CHAPTER 6
RESULTS AND DISCUSSION

6.1 INTRODUCTION

The aim of any machining process is to produce a neatly cut component of acceptable dimensions along with the required surface finish. The machining process should also ensure that the cutting forces are kept within the permissible limits of the machine tool. The cost of production is directly proportional to the cutting tool cost and hence the tool life has to be kept at the maximum. Selection of appropriate machining parameters is vital in order to achieve the above requirements.

Various machining parameters influence the outcome of the machining process. Among them, cutting speed, feed rate and depth of cut were considered for the present study. While considering the feed rate, in the existing method, a constant feed rate is considered for any cut segment. In this scenario the cutting tool accelerates from zero to the programmed feed rate instantly, thereby causing higher cutting forces, high surface roughness and high tool wear. Hence a concept of progressive feed rate was introduced where the feed rate was gradually increased thereby reducing the above mentioned negative effects. The output responses taken for the study were surface roughness, tool wear and cutting force.

This chapter discusses the outcome of the experimental results in the machining of AISI 1045 steel. Three types of cutting tool inserts, PVD
coated, CVD coated and uncoated carbide inserts were used. The effects of the cutting parameters on different performance indicators are discussed in detail. The results are discussed using graphs.

6.2 CONSTANT FEED RATE vs PROGRESSIVE FEED RATE

Experiments were conducted using L₉ orthogonal array for the existing constant feed rate method, and L₂₇ orthogonal array was used for conducting experiments for the proposed progressive feed rate method. The outcome of machining using constant feed rate was compared with equivalent trials of progressive feed rate for the responses, surface roughness, tool wear and cutting force.

6.2.1 Effect of Progressive Feed Rate on the Surface Roughness

Surface roughness plays a vital role in many areas and is a factor of great importance in the evaluation of machining accuracy. Although many factors influence surface roughness, machining parameters like cutting speed, feed rate and depth of cut have a significant influence on a given machine tool and work piece combination. The effect of various cutting tool materials on the surface roughness for varying cutting speed, feed rate and depth of cut were studied.

Table 6.1 gives the values of surface roughness for machining with the existing constant feed rate and the proposed progressive feed rate method and the percentage reduction. The same is represented diagrammatically in Figures 6.1 – 6.3.
Table 6.1 Comparison of surface roughness values

<table>
<thead>
<tr>
<th>Trial No [CF]</th>
<th>Trial No [PF]</th>
<th>Surface Roughness, $R_a$, $\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PVD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CF</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3.82</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>3.86</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>3.92</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>3.71</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>3.91</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>3.47</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>3.83</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>3.74</td>
</tr>
<tr>
<td>9</td>
<td>26</td>
<td>3.96</td>
</tr>
</tbody>
</table>

"# Constant Feed Rate; $^\$ Progressive Feed Rate; * Percentage reduction"

Table 6.1 shows that in case of PVD inserts, in trial number 6, there is no reduction in surface roughness. While machining with CVD inserts, in trial numbers 5 and 6 there is no reduction in surface roughness. However, while using uncoated carbide inserts it can be seen that there is reduction in surface roughness in all the trials.

![Comparison of Surface roughness between CF and PF for PVD inserts](image_url)

**Figure 6.1** Comparison of Surface roughness between CF and PF for PVD inserts
6.2.2 Effect of Progressive Feed Rate on Tool Flank Wear

During machining, the tool is subjected to continuous sliding on the work-hardened work surface, which has just been machined, past the flank surface, apart from the chip sliding over the rake face. The sliding of the just-machined surface over the flank surface usually results in intimate contact, which promotes adhesive wear. Damage to the work pieces or machine tools caused by catastrophic tool failure, resulting from large flank wear, needs to
be avoided. It is well-established that only flank wear has the greatest influence on the work piece dimensions and surface quality (Bhaumik et al 1995; Shane Y. Hong et al 2001).

Table 6.2 gives the values of tool flank wear for machining with the existing constant feed rate and the proposed progressive feed rate method and the percentage reduction. The same is represented diagrammatically in Figures 6.4 – 6.6.

