CHAPTER 6
PERFORMANCE COMPARISON OF OPTIMIZED HARD MILLING WITH MINIMAL FLUID APPLICATION WITH CONVENTIONAL WET MILLING AND DRY MILLING

6.1 INTRODUCTION

Preliminary comparison of hard milling with minimal fluid application in its optimized mode with conventional wet milling and dry milling clearly indicated that this new technique is superior to the other methods. This scheme is environment friendly and can be easily implemented on the shop floor. The cutting parameters and the fluid application parameters such as composition of cutting fluid, pressure at the fluid injector, rate of fluid delivery, the frequency of pulsing, the mode of fluid delivery and the configuration of the fluid jet were optimized using Taguchi’s statistical techniques and Response surface Methodology. But a systematic full scale comparison is necessary to get a clear idea of the benefits that can be achieved by adopting this new technique. It was decided to accomplish this through a variable speed test, a variable feed test and a tool life test.

6.2 SELECTION OF CUTTING PARAMETERS AND FLUID APPLICATION PARAMETERS

The optimization procedure based on response surface methodology as outlined in the previous section revealed that the fluid application parameters are to be kept at values available in Table 5.6. Accordingly the pressure at the fluid injector was maintained at 100 bar, frequency of pulsing at 500 pulses/min and the rate of fluid application at 6.7 ml/min. A twin fluid jet configuration was used as in Fig. 4.7(b) and the composition of the cutting fluid was maintained as 20% oil and the rest water. The injector nozzle had a specification DN0SD151 with 0º spray angle.

6.3 CUTTING EXPERIMENTS

The cutting speed was varied from 16 m/min to 63 m/min at 5 levels while the feed was kept constant at 0.14 mm/tooth and the depth of cut at 0.4 mm during the variable speed test.
During the variable feed test, feed was varied at 5 levels from 0.02 mm/tooth to 0.14 mm/tooth while the cutting speed and the depth of cut were held constant at 45 m/min and 0.4 mm respectively. The performance parameters such as surface roughness, the main cutting force and the tool wear were measured during dry milling, wet milling and during minimal fluid application in the optimized mode.

Tool life tests were conducted in the three modes at a cutting velocity of 45 m/min, feed 0.14 mm/tooth and depth of cut 0.4 mm. Measurement of surface roughness, cutting force and tool wear were done at intervals of 30 seconds for 2 minutes during each experiment.

6.3.1 Variable speed test

In variable speed test, the cutting speed was varied at 5 levels (16 m/min, 22.5 m/min, 31.5 m/min, 44.5 m/min and 63 m/min) as shown in Fig. 6.1 to Fig. 6.3 while the feed and depth of cut were kept constant at 0.14 mm/tooth and 0.4 mm respectively.

Fig. 6.1 shows the variation of surface roughness as a function of cutting speed.

![Fig. 6.1 Variation of surface roughness as a function of cutting speed (Feed = 0.14 mm/tooth and depth of cut = 0.4 mm)](image)
Fig. 6.2 shows the variation of flank wear as a function of cutting speed.

![Flank Wear vs Cutting Speed Graph](image)

**Fig. 6.2** Variation of flank wear as a function of cutting speed  
(Feed = 0.14 mm/tooth and depth of cut = 0.4 mm)

Fig. 6.3 shows the variation of cutting force as a function of cutting speed.

![Cutting Force vs Cutting Speed Graph](image)

**Fig. 6.3** Variation of cutting force as a function of cutting speed  
(Feed = 0.14 mm/tooth and depth of cut = 0.4 mm)
6.3.2 Variable feed test

Fig. 6.4 shows the variation of surface roughness as a function of feed.

Fig. 6.4 Variation of surface roughness as a function of feed
(Cutting speed = 45 m/min and depth of cut = 0.4 mm)

Fig. 6.5 shows the variation of flank wear as a function of feed.

Fig. 6.5 Variation of flank wear as a function of feed
(Cutting speed = 45 m/min and depth of cut = 0.4 mm)
Fig. 6.6 shows the variation of cutting force as a function of feed.

![Variation of cutting force as a function of feed](image1)

Fig. 6.6 Variation of cutting force as a function of feed (Cutting speed = 45 m/min and depth of cut = 0.4 mm)

6.3.3 Tool life test

Fig. 6.7 shows the results of the tool life test for the comparison of surface roughness(Ra).

