OPTIMIZATION OF MACHINING PARAMETERS IN FACE MILLING USING MULTI-OBJECTIVE TAGUCHI TECHNIQUE

Yusuf FEDAI, Funda KAHRAMAN, Hedie KIRLI AKIN, Gokhan BASAR

Abstract: In this research, the effect of machining parameters on the various surface roughness characteristics (arithmetic average roughness (Ra), root mean square average roughness (Rq) and average maximum height of the profile (Rz)) in the milling of AISI 4140 steel were experimentally investigated. Depth of cut, feed rate, cutting speed and the number of insert were considered as control factors; Ra, Rz and Rq were considered as response factors. Experiments were designed considering Taguchi L9 orthogonal array. Multi signal-to-noise ratio was calculated for the response variables simultaneously. Analysis of variance was conducted to detect the significance of control factors on responses. Moreover, the percent contributions of the control factors on the surface roughness were obtained to be the number of insert (71.89 %), feed (19.74 %), cutting speed (5.08 %) and depth of cut (3.29 %). Minimum surface roughness values for Ra, Rz and Rq were obtained at 325 m/min cutting speed, 0.08 mm/rev feed rate, 1 number of insert and 1 mm depth of cut by using multi-objective Taguchi technique.

Keywords: milling; optimization; surface roughness; Taguchi

1 INTRODUCTION

Machining processes like turning, milling, drilling and grinding, etc., have been commonly used in the manufacturing industries. Milling is one of the basic machining processes using rotary tools to remove material from a workpiece by feeding the tools into the workpiece at a certain direction [1]. Milling is a system consisting of a workpiece, cutting tool, machine tool, fixture and cutting parameters. The machinability of a material is defined by measuring factors such as tool life, cutting force and surface roughness. Surface roughness is a commonly encountered problem in machined surfaces. The quality of the surface plays a very important role in the performance of the milling as a milled surface of good quality significantly improves fatigue strength, corrosion resistance or creep life. Surface roughness is determined using Ra, Rz and Rq measurements [2, 3].


In this study, the effect of machining parameters on the various surface roughness characteristics; Ra, Rq and Rz in the milling of AISI 4140 steel with TiAlN+TiN, PVD-coated, R 390-11 T308M-PM 1030 solid carbide insert were experimentally investigated. Optimal machining parameters were determined using multi-objective Taguchi technique and a confirmation experiment was conducted to test the success of the optimization.

2 MATERIALS AND METHODS

Experiments were conducted in dry cutting conditions by using a SPINNER MVC1000 model CNC milling machine. The workpiece material used was AISI 4140 steel in the form of a 260 × 150 × 25 mm block. The chemical composition and mechanical properties of AISI 4140 steel
are given in Table 1. R 390-020B20-11M tool holder and a TiAlN+TiN, PVD-coated, R 390-11 T308M-PM 1030 solid carbide insert were used. The experimental set up is displayed in Fig. 1. The surface roughness characteristics; Ra, Rz and Rq values of workpieces were measured by MITUTOYO SJ-400 transportable surface roughness tester. The cut off length and evaluation length were constant at 0.8 mm and 4 mm respectively. Surface roughness measurements were made three times on the surfaces of workpieces, and their average roughness parameters were determined. Experiments were conducted according to the Taguchi L9 orthogonal design matrix and the results were evaluated using Minitab 17 software.

Table 1 The chemical compositions and mechanical properties of AISI 4140 workpiece material

<table>
<thead>
<tr>
<th>Chemical compositions (wt.%)</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.378</td>
<td>0.223</td>
<td>0.688</td>
<td>0.015</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>Cr</td>
<td>0.018</td>
<td>0.970</td>
<td>0.199</td>
<td>0.032</td>
<td>0.010</td>
<td>0.009</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>655</td>
<td>415</td>
<td>25.70</td>
<td>197</td>
<td>190-210</td>
<td>0.27-0.30</td>
</tr>
<tr>
<td>Yield strength</td>
<td>415</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>25.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brinell Hardness</td>
<td>197</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL RESULTS AND DISCUSSION

Taguchi technique has been widely used in engineering analysis. This technique exhibits a systematic way that is simple and effective in order to optimize designs for cost, performance and quality [18, 19]. Although the traditional Taguchi technique is successfully applied in the optimization of single response problems, it is not used to solve multi-response problems [20, 21].

