International Journal of Advanced Mechanical Engineering.
ISSN 2250-3234 Volume 4, Number 3 (2014), pp. 291-298

http://www.ripublication.com/ijame.htm

Optimization of Cutting Parameters on Tool Wear, Workpiece Surface Temperature and Material Removal Rate in Turning of AISI D2 Steel

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Abstract

Optimization methods in turning processes, considered being a vital role for continual improvement of output quality in product and processes include modeling of input-output and in process parameters relationship and determination of optimal cutting conditions. This paper presents an optimization method of the cutting parameters (cutting speed, depth of cut and feed) in dry turning of AISI D2 steel to achieve minimum tool wear, low workpiece surface temperature and maximum material removal rate (MRR). The experimental layout was designed based on the Taguchi's $L_9(3^4)$ Orthogonal array technique and analysis of variance (ANOVA) was performed to identify the effect of the cutting parameters on the response variables. The results showed that depth of cut and cutting speed are the most important parameter influencing the tool wear. The minimum tool wear was found at cutting speed of 150 m/min, depth of cut of 0.5 mm and feed of 0.25 mm/rev. Similarly low w/p surface temperature was obtained at cutting speed of 150 m/min, depth of cut of 0.5 mm and feed of 0.25 mm/rev. Whereas, at cutting speed of 250 m/min, depth of cut 1.00 mm and feed of 0.25 mm/rev, the maximum MRR was obtained. Thereafter, optimal range of tool wear, w/p surface temperature and MRR values were predicted. Finally, the relationship between factors and the performance measures were developed by using multiple regression analysis.

Keywords: AISI D2 steel w/p surface temperature, MRR, Taguchi method, ANOVA.

1. Introduction

Aspects such as tool life and wear, surface finish, cutting forces, material removal rate, power consumption, cutting temperature (on tool and workpiece's surface) decide the productivity, product quality, overall economy in manufacturing by machining and quality of machining. During machining, the consumed power is largely converted into heat resulting high cutting temperature near the cutting edge of the tool. The amount of heat generated varies with the type of material being machined and machining parameters especially cutting speed, which had the most influence on the temperature [9]. All the difficulties lead to high tool wear, low material removal rate (MRR)and poor surface finish [11]. In actual practice, there are many factors which affect these performance measures, i.e. tool variables (tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool overhang, tool point angle, etc.), workpiece variables (material, hardness, other mechanical properties, etc.) and cutting conditions (cutting speed, feed, depth of cut and cutting fluids). Many papers has been published in experimental based to study the effect of cutting parameters on surface roughness [1], tool wear [12], machinability [5], cutting forces [8], power consumption [7], material removal rate [3]. So it is necessary to select the most appropriate machining settings in order to improve cutting efficiency.Hence statistical design of experiments (DOE) and statistical/mathematical model are used quite extensively. Statistical design of experiment refers to the process of planning the experimental so that the appropriate data can be analyzed by statistical methods, resulting a in valid and objective conclusion. The specific cutting pressure was also strongly influenced by the feed rate. Design and methods such as factorial design, response surface methodology (RSM) and Taguchi method are now widely used in place of one factor-at-a-time experimental approach which is time consuming and exorbitant in cost [5]. Taguchi techniques have been widely used by lot of researchers for optimizing surface roughness [6], tool wear [10], tool life [4], cutting force [2], power consumption [9], material removal rate [6] and cutting temperature [6] etc.

2. Experimental Details

The aim of the experiments was to analyze the effect of cutting parameters on the tool wear, w/p surface temperature and material removal rate (MRR) of AISI D2 steel. The experiments were planned using Taguchi's orthogonal array in the design of experiments which help in reducing the number of experiments. The experiments were conducted according to a three level, L_9 (3^4) orthogonal array AISI D2 steel was selected due to its emergent range of applications in the field of manufacturing tools in mould industries. The chemical composition of AISI D2 steel is given in the Table 1.

Table 1: Chemical composition of AISI D2 steel work piece.