![Variation of surface roughness with time of cut](image2)

Fig. 6.7 Variation of surface roughness with time of cut during dry and wet milling and during milling with minimal fluid application in optimized condition (Pressure at the injector = 100 bar, Frequency of pulsing = 500 pulses/min and Rate of fluid application = 6.7 ml/min)
Fig. 6.8 shows the results of the tool life test for the comparison of flank wear.

Fig. 6.8 Variation of flank wear with time of cut during dry and wet milling and during milling with minimal fluid application in optimized condition
(Pressure at the injector = 100 bar, Frequency of pulsing = 500 pulses/min and Rate of fluid application = 6.7 ml/min)

Fig. 6.9 shows the results of the tool life test for the comparison of cutting force.

Fig. 6.9 Variation of cutting force with time of cut during dry and wet milling and during milling with minimal fluid application in optimized condition
(Pressure at the injector = 100 bar, Frequency of pulsing = 500 pulses/min and Rate of fluid application = 6.7 ml/min)
6.3.4 Comparison of tool wear

Fig. 6.10 SEM photograph on tool wear during dry milling
(Cutting speed – 45 m/min, Feed – 0.14 mm/tooth, Depth of cut – 0.4 mm, Cutting time- 120 sec)

Fig. 6.11 SEM photograph on tool wear during wet milling
(Cutting speed – 45 m/min, Feed – 0.14 mm/tooth, Depth of cut – 0.4 mm, Cutting time- 120 sec)

Fig. 6.12 SEM photograph on tool wear during milling with minimal fluid application
(Cutting speed – 45 m/min, Feed – 0.14 mm/tooth, Depth of cut – 0.4 mm, Cutting time- 120 sec)
6.3.5 Comparison of chip forms

Fig. 6.13 to Fig. 6.15 compares the types of chips formed during dry milling, wet milling and milling with minimal fluid application when the cutting speed, feed and depth of cut were kept at 45 m/min, 0.14 mm/tooth, 0.4 mm respectively. The fluid application parameters such as pressure at the fluid injector, frequency of pulsing and rate of fluid application were maintained at 100 bar, 500 pulses/min, 6.7 ml/min respectively. A twin jet configuration as in Fig. 4.7(b) was selected. The composition of cutting fluid was maintained as 20% oil and rest water.

Fig. 6.13 SEM photograph of chip sample during dry milling
(Cutting speed – 45 m/min, Feed – 0.14 mm/tooth, Depth of cut – 0.4 mm)

Fig. 6.14 SEM photograph of chip sample during wet milling
(Cutting speed – 45 m/min, Feed – 0.14 mm/tooth, Depth of cut – 0.4 mm)
6.4 RESULTS AND DISCUSSION

6.4.1 Main cutting force

Fig. 6.3 shows the variation of cutting force as a function of cutting speed when the feed and depth of cut were maintained at 0.14 mm/tooth and 0.4 mm respectively. Fig. 6.6 represents the variation of cutting force as a function of feed when cutting speed and depth of cut were maintained at 45 m/min and 0.4 mm respectively.

It is observed that the cutting force could be maintained at low values during minimal fluid application when compared to dry and conventional wet milling in both the cases. The reduction in cutting force is mainly attributed to the mechanisms already explained in section 4.5. The effectiveness of a lubricant depends on its ability to penetrate the interface and its ability to get absorbed on the surface producing a surface film with low shear strength. This reduces the effective sticking length of the chip on the tool face leading to an increase in shear angle.

Robinson and Varadarajan (2011), conducted X ray and ESCA analysis of chip samples collected during conventional wet turning and hard turning with minimal fluid application using the same cutting fluid formulation and the same tool-work combination in which cutting fluid was applied as a high velocity narrow pulsed jet using the fluid injector with the same specifications as in the present investigation. The results of the analysis indicated the formation of a complex compound at the front side of the chip. The ingredients in the cutting fluid formulated was responsible for the formation of such a
compound which appears to reduce friction at the tool-chip interface. But the presence of such compounds could not be detected for samples collected during conventional wet turning.

The cutting fluid that reaches the tool-chip interface due to better penetration possible during minimal fluid application can at least act as an anti-welding agent if not as a lubricant which reduces the interaction between tool and the chip that leads to the reduction of tool-chip contact length and hence the cutting force. Such a condition is not possible in conventional wet milling where the velocity of fluid particles is no way comparable to that during minimal fluid application.

According to De Chiffre, (1988) reduction on tool-chip contact length is an index of cutting efficiency and can lead to reduction in cutting force. A reduction in tool-chip contact length can occur due to the following mechanisms.

