REST Journal on Emerging trends in Modelling and Manufacturing
Vol:3(3),2017
REST Publisher
ISSN: 2455-4537

Website: www.restpublisher.com/journals/jemm

Modeling for investigation of effect of cutting parameters on the tool dynamics and surface roughness in turning operation with uncoated and coated cutting tools

Kuldip A.Baviskar, Umesh S.Chavan
Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India
kuldipbaviskar@gmail.com, umesh.chavan@vit.edu

Abstract

This paper presents the obtained mathematical models of Feed Force, Cutting Force, Thrust Force, and Surface Roughness during turning operation for uncoated and coated tool insert as a function of processing parameters cutting speed, feed and depth of cut. The turning operation has been performed on the CNC Lathe machine using tungsten carbide (uncoated and coated with Al2O3) tool inserts and the workpiece material is AISI 4340. Process influencing parameters considered are in the range between A = 150 and 300 m/min, B = 0.16 and 0.32 mm/rev and C = 0.5 and 1.5 mm. Cutting forces are measured using computerized experimental setup with KISTLER's three components piezoelectric dynamometer and surface roughness is measured with MITITOYO's portable surface roughness tester. Experiments are performed as per the first order three factorial experimental plan for coated and uncoated tool insert. Mathematical modeling of cutting forces and surface roughness has been prepared with regression by MINITAB 18 and with ANN by MATLAB 18.

Keywords: Mathematical Model, Cutting Forces, Surface Roughness, ANN.

I. Introduction

In machining process, prediction of outcome is of vital importance and major factors which affects the performance of machining are cutting speed, feed and depth of cut. High material removal rate is proposed to reduce manufacturing cost and machining time, while the productivity in terms of cost and machining time for an expected surface quality of work piece strongly depends on the tool wear which directly proportional to generated tool forces. The maximum utilization of cutting tool is one of the way to achieve reduction in manufacturing cost [2]. Getting the magnitudes of cutting forces and surface roughness formed on the workpiece in the turning operation as a condition of treatment is necessary for determining the cutting tool strength, selection of optimal processing parameters, forecasting the expected performance, tool wear, and quality of machining, determination of the time to change the tool inserts. Experiences show that the determination of cutting forces in an analytical way not fully reflect the actual situation [3]. Metal cutting is one of the most significant process in material removal. It has been proven that the quantitative predictions are very essential to develop optimization strategies preferably in the form of equations. [4]. Surface quality is one of the most indication of the quality of machined component which is surface roughness. Cutting parameters are the important influencers on the quality of surface of machined component. Cutting force is the important variable which provides information to understand critical machining attributes such as machinability, tool fracture, tool chatter, surface finish and accuracy. [5].Here, experiments are conducted as per first order three factorial experimental plan for uncoated and coated tool. The Mathematical regression model is prepared using MINITAB 18 and accuracy of the model is tested using analysis of variance (ANOVA). The second model is generated using artificial neuron network tool in MATLAB 18. The regression model and ANN model values are compared with the actual results.

II. Experimental Details

A. Experimental Plan

The planning of experiments means prior prediction of actions and all influential factors which will help in getting new knowledge effectively. The experiments have been carried out using first order three factorial design of experiment to achieve tool forces generated on tool insert and surface roughness obtained on workpiece. From the literature survey, it has been understood that there are three important parameters which affects tool forces and surface roughness most. So, in this paper three cutting parameters are considered as an influencing factor which are cutting speed, feed and depth of cut. Each factor is having two levels that is low and high as explained in Table 1.

Table 1: Cutting Parameters

Factors	Name	Low Levels	High Levels	Unit
A	Cutting Speed	150	300	m/min
B	Feed	0.16	0.32	mm/rev
C	Depth of cut	0.5	1.5	mm

Number of Factors (k) = 3
Number of levels (L) = 2

Number of experiments = Lk = 23 = 8

The first order three factorial plan of experiments is presented in Table 2. For each experimental run, magnitudes of Feed Force (Fx), cutting force (Fy), Thrust Force (Fz) and Surface Roughness (Ra) have been measured for coated and uncoated tungsten carbide tool from which later individual mathematical models are generated using Regression and ANN method.

