Experimental study and Analysis of Variance of Material Removal Rate in High Speed Turning of AISI 304L Alloy Steel

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Abstract- Material removal rate is one of the challenges encountered in the manufacturing process, due to the transformation of a raw solid material into desired shapes. This investigation involved studying the effects of the three variables (cutting speed, feed rate and depth of cut and their interaction) for material removal rate during turning of AISI 304L stainless steel with cemented carbide inserts cutting tool. Response surface methodology was employed in the experimental design and total number of 20 experiments runs were conducted using central composite design. The level of importance and performance characteristics of the machining parameters on MRR was determined by using analysis of variance (ANOVA). It was observed that the cutting speed had the most significant effects on the MRR (66.27%) followed by the depth of cut (21.55%), while feed rate (8.25%) had the least effect on MRR. The result also showed that the cutting speed and the depth of cut has good interactions during the turning operation.

Keywords: Turning operation; Material removal rate; Response surface methodology (RSM); Analysis of variance

1 Introduction

The reason for metal cutting process usually known as machining is to manufacture a preferred shape, dimension and finish of an element by eliminating the excess materials in the form of chips from raw chunk of work piece [1-3]. Today industry requires the production of less expensive and good quality products in short time [4-6]. The issue of Surface finishing, tool wear rate and material removal rate (MRR) are the major response parameters which attention is given to by most industries. Material removal rate is vital parameter that greatly influences production rate and cost [7-13]. Therefore, it is necessary to assess the MRR before the cutting process is started. MRR is a useful factor in the manufacturing, which will contribute to the minimization of cost of manufacturing and reduces the idle time to attain a preferred surface quality.

Ashish et al [1] studied surface roughness, tool wear and material removal rate in CNC turning of EN24 alloy steel and found out that the higher the machining rate the better surface finish are desirable for better performance of any machining process. In turning procedure, it is expected to have high metal removal rate in order to obtain optimum quality at reduced time and cost, the process of trying to remove this unwanted part of the work piece, it can lead to the damage of the cutting tool and the work piece as a result of vibration. Nwoke, et al., [14]; Okonkwo et al., [15] carried out studies on chatter vibration frequency on AISI 4340 alloy during turning operation. The result shows that there is need to reduce vibration in turning operation in order to have high material removal rate and good surface finishing.

Turning operation is one of the leading, highly proficient predictable machining procedures. Normally the work piece is rotating on a spindle and the cutting tool is fed into it radially, axially or both ways
concurrently to obtain the required shape or sides. Lawal, et al., [16] work on vegetable and mineral oil-in-water in turning operation of AISI 4340 alloy steel and found out that vegetable oil when applied in machining process reduces surface roughness, tool wear, vibration and increases the rate of metal removal. Authors agreed that vegetable oil will bring significant improvement on MRR and will also help during the investigation of the creep response on different materials [17-20].

Tejas et al. [21] work on the investigation and prediction of milling procedure on vertical milling machine by using RSM. The machining factors were examined to establish their importance on mild steel by carrying out experiments using response surface methodology to obtain material removal rate (MRR) and surface roughness (SR), while investigating the effects of spindle speed, depth of cut and feed on mild steel. The experimental results were evaluated using ANOVA and the importance of parameters upon performance measures was achieved. The results revealed that depth of cut and feed rate has superior effect on MRR.

Jaganjeet and Sanjeev [22] carried out an investigation on the effects of WEDM process factors for optima cutting quality for the machined components. In this work the effects of numerous process variables of WEDM, such as pulse on time, pulse off time, Servo voltage, peak current, Wire feed, and Wire tension, were study to know their influence on material removal rate of H13 Steel. And the instrument use for the surface roughness measurement is MarSurf PS1. Taguchi L18 Orthogonal Array was employed and the results of the testing were evaluated using MINITAB software. Material removal rate is very significant in machining process, because if not properly study it will affect the surface produce during the operation which can lead to high surface roughness, high wear rate of the cutting tools and the production output of the industry will be affected [23-30].

Moreover, the accomplishments of most researchers in related to the current study are recognized. Development in assessment, experimental examination of dry, wet and MQL in turning operation on material removal rate were reviewed. However, there is need to study MRR using ANOVA to determine the extent the cutting variables will have on the MRR and the interaction between the three variables has with the response parameters.

2 Material and Method

The work piece material used in this research study was AISI 304L stainless steel. It is a commonly used steel grade which has a minimum of 18% chromium and 8% nickel. Cemented carbide cutting tool was applied in the researcher, and Lactuca LT 3000 cutting fluid was also used.

