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Predictive Modeling of Tool Wear, Surface Roughness and Machining Force in Hard Turning Using Taguchi Approach

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Abstract
The present work concentrates on finding the influence of cutting factors on the responses. A series of experiments were conducted on the AISI 4340 steel to know the variation in the responses by changing the hardness of the material (45, 50 and 55 BHN) and the insert type (Conventional and wiper) along with the speed, feed and depth of cut. L18 mixed type orthogonal array has been selected for conducting the experiments. Tool wear, surface roughness and machining forces and taken as responses and are minimized using the single objective taguchi's method. ANOVA is also employed to find the influence of cutting parameters on the responses. The optimal designs for the responses are predicted based on the estimated average mean values and are more accurate.

Keywords: Tool Wear, Surface Roughness, Machining Force, Hard Turning, Taguchi Approach, wiper insert

I. Introduction

The machining of hardened steel components (45 to 65 HRC) with coated ceramic tools has been implemented in the manufacturing industries to replace the grinding. Hard machining offers lower manufacturing costs, reduced production time, improved product quality and eliminates the usage of coolants while machining, etc. Hard machining can be used in many machining operations like turning, milling, drilling, threading and broaching, etc.

Numerous researches had been directed to determine the effect of cutting parameters such as feed rate, cutting speed and depth of cut on machining characteristics [1-2]. In the aspect of price, ceramic inserts [3] and carbide inserts [4] are favored over the PCNB inserts all through the experimental evaluation. Kaladhar et al. [5] located that feed rate and nose radius are the most significant factors that influence the surface roughness. Work-piece hardness is additionally taken as one of the imperative machining parameters and studied below various situations [6].

Davim et al.[7] found out that Wiper ceramic inserts report low values of surface roughness and tool wear; however, conventional ceramic inserts show off low values of machining force and power consumption.

The present study concentrates on finding the effect of cutting parameters at the responses such as Tool wear, surface roughness and machining forces. ANOVA is likewise employed to find the impact on of cutting parameters at the responses. The most optimal designs for the responses are predicted based totally on the estimated average mean values. Insert type (Conventional and wiper) in conjunction with the Material hardness, speed, feed and depth of cut is considered as process parameters.

II. Material and Experimental setup details

For conducting the experiments, AISI 4340 specimen of cylindrical shapes (30 mm Ø and 150 mm L) has been selected. AISI 4340 is a medium carbon steel having specific applications in power transmission gears and shafts, aircraft landing gears and connecting rods, etc.

The design of experiments (DOE) concept has been used for the selection of suitable orthogonal array (OA). It is used to obtain the maximum information from the least number of experiments, thereby minimizes the experimentation cost and time. The minimum number of experiments to be conducted, for the specified factors and at certain levels can be calculated as N_{min} = 1+F(L -1). In the present work, the control factors (F) = 5 and levels (L) = 3, N_{min} = 1 + 5 (3-1) = 11. Hence, Taguchi's standard L18 OA (mixed type) has been chosen for the present work as it has more experiments than N_{min}.

In the present work, a series of experiments were done as per the selected L18 OA on a rigid high speed precision CNC lathe (CNC Jobber XL, Spindle speed: 5000 RPM, Power: 7.5 HP). For machining of specimens two inserts of Conventional ceramic type (CC6050) and WIPER ceramic types (CC6050WH) are used with tool holder having specification of PCLN L2525 M12. The tool flank wear (V_b) was measured by using a Nikon optical microscope, which is connected to a digital camera. After machining, the surface roughness was measured at three different points using Mitutoyo surface tester SJ-301 (cut off length: 0.8mm, Sampling length: 5mm) and the average is taken as final value. The machining force (Fm) is calculated as Fm =; Where, F_L = longitudinal force, F_c = tangential cutting force and F_r = radial force respectively, and measured with dynamometer (Kistler 5233A1 model, output signal: ±5 V, temperature range: 0 to 60° C) and recorded in online using dynoware software.

III. Experimental Results and Analysis

The measured tool flank wear, surface roughness and the machining force values and their corresponding signal to noise ratios are given in the Table 1. The signal to noise ratios (S/N) for the responses was calculated using the smaller the better characteristic given in the equation (1).

Smaller the better (LB): $-10\log_{10}[Y_i^2]$……………………….(1)

Where, Yi is response value.

