Journal Of Harmonized Research (JOHR)

Journal Of Harmonized Research in Engineering
1(1), 2013, 05-15

ISSN 2347 – 7393

Original Research Article

# Experimental Investigation on Tool Wear, Surface Roughness and Material Removal Rate during Dry Turning of AISI 52100 Steel

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**Abstract:**

Aspects such as tool life and wear, surface finish, cutting forces, material removal rate, power consumption, cutting temperature decide the productivity, product quality, overall economy in manufacturing by machining and quality of machining. The present paper is an experimental study to investigate the effect of cutting parameters (cutting speed, depth of cut and feed) on tool wear, surface roughness and material removal rate (MRR) during dry turning of AISI 52100 steel. Turning experiments were conducted with cutting speeds: 250, 300, 350 m/min, feeds: 0.15, 0.2, 0.25 mm/rev and depth oh cuts: 0.5, 1.0, 1.5 mm. 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 revealed that cutting speed (61.17%) is only the significant parameter on tool wear. On the other hand, cutting speed (59.42%) was found to be the dominant parameter among controllable parameters on surface roughness followed by feed (24.3%). However, depth of cut (78.8%) only showed significant parameters for material removal rate (MRR). Finally, the relationship between cutting parameters and the performance measures (tool wear, surface roughness and material removal rate) were developed by using multiple regression analysis.

**Keywords:** AISI 52100 steel, tool wear, surface roughness, MRR, Taguchi method, regression analysis.

## 1. Introduction

Present days increasing the productivity and the quality of the machined parts (in terms of workpiece dimensional accuracy, good surface finish, less tool wear on the cutting tools, high metal removal rate and economy of machining in terms of time per component, cost per component and the performance of the product) are the main challenges of metal cutting industry during different machining process [1]. The quality of design can be improved by improving the quality and productivity in companywide activities. Those

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Received on: August 2013
Accepted after revision: September 2013

activities concerned with quality, include in quality of product planning, product design and process design [2]. Usually wear test, power consumption, material removal rate and surface finish are the most desirable tests for quality measurement of machining process. Especially surface finish plays an important role on the product quality and it is a parameter of great importance in the evaluation of machining accuracy. In addition to surface finish quality, the tool wear and material removal rate are also importance characteristics in machining operation. In turning good surface finish, high material removal rate and low tool wear are desirable. Also dry turning is becoming important due to awareness towards the environment and worker's health. In addition to environment inputs, the cost associated cutting fluid is approximately 7-17% of total manufacturing cost which is very high [3], [4]. The machining parameter such as cutting speed, feed and depth of cut, features of tool, workpiece material and coolant conditions will highly affect these performance characteristics. Some works have studied the effect of cutting conditions (V, F, D) [5], [6], [7], the influence of workpiece hardness [8], [9], the tool geometry [9], [10], [11], cutting time [12], cutting tool materials [13], [14] and the effects of cutting fluids [15], [16]. It is necessary to select most appropriate machining settings in under to improve cutting efficiency, process at low cost and produce high quality products [17].

Hence statistical design of experiments and statistical or 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 [18]. Design and methods such as factorial design, response surface methodology (RSM) and Taguchi methods are now widely used in place of one factor-at-a-time experimental approach which is time consuming and exorbitant in cost [19]. Taguchi techniques have been widely used by lot of researchers for optimization of cutting parameters [5], [6], [7], [10], [12], [13], [14], [20] & [21]. A. Bhattacharya et al. [20] 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. Yang and Tarng [21] used the Taguchi method to find the optimal cutting parameters for turning of AISI 1045 steels using cemented carbide cutting tools. They found that cutting speed and feed rate were the significant cutting parameters for affecting the tool life. M. Kaladhar et al. [10] investigated the effects of process parameters on surface finish and MRR during turning of AISI 304 austenitic steel using PVD coated cermet insert of 0.4 and 0.8 mm nose radius. The results revealed that feed and nose radius are the most significant process parameters on surface roughness, however depth of cut and feed are the significant on MRR. Davim and Figueira [12] 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.