Table 6.2 Comparison of tool flank wear values

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Flank Wear (Vb), mm</th>
<th>PVD</th>
<th>CVD</th>
<th>Uncoated</th>
<th>%*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CF</td>
<td>PF</td>
<td>CF</td>
<td>PF</td>
<td>CF</td>
</tr>
<tr>
<td>1</td>
<td>0.09</td>
<td>0.08</td>
<td>0.10</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>0.12</td>
<td>0.11</td>
<td>0.15</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
<td>0.15</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>0.16</td>
<td>0.15</td>
<td>0.17</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>5</td>
<td>0.19</td>
<td>0.18</td>
<td>0.19</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>6</td>
<td>0.17</td>
<td>0.15</td>
<td>0.19</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.20</td>
<td>0.23</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>8</td>
<td>0.19</td>
<td>0.18</td>
<td>0.21</td>
<td>0.21</td>
<td>0.27</td>
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<tr>
<td>9</td>
<td>0.22</td>
<td>0.21</td>
<td>0.25</td>
<td>0.24</td>
<td>0.29</td>
</tr>
</tbody>
</table>

*% Constant Feed Rate; % Progressive Feed Rate; * Percentage reduction

Table 6.2 shows that there is reduction in tool flank wear in most of the trials. However, trial number 7 in PVD, 8 in CVD and 2 and 5 in uncoated inserts did not show improvement.
Figure 6.4  Comparison of tool flank wear between CF and PF for PVD inserts

Figure 6.5  Comparison of tool flank wear between CF and PF for CVD inserts

Figure 6.6  Comparison of tool flank wear between CF and PF for Uncoated carbide inserts
6.2.3 **Measurement of Forces in Machining**

The determination of cutting forces necessary for deforming the work material at the shear zone is essential to:

i) Survey the cutting characteristics of new work and cutting tool materials by investigating cutting tool forces.

ii) Estimate the power requirements of a machine tool.

iii) Estimate the straining actions that must be resisted by machine tool components, bearing, jigs and fixtures.

The removal of excess materials in the form of chips, by which the finished surface is produced, involves tool geometry, internal and frictional processes at the interfaces and several other physical and chemical factors. The analysis is made by means of experimental observations or by using simplified models of the actual cutting process.

In order to measure the three orthogonal force components (Cutting, \( F_x \), Tangential, \( F_y \), and Thrust, \( F_z \)) in the machining of AISI 1045 steel, a Kistler 3-component (Type 9257B with 9403) was used. The cutting force signal was measured by a pick-up and was passed on to a computer after Analog-to-Digital (A/D) conversion.

6.2.4 **Effect of Progressive Feed Rate on the Cutting Force**

Table 6.3 gives the values of cutting force for machining with the existing constant feed rate and the proposed progressive feed rate method and the percentage reduction. The same is represented diagrammatically in Figures 6.7 – 6.9.
Table 6.3 Comparison of cutting force values

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Trial No</th>
<th>Cutting Force ($F_x$), N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PVD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CF</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>223.7</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>285.5</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>366.6</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>242.3</td>
</tr>
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<td>5</td>
<td>15</td>
<td>324.1</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>172.4</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>301.3</td>
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<tr>
<td>8</td>
<td>22</td>
<td>139.6</td>
</tr>
<tr>
<td>9</td>
<td>26</td>
<td>189.1</td>
</tr>
</tbody>
</table>

$^#$Constant Feed Rate; $^\$Progressive Feed Rate; $^*$Percentage reduction

In Table 6.3, except for a few trials, like Trials 6, 8 for PVD and CVD and 6, 9 for uncoated inserts, all other trials showed improvement, i.e. reduction in cutting force due to the application of progressive feed rate concept.
Figure 6.7 Comparison of cutting force between CF and PF for PVD inserts

Figure 6.8 Comparison of cutting force between CF and PF for CVD inserts

Figure 6.9 Comparison of cutting force between CF and PF for Uncoated carbide inserts
6.2.5 Observation of Cutting Force Pattern

The cutting force was measured using Kistler dynamometer to study the effect of progressive feed rate on the cutting force. In case of constant feed rate method, at the start of any cut segment, the cutting tool starts from a stationary position, i.e. from zero feed rate to the programmed feed rate instantly, which causes the cutting force to start from a high value. In the proposed progressive feed rate method, the feed rate was increased from a low value to the programmed value gradually. This caused the cutting force to increase gradually.

