.Elbah, Experimental Investigation of Cutting Parameters influence on Surface Roughness and Cutting forces in Hard Turningof $X_38CrMoV_{5-1}$ with CBN Tool, Sadhana, Vol. 38, No. 3, 2013, pp. 429–445,

https://doi.org/10.1007/s12046-013-0147-z.

[13] Rohit Uppal, Dilbag Singh and Sunil Kumar, Experimental Investigations to Study the Effect of Carbide Insert Shapes on Machining of AISI 4140, International Journal of Surface Engineering & Materials Technology, Vol. 3, 2013.

[14] Harun Akkus and Ilhan Asilturk, Predicting Surface Roughness of AISI 4140 Steel in Hard Turning Process through Artificial Neural Network, Fuzzy Logic and Regression Models, Scientific Research and Essays, Vol. 6, No. 13, 2011, pp. 2729-2736.

[15] Y.Sahin, Comparison of Tool Life between Ceramic and Cubic Boron Nitride (CBN) Cutting Tools when Machining Hardened Steels, Journal of Materials Processing Technology, Vol. 209, No. 7, 2009, pp. 3478–3489, https://doi.org/10.1016/j.jmatprotec.2008.08.016.

[16] G.Venses and R.Sri Siva, Optimisation of Deep Cryogenic Treatment Process on the Wear Resistance of 100Cr6 Bearing Steel using Taguchi Technique, Journal of Advances in Mechanical Engineering and Science, Vol. 1, No. 2, 2015, pp. 9-20, http://doi.org/10.18831/james.in/2015021002.

[17] Ashok Kumar Sahoo and Bidyadhar Sahoo, Performance Studies of Multilayer Hard Surface Coatings (TiN/TiCN/Al_2O_3/TiN) of Index-able Carbide Inserts in Hard Machining: Part-I (An experimental approach), Measurement, Vol. 46, No. 8, 2013, pp. 2854–2867.

[18] Hamdi Aouici, Mohamed Athmane Yallese, Kamel Chaoui, Tarek Mabrouki and Jean-Francois Rigal, Analysis of Surface Roughness and Cutting Force Components in Hard Turning with CBN Tool: Prediction Model and Cutting Conditions Optimization, Measurement, Vol. 45, No. 3, 2012, pp. 344-353, https://doi.org/10.1016/j.measurement.2011.11.011.

[19] M.Balaji, B.S.N.Murthy and N.Mohan Rao, Optimization of Cutting Parameters in Drilling of Ti- 6Al-4V Alloy using Taguchi and ANOVA, Journal of Advances in Mechanical Engineering and Science, Vol. 2, No. 4, 2016, pp. 1-10, http://doi.org/10.18831/james.in/2016041001.

[20] R.Suresh, S.Basavarajappa and G.L. Samuel, Some Studies on Hard Turning of AISI 4340 Steel using Multilayer Coated Carbide Tool, Measurement, Vol. 45, No. 7, 2012, pp. 1872-1884, https://doi.org/10.1016/j.measurement.2012.03.024.

APPENDIX A

Table A1.Experimental results

Run No	V(m/min)	f(mm/rev)	d (mm)	F_x(N)	F_y(N)	F_z(N)
1	170	0.08	0.45	42.79	103.3	54.24
2	70	0.1	0.30	48.32	96	90
3	120	0.1	0.45	83.51	169.8	109
4	120	0.1	0.45	83.51	169.8	109
5	170	0.1	0.60	122.3	265.8	162
6	120	0.12	0.30	75.9	112.4	110.9
7	70	0.1	0.60	152	312.3	211.4
8	120	0.1	0.45	83.51	169.8	109
9	120	0.12	0.60	158.4	365	335.1
10	70	0.08	0.45	58.33	108.2	85.54
11	70	0.12	0.45	118.2	250.8	210
12	120	0.1	0.45	83.51	169.8	109
13	120	0.1	0.45	83.51	169.8	109
14	120	0.08	0.60	104.2	150.8	110.5
15	120	0.08	0.30	12	42.3	37.14
16	170	0.1	0.30	29.21	68	56.28
17	170	0.12	0.45	108	221	163