Table 2: Experimental Plan

Actual Run No.	Run No.	FactorA	FactorB	FactorC
2	1	150	0.16	0.5
4	2	300	0.16	0.5
6	3	150	0.32	0.5
8	4	300	0.32	0.5
1	5	150	0.16	1.5
3	6	300	0.16	1.5
5	7	150	0.32	1.5
7	8	300	0.32	1.5

B. Workpiece

From the literature survey, it has been concluded that, there is a variety of materials which can be used with CNC turning operation. The workpiece material selected in this thesis is AISI 4340 which is generally used to manufacture crankshafts in industry. The workpiece used for the experiments are having 100 mm length and 50 mm diameter as shown in below Figure 1. The

shows the mechanical properties of the workpiece.

Table 3: Properties of workpiece material AISI 4340

Property	Value	Unit
Density	7850	g/m3
Bulk Modulus	140	GPa
Shear Modulus	80	GPa
Tensile Strength	745	MPa
Yield Strength	470	MPa
Hardness	217	MPa
Poisson's Ratio	0.3	
Melting Point	1700	K

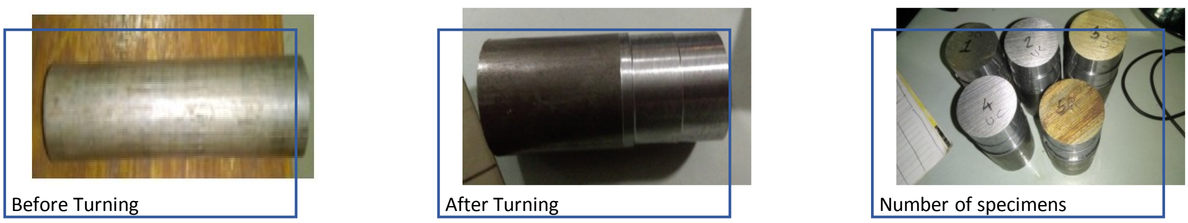
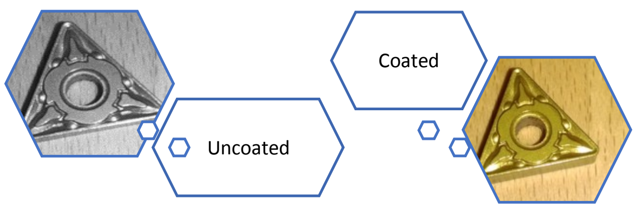


Figure 1: Workpiece before and after turning

C. Cutting Tool Insert

From the literature survey, it is found that there are different types, shapes and grades of tools which are made from different materials are extensively used in turning process. From the market survey, it has been concluded that there are number of companies which are making tool inserts. Here in this paper the tool inserts which is used is made by Carmet tools. Tool insert used are of Tungsten carbide material and coated with Al_2O_3 material by CVD coating method as shown in below figure.



Tool inserts shown in following figure are held by tool holder of size 12 x 25 mm in turret along with the Dynamometer as shown in Figure 2. Tool is held in tool holder by screw.

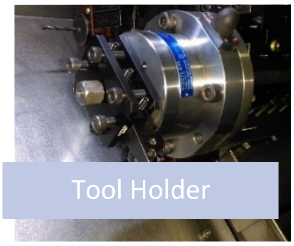


Figure 2: Tool with Dynamometer held in turret

Table 4shows the specifications and geometry of Tool insert used

Table 4: Tool Insert Specifications

Parameter	**Specification**
Insert Shape	Triangular
Clearance Angle	6^0
Hole Shape	Cylindrical
Cutting Edge Length	12 mm
Nose Radius	0.4 mm
Chip Breaker	Double Sided
Coating Thickness	0.3 mm
Manufacturing Option	Roughing

D. Experimental Setup

The experiments are performed on the CNC Lathe machine whose specifications are shown in Table 5 with the KISTLER'S Piezoelectric Dynamometer setup to get the three directional forces generated on the tool insert as shown inFigure 3.

