CHAPTER 7

CONCLUSIONS

7.1 INTRODUCTION

This chapter presents a list of major conclusions drawn from the studies related to experimental investigations and analysis of results pertaining to tool wear characterization in High Speed Milling (HSM). The following section presents the salient features and contributions of research work reported in this thesis. The scope for future work has also been identified and the same is listed in the section 7.3

7.2 SALIENT FEATURES AND CONTRIBUTIONS OF THE PRESENT RESEARCH WORK

The experimental investigations on high speed milling of aluminium alloy have been carried out with specific importance to tool wear characterization and their effect on components/parts manufactured using the above process. The effect of tool wear on both dimensional accuracy and surface finish of HSM components were established. A new method of delivering consistent part quality by developing a self-adjusting, on-line tool wear compensation system employing work datum shift was investigated; further an adaptive control system based on cutting speed control was also studied in detail. A process capability study is carried out to assess the improvement in process characteristics of HSM.
The experimental investigations were carried out on a CNC 3-axis vertical machining centre, fitted with a 5kW, 40000rpm integral motorized spindle. The work has been sub divided into four modules as indicated below:

Module-1: Tool wear monitoring and estimation using acoustic emission technique.

Module-2: Optimisation of process parameters in HSM.

Module-3: Development of self-adjusting on-line tool wear compensation system for improved dimensional accuracy.

Module-4: Development of an adaptive control system in HSM for improved surface finish.

Based on the experimental investigations on HSM of LM6 grade aluminium alloy and two flute Titanium aluminium nitrate coated carbide end milling cutter, the following major conclusions are drawn:

1. A methodology for indirect on-line tool wear monitoring using acoustic emission technique has been established for HSM process. An algorithm to predict the tool wear for solid carbide cutter using Artificial Neural Network (ANN) is also developed.

2. A partial factorial experimental study using L9 orthogonal array was employed to optimise the cutting parameters i.e. cutting speed, feed rate and depth of cut. ANOVA was also conducted to study the relative influence of cutting parameters in affecting tool life.
3. In module-1, the variation of tool wear with respect to tool life was found to be in agreement with the standard tool wear pattern of end milling cutter as reported in literature. [ISO-8688 (E) (1989)]

4. The acoustic emission signal parameter (Aerms, V) captured to monitor tool wear was found to increase with an increase in tool wear. Such a phenomenon may be attributed to an increase in strain energy at the tool work interface which results in an increase in the acoustic emission signal parameter. Among the various acoustic emission parameters considered, the above parameter, i.e. Aerms was observed to be explicitly indicative of tool wear as reported in literature.

5. A maximum tool life of 153 mins (9225s) was observed among the nine sets of experiments conducted for the following cutting conditions:

   Cutting speed = 376 m/min,
   Feed rate = 4000 mm/min,
   Depth of cut = 0.15 mm

   It can be seen that the above combination of parameters corresponds to minimum cutting speed, the other parameters being at the medium level. The observation needs to be investigated based on ANOVA study as well. The ANOVA study revealed that the contributions of individual parameters towards tool wear are as follows:

   Cutting speed has the maximum contributing influence of 9.3% followed by that of feed rate 6% and that of depth of cut (axial) 4.5%. Hence, it can be concluded that the primary cutting parameter that influences the tool wear in HSM is the
cutting speed as the above parameter decides the frequency of cutting edge passing over the work piece.

6. In contrast to the above combination of cutting parameters, a minimum tool life of 58 mins (3480s) was observed for the following cutting conditions:
   Cutting speed = 678 m/min
   Feed rate = 6000 mm/min
   Depth of cut = 0.15 mm

   In this case, the cutting parameter combination corresponds to maximum cutting speed and feed rate, the depth of cut being at medium level. The above situation also can be attributed to the same reason listed in the previous conclusion.

7. The study of analysis of means of the above set of experiments predicts the optimum cutting conditions for maximum tool life and the same is listed below.
   Cutting speed = 376 m/min
   Feed rate = 4000 mm/min
   Depth of cut = 0.15 mm

   The above cutting parameter combination was checked through a verification experiment and the tool was found to have a tool life of 180mins (9225s). The above combination corresponds to minimum cutting speed and medium values of feed rate and depth of cut. This situation represents generally a minimum force field and hence the same resulted in maximum tool life.

8. Based on the study of tool wear pattern observed in the experimental investigations, it was found that on an average,
the tool has an initial tool wear period of 13.08 ±6%, gradual tool wear period of 64.93 ± 20.5% and rapid tool wear period of 23.03 ± 19.5%. The scatter in the measured values of tool wear is observed to be significant and similar results have been reported in literature. The rapid wear period has the maximum value of scatter and hence it can be seen that there is a high degree of uncertainty in the stage of tool wear. The variations in the three different tool life wear periods are indicated as ± values in the preceding conclusions. It can be noted that among the three wear periods, the gradual wear period has a maximum span, and the same could be employed for obtaining consistent part quality.

9. A mathematical model has been developed using artificial neural network (ANN) based on the experimental results of the tool wear study capable of predicting the tool wear for various cutting conditions with input data pertaining to measured acoustic emission parameters. The prediction error was found to be closely within ± 4%

10. Optimum cutting condition was experimentally established in HSM process under study for each one of the following objective functions;

   i) Minimum of resultant cutting force
   ii) Minimum of work piece vibration
   iii) Minimum of surface finish value

The under mentioned observations were made:

a) The resultant cutting force reduced from 39N to 24N as cutting speed was increased from 376 m/min to 388 m/min, a decrease of 38% in resultant cutting force. This is due to
the reason that as cutting speed increases, the ploughing forces and chip thickness reduces resulting in a reduction in force required for shearing the material. The reduction in resultant cutting force also results in a reduction in vibration amplitude and improved surface finish.

b) An increase in the feed rate resulted in an increase in the resultant cutting force. This may be due to the reason that as the feed rate is increased, the resistance offered by the workpiece material increases; the rate of metal removal also increased thus demanding an increase in force required to shear the material. Even a small variation in feed rate was observed to contribute to a significant change in resultant cutting force and surface finish.

c) The experimentally predicted optimal cutting conditions based on analysis of means for various objective functions are listed in Table 7.1.