This experiment was conducted using DOE via response surface methodology (RSM). Minitab 16 software was used to analyze the data obtained from the experiment. The selection of the factors values depended on the response investigating and the manufactural. RSM was used in the experimental plan, applying central composite design (CCD). By taking all the factorial angle points, some of the central duplicates and all the axial points, central composite design required between 20 to 23 experimental runs depending on the number of the central duplicates considered, the experimental plan entail of three parameters at three levels such as cutting speed, feed rate and depth of cut as shown in Table 1. The experimental analysis was carry out to assess the effect of cutting speed (N), feed rate (f) and depth of cut on the material removal rate (MRR), and a total number of twenty (20) experiment were run according to central composite design as shown in Table 2.

| Variables       | Unit | -1 | Matrix levels | +1 |
|-----------------|------|----|---------------|----|
| Cutting speed   | (rpm)| 600| 1200          | 1800|
Table 2: Design matrix of variables

| Runs | Cutting speed (rpm) | Feed rate (mm/rev) | Depth of cut (mm) |
|------|---------------------|-------------------|------------------|
| 1.   | 1200                | 0.25              | 0.6              |
| 2.   | 1200                | 0.165             | 0.6              |
| 3.   | 1200                | 0.25              | 0.6              |
| 4.   | 600                 | 0.3               | 0.4              |
| 5.   | 190.9               | 0.25              | 0.6              |
| 6.   | 1200                | 0.25              | 0.6              |
| 7.   | 600                 | 0.2               | 0.4              |
| 8.   | 1200                | 0.25              | 0.6              |
| 9.   | 1800                | 0.3               | 0.4              |
| 10.  | 600                 | 0.2               | 0.8              |
| 11.  | 600                 | 0.3               | 0.8              |
| 12.  | 1200                | 0.25              | 0.6              |
| 13.  | 1200                | 0.25              | 0.936            |
| 14.  | 2209                | 0.25              | 0.6              |
| 15.  | 1200                | 0.334             | 0.6              |
| 16.  | 1200                | 0.25              | 0.263            |
| 17.  | 1800                | 0.3               | 0.8              |
| 18.  | 1800                | 0.2               | 0.8              |
| 19.  | 1800                | 0.2               | 0.4              |
| 20.  | 1200                | 0.25              | 0.6              |

2.1 Experimental procedure for turning operation

The experimental analysis was carried out in CNC lathe machine and the specification are model SPT-32; Mas –Czech Republic having maximum cutting speed of 4000 rpm, rapid oblique of 15,000 mm/min, 28 KW motor drive, diameter of 490 mm, length of 1500 mm and cemented carbide cutting tool (CNMG 120408-PM) were employed in the turning operation. The experiment was carried out under flood cutting condition with Lactuca LT 3000 conventional cutting fluid.

The dimensions of work piece used were 40 x 750 mm. To achieve the material removal rate, the work piece diameter is measured before and after each experimental run. The results are then substituted into equation (1) and the material removal rate gotten for each experimental operation

\[
MRR = \frac{\pi}{4} \times (D_i^2 - D_f^2) \times F \times N \tag{1}
\]

Where \(D_i\) = Initial diameter, mm, \(D_f\) = final diameter, mm, \(f\) = Feed rate, mm/rev, \(N\)=Spindle speed, rpm [3].

3 Result and Discussion

The design matrix and the result from experiment with the three cutting variables such as cutting speed, feed rate and depth of cut are shown in Table 3 respectively.
### Table 3: Experimental results for the material removal rate

| Runs | Cutting speed (rpm) | Feed rate (mm/rev) | Depth of cut (mm) | D1 (mm) | D2 (mm) | MRR (mm³/min) |
|------|---------------------|--------------------|------------------|---------|---------|----------------|
| 1    | 600                 | 0.2                | 0.4              | 40      | 39.2    | 5971.54        |
| 2    | 1800                | 0.2                | 0.4              | 39.2    | 38.4    | 17552.71       |
| 3    | 600                 | 0.3                | 0.4              | 38.4    | 37.6    | 8595.39        |
| 4    | 1800                | 0.3                | 0.4              | 37.6    | 36.8    | 25243.33       |
| 5    | 600                 | 0.2                | 0.8              | 35.2    | 33.6    | 10857.34       |
| 6    | 1800                | 0.2                | 0.8              | 33.6    | 32      | 14838.37       |
| 7    | 600                 | 0.3                | 0.8              | 32      | 30.4    | 42343.64       |
| 8    | 1800                | 0.3                | 0.6              | 30.4    | 28.8    | 17530.08       |
| 9    | 190.92              | 0.25               | 0.6              | 40      | 38.8    | 3544.78        |
| 10   | 2209                | 0.25               | 0.6              | 38.8    | 37.6    | 39764.93       |
| 11   | 1200                | 0.25               | 0.6              | 37.6    | 36.4    | 13930.72       |
| 12   | 1200                | 0.3                | 0.6              | 36.4    | 35.2    | 26722.64       |
| 13   | 1200                | 0.25               | 0.263            | 35.2    | 34.6    | 8561.94        |
| 14   | 1200                | 0.25               | 0.936            | 34.6    | 33.8    | 29891.25       |
| 15   | 1200                | 0.25               | 0.6              | 33.8    | 33.0    | 18208.67       |
| 16   | 1200                | 0.25               | 0.6              | 33.0    | 31.6    | 17530.08       |
| 17   | 1200                | 0.25               | 0.6              | 31.6    | 30.4    | 22280.18       |
| 18   | 1200                | 0.25               | 0.6              | 30.4    | 29.6    | 21601.59       |
| 19   | 1200                | 0.25               | 0.6              | 29.6    | 28.8    | 209.23         |
| 20   | 1200                | 0.25               | 0.6              | 28.8    | 27.6    | 20211.42       |

