CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

Full factorial \((L_{27})\) experiments with factors and levels as discussed earlier are conducted and effect of influencing parameters such as tool feed rate, applied voltage, electrolyte discharge rate and rotary speed on MRR and surface roughness in HCHC die steel, AISI 202 Austenitic stainless steel and AISI 1035 Medium carbon steel have been studied and presented. The material removed and MRR are calculated using Formulae 4.1 and 4.2 respectively.

\[
\text{Material removed (g)} = \text{Weight before machining} - \text{Weight after machining} \tag{4.1}
\]

\[
\text{MRR (mm}^3/\text{min}) = \frac{\text{Material removed (g)} \times 1000}{\text{Density of material (g/cc)} \times \text{Machining time (min)}} \tag{4.2}
\]

Practical application of ECM is limited in case of complicated shapes which results in lower machining accuracy (Masuzawa and Kimura 1991). One of the major problems is generation of spikes. Many research investigations revealed that surface roughness of workpiece can be improved substantially by using rotary motion of ECM tool (Kozak et al 1991; Davydov and Kozak 1992; Hewidy 2001; Rajurkar et al 1999a). Hence, it is decided to
bring in the rotating tool of ECM to enhance the surface finish by elimination of spikes over the machined surface. A characteristic of electrolyte used in the process also affects the quality of surface finish. NaCl aqua electrolyte solution tends to produce an etched, matte finish with steels whereas NaNO₃ tends to produce an etch free and glossy surface finish (Sorkhel and Bhattacharyaa 1994). Advanced industries like automobile and metal forming industries need to produce the dies using high carbon high chromium die steel with better surface finish. It is difficult to obtain better surface finish by conventional machining processes especially in materials having high hardness and poor machinability. Hence, investigations have been made to improve the performance of ECM in terms of better MRR and surface roughness using NaCl and NaNO₃ aqua electrolyte solutions under non-rotating and rotating tools.

### 4.2 MRR AND SURFACE ROUGHNESS ANALYSIS

Experimental MRR and surface roughness are found on HCHC die steel, AISI 202 and AISI 1035 using the following conditions.

1. Non-rotating tool with different electrolyte jet patterns, using NaCl aqua electrolyte solution.
2. Rotating tool with different electrolyte jet patterns, using NaCl aqua electrolyte solution.
3. Non-rotating tool with different electrolyte jet patterns, using NaNO₃ aqua electrolyte solution.
4. Rotating tool with different electrolyte jet patterns, using NaNO₃ aqua electrolyte solution.
4.2.1 HCHC Die Steel

Experimental investigations have been made for assessing the effects of influencing parameters on MRR and surface roughness in HCHC die steel, using non-rotating and rotating conditions of tool with different electrolyte jet patterns.

4.2.1.1 Non-rotating tool experiments with NaCl electrolyte

Figure 4.1 shows the effect of electrolyte jet patterns on MRR in HCHC die steel at various feed rates and electrolyte discharge rates under different voltage conditions, using non-rotating tools with 15% NaCl aqua electrolyte solution. At higher voltages, increased tool feed rate and electrolyte discharge rate increases the MRR progressively. Lower electrolyte discharge rate affects the performance of ECM at higher feed rates and voltages, since it is not possible to flush out the residues from the IEG effectively. The improved current intensity at IEG results in higher MRR due to high voltage. Among all electrolyte jet patterns, the straight jet in spiral pattern produced the maximum MRR.

A maximum MRR of 462.863 mm\(^3\)/min with a corresponding surface roughness of 2.21 µm Ra has been achieved by non-rotating tool with straight jet in spiral pattern under 18V, 0.54 mm/min feed rate and 12 l/min of electrolyte discharge rate. The maximum MRR is 21.49% higher than that of non-rotating tool with straight jet in circular pattern result.

Figure 4.2 shows the effect of influencing parameters on surface roughness in HCHC die steel, using non-rotating tools. Surface roughness decreases with increase in feed rate. It is obvious that electrolyte jet patterns improve the surface finish significantly. A trend of improved surface
Figure 4.1 MRR on HCHC die steel while using non-rotating tool with different jet patterns and NaCl electrolyte
Figure 4.2  Surface roughness on HCHC die steel while using non-rotating tool with different jet patterns and NaCl electrolyte
roughness has not been observed with all jet patterns due to the increase in electrolyte discharge rate. Among all electrolyte jet patterns, straight jet in spiral pattern yields lower surface roughness. A minimum surface roughness of 1.81 µm Ra with a corresponding MRR of 425.085 mm³/min is achieved by non-rotating tool with straight jet in spiral pattern under 15V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate. It is 39.46 % lower than that of straight jet in circular pattern under the above conditions. At minimum surface roughness, the achieved MRR is 8.16 % lower than maximum MRR, however, 18.1 % improved surface finish is observed. Experimental results reveal that the performance of non-rotating tool with straight jet in spiral pattern on the MRR and surface roughness is better, using NaCl aqua electrolyte.