Multi-objective Taguchi method was proposed by Tong et al. [22] and Anthony [23]. This method transforms multiple responses to single response by simply adding normalized quality loss values for analyzing multiple quality characteristics together. Fig. 2 demonstrates the flow chart for the multi-objective optimization.

In this study, depth of cut (mm), feed rate (mm/rev), cutting speed (m/min) and number of insert (pieces) were chosen as input parameters; the surface roughness characteristics Ra (µm), Rq (µm) and Rz (µm) were chosen as output parameters. Specified parameters and their levels are given in Tab. 2. Taguchi L9 orthogonal array and experimental results were given in Tab. 3.

Table 2 Control factors and their levels

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Factor</th>
<th>Unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>doc</td>
<td>mm</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>B</td>
<td>f</td>
<td>mm/rev</td>
<td>0.08</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>C</td>
<td>V</td>
<td>mm/min</td>
<td>175</td>
<td>250</td>
<td>325</td>
</tr>
<tr>
<td>D</td>
<td>N</td>
<td>(pieces)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Evaluation of data analysis:

Multiple responses are transformed to single response using the Taguchi quality loss function. This optimization procedure is given below and explained.

1. Compute the quality loss \( L_{ij} \)

Quality loss can be classified into three categories: “larger-is-better”, “smaller-is-better” and “normal-is-better”. In this study, the “smaller-is-better” category was selected for obtaining optimum machining parameters. Quality loss values for these responses were calculated using Eq. (1) and shown in Tab. 4.

\[
L_{ij} = \frac{1}{n_i} \sum_{k=1}^{n_i} y_{ijk}^2
\]  

where \( n_i \) is the number of experiment repetition for the \( i^{th} \) response, \( y_{ijk} \) is the observed value for the \( i^{th} \) response in the \( k^{th} \) repetition of the \( i^{th} \) experiment and \( L_{ij} \) is the loss function of the \( i^{th} \) response in the \( j^{th} \) experiment.
2. Establish the multi S/N ratio (MSNR):

Step 1: Calculation of Normalized Quality Loss

\[ C_{ij} = \frac{L_{ij}}{L_i} \]

\[ L_i^* = \max \{ L_{i1}, L_{i2}, ..., L_{ij} \} \]

where \( C_{ij} \) is the Normalized Quality Loss, \( L_{ij} \) is the quality loss and \( L_i^* \) is the maximum quality loss among the experimental runs. Normalized quality loss values for these responses were computed by using Eq. (2) and summarized in Tab. 5.

Step 2: Calculation of Total Normalized Quality Loss

\[ TNQL_j = \sum_{i=1}^{m} w_i C_{ij} \]

where \( TNQL_j \) is Total Normalized Quality Loss, \( w_i \) is the weight of \( i^{th} \) a normalized response (\( i = 1, 2, ..., m \)). \( m \) is the number of response factors.

Step 3: Determine the multi S/N ratio (MSNR)

\[ MSNR_j = -10 \log(TNQL_j) \]

\( TNQL_j \) values have been determined by using Eq. 3. Then for each response, a weight \( (w_i) \) was assigned, to indicate its importance relative to other responses. In this case each response has a different importance and weight. Weighting factors have been selected as \( w_1 = 0.333, w_2 = 0.333, w_3 = 0.333 \) for surface roughness. Multi signal-to-noise ratio (MSNR) was calculated by using Eq. 4. \( TNQL_j \) and \( MSNR_j \) values were given in Tab. 6.