Taguchi and ANOVA results of TWR

Single objective Taguchi method and Analysis of variance (ANOVA) has been employed for the optimization of the output characteristics. The mean values of the tool wear rate are given in the Table 2. For the obtained mean values of control factors the main effects plot has been drawn and shown in the Figure 1. From the figure 1, it is observed that the tool wear rate is mainly affected by the change in levels of cutting speed.

Table 1 . Control factors and experimental results

						Experimental Results			S/N Ratios of Results		
S.No.	Insert	H	Vc	F	Doc	TWR	Ra	Fm	TWR	Ra	Fm
1	CON	45	140	0.1	0.1	35	1.06	413	30.8814	0.5061	52.3118
2	CON	45	180	0.2	0.2	55	1.3	762	34.8073	2.2789	57.6359
3	CON	45	220	0.3	0.3	85	1.38	897	38.5884	2.7976	59.0605
4	CON	50	140	0.1	0.2	40	1.26	431	32.0412	2.0074	52.6849
5	CON	50	180	0.2	0.3	70	1.43	761	36.9020	3.1067	57.6260
6	CON	50	220	0.3	0.1	60	1.59	268	35.5630	4.0279	48.5786
7	CON	55	140	0.2	0.1	65	1.02	297	36.2583	0.1720	49.4654
8	CON	55	180	0.3	0.2	58	1.28	979	35.2686	2.1442	59.8137
9	CON	55	220	0.1	0.3	90	0.94	668	39.0849	0.54	56.4955
10	WIPER	45	140	0.3	0.3	50	0.54	914	33.9794	5.35	59.2202
11	WIPER	45	180	0.1	0.1	34	0.54	407	30.6296	5.35	52.1966
12	WIPER	45	220	0.2	0.2	60	0.51	638	35.5630	5.85	56.0986
13	WIPER	50	140	0.2	0.3	50	0.57	779	33.9794	4.88	57.8334
14	WIPER	50	180	0.3	0.1	44	0.6	504	32.8691	4.44	54.0409
15	WIPER	50	220	0.1	0.2	40	0.29	365	32.0412	10.75	51.2516
16	WIPER	55	140	0.3	0.2	50	0.37	861	33.9794	8.64	58.6999
17	WIPER	55	180	0.1	0.3	70	0.32	807	36.9020	9.90	58.1391
18	WIPER	55	220	0.2	0.1	75	0.39	483	37.5012	8.18	53.6743

ANOVA results of TWR are given in the Table 3. The ANOVA is conducted to test the Influence of the control factors on the response at a confidence level of 95% i.e. at α = 0.05. From the results, it is clear that depth of cut is the high influencing parameter on TWR and followed by speed, Hardness, Insert type and feed. The optimum cutting parameter and their levels are given in the Table 8.

Table 2. TWR Response table for means

Level	Insert	Hardness	Vc	F	Doc
1	62	53.17	48.33	51.5	52.17
2	52.56	50.67	55.17	62.5	50.5
3		68	68.33	57.83	69.17
Delta	9.44	17.33	20	11	18.67
Rank	5	3	1	4	2

Table 3. ANOVA of TWR

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance	% Contribution
Insert	1	401.39	401.39	401.39	17.22	0.003	significant	8.87
Hardness	2	1053.44	1053.44	526.72	22.6	0.001	significant	23.27
Vc	2	1240.11	1240.11	620.06	26.61	0	significant	27.39
F	2	365.78	365.78	182.89	7.85	0.013	Significant	8.08
Doc	2	1280.44	1280.44	640.22	27.47	0	Significant	28.28
Error	8	186.44	186.44	23.31				4.12
Total	17	4527.61						

Prediction of optimal design for TWR

For TWR, Cutting speed and depth of cut are the most significant factors at their first and second levels.