4.2.1.2 Rotating tool experiments with NaCl electrolyte

Figure 4.3 shows the effect of rotary action of tool on MRR in HCHC die steel under different voltage conditions. The obtained MRR under rotating tool condition is lower than that of non-rotating tools. The MRR increases with increase in feed rate at all speeds. Rotating tool with straight jet in spiral pattern has performed satisfactorily by yielding better MRR on HCHC die steel, using NaCl aqua electrolyte solution. At 100 RPM, the effect of voltage on MRR is considerable under 0.54 mm/min feed for this pattern. 18 V condition yields 18% higher MRR when compared to 12V. Experimental MRR at 100 RPM is higher than 200 RPM. Hence, it is observed that lower speed is preferable for obtaining better MRR under higher voltages and feed rates. A maximum MRR of 421.068 mm³/min with a corresponding surface roughness of 2.2 µm Ra is achieved by rotating tool with straight jet in spiral pattern under 18V, 0.54 mm/min feed rate and 100 RPM. This is 11.94 % higher when compared to that of straight jet in circular pattern.
Figure 4.4 shows the effect of influencing parameters on surface roughness in HCHC die steel, using rotating tool with different electrolyte jet patterns and 15 % NaCl aqua electrolyte solution. Improved surface finish has been observed by rotating tools under all voltage conditions when compared to non-rotating tool results. The experiments conducted on HCHC die steel with non-rotating tool yielded better results for discharge rate of 12 l/min. Based on these findings and to minimize the number of experiments, it was decided to conduct experiments with rotating tools at 12 l/min discharge rate alone. However, a complete picture on MRR and surface roughness for rotating tool could be assessed only after conducting further experiments. A minimum surface roughness of 1.32 µm Ra is achieved by rotating straight jet in spiral pattern under 12 V, 0.54 mm/min feed rate and 150 RPM which is better by 9.6 % when compared to straight jet in circular pattern result. This in turn, is 27.07 % better when compared to that of non-rotating tool with straight jet in spiral pattern result.

At minimum surface roughness, corresponding MRR of 371.88 mm³/min is achieved. This is 11.94 % lower than maximum MRR. However; 43.83 % of improved surface roughness has been obtained. But most of the surface roughness values are lower than non-rotating tool results which are clearly observed at lower feed rate. Experimental results reveal that rotating tool with straight jet in spiral pattern performs satisfactorily for obtaining better MRR and surface roughness when using NaCl aqua electrolyte solution compared to other electrolyte jet patterns.

4.2.1.3 Non-rotating tool experiments with NaNO₃ electrolyte

It is observed from literature review that NaNO₃ aqua electrolyte solution gives better surface finish whereas NaCl aqua electrolyte solution gives better MRR (Mohan Sen and Shan 2005a). The effect of influencing parameters on the MRR using NaNO₃ aqua solution is shown in Figure 4.5. The MRR on HCHC die steel with NaNO₃ aqua electrolyte solution is lesser
Figure 4.3 MRR on HCHC die steel while using rotating tool with different jet patterns and NaCl electrolyte
Figure 4.4 Surface roughness on HCHC die steel while using rotating tool with different jet patterns and NaCl electrolyte
than that with NaCl aqua electrolyte solution. Improved MRR has been observed under all electrolyte discharge rates except at 8 l/min, for all feed rate conditions. The IEG would not be maintained constant if feed rate of tool is not equivalent to dissolution rate of material resulting in short circuit or physical touch of tool with workpiece. The influence of higher electrolyte discharge rates on MRR in HCHC die steel is substantial. The variation in MRR indicates that electrolyte jet pattern plays a role in improving the performance of ECM.

Among all electrolyte jet patterns, inclined jet in spiral pattern performs distinctly, yielding better MRR under non-rotating conditions of tool. Current carrying capacity of NaNO₃ electrolyte solution is higher than that of NaCl electrolyte solution, as the inclined inward jet spiral pattern distributes electrolyte at IEG in even manner and the availability of electrolyte with an enriched current density results in improved MRR.