Composition	C	Cr	Mn	Si	Mo	W	S	P
Wt. %	1.55	11.8	0.4	0.4	0.7	0.6	0.03	0.03

Table 3: Experimental Set Up.

Machine tool	ACE Designer JOBBER-XL CNC lathe, max.spindle speed :3500 rpm ,max.power:16 kW
Work specimen materials	AISI D2 steel (Φ50 mm x 120 mm)
Cutting inserts	CNMG 120408 (ISO designation) (800 diamond shaped insert)
Tool holder	PCLNR 2525 M12 (ISO designation)
Infrared thermometer	MTX-2, temperature range:-300C to 5500C,optical resolution: 10:1,make: HTC instrument
Profile projector	Nikon V-12B, magnification : range of 5-500X
Cutting conditions	Dry

Table 2: Cutting parameters and levels.

Parameters	**Unit**	**Levels**		
		1	**2**	**3**
Depth of Cut (D)	mm	0.5	0.75	1.0
Feed (F)	mm/rev	0.15	0.2	0.25
Cutting speed(V)	m/min	150	200	250

3. Result and Discussions

The experimental results from Table 3 were analyzed with analysis of variance (ANOVA), which used for identifying the factors significantly affecting the performance measures.

Table 3: Orthogonal array L_9 of Taguchi experiment design and experimental results.

Run No.	**V**	**D**	**F**	**TW (mm)**	**T (0C)**	**MRR (mm3/sec)**
1	150	0.5	0.15	0.30	41.6	862.33
2	150	0.75	0.2	0.46	45.9	2115.07
3	150	1.0	0.25	0.38	41.7	2837.47
4	200	0.5	0.2	0.37	41.2	1420.03
5	200	0.75	0.25	0.55	43	2966.61
6	200	1.0	0.15	0.59	45.9	2250
7	250	0.5	0.25	0.38	43.7	2404.62
8	250	0.75	0.15	0.61	53.5	2194.5
9	250	1.0	0.2	0.57	47.5	3750

3.1 Analysis of variance (ANOVA)

The results of the ANOVA with the tool wear, surface roughness and material removal rate are shown in Tables 4. This analysis was carried out for significance level of α=0.1 i.e. for a confidence level of 90%. The sources with a P-value less than 0.1 are considered to have a statistically significant contribution to the performance measures. The last column of the tables shows the percent contribution of significant source of the total variation and indicating the degree of influence on the result. Table 4(a) shows the results of ANOVA for tool wear, TW. The depth of cut (60.15%) is the most significant cutting parameter followed by cutting speed (33.24%). (b) shows that P-value of cutting speed (0.064) and depth of cut (0.075) which are less than 0.1. The cutting speed and depth of cut have a contribution for the workpiece surface temperatures are 41.17% and 34.45% respectively. Table (c) shows that depth of cut is only found the significant parameter on MRR which contribution is 51.1%.

Table 4: Analysis of variance for tool wear workpiece surface temperature material removal rate.

(a) **Analysis of variance for tool wear**						
Source	**DOF**	**SS**	**MS**	**F**	**P**	**C(%)**
V	2	0.035089	0.017544	36.72	0.027	33.24
D	2	0.063489	0.031744	66.44	0.015	60.15
F	2	0.006022	0.003011	6.30	0.137	5.70
Error	2	0.000956	0.000478			0.91
Total	8	0.105556				100
S = 1.30937 R-sq = 97.20% R-sq(adj) = 88.81%						
(b) Analysis of variance for workpiece surface temperature						
V	2	50.469	25.234	14.72	0.064	41.17
D	2	42.229	21.114	12.32	0.075	34.45
F	2	26.462	13.231	7.72	0.115	21.58
Error	2	3.429	1.714			2.8
Total	8	122.589				100
S = 1.30937 R-sq = 97.20% R-sq(adj) = 88.81%						
(c) Analysis of variance for material removal rate						
V	2	1114480	557240	4.95	0.168	19.43
D	2	2929794	1464897	13.02	0.071	51.1
F	2	1465271	732635	6.51	0.133	25.55
Error	2	225090	112545			3.92
Total	8	5734635				100
S = 335.477 R-sq = 96.07% R-sq(adj) = 84.30%						