Table 5: Specifications of CNC Lathe Machine

CNC LATHE MACHINE		CONTROLLER SIEMENS 828D	
Make	MTAB Chennai	Model	Maxturn plus+
X-axis travel	140 mm	Z-axis travel	380 mm
Max. turning diameter	235 mm	Max. turning length	360 mm
Max. Speed	6000 rpm	Chuck size	165 mm
Turret Number of stations	8	Spindle Motor	5.5 Kw
Accuracy	10 u		

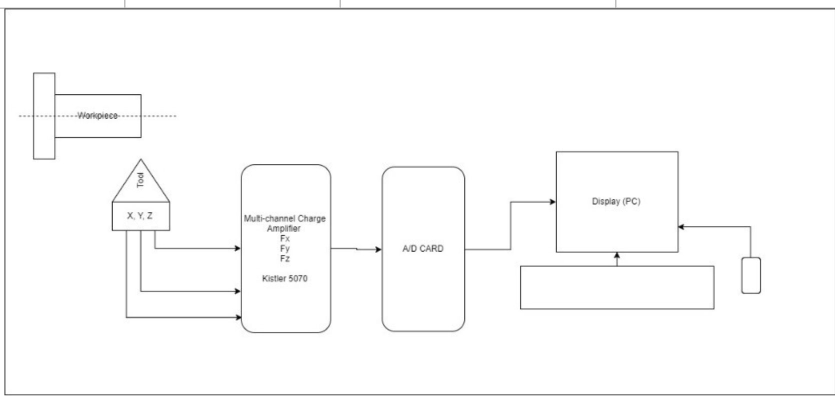


Figure 3: Schematic diagram of Piezoelectric Dynamometer

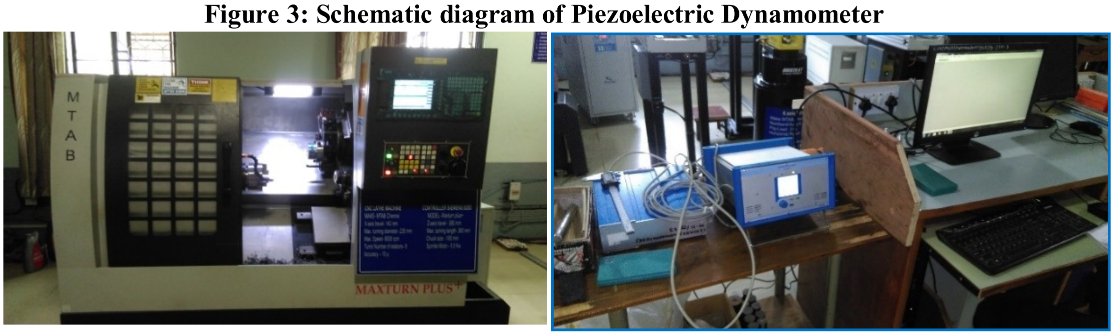
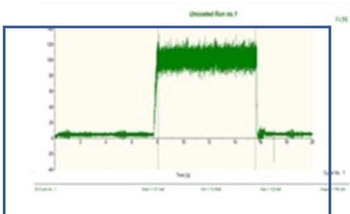


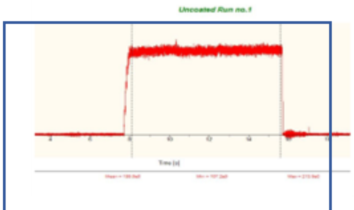
Figure 4: Experimental set up

KISTLER'S Piezoelectric Dynamometer attached with the base is used to measure the forces generated on the tool insert. Dynamometer is fixed in the turret on which tool holder is mounted and it relates to the computer through the 3 component signal's amplifier and A/D Card represented in schematic view of dynamometer setup as shown in Figure 3 and actual setup as shown in Figure 4.When the tool gets in contact with the workpiece, the electric signal from dynamometer are sent to signal amplifier which amplifies the signals and transfers amplified signals to A/D Card which converts AC signals to DC signals. These DC signals are read into the KISTLER's Dynoware software which are displayed on the computer monitor as shown in Figure 3. The individual graphs of three directional forces have been generated in Dynoware for each run separately as shown below.