A maximum MRR of 320.778 mm³/min in HCHC die steel with a corresponding surface roughness of 0.6 µm Ra is achieved by non-rotating tool with inclined jet in spiral pattern under 15V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate. This is 191.6 % higher than straight jet in circular pattern under the same conditions and 30.69 % lower than non-rotating tool with inclined jet in spiral pattern result using NaCl aqua electrolyte.

Figure 4.6 shows the effect of electrolyte jet patterns on surface roughness under different voltage conditions when using non-rotating tools with 15 % NaNO₃ aqua electrolyte solution. Surface roughness trend with feed rate is similar to that of NaCl electrolyte result. But, most of the values lie between 0.53 µm Ra and 1.93 µm Ra which are much lower when compared to NaCl results. Surface roughness decreases with increase in
Figure 4.5  MRR on HCHC die steel while using non-rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.6 Surface roughness on HCHC die steel while using non-rotating tool with different jet patterns and NaNO₃ electrolyte
voltage, preventing the formation of spikes and also decreases with the increase in electrolyte discharge rate at 18 V.

A minimum surface roughness of 0.53 µm Ra with a corresponding MRR of 294.829 mm³/min is achieved by non-rotating tool with inclined jet in spiral pattern under 12 V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate. It is observed that the minimum surface roughness value is 50% lower than that of straight jet in circular pattern result. At minimum surface roughness, the MRR is less by 8.09% when compared to that at maximum MRR. However, 11.66% improved surface roughness has been achieved when using non-rotating tool with inclined jet in spiral pattern and NaNO₃ aqua electrolyte solution.

Experiments reveal that the performance of non-rotating tool with inclined jet in spiral pattern is significant in obtaining better MRR and surface roughness.

4.2.1.4 Rotating tool experiments with NaNO₃ electrolyte

Experimental investigations were made to find the effect of influencing parameters on MRR in HCHC die steel while using rotating tool with different electrolyte jet patterns and NaNO₃ aqua electrolyte solution. Figure 4.7 shows the effect of different electrolyte jet patterns on MRR. It is lower when compared to MRR result using NaCl electrolyte. The inclined jet in spiral pattern under rotating condition shows the improved performance in terms of MRR. A maximum MRR of 300.577 mm³/min was achieved under 15V, 0.54 mm/min feed rate and 150 RPM. However, it is 6.3% and 35.06% lower when compared to results of non-rotating tool with NaNO₃ and NaCl respectively.
The maximum MRR is 58.69 % higher than that of straight jet in circular pattern. Improved trend of MRR is observed in inclined jet in spiral pattern at 150 RPM because of increase in voltage from 12 V to 15 V. There is a 62 % improvement in MRR under 15V, 0.54 mm/min feed rate and 150 RPM when compared to 12V, 0.54 mm/min feed rate and 150 RPM. The obtained trend of MRR differs completely from rotating tool with NaCl result. A surface roughness of 0.28 µm Ra is achieved under maximum MRR.

Figure 4.8 shows the effect of jet patterns on surface roughness in HCHC die steel when using rotating tool with 15 % NaNO₃ aqua electrolyte solution. Rotating tool with NaNO₃ aqua electrolyte presented a finer surface roughness when compared to that of non-rotating tool with NaNO₃. Surface roughness decreases with increase in feed rate which is similar to HCHC results. Better surface roughness is achieved by most of jet patterns under 200 RPM. Performance of inclined jet in spiral pattern is better, as it produces the best surface finish while using NaNO₃ aqua electrolyte solution. A minimum surface roughness of 0.2 µm Ra is achieved under 12 V, 0.54 mm/min feed rate and 200 RPM. It is observed that the minimum surface roughness value is 66.1 % lower than that of straight jet in circular pattern result.

It is much lower when compared to other jet patterns. Other influencing variables like gas layer at IEG, variation in temperature, concentration, conductivity of electrolyte, electrochemical equivalent of material, valance electron etc., also play a vital role for achieving the finest surface finish. At minimum surface roughness, the MRR was 253.846 mm³/min which is 15.55 % lower when compared to the maximum MRR i.e., 300.577 mm³/min. However, 28.57 % improvement in surface roughness is achieved. The summary of maximum MRR and minimum surface roughness on HCHC die steel is presented in Table 4.1.
Figure 4.7  MRR on HCHC die steel while using rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.8 Surface roughness on HCHC die steel while using rotating tool with different jet patterns and NaNO₃ electrolyte
Table 4.1 Summary of maximum MRR and minimum surface roughness in HCHC die steel

