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

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Abstract

Now-a-days increasing the productivity and the quality of the machined parts are the main challenges of metal cutting industry during turning processes. 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 workpiece 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, workpiece 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, tool wear, workpiece surface temperature, MRR.

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 [1]. Many of the economic and technical problems of machining are caused directly or indirectly by this heating action. Excessive temperatures directly influence the temperatures of importance to tool wear on the tool face and tool flank and inducing thermal damage to the machined surface [2]. All these difficulties lead to high tool wear, low material removal rate (MRR) and poor surface finish [3]. 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 [4, 5], tool wear [6], machinability [7], cutting forces [8], power consumption [9], material removal rate [10]. So it is necessary to select the most appropriate machining settings in order to improve cutting efficiency. Generally, this optimum parameter selection is determined by the operator's experience knowledge or the design data book which leads to decrease in productivity due to sub-optimal use of machining capability this causes high manufacturing cost and low product quality [11, 12].

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 in valid and objective conclusion [13]. Davim and Figueira [14] investigated the machinability evaluation in hard turning of cold work steel (D2) with ceramic tools using statistical techniques. It was concluded that the tool wear was highly influenced by the cutting velocity, and in a smaller degree, by cutting time. 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 [15]. Taguchi techniques have been widely used by lot of researchers for optimizing surface roughness [16, 17, 18], tool wear [19], tool life [20], cutting force [21], power consumption [9, 22], material removal rate [23] and cutting temperature [24] etc.

Sahin [20] compared the tool life of CBN and ceramic inserts in turning hard steels using the Taguchi method. The effects of cutting parameters (cutting speed, feed, tool hardness) on tool life were determined by using orthogonal array, signal–noise ratio and variance analysis. As a result, it was concluded that the effects of cutting speed, tool hardness and feed rate on tool life were 41.63%, 32.68% and 25.22%, respectively. A. Suhail et al. [25] optimize the cutting parameters on workpiece surface temperature and surface roughness by employing Taguchi technique and ANOVA. The results showed that the workpiece surface temperature can be sensed effectively as an in-process signal for cutting parameters optimization. Aslan et al. [26] conducted an optimization study by machining a hardened AISI 4140 grade (63HRC) steel on a lathe by using Al_2O_3+TiCN coated ceramic inserts. They determined that Al_2O_3 base ceramics are required for cutting tools in machining hard steels during wear resistance and high hardness. They ensured optimization in their experimental studies by using the Taguchi method. The experimental parameters chosen were: three different cutting speeds, feed rates and depths of cut. Flank wear (VB) and surface roughness were chosen as criteria for performance. The obtained results were analyzed by using variance analysis (ANOVA). As a result, it was seen that the VB value decreased as the cutting speed and the depth of cut increased; however, it first decreased and then increased as the feed rate increased. On the other hand, the surface roughness decreased as the cutting speed increased. In contrast surface roughness increased when the feed rate increased. A. Bhattacharya et al. [9] have investigated the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result showed a significant effect of cutting speed on surface roughness and power consumption, while the other parameters have not substantially affected the response.

The aim of this experimental investigation is to the effects of the cutting parameters on AISI D2 steel workpiece surface temperature, tool wear and material removal rate by employing Taguchi's orthogonal array design and analysis of variance (ANOVA) under dry environment.

2. Taguchi method

The Taguchi experimental design method is a well-known, unique and powerful technique for product or process quality improvement [27, 28]. It is widely used for analysis of experiment and product or process optimization. Taguchi has developed a methodology for the application of factorial design experiments that has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing. His contributions have also made the practitioner's work simpler by advocating the use of fewer experimental designs, and providing a clearer understanding of the nature of variation and the economic consequences of quality engineering in the world of manufacturing. Taguchi introduces his concepts to:

- Quality should be designed into a product and not inspected into it.
- Quality is best achieved by minimizing the deviation from a target.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi recommends a three-stage process to achieve desirable product quality by design-system design, parameter design and tolerance design. While system design helps to identify working levels of the design parameters, parameter design seeks to determine parameter levels that provide the best performance of the product or process under study. The optimum condition is selected so that the influence of uncontrollable factors causes minimum variation to system performance. Orthogonal arrays, variance and signal to noise analysis are the essential tools of parameter design. Tolerance design is a step to fine-tune the results of parameter design [29].