1. Promotion of plastic flow at the back side of the chip due to Rebinder effect.
2. Contamination of tool rake face.

Minimal fluid application appears to activate both the mechanisms. The penetration of fluid particles at the tool-work interface leads to the contamination of rake face and reduces the surface interaction between the tool and the chip and shifts the condition from sticking to one of sliding leading to reduction of cutting force.

Apparently ambient factors can affect the mobility of near surface dislocations on the back side of the chip and this chemomechanical effect is known as Rebinder effect (Hutchings, 1992; Usi et al., 1961). During minimal fluid application in the optimized mode, fluid droplets fall on the back side of the chip when the insert assumes the position (B) as shown in Fig. 4.14. These particles owing to their high velocity and smaller physical size can penetrate and firmly adhere to the work surface resulting in the promotion of plastic flow on the back side of the chip due to Rebinder effect. This results in the relief of a part of compressive stress on the back side of the chip and chip tends to bend away from the rake surface leading to reduction in tool-chip contact length and associated reduction in cutting force.

Moreover, pulsing slug of fluid particles as is the case with minimal fluid application upsets the ability of the lubricant molecules to fit comfortably between the tool-chip interface and prevents the formation of ordered layers leading to better rake face lubrication as discussed in section 4.5.3.
Capillaries can exist in the body of the chip as extensions of outer serrations (Varadarajan et al., 2002a). Penetration of the special cutting fluid through this route also can reduce cutting force during minimal fluid application. During conventional wet milling, long chain molecules of the lubricant can seldom penetrate deep in to the capillaries on account of their size and low velocities. But during minimal fluid application the clustered molecules are broken in to smaller particulate units which can find an easy passage through the capillaries leading to more effective lubrication.

Identification of a complex compound consisting of ingredients of the cutting fluid formulated at the front side of chip by Robinson and Varadarajan (2011) also supports the idea that the fluid particles injected at the tool-work interface can reach the tool-chip interface during minimal fluid application. Since the cutting fluid with the same ingredients are used in the present investigation along with the same tool-work combination, formation of a complex compound of sulfur can be expected in the present study as well which helps in reducing the cutting force by acting as a lubricant / as a compound with low shear strength at the tool-chip interface.

6.4.2 Tool wear

Fig. 6.2 shows the variation of flank wear as a function of cutting speed and the variation of flank wear as a function of feed is presented in Fig. 6.5. It is seen that tool wear is minimum during machining with minimal fluid application followed by conventional wet milling and dry milling throughout the range in both the cases. Improved rake face lubrication, brought out during minimal fluid application as described in the previous section leads to reduction in frictional forces which in turn results low cutting temperatures when compared to conventional wet milling and dry milling. Lowering of cutting force and cutting temperature results in the reduction of flank wear and improvement in tool life.

6.4.3 Surface roughness

Lowering of tool-work friction, reduction in cutting force and lowering of cutting temperature during minimal fluid application should bring forth relatively better surface finish. This is clearly evident from Fig. 6.1 and 6.4. In both the cases, the lowest surface roughness was recorded during minimal fluid application.
6.4.4 Tool life test

Fig. 6.7 presents the variation of surface roughness as a function of time when the cutting velocity was kept at 45 m/min, feed at 0.14 mm/tooth and depth of cut at 0.4 mm. It is observed that surface finish could be maintained at 0.4 μm after a cutting time of 120 seconds during minimal fluid application where as it was as high as 1.1 μm during conventional wet milling and 1.45 μm during dry milling.

Fig. 6.8 presents the variation of flank wear as a function of time of cut during dry and wet milling and during milling with minimal fluid application in the optimized condition. It is observed that the average flank wear was 0.014 mm during minimal fluid application where as it was 0.051 mm and as high as 0.127 mm during conventional wet milling and dry milling respectively.

The variation of cutting force as a function of time during dry milling, conventional wet milling and milling with minimal fluid application in its optimized mode is available in Fig. 6.9. It is observed that lower cutting force could be maintained during minimal fluid application when compared to dry milling and conventional wet milling throughout the range of the experiment. It is seen that the performance during minimal fluid application is superior to that is possible during conventional wet milling and dry milling.

6.4.5 Comparative tool wear studies

Average flank wear was measured during dry, wet and minimal fluid application keeping the cutting speed, feed and depth of cut at 45 m/min, 0.14 mm/tooth and 0.4 mm respectively. The fluid application parameters such as the pressure at the fluid injector, frequency of pulsing and the rate of fluid application were maintained as 100 bar, 500 pulses/min and 6.7 ml/min respectively. A twin jet configuration as in Fig. 4.7(b) was selected. The composition of cutting fluid was maintained as 20% oil and rest water and the time was 120 seconds. SEM photographs of flank wear during the three conditions are shown in Fig. 6.10, Fig. 6.11 and Fig. 6.12 respectively.