The present study is an experimental investigation to evaluate the influence of cutting parameters (cutting speed, depth of cut and feed ) on tool wear, surface roughness and material removal rate (MRR) by employing Taguchi's orthogonal array design and analysis of variance (ANOVA) during dry turning of AISI 52100 steel. The relationship between cutting parameters and the performance measures has been developed by multiple regression analysis.

## 1. Taguchi Method

The Taguchi experimental design method is a well-known, unique and powerful technique for product or process quality improvement [2]. 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 [22].

## 2. Experimental Details

### 2.1. Workpiece Material

The workpiece material was AISI 52100 steel in the form of round bars having 60 mm diameter and length of 120 mm. AISI 52100 steel is a difficult-to-machine material because of its low specific heat, tendency to high strain hardened [23]. And their typical applications are in manufacturing of machine tool parts like spindles, shafts, bearing and automobile products. The chemical composition of AISI 52100 steel is given in the Table 1.

### 2.2. Cutting Inserts

In tests, coated carbide inserts of ISO designation VNMG 160408 ($35^0$ 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 MVJNR 2020K16.

### 2.3. 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 16kW. A hole was drilled on the face of workpiece to allow it to be supported at the tailstock (Fig.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.

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

Where, $d_1$ and $d_2$ are diameters of workpiece before and after machining, L is length of machined work piece and N is spindle speed to achieve specific cutting speed.

### 2.4. Measurement Of Tool Wear And Surface Roughness

The surface roughness of the machined samples were measured with ZEISS & ACCT make Surfcom 130A with a cut-off length of 0.08 mm over the sampling lengths. The average value of surface roughness (Ra) was used to quantify the roughness achieved on the machined surfaces.

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.

### 2.5. Design Of Experiments

The aim of the experiments is to analyze the effect of cutting parameters on the tool wear, surface roughness and material removal rate (MRR) during dry turning of AISI 52100 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, $L_9$ $(3^3)$ 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 Table 2 and Table 3 respectively.

***Table 1. Chemical composition of AISI 52100 steel workpiece***

| Composition | C | Si | Mn | Cr | Co | S | P | Fe |
|---|---|---|---|---|---|---|---|---|
| Wt. % | 0.95 | 0.10 | 0.30 | 1 | 0.025 | 0.04 | 0.04 | Balance |

***Table 2. Cutting parameters and levels***

| Parameters | Unit | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Depth of Cut (D) | mm | 0.5 | 1 | 1.5 |
| Feed (F) | mm/rev | 0.15 | 0.2 | 0.25 |
| Cutting speed(V) | m/min | 250 | 300 | 350 |

***Fig. 1. View of cutting zone***

***Table 3. Experimental set-up and conditions***

| | |
|---|---|
| Machine tool | ACE Designer JOBBER-XL CNC lathe. |
| Work specimen materials | AISI 52100 steel |
| Size | Φ60 mm x 120 mm |
| Cutting inserts | VNMG 160408 (ISO specification) |
| Tool holder | MVJNR 2020 K16 (ISO specification) |
| Surface roughness tester | Surfcom 130A (ZEISS & ACCT make) |
| 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 | Tool wear (mm) | Ra (µm) | MRR ($mm^3$/sec) |
|---|---|---|---|---|---|---|
| 1 | 250 | 0.5 | 0.15 | 0.077 | 0.520 | 2728.47 |
| 2 | 250 | 1 | 0.2 | 0.181 | 0.666 | 6958.41 |
| 3 | 250 | 1.5 | 0.25 | 0.127 | 0.687 | 12586.718 |
| 4 | 300 | 0.5 | 0.2 | 0.138 | 0.871 | 4585.5234 |
| 5 | 300 | 1 | 0.25 | 0.169 | 3.813 | 9747.71 |
| 6 | 300 | 1.5 | 0.15 | 0.213 | 1.042 | 9537.9024 |
| 7 | 350 | 0.5 | 0.25 | 0.195 | 4.576 | 6459.2 |
| 8 | 350 | 1 | 0.15 | 0.273 | 3.748 | 10267.147 |
| 9 | 350 | 1.5 | 0.2 | 0.359 | 2.163 | 13361.88 |