3. Determine the optimal factor/level combinations

The effect of the control factors on the MSNR was obtained from Tab. 7. For the surface roughness parameters \( Ra, Rz \) and \( Rq \), the MSNR graphs of the control factors are shown in Fig. 3. The best factor / level combination was identified as \( A_2B_1C_3D_1 \). The optimum levels of different control factors minimum surface roughness are \( A \) at level 2
(1 mm) and B at level 1 (0.08 mm/rev), C at level 3 (325 m/min), D at level 1 (1).

where \( \eta_{opt} \) is the predicted MSNR, \( \eta_m \) is the overall average of the MSNR, \( \eta_{mi} \) is the average MSNR at the optimal level, and \( p \) is the number of the input factors that significantly influence the quality characteristic.

4. Variance analysis (ANOVA)

ANOVA was performed to calculate the effective factors on the surface roughness results and the contribution of these factors in the milling process (Tab. 8). From the ANOVA chart, the surface roughness parameters \( Ra \), \( Rz \) and \( Rq \) appear to be the most important factor in the feed rate. The effect of the factors as a percentage is examined, it is seen that the effect of number of insert is 71.89%, the effect of feed rate is 19.74%, the effect of cutting speed is 5.08%, and the effect of the depth of cut is 3.29%.

The final step of the optimization process is to test the condition giving the optimal values to verify that the proposed improvement has been met. Verification test results are given in Tab. 9. In this work, the optimum result \( \eta_{opt} \) is calculated.

\[
\eta_{opt} = \eta_m + \frac{\sum_{i=1}^{p} (\eta_{mi} - \eta_m)}{p}
\]  

5. Confirmation experiment

The results show that the number of insert was found to be the number of insert.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Degree of freedom (DOF)</th>
<th>Sum of squares (SS)</th>
<th>Mean square (MS)</th>
<th>Percent contribution (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( doc )</td>
<td>2</td>
<td>8.150</td>
<td>4.075</td>
<td>3.29</td>
</tr>
<tr>
<td>( f )</td>
<td>2</td>
<td>48.964</td>
<td>24.482</td>
<td>19.74</td>
</tr>
<tr>
<td>( f )</td>
<td>2</td>
<td>12.007</td>
<td>6.003</td>
<td>5.08</td>
</tr>
<tr>
<td>( N )</td>
<td>2</td>
<td>178.300</td>
<td>89.150</td>
<td>71.89</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>248.020</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

It is seen that an improvement of 10.246 dB in the MSNR when the optimal process parameter \( (A_2B_1C_3D_1) \) is used instead of the random parameter \( (A_2B_1C_2D_3) \). The results obtained from the confirmation experiments reflect the success of the multi-response optimization.

4 CONCLUSIONS

This study presented multi objective Taguchi technique to optimize performance parameters of AISI 4140 steel. The multiple quality characteristics were considered simultaneously using Taguchi quality loss function. The findings of the investigation are summarized as follows:

- The optimal levels of the machining parameters for minimum surface roughness for \( Ra \), \( Rz \) and \( Rq \) values were obtained to be 325 m/min cutting speed, 0.08 mm/rev feed rate, 1 mm depth of cut and 1 number of insert.
- \( Ra \), \( Rz \) and \( Rq \) have been decreased down to 0.117 µm, 0.933 µm and 0.143 µm, respectively against the random values of \( Ra \), \( Rz \) and \( Rq \) of 0.479 µm, 2.400 µm and 0.583 µm, respectively.
- The percent contribution of the control factors on the multiple quality characteristics was obtained to be number of insert (71.89%), feed rate (19.74%), cutting speed (5.08%), and depth of cut (3.29%) with ANOVA. The results show that the number of insert was found to be the significant factor among process parameters. The confirmation test conducted to determine optimal combination of machining parameters of AISI 4140 steel.
- Confirmation test results show that the increase of the MSNR ratio from the random input parameters to the optimal performance parameter was obtained to be 10.246 dB. These results show that the multi response optimization technique by using a Taguchi quality loss function can significantly improve the quality performance characteristics of the milling process.

5 REFERENCES


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