Application of Taguchi Method for Optimizing Material Removal Rate in Turning of En-47 Spring Steel

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Abstract

En-47, chromium-vanadium steel, has wide applications in automobile industry particularly in making high duty volute and leaf spring, heavy engine valve spring, helical and torsional bar springs. Experiments have been conducted using L-18 orthogonal array standardised by Taguchi. Each experiment is replicated three times on a centre lathe by using new cutting carbide insert for each trial to ensure accurate results of the material removal rate. The statistical methods of signal to noise ratio (S/N) and analysis of variance(ANOVA) are applied to investigate the effects of four turning process parameters (nose radius, cutting speed, feed rate, depth of cut) on material removal rate. The Figure 2 reveals the optimal setting of process parameters for optimized value of MRR. The optimized value of MRR is 1.344 g/sec. Confirmation test with the optimal levels of cutting parameters shows that the optimized value of MRR falls within 95% confidence level. Analysis of variance (Table 6) shows that all the four selected process parameters are significant at 95% confidence level in affecting the response since their p-values are less than 0.05.

Keywords: Turning process, Taguchi technique, En47 steel, MRR.

1 Introduction

Today’s fast growing manufacturing industry needs the application of optimization techniques in metal cutting processes to effectively respond to severe competitiveness and to meet the increasing demand of customizable quality product (low cost, high quality) in the world market. Taguchi method is one of the most effective systems of off-line quality control where the quality is in-built at the product design stage instead of controlling it at the manufacturing stage or through the inspection of final products (Ross, 1996). In true quality sense, a customer usually considers several correlated quality attributes/characteristics of a product. Accordingly, variability of a product’s response has to be reduced and mean needs to be brought close to the target.

Metal cutting is one of the important and widely used manufacturing processes in engineering industries. The metal cutting studies focus on the features of tools, work material composition and mechanical properties and above all the machine parameter settings that influence the process efficiency and output quality characteristics/responses. A significant improvement in process efficiency can be obtained by process parameter optimization that identifies and determines the regions of critical process control factors leading to desired outputs or responses with acceptable variations ensuring a lower cost of manufacturing (Montgomery, 1997).

Taguchi’s ideology has been built upon Deming’s observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker (Park, 1996). Taguchi developed the robust manufacturing systems, insensitive to daily and seasonal variations of environment, machine and wear. His approach optimizes the performance characteristics through the settings of process parameters and reduces the sensitivity of the system performance to source of variation. Consequently the Taguchi method (Taguchi, 1990) has become a powerful tool in the design of experiment methods (Roy, 1990).

The performance of any machining process is evaluated in terms of machining rate and surface finish produced. Higher machining rate and better surface finish are desirable for better performance of any machining process. Comprehensive qualitative and quantitative analysis of the material removal mechanism and subsequently the development of analytical models of material removal are necessary for a better understanding and to achieve the optimum process parameters. In this regard, various analytical and some
semi-empirical/empirical material removal models (approx. 40) are studied for different mechanical type advanced machining processes (Jain et al., 2001).

Taguchi technique has been applied by Singh et al. (2005) to optimize process parameters for turning of En 24 steel with TiC coated carbide inserts. The same methodology had been used by Aggarwal et al. (2009) to find the optimal process parameters, i.e. cutting speed, feed rate, depth of cut, nose radius and cutting environment for feed and radial force in CNC turning operation based on experimental results done on P-20 tool steel using TiN coated tungsten carbide inserts. Further, design optimization was carried out by Yang et al. (1998) to find the best optimal process parameters in turning of S45C steel using tungsten carbide inserts with the help of orthogonal array and analysis of variance. Lalwani et al. (2008) investigated the effects of cutting parameters on cutting forces and surface roughness in finish hard turning of MDN 250 steel using coated ceramic tool.

