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Effect on Surface Roughness and Tool Wear during Turning of AISI 1020 Steel using Coated Carbide Inserts

N. Dheera[1] Dr. P. Prasanna[2]
[1]PG Student [2]Assistant Professor
[1,2]Department of Mechanical Engineering
[1,2]JNT University, Hyderabad India

Abstract— The prediction of tool wear and surface roughness before machining has become an important task for the industry to be able to control and optimise the machining parameters effectively. In this paper the average surface temperature of the work-piece is obtained from the simulation model developed using DEFORM software. The work-piece used was AISI 1020 STEEL and the coated carbide tool insert was CNMG 432 TT 5100. The simulation model was validated by measuring temperature while machining. The surface roughness of the work-piece is then predicted using this DEFORM temperature as a parameter along with cutting speed, feed and depth of cut by using RSM Methodology. The experimental values and predicted values of surface roughness, tool wear comply with in the permissible interval. Optimisation of the values is done using Integrated PCA-Taguchi method. Results showed that surface roughness, tool wear were influenced the most by feed rate. Therefore the simulation model developed can be used for accurately forecasting the surface roughness for a given set of parameters.

Key words: Turning, Coated Carbide Tool, Surface Roughness, Tool Wear, DEFORM Software, RSM Methodology, Integrated PCA- Taguchi Method

I. INTRODUCTION

Traditional turning process differs from the advanced technological process used now-a days in the ability to control the process parameters to obtain the desired level of surface finish. Many numerical models have been developed in the recent years to know beforehand the expected values of surface roughness and tool wear. In this study an effort has been made to develop a simulation model by using DEFORM 2D/3D Version 11.0[1] software and test its efficiency in prediction of the surface roughness. The models generally are developed after conducting a series of experiments. This increases the cost and also the time involved in obtaining the results. This model differs from other prediction models as it is developed using a software simulation which in turn reduces both the cost and time. Researchers used work-piece temperature found by experiments in predicting surface roughness and found that temperature influences surface roughness considerably [2], that spindle speed instead of cutting velocity is an efficient parameter influencing surface roughness [3].Many studies reveal different optimisation methods used for minimising surface roughness[4,5,6] and tool wear[7,8,9,10]. The main objective of this study is to find the average work-piece surface temperature during turning on AISI 1020 steel by a simulation process using DEFORM software and predict the surface roughness using this temperature along with other parameters of cutting speed, feed and depth of cut. In addition the effect on tool wear is also studied. ANOVA analysis is done to verify the significance of the model developed, RSM methodology was used to develop the relation between the parameters and optimisation was done using Integrated PCA-Taguchi method.

II. EXPERIMENTAL DETAILS

A. *Work-piece material and cutting tool*

The work-piece material is AISI 1020 steel of 200mm length and 50 mm diameter, the CVD coated tungsten carbide (WC) cutting tool insert used was CNMG 432 TT 5100.The inserts were mounted on PCLNR 2525M/12 tool holder. The cutting edge length of the insert is 12 mm, insert thickness is 4 mm, nose radius is 0.8 mm, clearance angle is 0°. The composition of AISI 1020 is given in Table I below and its yield strength is 245 N/mm^2, its tensile strength is 400 N/mm^2

C	0.2%
Si	0.15%
Mn	0.72%
P	0.011%
S	0.023%

Table 1: Chemical Composition of AISI 1020 STEEL

B. *Experimental Procedure*

The turning process was carried out on the Hardinge CNC Lathe whose maximum speed is 6000 rpm. The photograph of the experimental set-up is shown in Fig.1. The surface roughness of the work-piece was measured using Taylor Hobson Surtronic 3+, the tool wear was measured using Tool Maker's Microscope. The surface temperature of the work-piece was obtained using an infra-red gun and this temperature was used to validate the results obtained from the DEFORM software. The error obtained was with in permissible range.

Fig. 1: Hardinge CNC Lathe

C. *Process parameters and their levels*

The process parameters considered for turning process are cutting speed, feed rate and depth of cut. The responses are surface roughness and tool wear. The parameter levels are given in the Table II below. The design of experiments table is developed from the L27 orthogonal array and is shown in the Table 3 below.