3. Experimental details

3.1. Workpiece material

The workpiece material was AISI D2 steel in the form of round bars having 50 mm diameter and length of 120 mm. 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 workpiece in percentage by weight

C	Cr	Mn	Si	Mo	W	S	P
1.55	11.8	0.4	0.4	0.7	0.6	0.03	0.03

3.2. Cutting inserts

In tests, coated carbide inserts of ISO designation CNMG 120408 (80^0 diamond shaped inset) without chip breaker geometry has been used for experimentation. The cutting inserts were clamped onto a right hand tool holder having ISO designation PCLNR 2525 M12.

3.3. Experimental procedure

The turning tests on the workpiece were conducted under dry conditions on a CNC lathe (JOBBER XL, ACE India) which have a maximum spindle speed of 3500 rpm and maximum power of 16 kW. A hole was drilled on the face of work piece to allow it to be supported at the tailstock (Figure 1). Prior to actual machining, the rust layers were removed by a new cutting insert in order to minimize any effect of in homogeneity on the experimental results.

Material removal rate (MRR) has been calculated from the difference of volume of workpiece before and after each experiment by using the following formula.

$$\text{MRR} = \frac{\text{Volume removed}}{\text{Cutting time}} = \frac{\pi.L(d_1^2-d_2^2)}{\frac{4.L}{F.N}} \quad \text{mm}^3/\text{min}$$

Where, d_1 and d_2 is diameter workpiece before and after machining, L is length of machined workpiece and N is spindle speed to achieve specific cutting speed.

Figure 1 View of cutting zone

3.4. Measurement of tool wear and workpiece surface temperature

The surface temperature of the machined samples were measured by the use of infrared thermometer (make: HTC MTX-2) having temperature range of -30^0C to 550^0C and with optical resolution of 10:1.

During the course of experimentation the tool flank wear of worn out inserts were measured with the help of a profile projector (make: Nikon V-12B) having magnification in the range of 5-500X.

3.5. Design of experiments

The aim of the experiments was to analyze the effect of cutting parameters on the tool wear, workpiece 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. The cutting parameters identified were cutting speed, depth of cut and feed. The control parameters and the levels used in experiment, experimental set up and conditions are given in the Tables 2 and 3.

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

Table 3: Experimental setup and conditions

Machine tool	ACE Designer JOBBER-XL CNC lathe.
Workpiece materials	AISI D2 steel
Size	Φ50 mm x 120 mm
Cutting inserts	CNMG 120408 (ISO designation)
Tool holder	PCLNR 2525 M12 (ISO designation)
Infrared thermometer	MTX-2 (make: HTC instrument)
Profile projector	Nikon V-12B
Cutting conditions	Dry

Table 4: Orthogonal array L_9 of Taguchi experiment design and experimental results

Run No.	V	D	F	TW (mm)	T (^{0}C)	MRR (mm^3/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

4. Results and discussion

4.1. Analysis of variance (ANOVA)

The experimental results from Table 4 were analyzed with analysis of variance (ANOVA), which used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with the tool wear, workpiece surface temperature and material removal rate are shown in Tables 5, 6 and 7 respectively. 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 5 shows the results of ANOVA for tool wear, TW. It is observed from the ANOVA table, the depth of cut (60.15%) is the most significant cutting parameter followed by cutting speed (33.24%). However, feed has least effect (5.7%) in controlling the tool wear which is not statistically significant. From the analysis of the Table 6 shows that P-value of cutting speed (0.064) and depth of cut (0.075) which are less than 0.1. It means that cutting speed and depth of cut influence significantly on workpiece surface temperature, T. The cutting speed and depth of cut have a contribution for the workpiece surface temperature are 41.17% and 34.45% respectively. The next largest contribution comes from feed (21.58%) which is not statistically significant. Table 7 shows the ANOVA results for material removal rate, MRR. The results indicate that depth of cut is only found the significant parameter on MRR which contribution is 51.1%. The feed and cutting speed does not present a statistical significance on MRR, which contributions are 25.55% and 19.43% respectively.

The error contribution is 0.91%, 2.8% and 3.92% for tool wear, workpiece surface temperature and material removal rate respectively. As the percent contribution due to error is very small it signifies that neither any important factor was omitted nor any high measurement error was involved [29].