Bartarya et al. (2012) in the study showed that the type of tool material, cutting edge geometry and cutting parameter (cutting speed, feed rate and depth of cut) have considerable effects on the process efficiencies in terms of tool forces, surface integrities and white layer. Also, adequate machine rigidity is essential to reduce the process inaccuracies. For finish hard turning, it was concluded that the forces deviate from the conventional trends as the radial force component is the maximum and axial force component becomes minimum in such cases, where the depth of cut is less than the nose radius of the tool. Suresh et al. (2012) found that abrasion was the principle wear mechanism observed at all the cutting conditions during hard turning of AISI 4340 steel using multilayer coated carbide tool. They concluded that machining power and cutting tool wear increase almost linearly with increase in cutting speed and feed rate. By increasing cutting speed in hard turning significantly increases the temperature at the contact zone, which results in drastic increase of the tool wear. The literature survey reveals that the machining of difficult to machine materials like EN-47 spring steel is relatively a less researched area.

The objective of this case study is to obtain optimal settings of turning process parameters (nose radius, cutting speed, feed rate and depth of cut) to yield optimal material removal rate (MRR) while machining En-47 chromium-vanadium spring steel with carbide inserts. Taguchi’s parameter design approach has been used to accomplish the objective.

2 Material

The work material selected for the study was En-47 spring steel. En-47 is high carbon alloy steel with good harden ability developed for the application in making crank shafts, steering knuckles, gears spindle and pumps. It can be used in high duty volute and leaf springs, heavy engine valve springs, helical and torsional bar springs. It is a tough oil quenching spring steel which when heat treated, offers good wear resistance.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>V</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>W %</td>
<td>0.45-0.55</td>
<td>0.50</td>
<td>0.5-0.8</td>
<td>0.8-1.20</td>
<td>0.15</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

3 Turning process parameters

In order to identify the process parameters that may affect the machining quality characteristics of turned parts, an Ishikawa cause-effect diagram was constructed as shown in Fig. 1. The following process parameters were selected for present work: nose radius (A), cutting speed (B), feed rate (C), and depth of cut (D).

The ranges of the selected turning process parameters (cutting speed, feed rate and depth of cut) were ascertained by conducting some preliminary experiments using one variable at a time approach. The following parameters were kept constant in the entire scheme of experiments:

- Work material: EN-47 spring steel
- Inserts geometry: CCMT 060204, 060208 (ISO designation)
- Cutting clearance angle: 0°
- Nose radius: 0.4 mm, 0.8 mm
- Insert thickness: 2 mm
- Cutting conditions: Dry

4 Selection of orthogonal array

Design of experiment (DOE) methodology was used to plan the experiment. Before finalizing a particular OA, the following two things must be established (a) the number of levels for the parameters of interest, (b) the number of parameters and their interaction of interest. In the present study four different process parameters have been selected as already discussed. The spindle speed, feed rate, and depth of cut have three levels and nose radius has two levels. The process parameters and their values are given in Table 2. In present case according to above two conditions mentioned L18
orthogonal array was selected for this study and is given in Table 3.

![Ishikawa cause-effect diagram of a turning process](image)

### Fig. 1—Ishikawa cause-effect diagram of a turning process

#### 5 Experimental analysis

En 47 spring steel rods of 27 mm diameter and 500 mm length were turned on a NH-22 centre lathe of H.M.T. The carbide inserts were used to machine En 47 steel. Three specimens for each trial condition were prepared using randomization technique.

**Table 2 process parameters with their values**

<table>
<thead>
<tr>
<th>factors</th>
<th>Process parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Nose radius (mm)</td>
<td>0.4</td>
<td>0.8</td>
<td>---</td>
</tr>
<tr>
<td>B</td>
<td>Cutting speed (m/min.)</td>
<td>46.65</td>
<td>78.88</td>
<td>102.63</td>
</tr>
<tr>
<td>C</td>
<td>Feed rate (mm/rev.)</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>D</td>
<td>Depth of cut (mm)</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The material removal rate is calculated by using the Eq. 1.

\[
MRR = \frac{\text{WEIGHT REMOVED IN GRAM}}{\text{TIME IN SECOND}} \text{g/sec.}
\]

\[
= \frac{W}{T}
\]

Where,

\[
W = \text{weight removal during turning of part} = (\text{initial weight} - \text{final weight}) \text{ of work piece}\]

\[
T = \text{time taken during turning of part}
\]

**Table 3 L\textsubscript{18} Orthogonal Array**

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

In this study, larger-the-better principle is considered to maximize material removal rate. The corresponding loss function is expressed as follow (Ross, 1988):

\[
(S/N)_{LB} = -10 \log \frac{1}{n} \sum \frac{1}{y^2}
\]

(2)

Where \(n\) is the number of observations and \(y\) is the observed data.