The average flank wear was 0.127 mm during dry milling, 0.051 mm during conventional wet milling and was as low as 0.014 mm during milling with minimal fluid application. Reduction in the mechanical abrasion due to improved tribology at the flank face owing to effective lubrication and heat reduction achieved both by better tribology
and more effective heat transfer facilitated by evaporative cooling are responsible for reduction in tool wear during minimal fluid application.

6.4.6 Comparison of chip forms

The form of chip produced is an index of the effectiveness of cutting process. Chips with signs of severe deformation are produced during cutting conditions characterized by poor rake face lubrication whereas chips with smooth outer surface with less deformation are produced when cutting is performed with adequate rake face lubrication. According to Kaldor et al. (1979), there are two groups of chip forms (1) Acceptable chips and (2) Unacceptable chips based on the convenience of handling. Acceptable chips do not interfere with the work and the machine tool and do not cause problems of disposal. Unacceptable chips interrupt regular manufacturing operation as they tend to tangle around the tool and the workpiece and pose safety problems to operators. Entangling chips can harm the surface finish and even lead to unexpected tool failure.

SEM photograph in Fig. 6.13 presents the chips formed during dry milling. The chips produced during conventional wet milling is shown in Fig. 6.14. The SEM photograph of chips produced during milling with minimal fluid application is shown in Fig. 6.15. Long snarled chips with serrated edges were seen during dry milling. This is due to the intense thermal stress created at the cutting zone due to the absence of cutting fluid. The deformation is comparatively less on chips during conventional wet milling. Tightly coiled chips with less degree of deformation were seen during minimal fluid application. These chips were shorter in length and could be handled easily. Better tribological condition prevailing at the rake face during minimal fluid application is the main reason for the formation of acceptable chips during minimal fluid application. Embrittlement of the chip caused by Rebinder effect also aids in the formation of chips of shorter length with ease of handling.

Table 6.1 presents a comparison of surface roughness, flank wear and cutting force during dry milling, conventional wet milling and milling with minimal fluid application with the fluid application parameters in the optimized mode when the cutting speed, feed and depth of cut were kept at 45 m/min, 0.14 mm/tooth, 0.4 mm respectively.
It is seen that during minimal fluid application in the optimized mode, there is 34.92% reduction in surface roughness, 27.46% reduction in flank wear and 41.53% reduction in cutting force when compared to conventional wet milling where the quantities of cutting fluid was only 0.16% of that used in conventional wet milling which is a clear indication of the technological superiority of the new technique.

### 6.5 SUMMARY

- Hard milling with minimal fluid application in its optimized mode was compared with conventional wet milling and dry milling under identical cutting conditions by conducting variable speed test, variable feed test and tool life test.
- The overall performance during milling with high velocity pulsed jet minimal fluid application was found to be superior to that during dry milling and conventional wet milling on the basis of cutting force, tool life and surface finish.
- It was observed that tightly coiled acceptable chips that could be handled easily were formed during minimal fluid application.
- SEM analysis revealed that tool damage during milling with minimal fluid application was less when compared to that during conventional wet milling and dry milling.
- During minimal fluid application a very small quantity of cutting fluid performs the duel function of cooling and lubrication. Hence some performance enhancers may be thought of that will aid the cooling and lubrication actions of the cutting fluid and improve the cutting process still further.

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Table 6.1 Comparison of performance during dry, wet and optimized milling with minimal fluid application

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Output parameter</th>
<th>Dry milling</th>
<th>Wet milling</th>
<th>Optimized milling with minimal fluid application (Twin jet)</th>
<th>Percentage decrease when compared to wet milling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Surface roughness (µm)</td>
<td>1.543</td>
<td>1.177</td>
<td>0.411</td>
<td>34.92</td>
</tr>
<tr>
<td>2.</td>
<td>Flank wear (mm)</td>
<td>0.127</td>
<td>0.051</td>
<td>0.014</td>
<td>27.46</td>
</tr>
<tr>
<td>3.</td>
<td>Cutting force (N)</td>
<td>471.73</td>
<td>228.25</td>
<td>94.79</td>
<td>41.53</td>
</tr>
</tbody>
</table>