μA1B2 = A1 + B2 - T
where, A1 = 48.33, B2 = 50.50 and T = 57.27 (From Table 2)

μA1B2 = 48.33 + 50.50 - 57.27 = 41.56

$$CI = \sqrt{\frac{(F_{95\%,1,dof error} \times V_{error})}{\eta_{eff}}}$$

where, $\eta_{eff} = \frac{N}{(1+dof)}$

N = Total number of experiments = 18

$\eta_{eff} = \frac{18}{(1+2+2)}$ = 3.6

$V_{error} = 23.31$
$F_{95\%,1,8} = 5.3177$

$$CI = \sqrt{\frac{(5.3177 \times 23.31)}{3.6}} = 5.86$$

The predicted optimal range = μA1B2 - CI ≤ μA1B2 ≤ μA1B2 + CI
= 41.56 - 5.86 ≤ μA1B2 ≤ 41.56 + 5.86
= 35.7 ≤ μA1B2 ≤ 47.42

Taguchi and ANOVA results of Ra

Table 4 shows the mean values of surface roughness values measured. The Main effects plot, Fig. 2 for the means shows that the main effect is due to the change in the insert type. From the ANOVA results of surface roughness given in the Table 5, it is clear that the insert type is the most influencing parameter and followed by hardness, feed, speed and depth of cut. The optimum combination to achieve the minimum surface roughness are given in the Table 8.

Table 4. R_a Response table for means

Level	Insert	Hardness	Vc	F	Doc
1	1.2511	0.8883	0.8033	0.735	0.8667
2	0.4589	0.9567	0.9117	0.87	0.835
3		0.72	0.85	0.96	0.8633
Delta	0.7922	0.2367	0.1083	0.225	0.0317
Rank	1	2	4	3	5

Table 5. ANOVA of Ra

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance	% Contribution
Insert	1	2.82427	2.82427	2.82427	248.4	0	Significant	85.94
Hardness	2	0.17803	0.17803	0.08902	7.83	0.013	Significant	5.42
Vc	2	0.03543	0.03543	0.01772	1.56	0.268		1.08
F	2	0.1539	0.1539	0.07695	6.77	0.019	Significant	4.68
Doc	2	0.00363	0.00363	0.00182	0.16	0.855		0.11
Error	8	0.09098	0.09098	0.01137				2.77
Total	17	3.28625						

Prediction of optimal design for Ra

For Ra, Insert type and hardness are the most significant factors at their second and third levels.

μA2B3 = A2 + B3 - T

where, A2 = 0.4589 , B3 = 0.7200 and T = 0.855 (From Table 4)
μA2B3 = 0.4589 + 0.72 - 0.855 = 0.3239

$$CI = \sqrt{\frac{(F_{95\%,1,doferror} \times V_{error})}{\eta_{eff}}}$$

where, $\eta_{eff} = \frac{N}{(1+dof)}$

N = Total number of experiments = 18

$\eta_{eff} = \frac{18}{(1+1+2)}$ = 4.5

V_{error} = 0.01137

$F_{95\%,1,8}$ = 5.3177

$CI = \sqrt{\frac{(5.3177 \times 0.01137)}{4.5}}$ = 0.0134

The predicted optimal range = μA1B2 - CI ≤ μA1B2 ≤ μA1B2 + CI
= 0.3239 - 0.0134 ≤ μA1B2 ≤ 0.3239 + 0.0134
= 0.3105 ≤ μA1B2 ≤ 0.3373

Taguchi and ANOVA results of Fm

The mean values of machining force obtained are given in the Table 6 and the main effects plot is drawn. From the Fig. 5 it is observed that the main effect is due to change in levels of depth of cut. Similarly from the ANOVA results given in the Table 7, it is concluded that the depth of cut is the most influencing parameter in affecting the machining force and followed by feed, hardness, cutting speed and insert type. The optimum combination corresponding to lower machining force are given in the Table 8.

Prediction of optimal design for Fm

For Fm, depth of cut and feed are the most significant factors at their first levels.

μA1B1 = A1 + B1 - T
where, A1 = 395.3, B1 = 515.2 and T = 624.1428 (From Table 7)
μA1B1 = 395.3 + 515.2 - 624.1428 = 286.3572

$$CI = \sqrt{\frac{(F_{95\%,1,doferror} \times V_{error})}{\eta_{eff}}}$$

where, $\eta_{eff} = \frac{N}{(1+dof)}$

N = Total number of experiments = 18

$\eta_{eff} = \frac{18}{(1+2+2)}$ = 3.6

V_{error} = 7057

$F_{95\%,1,8}$ = 5.3177

$$CI = \sqrt{\frac{(5.3177 \times 7057)}{3.6}} = 102.0988$$

The predicted optimal range = μA1B1 - CI ≤ μA1B2 ≤ μA1B1 + CI
= 286.3572 - 102.0988 ≤ μA1B1 ≤ 286.3572 + 102.0988
= 184.2584 ≤ μA1B1 ≤ 388.456