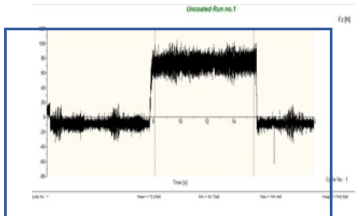
Sample Force Graphs for Run:



Feed Force (Fx)



Cutting Force (Fy)



Thrust Force (Fz)

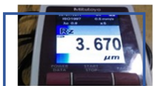
To measure the surface roughness of workpiece, MITUTOYO's portable surface roughness tester has been used. MITUTOYO's portable surface roughness tester is very sensitive measuring device with the stylus which detects the profile of the measuring surface. This stylus is the main and sensitive part of the tester which should not fall on the floor or hit by any means.

Sample Roughness Graphs and Ra values for Run:

Run No. 3

Ra

Rq



Rz

Profile

Profile Plot

E. Experimental Data

The following results were obtained after going through above steps for each experiment mentioned in **Error! Reference source not found.** for uncoated tungsten carbide tool and in **Error! Reference source not found.** for coated tungsten carbide tool.

Run No.	**Uncoated Tool**				**Coated Tool**			
	Fx(N)	**Fy**(N)	**Fz**(N)	**Ra**(μm)	**Fx**(N)	**Fy**(N)	**Fz**(N)	**Ra**(μm)
1	101.8	188.6	73.24	1.412	130.1	209.3	94.03	0.501
2	96.61	174	68.41	1.245	127.3	168.7	82.38	0.334
3	166.5	324.2	107.3	1.644	175.3	730.7	412.6	0.733
4	124.4	274.4	83.28	1.618	126.2	282.8	122.9	0.707
5	102.2	370.5	223	1.693	121.8	390.6	269.3	0.782
6	107.3	455.9	237.9	1.434	149.6	481.1	300.7	0.523
7	215.6	907.9	414.7	1.711	132.6	554.6	487.7	0.821
8	170.2	731	336.8	1.699	144.8	565.8	292.9	0.788

III. Mathematical Modeling

a. Regression Model

In this paper, regression method is applied to develop mathematical model to predict the tool forces and surface roughness. The regression model is generated on the MINITAB 18 software of student's version and analyzed the models with ANOVA technique. The individual mathematical models were obtained for Fx (Feed Force), Fy (Cutting Force), Fz (Thrust Force), Ra (Surface Roughness) for uncoated and coated tool insert separately. The effect of input parameters on output are also observed. Mathematical models for uncoated and coated tool are shown in Table 6 and Table 7 respectively.

Table 6: Mathematical Models for Uncoated Tool

Fx	=	41.0 - 0.146 v + 420.1 f + 26.5 d
Fy	=	-282 - 0.260 v + 1638 f + 376.0 d
Fz	=	-119.8 - 0.153 v + 531 f + 220.0 d
Ra	=	1.243 - 0.000773 v + 1.388 f + 0.1545 d

Table 7: Mathematical Models for Coated Tool

Fx	=	126.7 - 0.020 v + 78.3 f - 2.5 d
Fy	=	86 - 0.645 v + 1382 f + 150 d
Fz	=	59 - 0.775 v + 890 f + 159.7 d
Ra	=	0.330 - 0.000808 v + 1.420 f + 0.1597 d

In the mathematical equation, values along with parameter v, f, d are coefficients which indicates that how much influencing that particular parameter is. Negative coefficient indicates that the parameter will reduce the outcome value. In regression models, interaction variables are not taken into consideration to simplify the model.