Factor/level	1	2	3
Speed (S) (rpm)	950	1150	1400
Feed(F) (mm/rev)	0.05	0.1	0.15
Depth of cut(D) (mm)	0.5	1	1.5

Table 2: Parameters and their Levels

Trail No.	S	F	D
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Table 3: Design of Experiments

D. DEFORM Simulation

The simulation runs were conducted for the design of experiments table and the temperatures were tabulated. The interface of simulation software after loading the tool and the work-piece from its library is given in the Fig.2 below. The average surface temperature of the work-piece is obtained from the histogram given by the software. The histogram is as shown in Fig.3. This temperature is compared with the temperature obtained by using infra-red gun for the trails of 7, 11, 14,21as given in the Table IV and the results are found to be satisfactory.

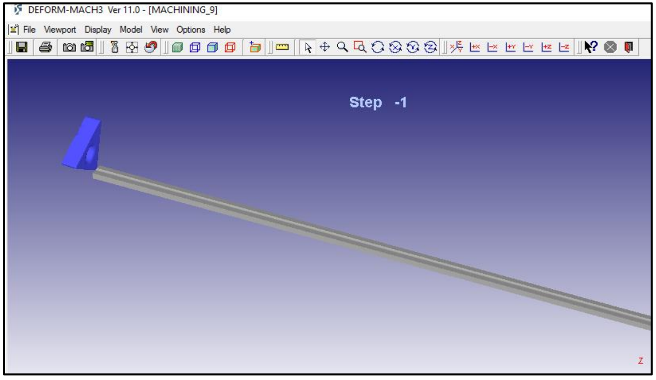

Fig. 2: DEFORM Interface

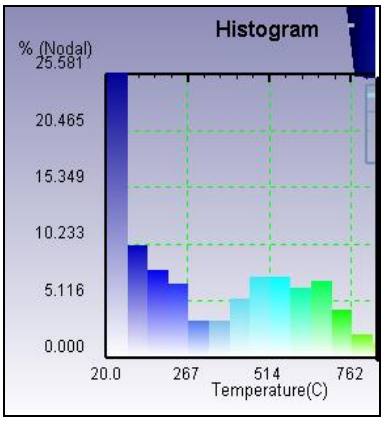

Fig. 3: Histogram of temperature

Trail No.	DEFORM Temperature(℃)	Experimental Temperature(℃)	Error (%)
7	63.2	61	3.6
11	77.87	74.78	4.13
14	70.18	67.81	3.5
21	85	83.2	2.16

Table 4: Validation of Deform Temperature

The error in experimental temperature can be attributed to radiation losses, instrumentation error and dynamic nature of machining.

E. Responses

The experimental results of surface roughness, tool wear and simulation temperature for all the trails are tabulated in Table V as shown below.

Trail No.	Deform Temperature (℃)	Surface roughness Ra (μm)	Tool Wear (mm)
1	63.2	1.265	0.52
2	72.5	2.678	0.232
3	86	1.456	0.196
4	56.98	1.498	0.752
5	77.87	2.167	0.708
6	88.56	2.029	0.695
7	62.29	2.257	1.193
8	70.18	3.129	0.596
9	83.26	2.662	0.578
10	59	1.209	0.257
11	65.88	1.465	0.142
12	68.98	1.266	0.205
13	67.45	1.335	0.569
14	76.78	1.494	0.438
15	85	1.459	0.301
16	66.13	2.167	0.805
17	70.81	2.587	0.674
18	86	2.159	0.628
19	56.68	1.056	0.497
20	61.8	0.986	0.131
21	89	0.735	0.142
22	63.2	1.262	0.655
23	72.5	1.379	0.604
24	86	0.654	0.377
25	56.98	1.832	0.738
26	77.87	1.973	0.397
27	88.56	1.426	0.248

Table 5: Responses of Trails

III. RESULTS AND DISCUSSION

A. Analysis of Variance (ANOVA)

ANOVA analysis is done on the obtained experimental data to check the significance of the model. The Tables Ⅵ and Ⅶ show the ANOVA results for surface roughness and tool wear respectively.