**Table 7.1 Predicted optimal cutting conditions**

<table>
<thead>
<tr>
<th>Cutting parameter Objective function</th>
<th>Cutting speed, $V_c$, (m/min)</th>
<th>Feed rate, $V_f$, (mm/min)</th>
<th>Depth of cut, $b$, (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum of Resultant cutting force</td>
<td>678</td>
<td>2000</td>
<td>0.15</td>
</tr>
<tr>
<td>Minimum of Vibration amplitude</td>
<td>678</td>
<td>2000</td>
<td>0.05</td>
</tr>
<tr>
<td>Minimum of Surface finish</td>
<td>678</td>
<td>2000</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum tool life</td>
<td>376</td>
<td>4000</td>
<td>0.15</td>
</tr>
<tr>
<td>Maximum MRR</td>
<td>678</td>
<td>6000</td>
<td>0.15</td>
</tr>
<tr>
<td>Improved Surface finish</td>
<td>528</td>
<td>4000</td>
<td>0.25</td>
</tr>
<tr>
<td>Improved product quality</td>
<td>376</td>
<td>4000</td>
<td>0.15</td>
</tr>
</tbody>
</table>
From the results in Table 7.1, it is inferred that in order to obtain minimum cutting force, minimum vibration amplitude and better surface finish, the optimal cutting condition out of the nine set of experiments relate to maximum cutting speed, minimum feed rate and depth of cut. This may be due to reduction in cutting forces as the cutting speed increases resulting in minimum vibration and thereby better surface finish. These results agree with the experimental results in the literature.

d) The ANOVA study reveled that the contributions of individual parameters towards the various objective functions are given in Table 7.2.

Table 7.2 Contribution of individual cutting parameters

<table>
<thead>
<tr>
<th>Objective function</th>
<th>Resultant cutting force</th>
<th>Vibration amplitude</th>
<th>Surface finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influencing Cutting parameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting speed, (V_c), (m/min)</td>
<td>17%</td>
<td>22%</td>
<td>24%</td>
</tr>
<tr>
<td>Feed rate, (V_f), (mm/min)</td>
<td>80%</td>
<td>43.6%</td>
<td>49%</td>
</tr>
<tr>
<td>Depth of cut, (b_{as}), (mm)</td>
<td>1.4%</td>
<td>14%</td>
<td>4.7%</td>
</tr>
</tbody>
</table>

From the results in Table 7.2, it is inferred that the most significant contributing parameter affecting cutting force, vibration amplitude and surface finish is feed rate as reported in literature. The may be due to the reason that as the feed rate increases, the resistance offered by work piece also increases, resulting in higher values of cutting force, vibration amplitude and surface finish.
11. In module-3, a self-adjusting on-line tool wear compensation system was developed and applied to end milling of ‘O’ ring of groove depth 1007μm. A process capability study was carried out and the study revealed the following;

a) The standard deviation of the depth of the groove reduced from 2.33μm to 1.66 μm due to less scatter, signifying better process control.

b) The process capability index ($C_p$) of the above end milling process improved from 1.04 to 1.39 and the critical process capability index ($C_{pk}$) also improved from 0.996 to 1.12. The observed critical process capability index ($C_{pk}$) was less than the measured process capability index ($C_p$) value due to the fact the process mean had shifted to the right. (i.e. from 1006.72 μm to 1008.38 μm)

12. In module-4, an Adaptive Control based on Constraints (ACC) was developed and applied to end milling of flat surfaces used in hydraulic equipment. The desired surface finish value (Ra) using HSM was set between 0.8 to 1.6μm. A process capability study was carried out and the study revealed the following;

a) The standard deviation of the surface roughness (Ra) of the machined surface reduced from 0.3μm to 0.2 μm due to less scatter, signifying real time adaptive control.

b) The process capability index ($C_p$) of the above end milling process improved from 1.032 to 1.296 and the critical process capability index ($C_{pk}$) also improved from 0.939 to 1.274. The observed critical process capability index ($C_{pk}$) was less than the measured process capability index ($C_p$) as before.
7.3 SCOPE OF FUTURE STUDY

1. The study is carried out in a specific VMC. The results of the study need to be verified for other milling machines and their stiffness condition over a period of time.

2. The experimental study was carried out for particular work-tool combination i.e. aluminium and coated carbide cutter; however further experimental work needs to be carried out for other work-tool combinations to generalize the results of the present investigations.

3. The experimental work has assumed that the parameters under study are mutually independent. However, these parameters could have interaction among them and hence further studies on parameter interaction effects may be undertaken.

4. The work could be further extended to include bulk tool wear aspects like tool fracture, chipping etc., in order to holistically compensate for the tool wear phenomenon.

5. The characterization of the surface quality produced from the experimental work could be analyzed using Scanning Electron Microscope, in order to investigate into the microscopic aspects of the machined surfaces. In the present work, the work-tool interface temperature would not have been high as the depth of cut was of the order of 250 µm; such a situation might not bring about changes in microstructure, as the temperature being less than the critical temperature of the work piece material.