## 3. Results and Discussion

### 3.1. 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, surface roughness and material removal rate are shown in Tables 5, 6 and 7 respectively. This analysis was carried out for significance level of α=0.05 i.e. for a confidence level of 95%. The sources with a P-value less than 0.05 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. Analysis of variance for tool wear***

| Source | DOF | SS | MS | F | P | C(%) |
|---|---|---|---|---|---|---|
| V | 2 | 0.0342042 | 0.0171021 | 41.91 | 0.023 | 61.17 |
| D | 2 | 0.0149629 | 0.0074814 | 18.33 | 0.052 | 26.76 |
| F | 2 | 0.0059309 | 0.0029654 | 7.27 | 0.121 | 10.61 |
| Error | 2 | 0.0008162 | 0.0004081 | | | 1.46 |
| Total | 8 | 0.0559142 | | | | 100 |

S = 0.0202018 R-sq = 98.54% R-sq(adj) = 94.16%

***Table 6. Analysis of variance for surface roughness***

| Source | DOF | SS | MS | F | P | C(%) |
|---|---|---|---|---|---|---|
| V | 2 | 12.4126 | 6.2063 | 46.21 | 0.021 | 59.42 |
| D | 2 | 3.1339 | 1.5670 | 11.67 | 0.079 | 15.00 |
| F | 2 | 5.0751 | 2.5376 | 18.89 | 0.050 | 24.3 |
| Error | 2 | 0.2686 | 0.1343 | | | 1.28 |
| Total | 8 | 20.8903 | | | | 100 |

S = 0.366479 R-sq = 98.71% R-sq(adj) = 94.86%

***Table 7. Analysis of variance for material removal rate***

| Source | DOF | SS | MS | F | P | C (%) |
|---|---|---|---|---|---|---|
| V | 2 | 11363642 | 5681821 | 3.30 | 0.232 | 11.22 |
| D | 2 | 79798310 | 39899155 | 23.18 | 0.041 | 78.80 |
| F | 2 | 6659093 | 3329547 | 1.93 | 0.341 | 6.58 |
| Error | 2 | 3442053 | 1721027 | | | 3.40 |
| Total | 8 | 101263098 | | | | 100 |

S = 1311.88 R-sq = 96.60% R-sq(adj) = 86.40%

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

From the analysis of the Table 5 shows that the only significant parameter for the tool wear is cutting speed which contributes 61.17% of the total variation. The next largest contribution comes from depth of cut (26.76%) then feed (10.65%), which is not statistically significant. Table 6 shows the results of ANOVA for surface roughness. It is observed that, the cutting speed (59.42%) is the most significant parameter followed by the feed (24.3%). However, the insignificant parameter (depth of cut) has the least effect (15%) in controlling the surface roughness. Table 7 shows the ANOVA results for the material removal rate (MRR). The results indicate that the depth of cut is the only found the significant parameter on material removal rate, which contribution is 78.8%. The cutting speed and feed does not present a statistical significance on material removal rate; which contribution are 11.22% and 6.58% respectively.

The error contribution is 1.46%, 1.28% and 3.4% for tool wear, surface roughness 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 [22].

3.2. 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 the tool wear, surface roughness and material removal rate were analyzed with the help of software package MINITAB 15 and shown Fig. 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.