The S/N ratios were computed using Eq. 2 for each of the 18 trials and the values are reported in Table 4 along with the raw data value.
The mean response refers to the average value of the performance characteristics for each parameter at different levels. The average values of material removal rate for each parameter at different levels are calculated and plotted in Fig. 2. Also, the average values of S/N ratio of various parameters at different levels are also plotted in Fig. 3.

**Table 4 Experimental Data of Material Removal Rate**

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>Material Removal Rate (g/sec.)</th>
<th>R-1</th>
<th>R-2</th>
<th>R-3</th>
<th>S/N (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.096</td>
<td>0.094</td>
<td>0.091</td>
<td>-20.574</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.423</td>
<td>0.429</td>
<td>0.437</td>
<td>-7.339</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.015</td>
<td>1.018</td>
<td>1.012</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.345</td>
<td>0.351</td>
<td>0.368</td>
<td>-9.013</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.773</td>
<td>0.776</td>
<td>0.767</td>
<td>-2.248</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.298</td>
<td>1.289</td>
<td>1.292</td>
<td>2.231</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.427</td>
<td>0.441</td>
<td>0.435</td>
<td>-7.245</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.758</td>
<td>0.749</td>
<td>0.755</td>
<td>-2.452</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.712</td>
<td>0.714</td>
<td>0.719</td>
<td>-2.914</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.582</td>
<td>0.587</td>
<td>0.578</td>
<td>-4.697</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.389</td>
<td>0.379</td>
<td>0.384</td>
<td>-8.314</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.762</td>
<td>0.765</td>
<td>0.758</td>
<td>-2.364</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.692</td>
<td>0.695</td>
<td>0.687</td>
<td>-3.206</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.112</td>
<td>1.104</td>
<td>1.114</td>
<td>0.906</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.856</td>
<td>0.861</td>
<td>0.847</td>
<td>-1.364</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.738</td>
<td>0.734</td>
<td>0.744</td>
<td>-2.631</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.684</td>
<td>0.692</td>
<td>0.687</td>
<td>-3.252</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.981</td>
<td>0.987</td>
<td>0.976</td>
<td>-0.163</td>
<td></td>
</tr>
</tbody>
</table>

It is evident from the Fig. 2 that material removal rate is maximum at third level of feed rate and depth of cut. Also it can be seen that moderate cutting speed gives higher material removal rate. As we increase the nose radius, the rate of increase of material removal rate will occur. Thus second level of nose radius, second level of cutting speed, third level of feed rate and third level of depth of cut represent the optimal levels of various turning process parameters to yield maximum material removal rate. The S/N ratio analysis (Fig. 3) also suggests the same levels of the parameters ($A_2$, $B_2$, $C_3$, $D_3$) as the best levels for maximizing material removal rate of En 47 steel turned parts.

In order to quantify the influence of process parameters on the material removal rate, analysis of variance (ANOVA) was performed. The ANOVA of the raw data and S/N data (material removal rate) is given in Table 6 and 7. All the factors are significant in both.
6 Estimation of Optimum Values of MRR.

The optimal material removal rate is predicted at the selected optimal setting of process parameters. The significant parameters with optimal levels for material removal rate are $A_2$, $B_2$, $C_3$, $D_3$.