Source	SS	DF	MS	f-Value	P Value >F
Model	9.765	9	1.085	17.12	< 0.0001
S	3.416	1	3.416	53.91	< 0.0001
F	4.09	1	4.095	64.62	< 0.0001
D	1.982E-004	1	2.308	3.642E-3	0.9526
SF	0.011	1	1.132	0.18	0.6779
SD	0.46	1	4.615	7.28	0.0152
FD	9.075E-005	1	1.203	1.899E-3	0.9658
S^2	0.039	1	3.863	0.61	0.4457
F^2	0.62	1	6.202	9.79	0.0061
D^2	1.12	1	1.124	17.74	0.0006
Residual	1.08	17	0.063		
Cor Total	10.84	26			

Table 6: ANOVA Analysis of Surface Roughness

From the above analysis it was found that speed and feed are the most significant terms affecting the surface roughness as their p-values are <0.0001. R^2=0.9006 which is 90.06%. The desirable value is close to 1 which indicates that the model has a variance of 9.94% and hence is within the acceptable limits.

Source	SS	DF	MS	f-Value	P-Value
Model	1.46	9	0.16	11.20	< 0.0001
S	0.16	1	0.16	10.79	0.0044
F	0.68	1	0.68	46.53	<0.0001
D	0.38	1	0.38	26.32	< 0.0001
SF	0.059	1	0.059	4.03	0.0607
SD	2.361E-3	1	2.361E-3	0.16	0.6918
FD	0.025	1	0.025	1.74	0.2043
S^2	0.037	1	0.037	2.52	0.1305
F^2	0.075	1	0.075	5.19	0.0359
D^2	0.042	1	0.042	2.90	0.1067
Residual	0.25	17	0.015		
Cor Total	1.71	26			

Table 7: ANOVA Analysis of Tool Wear

From the above analysis it was found that feed and depth of cut are the most significant terms affecting the tool wear. R^2=0.8557 which is 85.57% and is acceptable.

B. Response Tables

The response tables of surface roughness and tool wear are given below in Tables Ⅷ and Ⅸ respectively.

Level	S(rpm)	F(mm/rev)	D(mm)
1	-53.90	-58.34	-56.79
2	-56.13	-57.13	-54.78
3	-58.61	-53.17	-57.06
Delta	4.71	5.17	2.28
Rank	2	1	3

Table 8: Response Table of Surface Roughness

Level	S(rpm)	F(mm/rev)	D(mm)
1	-5.432	-12.859	-4.177
2	-8.263	-5.296	-8.639
3	-8.882	-4.423	-9.761
Delta	3.451	8.436	5.584
Rank	3	1	2

Table 9: Response Table of Tool Wear

C. Main Effect Plots

The main effect plots of surface roughness and tool wear are given below in Fig.4 and Fig.5 respectively.

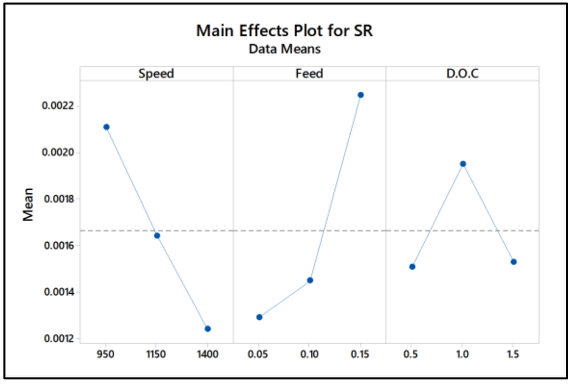

Fig. 4: Main effects plots of surface roughness

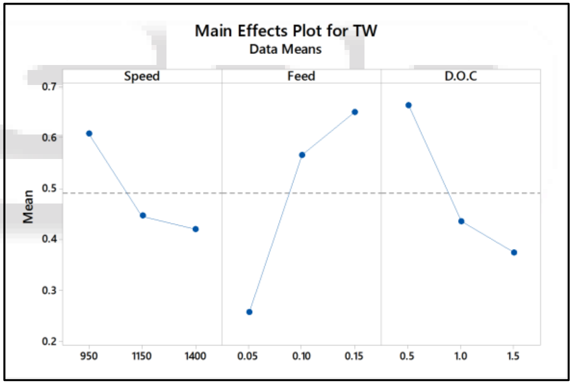

Fig. 5: Main effects plots of tool wear

D. RSM Methodology

The RSM methodology is an effective tool to inter-relate the process parameters and responses according to their significance. The developed regression equations to predict surface roughness and tool wear are as given below.