3.2 Main effect plots

In the plots, the X-axis indicates the value of each process parameters at three level and Y-axis the response value. The main effect plots are used to determine the optimal design conditions to obtain the low tool wear, good surface finish and high material removal rate. Fig.2 shows the main effect plot for tool wear, TW which show that with the increase in cutting speed there is a continuous increase in tool wear at cutting speed of 150 m/min (level-1), DOC of 0.5 mm (level-1) and feed of 0.25 mm/rev (level-3). Fig. 3 shows that same levels of cutting parameters (V: 150 m/min, D: 0.5 mm and F: 0.25 mm/rev) produce lower w/p surface temperature, T. Fig. 4 shows the main effect plot for workpiece MRR shows that with the increasing in cutting speed, depth of cut and feed give high value of MRR i.e. high production rate. At cutting speed of 250 m/min (level-3), 1 mm (level-3) of depth of cut and feed of 0.25 mm/rev (level-3) the maximum MRR is obtained.

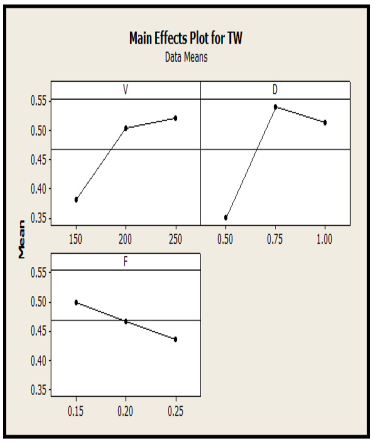

Fig. 2: Toolwear Rate

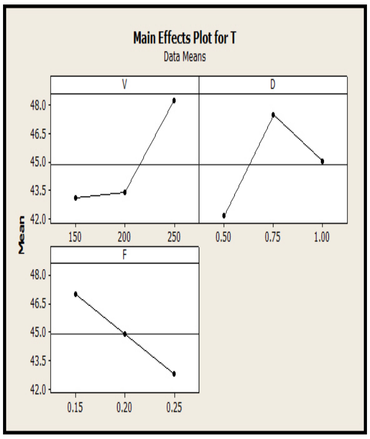

Fig. 3: Surface Temperature

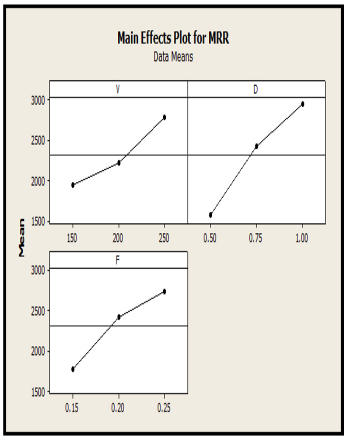

Fig. 4: Material Removal Rate

3.3 Prediction of optimal design

When tool wear (TW) is considered from Table 4, an estimated average when the two most significant factors are at their better level is

$\mu_{TW} = \overline{V}_1 + \overline{D}_1 - \overline{T}_{TW}$ (from Table 3, $\overline{T}_{TW}$ = 0.4677) = (0.3800 + 0.3500) – 0.4677 = 0.2623

$CI = \sqrt{\frac{F_{90\%.1,DOF\ error} \times V_{error}}{\eta_{eff}}}$ Where $\eta_{eff} = \frac{N}{1 + \text{DOF associated to that level}} = \frac{9}{1+2+2} =$ 1.8,

Thus, $CI = \sqrt{\frac{8.53 \times 0.000478}{1.8}}$ = 0.0476 where $F_{90\%.1,\ 2}$ = 8.53 and V_{error} = 0.000478 (from Table 4.(a))

Finally, the estimated average with the confidence interval at 90% confidence (when the two most significant factors are at their better level) is