Table 5: 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 = 0.0218581 R-sq = 99.09% R-sq(adj) = 96.38%

DOF= Degree of freedom, SS= Sum of squares, MS= Mean squares, C= Contribution

Table 6: Analysis of variance for workpiece surface temperature

Source	DOF	SS	MS	F	P	C (%)
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%

Table 7: Analysis of variance for material removal rate

Source	DOF	SS	MS	F	P	C (%)
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%

4.2. Main effect plots

The data was further analyzed to study the interact on amount cutting parameters (V, D, F) and the main effect plots on tool wear, workpiece surface temperature and material removal rate were analyzed with the help of software package MINITAB15 and shown in Figures 2, 3 and 4 respectively. The plots show the variation of individual response with the three parameters; cutting speed, depth of cut and feed separately. 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, low surface temperature & high MRR.

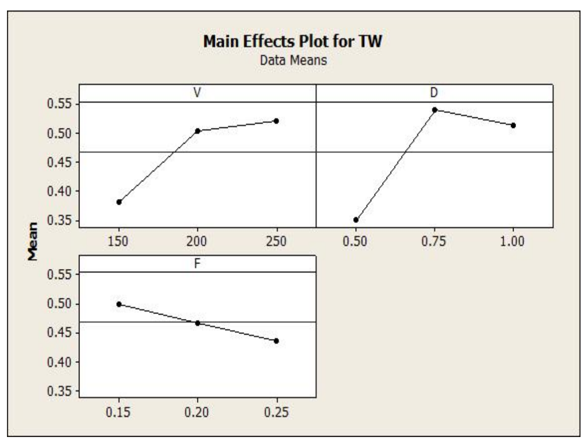

Figure 2 Main effects plot for tool wear (TW)

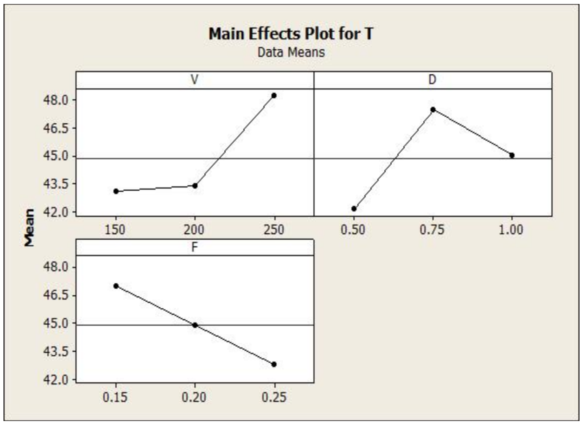

Figure 3 Main effects plot for workpiece surface temperature (T)

Figure 2 shows the main effect plot for tool wear, TW. The results show that with the increase in cutting speed there is a continuous increase in tool wear. On the other hand, as the feed increases the tool wear decreases. However, with the increase in depth of cut there is an increase in tool wear up to 0.75 mm. A depth of cut of 0.75 mm produces a highest tool wear and 0.5 mm show the lowest tool wear. Based on analysis using Figure 2 low value of tool wear was obtained 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). For comparison, the main effects plot for workpiece surface temperature Figure 3 shows that same levels of cutting parameters (V: 150 m/min, D: 0.5 mm and F: 0.25 mm/rev) produce lower workpiece surface temperature, T. Thus, the lower surface temperature gives less tool wear on the cutting tools.

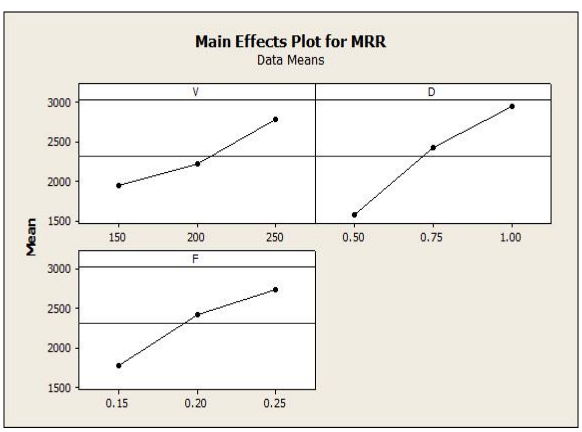

Figure 4 Main effects plot for material removal rate (MRR)

Figure 4 shows the main effect plot for workpiece MRR for cutting speed, depth of cut and feed. The results show that with the increasing in cutting speed, depth of cut and feed give high value of MRR i.e. high production rate. It was observed that the maximum MRR is obtained 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).