The Kistler dynamometer images for the cutting force $F_x$ obtained while machining using PVD inserts during Trial Number 1 is shown in Figures 6.10 – 6.13. Figures 6.10 and 6.11 show the cutting force while machining with constant feed rate and progressive feed rate respectively. The cutting force is shown for a machining distance of 8 mm. In the proposed progressive feed rate method the feed rate is varied only through this distance. Beyond 8 mm the feed rate is constant for the rest of the cut. In Trial Number 1 the feed rate for the existing constant feed rate method is 40 mm/min. In case of progressive feed rate method the feed rate steps along the 8 mm cut are 6, 14.50, 23.00 and 31.50 mm/min and beyond 8 mm it is 40 mm/min, which is the same as that for constant feed rate method. Due to this the cutting force increases proportionate to the feed rate i.e. it increases gradually. This can be seen in Figure 6.13. The graphs consist of two zones. ‘Zone 1’ shows the $F_x$ component when the tool enters the work piece in the Z-axis and ‘Zone 2’ shows the $F_x$ component when the tool moves along the X-axis.
Figure 6.10 Cutting force while machining with constant feed rate for PVD insert

Figure 6.11 Cutting force while machining with progressive feed rate for PVD insert

Figure 6.12 compares the cutting forces between the existing and the proposed methods in ‘Zone 1’. It shows that there is reduction in cutting forces while using the proposed progressive feed rate method.
Figure 6.12 Comparison of cutting forces in ‘Zone 1’ while using PVD insert

Figure 6.13 shows the cutting forces between the existing and the proposed methods in ‘Zone 2’. It can be seen from the figure that the cutting force in case of progressive feed rate increases gradually and also the maximum cutting force is less when compared to the existing constant feed rate method.

Figure 6.13 Comparison of cutting forces in ‘Zone 2’ while using PVD insert

6.3 OBSERVATION OF OUTPUT PARAMETERS IN PROGRESSIVE FEED RATE METHOD

In the previous sections, the effect of progressive feed rate on the output parameters was studied. The comparison between the output
parameters like surface roughness, tool flank wear and cutting force was represented in table form and also in graphical form, for easy visualization. In the following sections the effect of cutting parameters on the output parameters using progressive feed rate method will be studied.

6.3.1 Main effects plot for surface roughness

Figure 6.14 shows the main effects plot for surface roughness while machining using PVD coated inserts.

![Main Effects Plot for Surface Roughness](image)

Figure 6.14 Main effects plot for Surface Roughness (PVD insert)

Figure 6.14 shows that for a given feed rate and depth of cut the surface roughness reduces with increase in the cutting speed. For a given spindle speed and depth of cut the surface roughness increases with the increase in the feed rate. Finally, it can be seen that surface roughness increases with increase in the depth of cut for a given spindle speed and feed rate. The concept behind this will be explained in section 6.3.4.
6.3.2 Main effects plot for tool flank wear

Figure 6.15 shows the main effects plot for tool flank wear while machining using PVD coated inserts.

![Main Effects Plot for Flank Wear, mm](image)

Figure 6.15 Main effects plot for Tool flank Wear (PVD insert)

It can be inferred from Figure 6.15 that for a given cutting speed and feed rate the tool flank wear is directly proportional to the depth of cut, i.e. the tool wear increases with increase in the depth of cut. The same trend is seen with respect to the feed rate. In case of the effect of cutting speed on the tool wear it can be seen that the curve is steep indicating that the effect of spindle speed is more prominent on the tool wear than the other two cutting parameters. The mechanism behind this is explained in section 6.3.5.

6.3.3 Main Effects Plot for Cutting Force

Figure 6.16 shows the main effects plot for cutting force while machining using PVD coated inserts.
Main effects plot for cutting force shown in Figure 6.16 indicates that cutting force decreases with the increase in cutting speed for a given feed rate and depth of cut. The effect of feed rate on the cutting force is the opposite to that of cutting speed, i.e. for a given cutting speed and depth of cut the cutting force increases with increase in the feed rate. This trend is observed with the depth of cut also. Section 6.3.6 explains the mechanism involved.