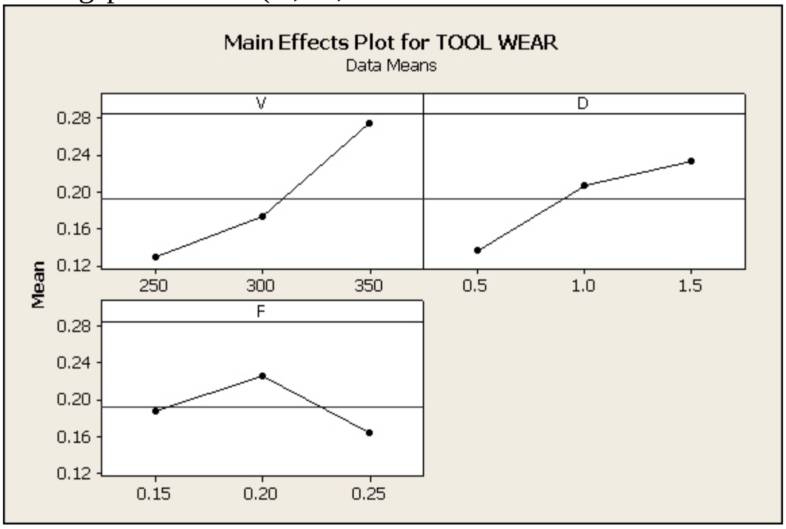


***Fig. 2. Main effects plot for tool wear***

Figure 2 shows the main effect plot for tool wear. The results show that with the increase in the cutting speed and depth of cut there is a continuous increase in tool wear value that means the tool wear is an increasing function of cutting speed and depth of cut. However, with the increase in feed there is an increase in tool wear up to 0.2 mm/rev. A feed 0.2 mm/rev produces a highest tool wear and 0.25 mm/rev show the lowest tool wear. Based on the analysis using Fig. 2, low tool wear was obtained at cutting speed (250 m/min), depth of cut (0.5 mm) and feed (0.25 mm/rev).

Figure 3 shows the main effect plot for workpiece surface roughness (Ra) for cutting speed, depth of cut and feed. The surface roughness appears to be an almost linear increasing function of cutting speed. This result contradicts with the common expectations that the surface roughness usually decreases with increasing cutting speed. As the increase in surface roughness with increased feed. According to this main effect plot, the conditions for good surface finish are: cutting speed at 250 m/min, feed at 0.20 mm/rev and depth of cut at 1.5 mm.

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 there is a continuous increase in material removal rate. The high value of cutting speed, depth of cut and feed give high value of material removal rate i.e. high production rate. It was observed that the maximum MRR is obtained at the cutting speed of 350 m/min, 1.5mm depth of cut and 0.25 mm/rev of feed.