$(0.2623-0.0476) \leq \mu_{TW} \leq (0.2623+0.0476) = 0.21 \leq \mu_{TW} \leq 0.31$

Similarly, when workpiece surface temperature (T) is concerned, estimated average is at V_1D_1 level. Then,

$\mu_T = \overline{V}_1 + \overline{D}_1 - \overline{T}_T$ (from Table 3, $\overline{T}_T$ = 44.88) = (43.07 + 42.17) – 44.88 = 40.36

Thus, $CI = \sqrt{\frac{8.53 \times 1.714}{1.8}}$ = 2.85, where $F_{90\%.1,\ 2}$ = 8.53, η_{eff} = 1.8 and V_{error} = 1.714 (from table 4.9b))

Finally, the estimated average with the confidence interval at 90% confidence (when the two most significant factors are at their better level) is (40.36-2.85) ≤ μ_T ≤ (40.36+2.85) = 37.51 ≤ μ_T ≤ 43.21

Again when material removal rate (MRR) is concerned the estimated average is at D_3F_3 level. Then,

$\mu_{MRR} = \bar{D}_3 + \bar{F}_3 - \bar{T}_{MRR}$ (from Table 3, $\bar{T}_{MRR}$ = 2311.18) = (2946 + 2736) – 2311.18 = 3370.82

Thus, CI $= \sqrt{\frac{8.53 \times 112545}{1.8}}$ = 730.3, where $F_{90\%.1,\ 2}$ = 8.53, η_{eff} = 1.8 and V_{error} = 112545 (from table 4(c))

The predicted optimal range of MRR at 90% confidence level is obtained as,

(3370.82-730.3) ≤ μ_{MRR} ≤ (3370.82+730.3) = 2640.52 ≤ μ_{MRR} ≤ 4101.12

Table 5: Means of tool wear, w/p surface temperature and material removal rate at different levels.

Level	**Tool wear TW (mm)**			**Workpiece surface temperature T (^{0}C)**			**Material removal rate MRR (mm^3/sec)**		
	$\bar{V}$	**$\bar{D}$**	**$\bar{F}$**	**$\bar{V}$**	**$\bar{D}$**	**$\bar{F}$**	**$\bar{V}$**	**$\bar{D}$**	**$\bar{F}$**
1	0.3800	0.3500	0 .5000	43.07	42.17	47.00	1938	1562	1769
2	0.5033	0.5400	0.4667	43.37	47.47	44.87	2212	2425	2428
3	0.5200	0.5133	0.4367	48.23	45.03	42.80	2783	2946	2736
Delta	0.1400	0.1900	0.0633	5.17	5.30	4.20	845	1383	967
Rank	2	1	3	2	1	3	3	1	2

Bold values indicate the levels of significant parameters for which the best result obtained and the optimal design is calculated.

3.4 Regression equations

The relationship between the factors cutting parameters and the performance measures were modeled by multiple linear regression which are in following equations forms

Tool wear (TW):TW= 0.069 + 0.00140V + 0.327D - 0.633F (R=0.85) - (1)

Workpiece surface temperature (T): T=38.7 + 0.0517V + 5.73D - 42.0F (R=0.80) --------- (2)

Material removal rate (MRR): MRR= -3388 + 8.45V + 2767D + 9673F (R=0.96) --- ------- (3)

The residuals could be said to follow a straight line in normal plot of residuals implying that the errors were distributed normally for tool wear, w/p surface temperature and material removal rate respectively. The residuals were randomly scattered with in constant variance across the residuals versus the predicted plot as shown in fig.5 indicated there is no obvious pattern and unusual structure present in the data which implies that the residual structure analysis does not indicate any model inadequacy.