The main effects plots are shown only for machining using PVD coated inserts. Machining was also done using CVD coated inserts and Uncoated inserts. The same trend was observed in these inserts also.
6.3.4 Interaction Effects Plot for Surface Roughness - PVD Coated Inserts

In the previous sections, 6.3.1 – 6.3.3, the effect of the individual cutting parameters on the output responses were studied. Also, it is important to study the interaction effects of two or more input parameters on the output responses. The interaction effects are discussed in the following sections.

6.3.4.1 Effect of depth of cut and feed rate on surface roughness

Figure 6.17 shows the interaction effect of the depth of cut and feed rate on the surface roughness.

![Interaction Plot for Surface Roughness](image)

Figure 6.17 Effect of depth of cut and feed rate on surface roughness (PVD inserts)

It can be seen that for a given feed rate the surface roughness increases with the increase in depth of cut. Higher depth of cut increases the volume of metal removal and the temperature increases at the work piece tool.
tip interface. As the experiments were conducted under dry machining conditions the scope of heat removal was minimal. This led to adherence of the work piece material to the tool tip thereby causing poor surface finish.

6.3.4.2 Effect of feed rate and cutting speed on surface roughness

Figure 6.18 shows the interaction effect of feed rate and cutting speed on the surface roughness.

![Interaction Plot for Surface Roughness](image)

Figure 6.18 Effect of feed rate and cutting speed on surface roughness (PVD inserts)

The graph, Figure 6.18, shows that, for a given cutting speed, increase in feed rate increases the surface roughness. Higher feed rate increases the Material Remove Rate (MRR). This leads to increase in the temperature and softens the work piece material. As a result of this, adherence of work piece material to the cutting tool tip may happen which leads to poor surface finish. Also, higher feed rate increases the distance between successive cut marks made by the tool which increases the surface roughness.
6.3.4.3 Effect of cutting speed and depth of cut on surface roughness

Figure 6.19 shows the interaction effect of cutting speed and depth of cut on the surface roughness.

![Interaction Plot for Surface Roughness](image)

Figure 6.19 Effect of cutting speed and depth of cut on surface roughness (PVD inserts)

It can be inferred from the graph, Figure 6.19, that for a given depth of cut, increase in cutting speed reduces the surface roughness. At lower spindle speeds the adhesion of work piece material to the tool tip takes place, which increases the surface roughness. However, at high cutting speeds continuous reduction in the build-up edge takes place, thus there is improvement in the surface finish.
6.3.5 Interaction effects plot for tool flank wear - PVD coated inserts

6.3.5.1 Effect of depth of cut and feed rate on tool flank wear

Figure 6.20 shows the interaction effect of the depth of cut and feed rate on the tool flank wear.

Figure 6.20 Effect of depth of cut and feed rate on the tool flank wear (PVD inserts)

Figure 6.20 shows that for a given feed rate, increase in the depth of cut increases the tool wear. When the depth of cut is less, there is less work piece material adhering to the flank than at higher depth of cut. Higher depth of cut leads to an increased contact area of the work piece. Higher depth of cuts combined with high feed rate generates more heat and cutting forces. The heat softens the tool tip thereby accelerating the tool wear.
6.3.5.2 Effect of feed rate and cutting speed on tool flank wear

Figure 6.21 shows the interaction effect of feed rate and cutting speed on the tool flank wear.

![Interaction Plot for Flank Wear](image)

**Figure 6.21** Effect of feed rate and cutting speed on the tool flank wear (PVD inserts)

It can be seen from Figure 6.21 that, for a given cutting speed the tool wear increases with the increase in feed rate. Increasing feed rate increases the metal removal rate which in turn increases the cutting temperature which softens the tool tip. Also, high feed rates create a ploughing action which, combined with high temperatures, increases the tool wear. However, the effect of feed rate on the tool wear is less compared to the effect of cutting speed (Figure 6.22).
6.3.5.3 Effect of cutting speed and depth of cut on tool flank wear

Figure 6.22 shows the interaction effect of cutting speed and depth of cut on the tool flank wear.