4.3. Prediction of optimal design

When tool wear (TW) is considered from Table 8, 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 4, $\overline{T}_{TW}$ = 0.4677)

= (0.3800 + 0.3500) – 0.4677 = 0.2623

$CI = \sqrt{\frac{F_{90\%.1,\text{DOF error}} \times V_{error}}{\eta_{eff}}}$

Where $\eta_{eff} = \frac{N}{1 + \text{DOF associated to that level}} = \frac{9}{1+2+2} = 1.8$

$F_{90\%.1,2}$ = 8.53 and V_{error} = 0.000478 (from Table 5)

Thus, $CI = \sqrt{\frac{8.53 \times 0.000478}{1.8}} = 0.0476$

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 4, $\overline{T}_T$ = 44.88)

= (43.07 + 42.17) – 44.88 = 40.36

$F_{90\%.1,2}$ = 8.53, η_{eff} = 1.8, V_{error} = 1.714 (from Table 6)

Thus, $CI = \sqrt{\frac{8.53 \times 1.714}{1.8}} = 2.85$

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

$(40.36-2.85) \leq \mu_T \leq (40.36+2.85)$

$37.51 \leq \mu_T \leq 43.21$

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

$\mu_{MRR} = \overline{D}_3 + \overline{F}_3 - \overline{T}_{MRR}$ (Table 4, $\overline{T}_{MRR}$ =2311.18)

= (2946 + 2736) – 2311.18 = 3370.82

$F_{90\%.1,2}$ =8.53, η_{eff} =1.8, V_{error} = 112545 (from Table 7)

Thus, CI = $\sqrt{\frac{8.53 \times 112545}{1.8}}$ = 730.3

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

$(3370.82-730.3) \leq \mu_{MRR} \leq (3370.82+730.3)$

$2640.52 \leq \mu_{MRR} \leq 4101.12$

Table 8: Means of tool wear, workpiece 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.

4.4. Regression equations

The relationship between the factors (cutting speed, depth of cut and feed) and the performance measures (tool wear, workpiece surface temperature and material removal rate) were modeled by multiple linear regression. The following equations are the final regression models in terms of coded parameters for:

Tool wear (TW):
TW= 0.069 + 0.0014V + 0.327D - 0.633F (R=0.85)

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

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

Inspection of some diagnostic plots of the model was done to test the statistical validity of the models. The residuals could be said to follow a straight line in normal plot of residuals implying that the errors were distributed normally, shown in Figures 5, 7 and 9 for tool wear, workpiece surface temperature and material removal rate respectively. This gives the support that terms mentioned in the model are significant. The residuals were randomly scattered with in constant variance across the residuals versus the predicted plot (Figure 6, 8 and 10). Figure 5-10 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.

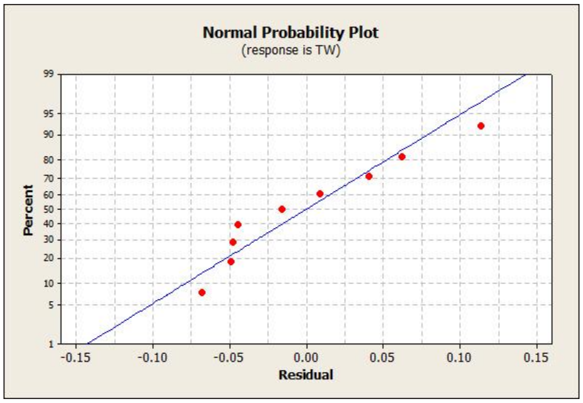

Figure 5 Normal probability plot of the residuals for tool wear (TW)

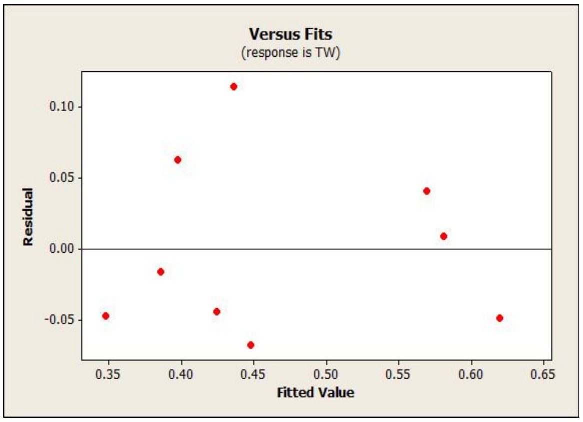

Figure 6 Residuals versus the fitted values for tool wear (TW)