Table A2.ANOVA for F_x

Source	S S	df	M S	F Value	p-value Prob> F	Significant
Model	25507.77	9	2834.2	148.6054	< 0.0001	Yes
V-Velocity	694.7128	1	694.713	36.4259	0.0005	Yes
f-feed	7392.064	1	7392.06	387.5879	< 0.0001	Yes
d-Depth of cut	17248.75	1	17248.7	904.4030	< 0.0001	Yes
V×f	7.1289	1	7.1289	0.3738	0.5603	No
V×d	28.03702	1	28.037	1.4701	0.2647	No
f×d	23.5225	1	23.5225	1.2334	0.3034	No
V^2	1.911322	1	1.91132	0.1002	0.7608	No
f^2	4.263322	1	4.26332	0.2235	0.6507	No
d^2	110.4303	1	110.43	5.7902	0.0470	No
Residual	133.5038	7	19.072			
Lack of Fit	133.5038	3	44.5013			
Error	0	4	0			
Total	25641.28	16				

Table A3.Analysis of variance (ANOVA) for F_y

Source	S S	df	M S	F Value	p-value Prob> F	Significant
Model	119925.2	9	13325	150.1701	< 0.0001	Yes
V-Velocity	1490.58	1	1490.58	16.7985	0.0046	Yes
f-feed	37073.65	1	37073.6	417.8119	< 0.0001	Yes
d-Depth of cut	75116.88	1	75116.9	846.5509	< 0.0001	Yes
V×f	155.0025	1	155.002	1.7468	0.2278	No
V×d	85.5625	1	85.5625	0.9643	0.3588	No
f×d	5191.203	1	5191.2	58.5037	0.0001	Yes
V^2	377.0059	1	377.006	4.2488	0.0782	No
f^2	299.7533	1	299.753	3.3782	0.1087	No
d^2	165.1322	1	165.132	1.8610	0.2147	No
Residual	621.13	7	88.7329			
Lack of Fit	621.13	3	207.043			
Error	0	4	0			
Total	120546.3	16				

Table A4.ANOVA for F_z

Source	Sum of squares	df	M S	F Value	p-value Prob> F	Significant
Model	82286.37	9	9142.93	55.4823	< 0.0001	Yes
V-Velocity	3257.052	1	3257.05	19.7649	0.0030	Yes
f-feed	35322.16	1	35322.2	214.3464	< 0.0001	Yes
d-Depth of cut	34411.14	1	34411.1	208.8180	< 0.0001	Yes
V×f	61.6225	1	61.6225	0.3739	0.5602	No
V×d	61.4656	1	61.4656	0.3730	0.5607	No
f×d	5688.176	1	5688.18	34.5177	0.0006	Yes
V^2	0.523184	1	0.52318	0.0032	0.9566	No
f^2	1494.904	1	1494.9	9.0716	0.0196	No
d^2	1781.146	1	1781.15	10.8086	0.0133	No
Residual	1153.531	7	164.79			
Lack of Fit	1153.531	3	384.51			
Error	0	4	0			
Total	83439.9	16				

Table A5.Measured and Predicted values for validation data set

Input parameters				Machinability characteristics					
				Experimental			Predicted		
Ex.no	V(m/min)	f(mm)	d(mm)	F_x(N)	F_y(N)	F_z(N)	F_x(N)	F_y(N)	F_z(N)
1	70	0.08	0.3	11.3	70.45	66.02	15.70	50.94	66.77
2	120	0.08	0.3	12	42.3	37.14	8.37	38.67	54.09
3	70	0.1	0.3	48.32	96	90	48.20	97.65	80.59
4	120	0.1	0.3	33.97	75	70	42.20	79.16	63.98
5	170	0.1	0.3	29.21	68	56.28	34.85	79.60	48.08
6	70	0.08	0.45	58.33	108.2	85.54	62.09	110.17	78.00
7	120	0.08	0.45	56.34	106	67.88	52.11	93.29	61.39
8	170	0.08	0.45	42.79	103.3	54.24	40.78	95.32	45.49
9	70	0.12	0.6	164	380	338	171.99	402.59	346.53
10	120	0.12	0.6	158.4	365	335.1	162.03	368.62	318.15
11	170	0.12	0.6	154.8	318.5	278.2	150.73	353.59	290.48

Table A6.Optimization results for the cutting forces

No.	Velocity (V) m/min	Feed (f) mm/rev	Depth of cut (a_p) mm	F_x N	F_y N	F_z N	Desirability
1	87.72	0.08	0.3	13.2571	44.4271	62.1960	0.9746
2	88.24	0.08	0.3	13.3224	44.4892	62.0373	0.9735
3	88.8	0.08	0.3	13.1103	44.1187	61.9174	0.9733
4	80.31	0.08	0.3	14.3004	46.8617	64.0996	0.9693
5	96.48	0.08	0.3	11.9860	42.0862	59.9668	0.9637