It can be observed from the graph, Figure 6.22, that for a given depth of cut, increase in the cutting speed increases tool wear. It increases the cutting temperature and results in shortening the tool life. Cutting speed accelerates the tool wear as higher cutting speed accelerates thermally activated wear mechanisms. An increased thermal gradient takes place due to the increase in thermal crack generation rate, which in turn increases the tool wear.
6.3.6 Interaction effects plot for cutting force - PVD coated inserts

6.3.6.1 Effect of depth of cut and feed rate on the cutting force

Figure 6.23 shows the interaction effect of the depth of cut and feed rate on the cutting force.

![Interaction Plot for Cutting Force](image)

Figure 6.23 Effect of depth of cut and feed rate on the cutting force (PVD inserts)

From Figure 6.23 it can be seen that, for a given feed rate, the cutting force increases with the increase in depth of cut. Higher axial depth of cut increases the volume of metal removal and also leads to an increased contact area of the work piece, which increases the cutting force and the induced mechanical load.
6.3.6.2 Effect of feed rate and cutting speed on the cutting force

Figure 6.24 shows the interaction effect of feed rate and cutting speed on the cutting force.

![Interaction Plot for Cutting Force](image)

**Figure 6.24** Effect of feed rate and cutting speed on the cutting force (PVD inserts)

It can be observed from Figure 6.24 that, for a given cutting speed, increase in the feed rate increases the cutting force. Higher feed rate increases the Material Removal Rate (MRR). Also, with high feed rate the metal may be pushed instead of being cut. This will result in higher cutting force and higher temperature. The high temperature may lead to work hardening of the work piece which in turn increases the cutting force.
6.3.6.3  Effect of cutting speed and depth of cut on the cutting force

Figure 6.25 shows the interaction effect of cutting speed and depth of cut on the cutting force.

![Interaction Plot for Cutting Force](image)

Figure 6.25  Effect of cutting speed and depth of cut on the cutting force (PVD inserts)

It can be inferred from Figure 6.25 that, for a given depth of cut, increase in the cutting speed reduces the cutting force. At lower cutting speeds the adhesion of work piece material to the tool tip takes place which reduces the effectiveness of machining thereby increasing the cutting force. However, at high cutting speeds continuous reduction in the build-up edge takes place and thus the cutting force required to cut the material comes down.
6.3.7 Interaction Effects Plot for CVD Coated Inserts

Figures 6.26 – 6.28 show the interaction effects of the cutting parameters on the output responses, surface roughness, tool wear and cutting force. It can be seen that the effects are similar to the ones which were seen for PVD coated inserts.

Figure 6.26 Interaction effect plot for surface roughness – CVD insert
Figure 6.27 Interaction effect plot for tool flank wear – CVD insert
Figure 6.28 Interaction effect plot for cutting force – CVD insert
6.3.8 Interaction Effects Plot for Uncoated Carbide Inserts

Figures 6.29 – 6.31 show the interaction effects of the cutting parameters on the output responses, surface roughness, tool flank wear and cutting force respectively. It can be seen that the effects are similar to the ones which were seen for PVD coated inserts.

Figure 6.29 Interaction effects plot for surface roughness – Uncoated carbide insert
Figure 6.30 Interaction effects plot for tool flank wear – Uncoated carbide insert
Figure 6.31  Interaction effects plot for cutting force – Uncoated carbide insert
6.4 SUMMARY

Experimental results for the existing constant feed rate method and the proposed progressive feed rate method were compared. With respect to the output parameters, surface roughness, tool flank wear and cutting force, it was found that except in a couple of trials in all other trials there was improvement due to the application of progressive feed rate.

The effects of the process variables such as cutting speed, feed rate and axial depth of cut on the output responses like surface roughness, tool flank wear and cutting force were studied. The effects due to the main factors and also the interaction effects of the cutting parameters were studied for three different tool inserts. Though there was variation in the numerical values, the trends of the graphs were similar across all the three types of inserts - PVD, CVD and Uncoated carbide inserts.