Table 6. Fm Response table for means

Level	Insert	Hardness	Vc	f	Doc
1	608.5	671.9	615.9	515.2	395.3
2	639.8	518	703.2	620	672.6
3		682.5	553.4	737.2	804.5
Delta	31.4	164.5	149.9	222.1	409.1
Rank	5	3	4	2	1

Table 7. ANOVA of Fm

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance	% Contribution
Insert	1	4428	4428	4428	0.63	0.451		0.49
Hardness	2	101683	101683	50842	7.2	0.016	Significant	11.27
Vc	2	67992	67992	33996	4.82	0.042	Significant	7.54
F	2	148088	148088	74044	10.49	0.006	Significant	16.42
Doc	2	523330	523330	261665	37.08	0	Significant	58.02
Error	8	56452	56452	7057				6.26
Total	17	901972						

Fig. 1. TWR main effects plot for means

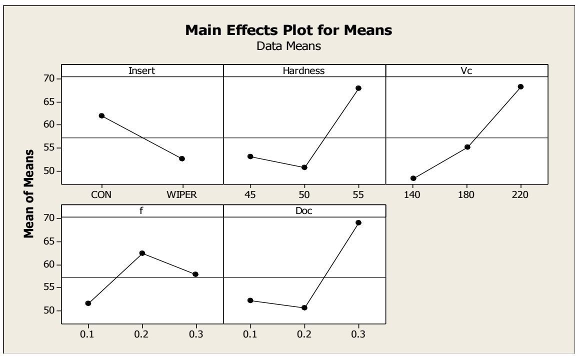

Fig. 2. Ra main effects plot for means

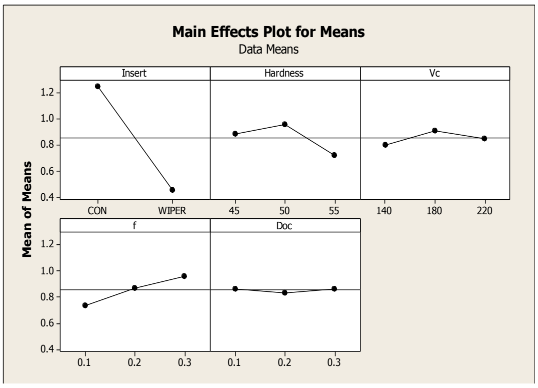

Fig. 3. Fm main effects plot for means

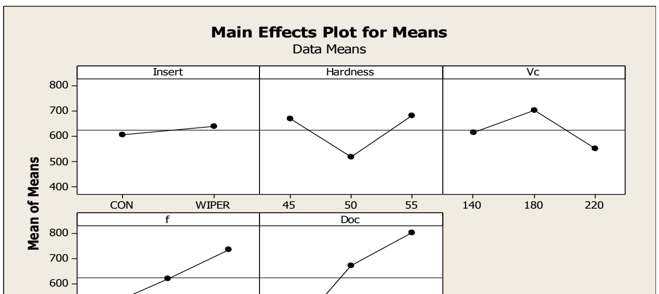

Table 8. Optimum cutting parameter and their levels

Parameter	TWR		Ra		Fm	
	Optimum level	Value	Optimum level	Value	Optimum level	Value
Insert	2	Wiper	2	Wiper	1	Conventional
Hardness	2	50	3	55	2	50
Speed	1	140	1	140	3	220
Feed	1	0.1	1	0.1	1	0.1
Doc	2	0.2	2	0.2	1	0.1

IV. Conclusions

From the experimental results the subsequent conclusions can be drawn.

1. The optimal combination of cutting parameters to attain low tool wear is found with wiper insert and at 50 BHN, 140 RPM, 0.1 mm/rev and 0.2 mm.
2. The optimum combination of cutting parameters to low surface roughness is achieved with wiper insert and at at 55 BHN, 140 RPM, 0.1 mm/rev and 0.2 mm.
3. The finest combination of cutting parameters to attain the low machining force is discovered with conventional insert and at 50 BHN, 220 RPM, 0.1 mm/rev and 0.1 mm.
4. Depth of cut and speed are the primary influencing parameters of tool wear rate, insert type is the most effective for Surface roughness and depth of cut has major contribution in effecting the machining force.
5. Predicted models organized for the responses are more effective and accurate.

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