Surface Roughness (Ra) and Tool wear (TW) predicted with S, F, D are

$$Ra\ Pr=2.4012-0.003726*S-12.93*F+5.518*D-0.11*F*D+128.71F^2-1.7302D^2 \quad (1)$$

$$TW=1.83625-0.00335*S+21.96062*F\ 0.63206*D-1.83667*F*D-44.822F^2+0.33511D^2 \quad (2)$$

Surface Roughness predicted with S, F, D along with DEFORM Temperature (T) is

$$RaPrT=13.129+0.00587*S+31.8375*F+1.32488*D+0.2498*T-0.002473*S*F+7.42605*F*D-0.35530*F*T-0.050230*D*T \quad (3)$$

E. Predicted Values

The values of surface roughness predicted using the above regression equations are tabulated in the table Ⅹ below.

Trail No.	Ra EXP(µm)	Ra Pr (µm)	Error (%)	Ra Pr T(µm)	Error (%)
1	1.224	1.365	11.519	1.362	11.274
2	2.697	1.998	-25.917	2.036	24.508
3	1.422	1.767	24.261	1.593	12.025
4	1.499	1.553	3.602	1.921	28.152
5	2.067	2.184	5.660	2.061	0.290
6	2.019	1.9506	-3.387	2.035	0.792
7	2.277	2.385	4.743	2.376	4.347
8	3.109	3.014	-3.055	2.775	10.743
9	2.682	2.777	3.542	2.739	2.125
10	1.009	1.097	8.721	1.063	5.351
11	1.485	1.557	4.848	1.573	5.925
12	1.066	1.153	8.161	1.222	14.634
13	1.33	1.259	-5.338	1.556	16.992
14	1.394	1.716	23.099	1.773	27.187
15	1.479	1.309	-11.494	1.625	9.871
16	2.127	2.064	-2.961	1.958	7.945
17	2.697	2.518	-6.637	2.291	15.053
18	2.195	2.108	-3.963	2.323	5.831
19	1.001	0.944	-5.694	1.009	0.799
20	0.934	1.187	27.087	0.963	3.105
21	0.798	0.565	-29.198	0.597	25.188
22	1.249	1.072	-14.171	1.379	10.408
23	1.309	1.313	0.305	1.376	5.118
24	0.699	0.688	-1.573	0.896	28.183
25	1.867	1.843	-1.285	1.721	7.820
26	1.879	2.081	10.75	2.05	9.101
27	1.413	1.454	2.901	1.392	-1.486

Table 10: Surface Roughness Predicted Values

F. Principal Component Analysis (PCA) Integrated Taguchi Analysis

PCA is an optimisation tool which converts several multiple correlated responses data into several uncorrelated quality indices. It maximises the variability of the data while minimizing the dimensionality of the data. The following steps are involved in the process.

1) Normalisation of data

The normalized values are calculated using the formula given below.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (4)$$

Where y denotes the experimental data and x denotes the normalized data.

Trail No.	Ra(µm)	TW(mm)
1	0.784232	0.63371
2	0.170954	0.904896
3	0.7	0.938795
4	0.66805	0.415254
5	0.432365	0.456685
6	0.452282	0.468927
7	0.345228	0
8	0	0.562147
9	0.177178	0.579096
10	0.871369	0.881356
11	0.673859	0.989642
12	0.847718	0.93032
13	0.738174	0.587571
14	0.711618	0.710923
15	0.676349	0.839925
16	0.407469	0.365348
17	0.170954	0.488701
18	0.379253	0.532015
19	0.874689	0.655367
20	0.90249	1
21	0.958921	0.989642
22	0.771784	0.506591
23	0.746888	0.554614
24	1	0.768362
25	0.515353	0.428437
26	0.510373	0.747646
27	0.703734	0.889831

Table 11: Normalised Data

	PC1	PC2
Eigen vectors	0.707	-0.707
	0.707	0.707
Eigen values	1.4761	0.5239
Accountability Proportion (AP)	0.738	0.262
Cumulative AP	0.738	1.000

Table 12: Eigen Values and Eigen Vectors Table

2) Calculating Principal Components (PC)

