CHAPTER 5
SENSITIVITY ANALYSIS

5.1 INTRODUCTION

The impact of input parameters on tool flank wear and surface roughness of the workpiece were evaluated by using Response Surface Methodology (RSM) and Back Propagation Neural Network (BPNN) models discussed in the previous chapter. In this research, sensitivity analysis was performed and compared to the relative impact of input parameters on tool flank wear and surface roughness. This type of analysis enables a measurement of the accuracy of the important machining parameters and helps to determine those input parameters exerting the most influence on the model outputs.

5.2 ANALYSIS OF FLANK WEAR

The equation (5.1) has been used to predict the percentage deviation of the calculated flank wear and the fitness and closeness of the model has been predicted to compare with the experimental value.

\[ \lambda = \frac{R_c - R_E}{R_E} \]  \hspace{1cm} (5.1)

where \( \lambda \) = percentage error
\( R_c \) = calculated results
\( R_E \) = experimental results.
The percentage of errors is grouped into five categories.

- below 0%
- 0-0.999 %
- 1-1.999 %
- 2.0 – 2.999 %
- above 3 %.

The results of this analysis for the flank wear were presented in Figure 5.1. The model proposed for flank wear yields acceptable results. The calculated results predict the experimental/measured values with consistent accuracy. The below 0 % error shows that the experimental value of flank wear was higher than calculated values. The Figure 5.1 presents that in 8 samples the percentage of error was below 0 %, those experimental values were higher than calculated value of flank wear.

![Flank wear accuracy analysis graph]

**Figure 5.1** Accuracy analysis of the mathematical model for flank wear
5.2.1 Sensitivity analysis of flank wear

Sensitivity analysis is a method to identify critical parameters and rank them by their order of importance, and compare the calculated output with the experimental data. The qualitative and quantitative effectiveness of process parameters have been measured using sensitive analysis. The sensitivity equations are obtained by differentiating the wear model with respect to the factors of cutting speed, feed rate and depth of cut. To obtain the equation for cutting speed, feed rate and depth of cut, the flank wear model given in equation (4.6) in chapter 4 is differentiated with respect to cutting speed, feed rate and depth of cut.

The equations (5.2), (5.3) and (5.4) represent the sensitivity of wear for cutting speed, feed rate and depth of cut respectively.

\[
\frac{dW}{dV} = 0.039 + 0.022V - 0.029F + 0.006T + 0.005Fr \quad (5.2)
\]

\[
\frac{dW}{dF} = 0.048 + 0.006F - 0.029V + 0.016T - 0.001Fr \quad (5.3)
\]

\[
\frac{dW}{dT} = -0.051 + 0.012T + 0.006V + 0.016F - 0.004Fr \quad (5.4)
\]

The investigation has shown the effectiveness of the factors by using the direct sensitivity analysis technique on the predictive equation. Results of wear on sensitivities for cutting speed, feed rate and depth of cut are shown in Table 5.1.
Table 5.1 Sensitivity analysis of flank wear

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Cutting speed, V m/min</th>
<th>Feed rate, F mm/rev</th>
<th>Depth of cut, T, mm</th>
<th>Calculated flank wear, mm</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>dW/dV</td>
</tr>
<tr>
<td>1</td>
<td>170</td>
<td>0.110</td>
<td>2.0</td>
<td>0.202</td>
<td>0.076</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.231</td>
<td>0.087</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>0.220</td>
<td>2.0</td>
<td>0.266</td>
<td>0.098</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>0.159</td>
<td>2.0</td>
<td>0.195</td>
<td>0.025</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.231</td>
<td>0.047</td>
</tr>
<tr>
<td>6</td>
<td>264</td>
<td>0.159</td>
<td>2.0</td>
<td>0.289</td>
<td>0.069</td>
</tr>
<tr>
<td>7</td>
<td>170</td>
<td>0.159</td>
<td>1.5</td>
<td>0.228</td>
<td>0.041</td>
</tr>
<tr>
<td>8</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.231</td>
<td>0.047</td>
</tr>
<tr>
<td>9</td>
<td>170</td>
<td>0.159</td>
<td>2.5</td>
<td>0.246</td>
<td>0.053</td>
</tr>
</tbody>
</table>

5.2.2 Results and discussions

The sensitivity analysis results are given in Table 5.1 by varying one variable at a time and keeping the remaining two variables at the middle level. The sensitivity of tool flank wear is then measured. The positive values of sensitivity indicate an increase in response with an increasing value of the input variables.