The estimated mean of the response characteristic can be computed for material removal rate as (Ross, 1988):

$$\mu_{MRR} = \bar{A}_2 + \bar{B}_2 + \bar{C}_3 + \bar{D}_3 - 3\bar{T}_{MRR}(3)$$

Where

$\bar{T}_{MRR} = \text{overall mean of material removal rate}$

$= 0.7029 \text{ g/sec.}$

$\bar{A}_2 = \text{average value of MRR at the second level of nose radius in g/sec.} = 0.7546 \text{ (Table 5)}$

$\bar{B}_2 = \text{average value of MRR at the second level of spindle speed in g/sec.} = 0.8459 \text{ (Table 5)}$

$\bar{C}_3 = \text{average value of MRR at the third level of feed rate in g/sec.} = 0.9368 \text{ (Table 5)}$

$\bar{D}_3 = \text{average value of MRR at the third level of depth of cut in g/sec.} = 0.9155 \text{ (Table 5)}$

Substituting the values of various terms in the above Eq. 3.

$$\mu_{MRR} = 0.7546 + 0.8459 + 0.9368 + 0.9155 - 3 \times (0.7029)$$

Hence, $\mu_{MRR} = 1.344 \text{ g/sec.}$

The 95% confidence intervals of confirmation experiment (CI$_{CE}$) and population (CI$_{POP}$) are calculated by using the following equations:

$$\text{CI}_{CE} = \sqrt{F_{\alpha}(1, fe)Ve\left[\frac{1}{N_{eff}} + \frac{3}{R}\right]}$$

(4)

$$\text{CI}_{POP} = \sqrt{F_{\alpha}(1, fe)Ve\left[\frac{1}{N_{eff}}\right]}$$

(5)

Where $F_{\alpha}(1, fe) = F$ ratio at the confidence level of $(1 - \alpha)$ against DOF 1 and error degree of freedom fe.

$$N_{eff} = \text{effective no. of replication}$$

$$= N \times \left[1 + \frac{\text{Total DOF associated in the estimate of mean}}{N}\right]$$

$R = \text{number of repetitions for confirmation experiment}$

$= 3$
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N = total number of experiments = 18 × 3 = 54

\[ V_e = \text{Error variance} = 0.00325 \] (Table 6)

\[ f_e = \text{error DOF} = 46 \] (Table 6)

\[ F_{0.05};1, 46 = 4.0157 \] (Tabulated F value; Roy, 1990)

So, \[ CI_{CE} = \pm 0.0792 \]

\[ CI_{POP} = \pm 0.0439 \]

Therefore, the predicted confidence interval for confirmation experiments is:

\[ [\mu_{MRR} - CI_{CE}] < \mu_{MRR} (g/sec.) < [\mu_{MRR} + CI_{CE}] \]

\[ 1.2648 < \mu_{MRR} (g/sec.) < 1.4232 \]

The 95% confidence interval of the population is:

\[ [\mu_{MRR} - CI_{POP}] < \mu_{MRR} (g/sec.) < [\mu_{MRR} + CI_{POP}] \]

\[ 1.3001 < \mu_{MRR} (g/sec.) < 1.3879 \]

7 Confirmation Experiments

Three confirmation experiments were conducted at the optimal setting of turning process parameters recommended by the investigation. The average value of material removal rate was found to be 1.358 g/sec. this result was within the limit for both CI_{CE} and CI_{POP} of the predicted optimal material removal rate.

8 Conclusions

1. The order of significance for affecting the material removal rate is: feed rate, depth of cut, cutting speed and nose radius.

2. The optimal settings of various process parameters for turned parts to yield optimal material removal rate are: nose radius = 0.8 mm, cutting speed = 78.88 m/min., feed rate = 0.2 mm/rev. and depth of cut = 0.8 mm.

3. The predicted optimal range (95% CI_{CE}) of the material removal rate is:

\[ CI_{CE}: 1.2648 < \mu_{MRR} (g/sec.) < 1.4232 \]

4. The predicted optimal range for the population (CI_{POP}) for material removal rate is:

\[ CI_{POP}: 1.3001 < \mu_{MRR} (g/sec.) < 1.3879 \]

References