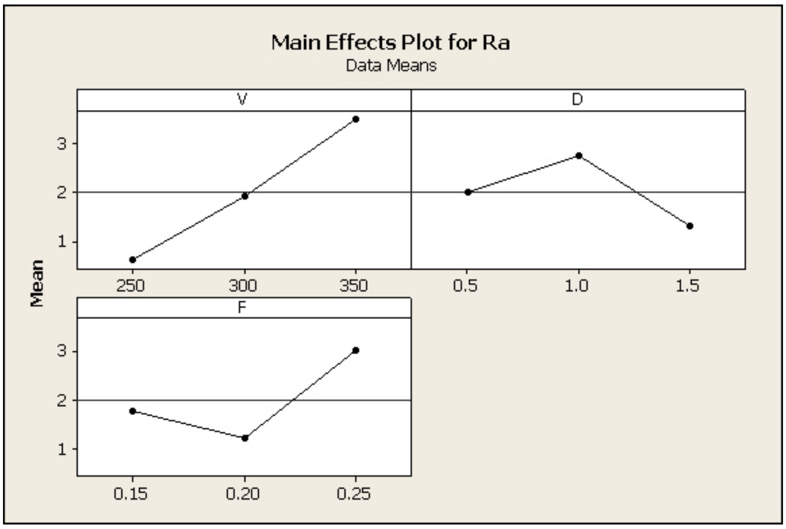


***Fig. 3. Main effect plot for surface roughness (Ra)***

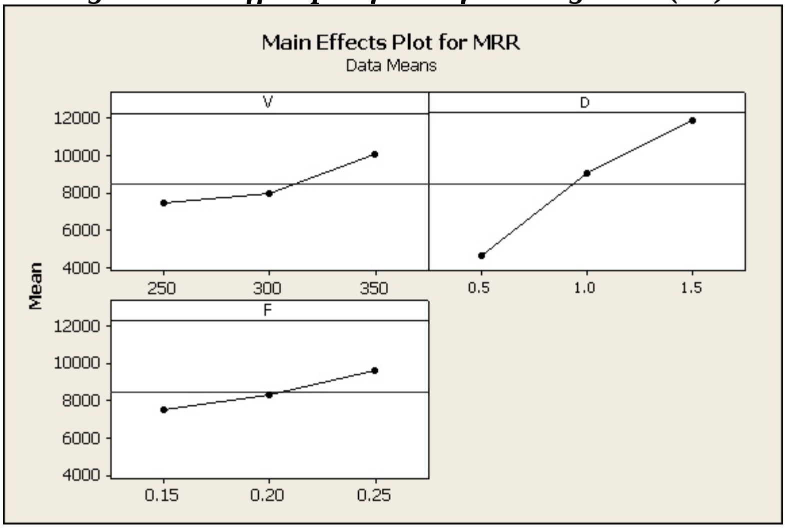


***Fig. 4. Main effect plot for material removal rate, MRR***

4.4 REGRESSION EQUATIONS

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

Tool wear (TW):

$$TW= -0.298+ 0.00147V+ 0.0963D -0.240F \quad (R=0.87) \ (1)$$

Surface roughness (Ra):

$$Ra= -8.42 + 0.0287V - 0.692D + 12.6F \quad (R=0.76) \ (2)$$

Material removal rate (MRR):

$$MRR= -10755 + 26V + 7238D + 20867F \quad (R=0.95) \ (3)$$

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, surface roughness 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 (Figures 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.