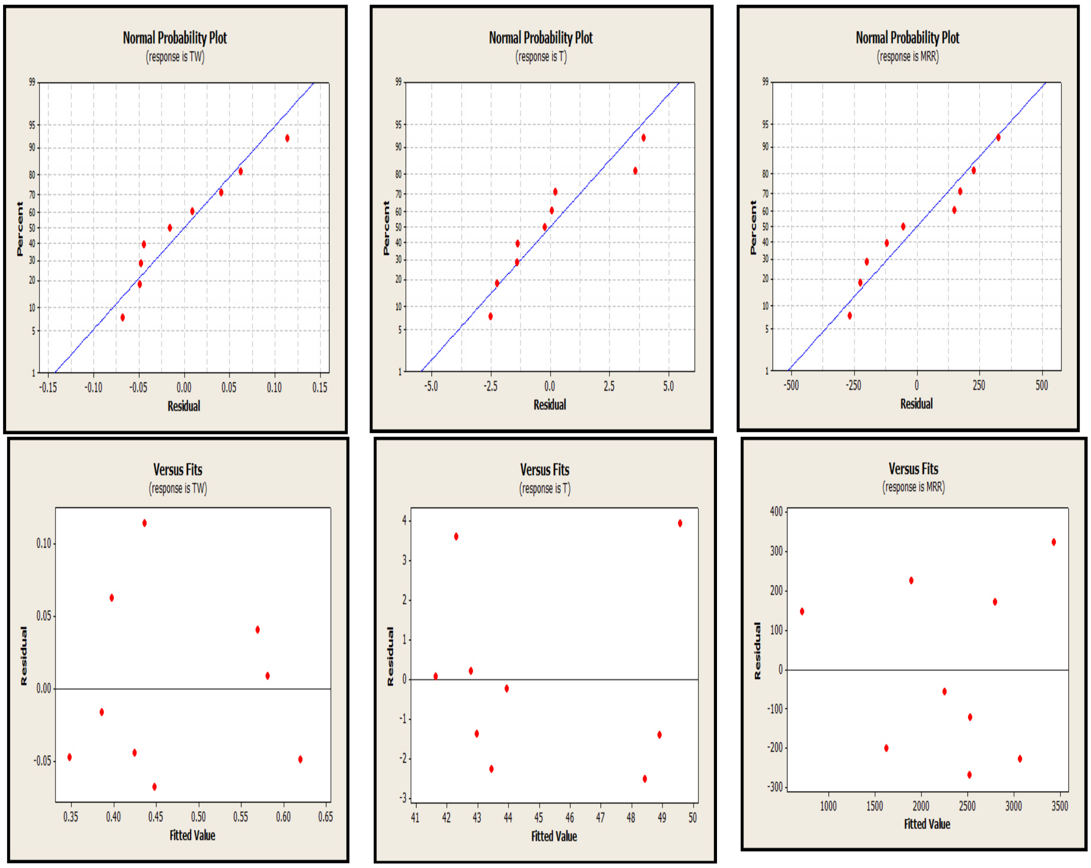

Fig. 5: Residuals versus the predicted plot.

4. Conclusions

1. The experimental results showed that the Taguchi parameter design is an effective way of determining the optimal cutting parameters for achieving low tool wear, low w/p surface temperature and high MRR.
2. The percent contributions of depth of cut (60.85%) and cutting speed (33.24%) in affecting the variation of tool wear are significantly larger as compared to the contribution of the feed (5.70%).
3. The significant parameters for w/p surface temperature were cutting speed and depth of cut with contribution of 41.17% and 34.45% respectively. Although not statistically significant, the feed has a physical influence explaining 21.58% of the total variation.
4. Depth of cut (51.1%) was only found the significant parameter followed by feed (25.5%) on material removal rate (MRR).So the optimal combination of cutting parameters for maximum MRR was obtained at 250 m/min cutting speed, 1 mm depth of cut and 0.25 mm/rev feed.

5. The predicted optimal range of tool wear is $0.21 \le \mu_{TW} \le 0.31$, for work surface temperature is $37.51 \le \mu_T \le 43.21$ and for material removal rate is $2640.52 \le \mu_{MRR} \le 4101.12$.
6. The relationship between cutting parameters and the performance measures are expressed by multiple regression equation which can be used to estimate the expressed values of the performance level for any parameter levels.

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