The negative values of sensitivity predict a decrease in response with an increasing value of the input variables. The sensitivity of the cutting speed has a greater impact on wear due to an increase in feed rate as shown in Figure 5.2. The sensitivity of feed rate increased at higher feed rate as shown in Figure 5.3. If the feed rate is increased as shown in Figure 5.4 the sensitivity of depth of cut increases.
Figure 5.2  Sensitivity analysis results of cutting speed (V) on flank wear at V = 170 m/min and T = 2.0 mm

Figure 5.3  Sensitivity analysis results of feed rate (F) on flank wear at V = 170 m/min and T = 2.0 mm
Figure 5.4  Sensitivity analysis results of depth of cut (T) on flank wear at V = 170 m/min and T = 2.0 mm

The Figure A1.10, it is observed that the sensitivity of feed rate on wear has a greater impact at higher depth of cut with constant cutting speed and feed rate. The Figure 5.5 indicates that the comparisons of the sensitivity of flank wear of the three input parameters cutting speed, feed rate and depth of cut. Based on the plot, the cutting speed is more sensitive than depth of cut. If the cutting speed increased the sensitivity of feed rate decreases.
Figure 5.5 Sensitivity analysis of flank wear

The variation of depth of cut causes small changes in flank wear and change of cutting speed affects the flank wear. It is concluded that sensitivity of cutting speed is much higher than that of depth of cut. The change of cutting speed and feed rate are more useful to control the flank wear.

5.3 ANALYSIS OF SURFACE ROUGHNESS

The percentage deviation of the proposed surface roughness model has been compared with the actual values. The percentage of errors is grouped into four categories.

- below 0 %,
- 0-0.999 %,
- 1-1.999 % and
- above 2 %.
The results of this analysis for the surface roughness are presented in Figure 5.6. During the analysis of the results, it was observed that the model proposed for the surface roughness yields acceptable results. The conclusion from the results of this analysis for the experimental runs is that the calculated results can predict the experimental measured values with consistent accuracy. The Figure 5.6 shows that in 15 samples the percentage of error was below 0%, those experimental values were lesser than calculated value of surface roughness.

![Graph showing error analysis](image)

**Figure 5.6  Accuracy analysis of the mathematical model for surface roughness**

### 5.3.1 Sensitivity analysis of surface roughness

The sensitivity equations are obtained by differentiating the surface roughness model with respect to the factors of cutting speed, feed rate and depth of cut and nose radius. To obtain the equation for cutting speed, feed rate, depth of cut and nose radius, the surface roughness model given in equation (4.9) in chapter 4 is differentiated with respect to cutting speed, feed rate, depth of cut and nose radius.
The sensitivity equations (5.5) to (5.8) represent the sensitivity of surface roughness for cutting speed, feed rate and depth of cut and nose radius respectively.

\[
\frac{dRa}{dV} = -1.994 + 0.392V + 0.057F + 0.354T - 0.050R \tag{5.5}
\]

\[
\frac{dRa}{dF} = 0.224 - 0.066F + 0.057V - 0.209T + 0.402R \tag{5.6}
\]

\[
\frac{dRa}{dT} = -0.0663 - 0.098T + 0.354V - 0.209F + 0.256R \tag{5.7}
\]

\[
\frac{dRa}{dR} = -1.515 + 0.052R - 0.050V + 0.402F + 0.256T \tag{5.8}
\]

This investigation shows the effectiveness of the factors by using the direct sensitivity analysis technique on the predictive equation for obtaining surface roughness. The results of surface roughness on sensitivities for cutting speed, feed rate, depth of cut and nose radius are shown in Table 5.2.
Table 5.2  Sensitivity analysis of surface roughness

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Cutting speed, V m/min</th>
<th>Feed rate, F mm/rev</th>
<th>Depth of cut, T mm</th>
<th>Nose radius, mm</th>
<th>Calculated value of surface roughness, microns</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>dRa/dV</td>
</tr>
<tr>
<td>1</td>
<td>170</td>
<td>0.110</td>
<td>2.0</td>
<td>0.75</td>
<td>3.194</td>
<td>-0.545</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>3.819</td>
<td>-0.488</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>0.220</td>
<td>2.0</td>
<td>0.75</td>
<td>4.378</td>
<td>-0.431</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>4.503</td>
<td>0.880</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>3.819</td>
<td>0.488</td>
</tr>
<tr>
<td>6</td>
<td>264</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>3.527</td>
<td>-0.096</td>
</tr>
<tr>
<td>7</td>
<td>170</td>
<td>0.159</td>
<td>1.5</td>
<td>0.75</td>
<td>3.827</td>
<td>-0.842</td>
</tr>
<tr>
<td>8</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>3.819</td>
<td>-0.488</td>
</tr>
<tr>
<td>9</td>
<td>170</td>
<td>0.159</td>
<td>2.5</td>
<td>0.75</td>
<td>3.713</td>
<td>-0.134</td>
</tr>
<tr>
<td>10</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.5</td>
<td>4.04</td>
<td>-0.438</td>
</tr>
<tr>
<td>11</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>0.75</td>
<td>3.819</td>
<td>-0.488</td>
</tr>
<tr>
<td>12</td>
<td>170</td>
<td>0.159</td>
<td>2.0</td>
<td>1.0</td>
<td>3.650</td>
<td>-0.538</td>
</tr>
</tbody>
</table>
5.3.2 Results and discussions

The sensitivity results obtained by varying one variable at a time and keeping remaining two variables in the middle level are given in Table 5.2. The positive values of sensitivity indicate an increase in response with an increasing value of the input variables. The negative values of sensitivity predict a decrease in response with an increasing value of the input variables. The Figure 5.7 shows that for low feed rate the sensitivity on surface roughness is less, yielding good surface finish.