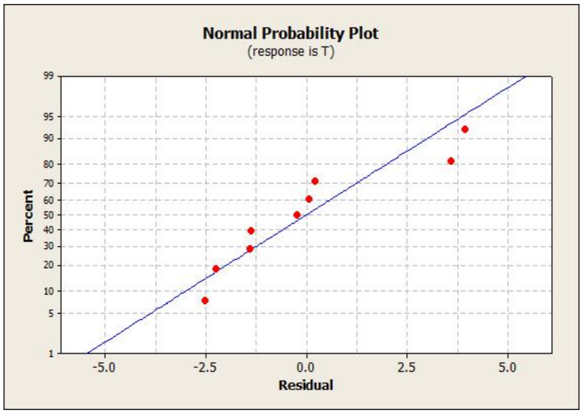

Figure 7 Normal probability plot of the residuals for workpiece surface temperature (T)

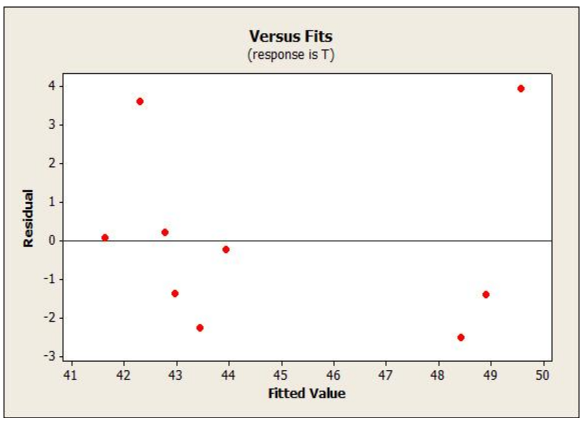

Figure 8 Residuals versus the fitted values for workpiece surface temperature (T)

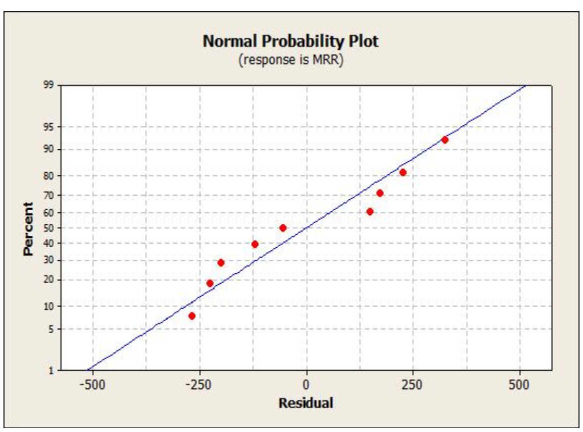

Figure 9 Normal probability plot of the residuals for material removal rate (MRR)

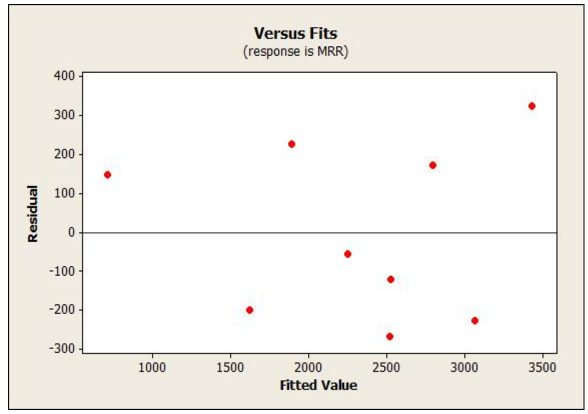

Figure 10 Residuals versus the fitted values for material removal rate (MRR)

5. 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 workpiece 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 workpiece 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). Moreover, MRR is apparently to have an increasing trend with increase cutting speed, depth of cut and feed. 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 $0.21 \leq \mu_{TW} \leq 0.31$, for workpiece surface temperature is $37.51 \leq \mu_{T} \leq 43.21$ and for material removal rate is $2640.52 \leq \mu_{MRR} \leq 4101.12$.
6. The relationship between cutting parameters (cutting speed, depth of cut, feed) and the performance measures (tool wear, workpiece surface temperature and MRR) are expressed by multiple regression equation which can be used to estimate the expressed values of the performance level for any parameter levels.

6. References

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