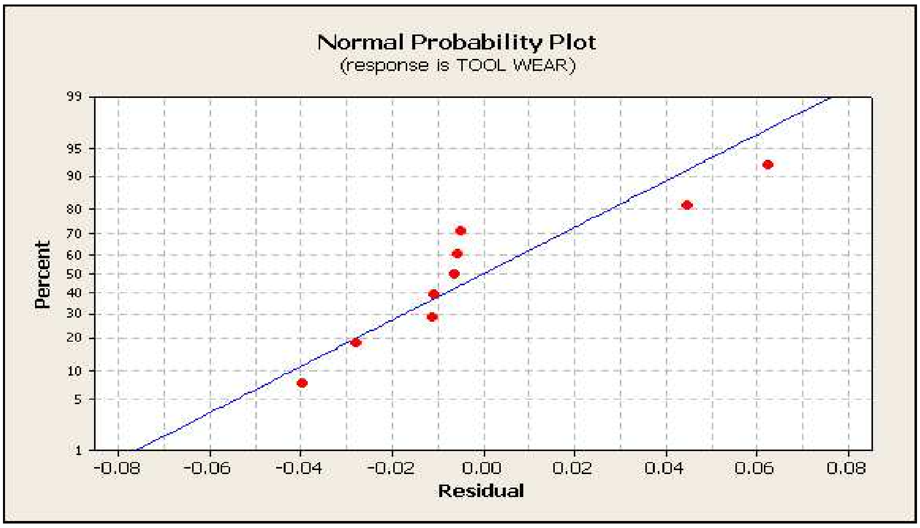


***Fig. 5. Normal probability plot of the residuals for tool wear***

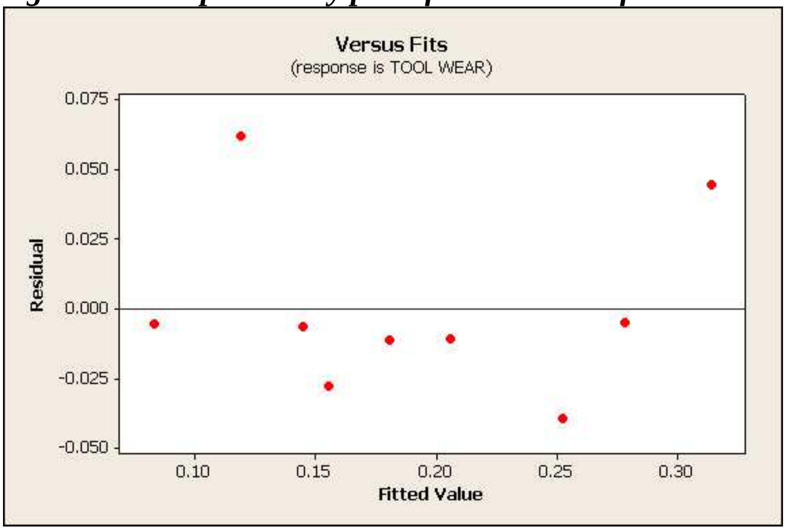


***Fig. 6. Residuals versus the fitted values for tool wear***

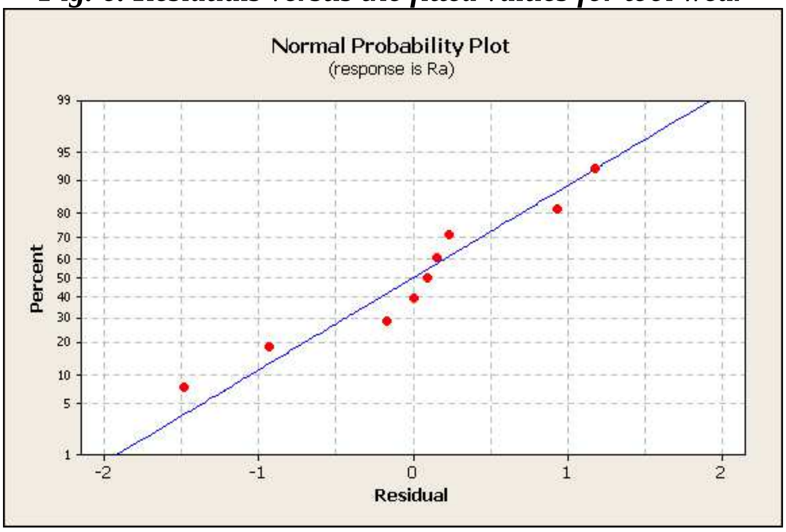


***Fig. 7. Normal probability plot of the residuals for surface roughness (Ra)***

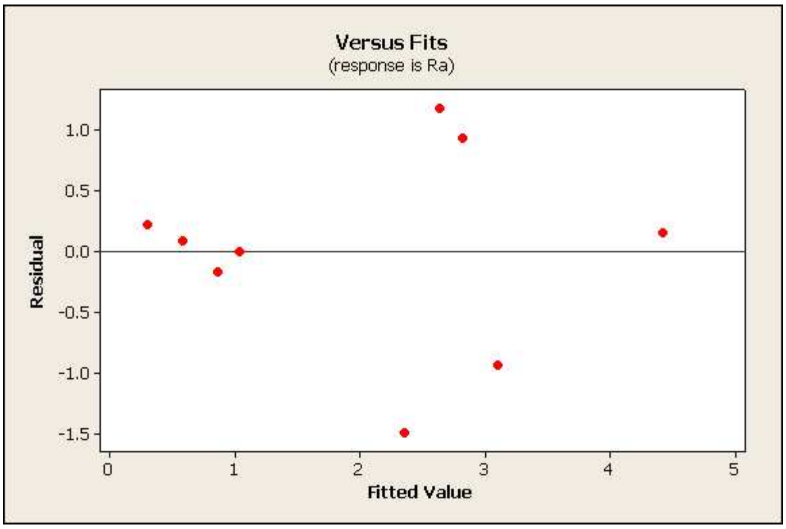


***Fig. 8. Residuals versus the fitted values for surface roughness (Ra)***

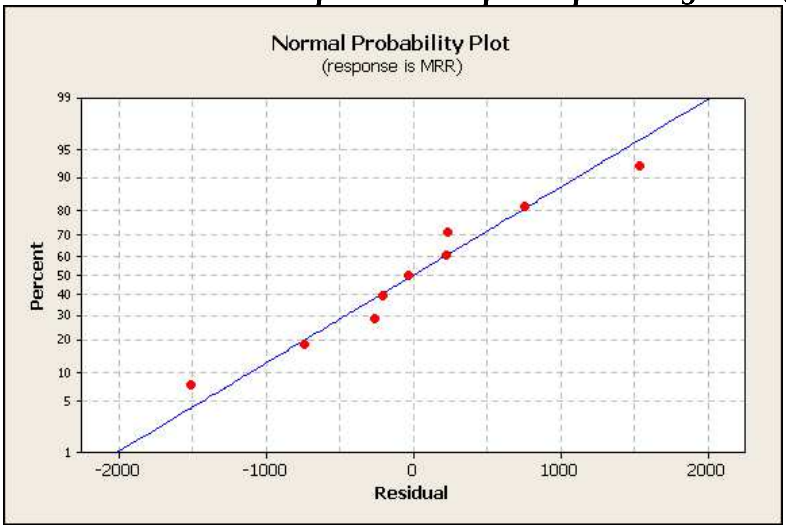


***Fig. 9. Normal probability plot of the residuals for material removal rate (MRR)***

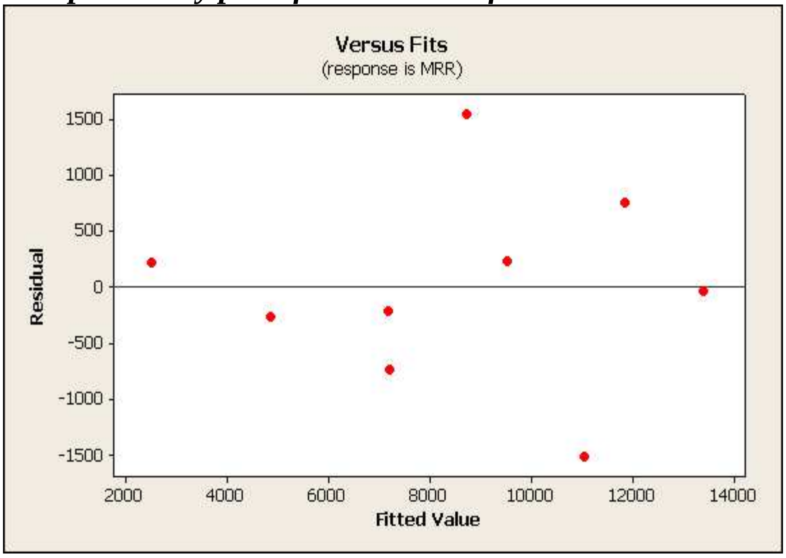


***Fig. 10. Residuals versus the fitted values for material removal rate (MRR)***

## 4. Conclusions

1. The study shows that Taguchi experimental design method is an effective way of determining the optimum cutting parameters to achieve less tool wear, good surface finish and maximum material removal rate by Taguchi parameter design process.

2. The tool wear is highly influenced by the cutting speed (61.17%) in a smaller degree, by depth of cut (26.76%) and smallest influencing by feed (10.61%). In order to minimize the tool wear, the low level of the cutting speed (250m/min), low level of depth of cut (0.5mm) and feed (0.25mm/rev) should be preferred.
3. The significant factors for the surface roughness were cutting speed and feed with contribution of 59.42% and 23.3% respectively. Although not statistically significant, the depth of cut has a physical influence explaining 15% of the total variation.
4. Depth of cut (78.8%) was only found the significant parameters followed by cutting speed (11.22%) 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 material removal rate is obtained at 350 m/min cutting speed, 1.5 mm depth of cut and 0.25 mm/rev feed.
5. The relationship between the cutting parameters and performance measures are expressed by multiple regression equation, which can be used to estimate the expressed values of the performance level for any parameters levels.

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