![Sensitivity analysis results of cutting speed (V) on surface roughness at V =170 m/min, T = 2.0 mm and R = 0.75 mm](image)

**Figure 5.7** Sensitivity analysis results of cutting speed (V) on surface roughness at V =170 m/min, T = 2.0 mm and R = 0.75 mm

The Figure 5.8 shows that the impact of cutting speed on surface roughness is less at higher speed with constant feed rate and depth of cut that resulting good surface finish.
Figure 5.8  Sensitivity analysis results of cutting speed (V) on surface roughness at F = 0.159 mm/rev, T = 2.0 mm and R = 0.75 mm

Figure 5.9  Sensitivity analysis results of feed rate (F) on surface roughness at F = 0.159 mm/rev, T = 2.0 mm and R = 0.75 mm
From the Figure 5.9, it is observed that the sensitivity of feed rate is more at higher speed. The results reveal that sensitivity of feed rate on surface roughness gradually increases if the cutting speed increases. The Figure 5.10 shows that the impact of nose radius on surface roughness is less at high speed with constant feed rate and depth of cut that resulting good surface finish.

From the Figure A1.11, it is observed that the sensitivity of feed rate on surface roughness has more impact at low depth of cut with constant cutting speed. The increase in depth of cut yields the smoother surface finish.

![Graph](image)

**Figure 5.10**  Sensitivity analysis results of nose radius (R) on surface roughness at \( F = 0.159 \) mm/rev, \( T = 2.0 \) mm and \( R = 0.75 \) mm

Based on the Figure A1.12, it is observed that the sensitivity of depth of cut is more at low depth of cut. The results reveal that the increase in depth of cut is less sensitive at constant cutting speed and feed rate, yielding good surface finish at high depth of cut. The sensitivity of the cutting speed is less at larger nose radius as shown in Figure 5.11. The larger nose radius with higher speed can tend to produce smoother surface. The sensitivity of nose
radius is more at small nose radius producing higher surface roughness as shown in Figure 5.12.

![Figure 5.11](image1)

**Figure 5.11** Sensitivity analysis results of cutting speed (V) on surface roughness at \( V = 170 \text{ m/min} \), \( F = 0.159 \text{ mm/rev} \) and \( T = 2.0 \text{ mm} \)

![Figure 5.12](image2)

**Figure 5.12** Sensitivity analysis results of nose radius (R) on surface roughness at \( V = 170 \text{ m/min} \), \( F = 0.159 \text{ mm/rev} \) and \( T = 2.0 \text{ mm} \)
Figure 5.13 Sensitivity analysis of surface roughness

The comparison of the sensitivity of four input parameters cutting speed, feed rate, depth of cut and nose radius on surface roughness are shown in Figure 5.13. The results show that cutting speed is more sensitive than the other parameters. The variation of cutting speed causes more changes in surface roughness. The change in depth of cut and nose radius affect the surface roughness. It is concluded that sensitivity of cutting speed is much higher than that of other parameters. The change of cutting speed is more useful to control the surface roughness.

5.4 CONCLUSION

The effectiveness of the process parameters in controlling tool flank wear and surface roughness of the workpiece has been analyzed. The models proposed from the experimental data for tool flank wear and surface roughness of the workpiece can be employed to analyze the relationship between process parameters.
Sensitivity analysis has been performed to represent the effectiveness of the process parameters on the empirical equation and found that the change of process parameters affects the flank wear and surface roughness.

- The sensitivity of cutting speed has more impact on wear to the increase in feed rate as shown in Figure 5.2. The sensitivity of feed rate increases if feed rate is increased as shown in Figure 5.3.

- The Figure 5.5 indicates that the comparisons of the sensitivity of flank wear of the three input parameters cutting speed, feed rate and depth of cut. Based on the plot, the cutting speed is more sensitive than depth of cut. If the cutting speed is increased the sensitivity of feed rate decreases.

The variation of depth of cut causes small changes in flank wear and change of cutting speed affects the flank wear. It is concluded that sensitivity of cutting speed is much higher than that of depth of cut. The change of cutting speed and feed rate are more useful to control the flank wear.

The Figure 5.8 shows that the impact of cutting speed on surface roughness is less at higher speed with constant feed rate and depth of cut resulting good surface finish.

- The Figure 5.10 shows that the impact of nose radius on surface roughness is less at high speed with constant feed rate and depth of cut that resulting good surface finish.

- The comparison of the sensitivity of four input parameters cutting speed, feed rate, depth of cut and nose radius on surface roughness are shown in Figure 5.13. The result shows that
cutting speed is more sensitive than the other parameters. The variation of cutting speed causes more changes in surface roughness.

The change in depth of cut and nose radius affects the surface roughness. It is concluded that sensitivity of cutting speed is much higher than that of other parameters. The change of cutting speed is more useful to control the surface roughness.

To achieve higher accuracy and damping capacity, it is necessary to design the machine tool with static considerations and dynamic stability of the cutting tools. The dynamic behavior of the cutting tool (with and without laminates) has been simulated using ANSYS and presented in chapter 6.