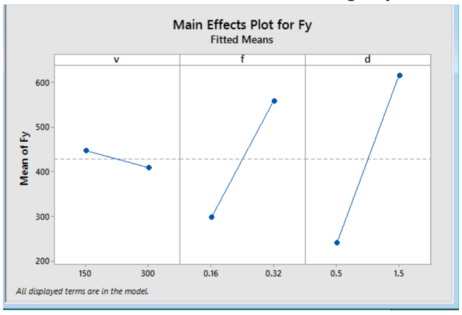


Figure 5: Main effect plot for sample run

b. Accuracy of Regression Model

The accuracy of regression model is verified using analysis of variance (ANOVA). According to the principles of this technique, p values for the model must be lower, higher the value of R-sq, the more successful is the regression model at the desired level of confidence of 95%, adjusted R2 < R2, variance should be minimal [2]. Table 8: ANOVA Results shows that the model is satisfactory in terms of the value of R2.

Table 8: ANOVA Results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.17322	0.057740	6.80	0.047
Linear	3	0.17322	0.057740	6.80	0.047
V	1	0.02691	0.026912	3.17	0.150
F	1	0.09857	0.098568	11.62	0.027
D	1	0.04774	0.047741	5.63	0.077
Error	4	0.03394	0.008486		
Total	7	0.20716			

S	R-sq	R-sq(adj)	R-sq(pred)
0.0921188	83.62%	71.33%	34.46%

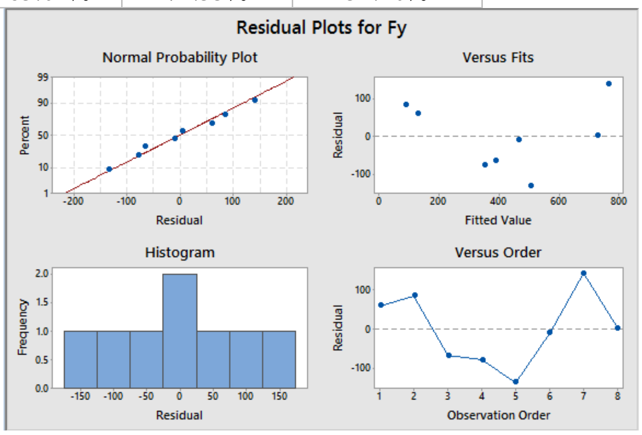


Figure 6: Results of ANOVA Technique

IV. Artificial Neuron Network Model

ANN models are generated in MATLAB 18 student's version which consists of processors called Neurons that are linked by weighted interconnections. It can easily predict the output results from huge and complicated data base. It develops analytical model to solve problem of prediction, diagnosis and decision-making. It includes learning data as an experimental result for preparation of model and generated model can predict output for any number of variation of input parameter. The main advantage of ANN model are its simplicity and the ease of implementation. The learning abilities of these models are very impressive [5]. Input data has been added in Input Sheet, target data has been added in Target Sheet and inputs whose results have to be predicted are added in Sample Sheet. These three sheets are imported in Neural Network/Data Manager and created new network with Feed-Forward backprop network type. There are 3 types of layer in each ANN model which are Input Layer, Hidden Layer and Output Layer.

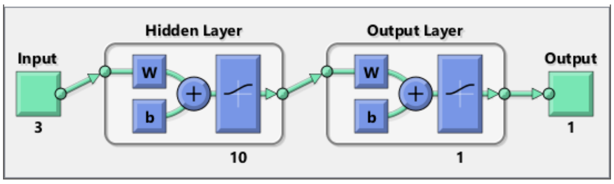


Figure 7: ANN Neural Network Model

Network Model shown in Figure 7 is applied to all the runs in experimental plan. Figure 8 shows the analysis report of the sample ANN model. R value measures the agreement between the output and target values. R value is equal to 0.87922 which means the model is 88% acurate to give results for any input variable. Our aim is to get R value closer to 1. Matlab is employed for training the model. Parameter settings for neural network: 3 input nodes, 10 hidden nodes, 1 output node, supervised learning, Back propogation algorithm, gradient decent rule as a learning rule, 20 learning patterns, 10000 epochs.