Composite Principal Components (CPC) and S/N values

$$PC_1 = 0.707*Ra+0.707*TW \quad (5)$$

$$PC_2 = -0.707*Ra+0.707*TW \quad (6)$$

$$CPC = (PC_1^2+PC_2^2+PC_3^2+\dots)^{1/\text{No. of responses}} \quad (7)$$

$$CPC = (PC_1^2+PC_2^2)^{0.5} \quad (8)$$

$$\eta = -10 \ln_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \quad (9)$$

Where η is S/N Value and y is CPC Value

Trail No.	PC1	PC2
1	1.002485	-0.10642
2	0.760627	0.518897
3	1.158628	0.168828
4	0.765896	-0.17873
5	0.628559	0.017194
6	0.651295	0.011768
7	0.244076	-0.24408
8	0.397438	0.397438
9	0.534686	0.284156
10	1.239177	0.007061
11	1.176095	0.223259
12	1.257073	0.0584
13	0.937302	-0.10648
14	1.005737	-0.00049
15	1.072005	0.115648
16	0.546382	-0.02978
17	0.466376	0.224647
18	0.644267	0.108003
19	1.08175	-0.15506
20	1.34506	0.06894
21	1.377634	0.02172
22	0.903812	-0.18749
23	0.920162	-0.13594
24	1.250232	-0.16377
25	0.667259	-0.06145
26	0.88942	0.167752
27	1.12665	0.13157

Table 13: Principal Components Table

Trail No.	CPC	SN Low
1	1.008118	-0.07023
2	0.920764	0.717031
3	1.170864	-1.37013
4	0.786473	2.086324
5	0.628794	4.029833
6	0.651401	3.723033
7	0.345176	9.239186
8	0.562062	5.004315
9	0.605503	4.357677
10	1.239197	-1.86281
11	1.197098	-1.5626
12	1.258429	-1.99657
13	0.94333	0.506726
14	1.005737	-0.04969
15	1.078225	-0.65419
16	0.547193	5.237194
17	0.517661	5.719095
18	0.653256	3.698325
19	1.092806	-0.77086
20	1.346826	-2.58623
21	1.377805	-2.78376
22	0.923054	0.69546
23	0.930149	0.628951
24	1.260912	-2.0137
25	0.670083	3.477431
26	0.905101	0.866058
27	1.134307	-1.09461

Table 14: CPC and S/N Values Table

From the above analysis the mean of S/N values plot was obtained, Fig.6.

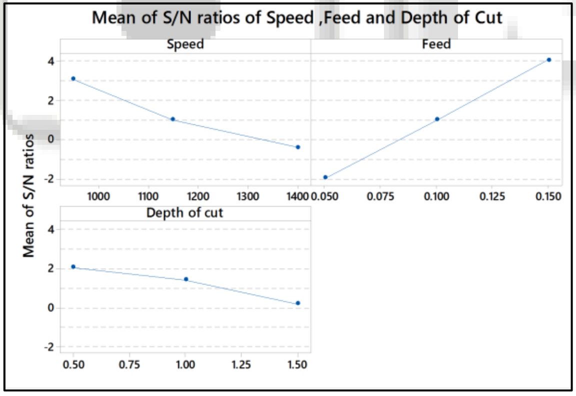

Fig. 6: Mean of S/N values plot

The optimal values of Surface roughness and Tool wear 0.798µm and 0.131 mm respectively were obtained at a cutting speed of 1400 rpm, feed rate of 0.05 mm/rev, depth of cut of 1.5 mm.

IV. CONCLUSIONS

Feed rate was the most influential parameter on surface roughness and tool wear. As the feed rate increased both the responses increased which can be because of the increased vibrations and chatter.

It was found that cutting speed influenced surface roughness more than depth of cut and depth of cut influenced tool wear more than cutting speed. As the cutting speed increased both the surface roughness and tool wear decreased. The surface roughness increased with increase in depth of cut. The tool wear decreased rapidly with increase in depth of cut from 0.5 mm to 1 mm and a slight decrease was observed from 1 mm to 1.5 mm.

It was found that the average surface temperature of the workpiece was affecting the surface roughness considerably. The simulation temperature obtained from the DEFORM software proved to be an effective alternative in finding the average surface temperature of the workpiece which in turn was used in accurately predicting the surface roughness.

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