### 3.1 Analysis of Variance for MRR

A response material removal system was designed and analyzed using Minitab 16 software. Table 4 and 5 show the Analysis of Variance (ANOVA) result used to analyzed the effect of cutting variables on the material removal rate and their interactions, lack-of-Fit and residual error on the MRR. Table 5 can also be used to predicted the MRR when the need arises.

### Table 4: The material removal rate ANOVA for AISI 304L Alloy Steel

| Source                                      | DF | Seq SS     | Adj SS     | Adj MS     | F     |
|---------------------------------------------|----|------------|------------|------------|-------|
| Regression                                  | 9  | 1189155910 | 1189155910 | 132128434  | 1.04  |
| Linear                                      | 3  | 146553375  | 146553375  | 48851125   | 0.38  |
| Cutting speed                               | 1  | 11491378   | 11491378   | 11491378   | 0.09  |
| Feed rate                                   | 1  | 99779069   | 99779069   | 99779069   | 0.79  |
| Depth of cut                                | 1  | 35282928   | 35282928   | 35282928   | 0.28  |
| Square                                      | 3  | 551593797  | 551593797  | 183864599  | 1.45  |
| Cutting speed*Cutting                       | 1  | 223385     | 2855184    | 2855184    | 0.02  |
| Feed rate*Feed rate                         | 1  | 98453745   | 60220465   | 60220465   | 0.47  |
| Depth of cut*Depth of cut                   | 1  | 452916667  | 452916667  | 452916667  | 3.57  |
| Interaction                                 | 3  | 491008737  | 491008737  | 163669579  | 1.29  |
| Cutting speed*Feed rate                     | 1  | 344910273  | 344910273  | 344910273  | 2.72  |
| Cutting speed*Depth of cut                  | 1  | 35048834   | 35048834   | 35048834   | 0.28  |
| Feed rate*Depth of cut                      | 1  | 111049630  | 111049630  | 111049630  | 0.88  |
| Residual Error                              | 10 | 1268939042 | 1268939042 | 1268939042 | 1.22  |
| Lack-of-Fit                                 | 5  | 698108363  | 698108363  | 698108363  | 1.22  |
| Pure Error                                  | 5  | 570830678  | 570830678  | 570830678  | 1.22  |
| Total                                       | 19 | 2458094951 | 2458094951 | 2458094951 | 1.22  |
Table 5: The Predictable regression coefficients for MRR using data in uncoded units

| Term                          | Coef         |
|-------------------------------|--------------|
| Constant                      | 14696.9      |
| Cutting speed                 | 69.6793      |
| Feed rate                     | -423798      |
| Depth of cut                  | 87932.5      |
| Cutting speed*Cutting speed   | 0.00123641   |
| Feed rate*Feed rate           | 817675       |
| Depth of cut*Depth of cut     | 140151       |
| Cutting speed*Feed rate       | 218.870      |
| Cutting speed*Depth of cut    | 17.4426      |
| Feed rate*Depth of cut        | 372575       |

Figure 1-4 showed the interaction and the effects of the three variables on the material removal rate, it can be seen that the most interactive parameters were cutting speed and depth of cut. From Table 4, the cutting speed was the most significant parameters follow by the depth of cut, this also means that at the increase of the cutting speed, the MRR increase and at increase of the feed rate the MRR decreases, why the depth of cut increases the MRR increases. This result is in line with the observation made by Jaganjeet and Sanjeev [22]. Therefore, with a good combination and interactions between the cutting speed and the depth of cut will lead to a more preferred material removal rate.

Figure 1: Interaction plot for MRR and the three cutting variables
Figure 2: Contour plot for MRR vs. cutting speed and feed rate while depth of cut is constant at 0.6mm.

Figure 3: Contour plot for MRR vs. cutting speed and depth of cut while feed rate is constant at 0.25 mm/rev.

Figure 4: Contour plot for MRR vs. feed rate and depth of cut while cutting speed is constant at 1200 rpm.
4. Conclusions

The material removal rate could be effectively predicted by using predictable regression coefficients for the uncoded factors such as: cutting speed, depth of cut, feed rate as the independent variables. In analyzing the individual parameters, it was found that cutting speed has the most significant effect on MRR with 66.27%, followed by depth of cut with 21.55% and feed rate has the least significant effect on MRR with 8.25%. In terms of interactions the cutting speed and the depth of cut has good level of interactions with each other than the combination of feed rate in other to achieve good process for the material removal rate.

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