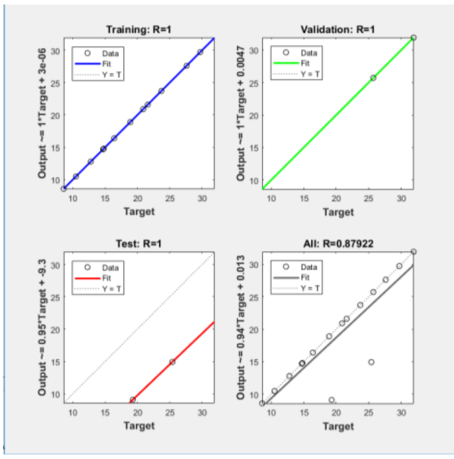


Figure 8: Results of sample ANN model analysis

V. Results and Discussion

Table 9 shows the results obtained from regression model for particular run with the percentage error or deviation from the actual results when machined with uncoated tungsten carbide tool. When the cutting speed increases the feed force (Fx) decreases. Feed force increases with increase in feed and depth of cut. Feed is the most influencing parameter for the feed force. For the cutting force (Fy) depth of cut is the most influencing factor. When the cutting speed increases cutting force decreases means lesser amount of force is required to remove material. Cutting force increases with increase in feed and depth of cut as per Figure 9. For the Thrust Force (Fz), depth of cut is the most influencing factor. Very less effect of cutting speed on thrust force. Thrust force increases with increase in depth of cut. For the surface roughness (Ra), feed is the most influencing factor. Surface roughness value decreases with increase in cutting speed which means surface quality of machined component is achieved by increasing cutting speed. Surface roughness increases with increase in feed and depth of cut as indicated in Figure 10.

Table 9: Results and % errors of Regression Model for uncoated tool

	Force						Surface Roughness	
Run No.	Fx (N)	Error (%)	Fy (N)	Error (%)	Fz (N)	Error (%)	Ra (µm)	Error (%)
1	99.566	2%	129.08	32%	52.21	0.2871382	1.42638	1%
2	77.666	20%	90.08	48%	29.26	0.5722848	1.31043	5%
3	166.782	0%	391.16	21%	137.17	0.2783784	1.64846	0%
4	144.882	16%	352.16	28%	114.22	0.3715178	1.53251	5%
5	126.066	23%	505.08	36%	272.21	0.2206726	1.58088	7%
6	104.166	3%	466.08	2%	249.26	0.0477512	1.46493	2%
7	193.282	10%	767.16	16%	357.17	0.1387268	1.80296	5%
8	171.382	1%	728.16	0%	334.22	0.0076603	1.68701	1%
	Avg. =	9%	Avg. =	23%	Avg. =	24%	Avg. =	3%
	Total Average Relative error = 12%							

Table 10 shows the results obtained from regression model for particular run with the percentage error or deviation from the actual results when machined with coated tungsten carbide tool.

Table 10: Results and % errors of Regression Model for Coated tool

	Force						Surface Roughness	
Run No.	Fx (N)	Error (%)	Fy (N)	Error (%)	Fz (N)	Error (%)	Ra (µm)	Error (%)
1	134.978	4%	285.37	36%	165	0.7547591	0.51585	3%
2	131.978	4%	188.62	12%	48.75	0.4082302	0.39465	18%

3	147.506	16%	506.49	31%	307.4	0.2549685	0.74305	1%
4	144.506	15%	409.74	45%	191.15	0.5553295	0.62185	12%
5	132.478	9%	435.37	11%	324.7	0.2057185	0.67555	14%
6	129.478	13%	338.62	30%	208.45	0.3067842	0.55435	6%
7	145.006	9%	656.49	18%	467.1	0.0422391	0.90275	10%
8	142.006	0.01929558	559.74	0.0107105	350.85	0.1978491	0.78155	0.00818528
	Avg. =	9%	Avg. =	23%	Avg. =	34%	Avg. =	8%
	Total Average Relative error = 15%							

Table 11 shows the results obtained from ANN model for each run with the percentage error or deviation from the actual results when machined with uncoated tungsten carbide tool.

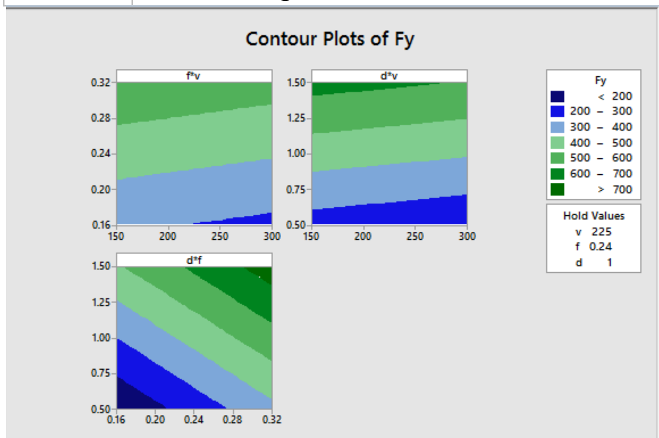
Table 11: Results and % errors for ANN Model for Uncoated tool

	Force						Surface Roughness	
Run No.	Fx (N)	Error (%)	Fy (N)	Error (%)	Fz (N)	Error (%)	Ra (µm)	Error (%)
1	97.5325	4%	224.6603	19%	69.3934	5%	1.412	0%
2	97.5841	1%	172.68953	1%	68.729	0%	1.235	1%
3	155.4434	7%	289.70793	11%	102.7496	4%	1.644	0%
4	128.4434	3%	189.7901	31%	69.7661	16%	1.608	1%
5	97.0002	5%	299.1921	19%	207.6595	7%	1.623	4%
6	96.6145	10%	487.4088	7%	145.1122	39%	1.424	1%
7	168.4434	22%	867.8593	4%	395.1679	5%	1.659	3%
8	169.2497	1%	895.9791	23%	302.1768	10%	1.669	2%
	Avg. =	7%	Avg. =	14%	Avg. =	11%	Avg. =	1%
	Total Average Relative error = 7%							

Table 12 shows the results obtained from ANN model for each run with the percentage error or deviation from the actual results when machined with coated tungsten carbide tool.

Table 12: Results and % error of ANN Model for coated tool

	Force						Surface Roughness	
Run No.	Fx (N)	Error (%)	Fy (N)	Error (%)	Fz (N)	Error(%)	Ra (µm)	Error (%)
1	128.8241	1%	227.9383	9%	48.77	48%	0.434	13%
2	134.1909	5%	189.927	13%	82.3818	0%	0.334	0%
3	158.4375	10%	590.5155	19%	487.7	18%	0.634	14%
4	134.9349	7%	318.9887	13%	48.75511	60%	0.707	0%
5	138.9753	14%	305.1584	22%	287.7	7%	0.734	6%
6	155.2653	4%	446.7837	7%	282.3833	6%	0.434	17%
7	153.4662	16%	610.6247	10%	487.7	0%	0.734	11%
8	155.2078	7%	586.8958	4%	387.6762	32%	0.747	5%
	Avg. =	8%	Avg. =	12%	Avg. =	21%	Avg. =	8%
	Total Average Relative error = 11%							



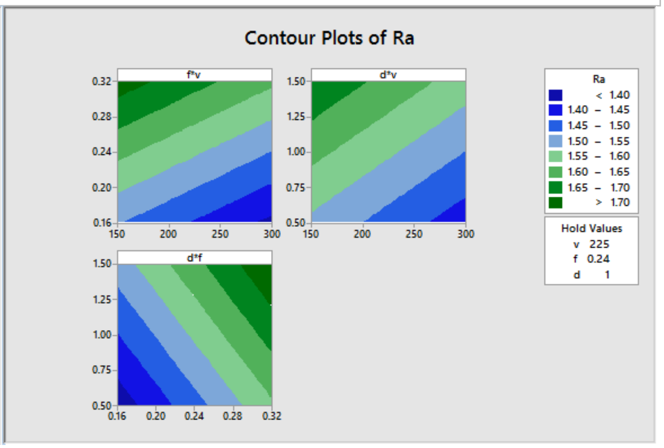
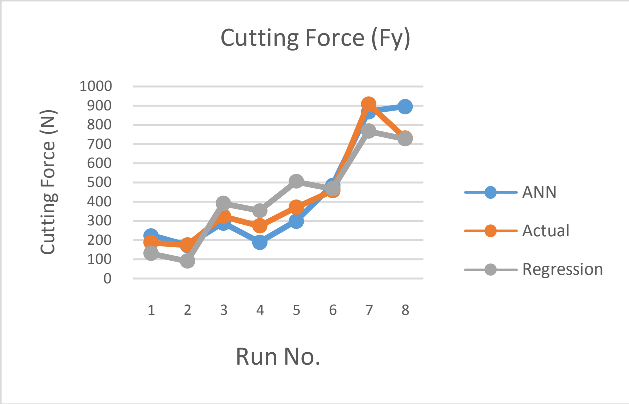


Figure 9: Contour plot for cutting forceFigure 10: Contour plot for surface roughness

Total average error for ANN is 7% and 11% and for regression is 12% and 15%. From the Figure 11 and Figure 11 : Comparison of models for cutting forceFigure 12, it is seen that the ANN results are more accurate than the regression model results. Large variation is seen in few runs of regression model but in other case ANN model follows the actual closely. There is a large variation in force results compared to surface roughness results because there are vibrations of machine tool which take part during getting results of tool forces. From the result tables, it is seen that the generated cutting forces for coated tool are high compared to uncoated tool but the surface roughness values are much lesser in case of coated tool.



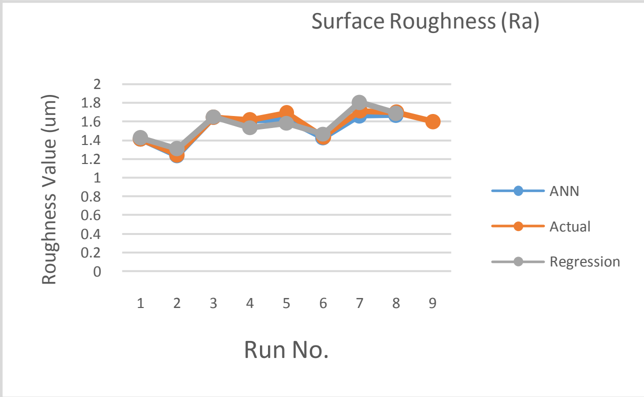


Figure 11 : Comparison of models for cutting forceFigure 12: Comparison of models for surface roughness

VI. Conclusion

The following conclusions were made on the basis of experimentation and mathematical modelling performed. Cutting speed is indirectly proportional to tool forces and surface roughness.Feed is directly proportional to tool forces and surface roughness.Depth of cut is also directly proportional to tool forces and surface roughness.Individual effects of process parameters on response are studied. It is observed that the feed plays significant role in feed force, cutting speed plays significant role in cutting force, depth of cut plays significant role in thrust force and feed plays significant role in surface roughness value. ANN model proved to provide a better prediction of tool forces and surface roughness. Also it provides less variation in number of predicted results.Surface quality of workpiece surface after machining with the coated tool is good compared with the uncoated tool. Even though ANN is predicting results effectively, percentage error for regression model is less than 15% so it proves that mathematical models are extremely useful in machining processes for predicting results.

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