<table>
<thead>
<tr>
<th>S. No</th>
<th>Tool jet pattern</th>
<th>Conditions of tool</th>
<th>Electrolyte solution</th>
<th>Voltage (V)</th>
<th>Feed rate (mm/min)</th>
<th>Electrolyte discharge rate (l/min)</th>
<th>Rotary speed (RPM)</th>
<th>Maximum MRR (mm³/min) and corresponding surface roughness (Ra)</th>
<th>Minimum surface roughness (Ra) and corresponding MRR (mm³/min)</th>
<th>% of improvement*</th>
<th>Increased MRR</th>
<th>Decreased surface roughness</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Straight jet in spiral</td>
<td>Non-rotating</td>
<td>15 % NaCl</td>
<td>18</td>
<td>0.54</td>
<td>12</td>
<td>NA</td>
<td>462.863 and 2.21</td>
<td>--</td>
<td>21.49</td>
<td>9.05</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>0.54</td>
<td>12</td>
<td>NA</td>
<td>--</td>
<td>1.81 and 425.085</td>
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<td>39.46</td>
<td></td>
</tr>
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<td>15 % NaCl</td>
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<td>0.54</td>
<td>NA</td>
<td>100</td>
<td>421.068 and 2.2</td>
<td>--</td>
<td>11.94</td>
<td>12.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.54</td>
<td>NA</td>
<td>150</td>
<td>--</td>
<td>1.32 and 371.88</td>
<td>9.6</td>
<td>43.83</td>
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<td>Inclined jet in spiral</td>
<td>Non-rotating</td>
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<td>0.54</td>
<td>12</td>
<td>NA</td>
<td>320.778 and 0.60</td>
<td>--</td>
<td>191.6</td>
<td>24.05</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.54</td>
<td>12</td>
<td>NA</td>
<td>--</td>
<td>0.53 and 294.829</td>
<td>67.29</td>
<td>50</td>
<td></td>
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<td>4</td>
<td>Inclined jet in spiral</td>
<td>Rotating</td>
<td>15 % NaNO₃</td>
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<td>0.54</td>
<td>NA</td>
<td>150</td>
<td>300.577 and 0.28</td>
<td>--</td>
<td>58.69</td>
<td>54.09</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.54</td>
<td>NA</td>
<td>200</td>
<td>--</td>
<td>0.2 and 253.846</td>
<td>155.2</td>
<td>66.1</td>
<td></td>
</tr>
</tbody>
</table>

*With reference to straight jet in circular pattern
4.2.2 AISI 202 Austenitic Stainless Steel

Similarly, experiments have been conducted on AISI 202 Austenitic stainless steel and the effect of influencing parameters on the MRR and surface roughness are presented.

4.2.2.1 Non-rotating tool experiments with NaCl electrolyte

Figure 4.9 shows the effect of influencing parameters on MRR in AISI 202 when using non-rotating tool with different electrolyte jet patterns and NaCl aqua electrolyte solution. Here too, the effect of feed rate on MRR is clearly noticed. The obtained pattern of MRR with respect to feed rate is similar when compared to that of HCHC die steel. The MRR on AISI 202 is generally lower than that of HCHC die steel. The effect of electrolyte jet patterns on MRR is identical. Non-rotating tool with straight jet in spiral pattern performs satisfactorily for achieving better MRR. Apart from this, improved MRR has been obtained in straight jet in circular pattern and inclined jet in circular pattern. The MRR increases with voltage under 12 l/min electrolyte discharge rate.

A maximum MRR of 425.385 mm$^3$/min is achieved under 18V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate. This is 26% higher when compared to 12 V condition. This kind of improvement has not been observed at 8 l/min electrolyte discharge rate under all three voltage conditions. Hence, it is concluded that the effect of voltage on MRR is insignificant at lower electrolyte discharge rates. The maximum MRR on AISI 202 is 3.67% and 7.7% higher than that of straight jet in circular pattern and inclined jet in circular pattern respectively. The corresponding surface roughness of 1.84 µm Ra is observed under maximum MRR condition.
Figure 4.10 shows the effect of feed rate on surface roughness on AISI 202 under various voltage conditions. Surface roughness trend is almost similar to that of HCHC die steel. Variation in surface roughness indicates the importance of electrolyte jet pattern for improving the performance of ECM. Surface roughness decreases with increase in feed rate. The effect of electrolyte discharge rate on surface roughness is clearly noticed. Higher electrolyte discharge rate enhances the quality of surface finish. A minimum surface roughness of 1.33 µm Ra has been yielded by non-rotating tool with straight jet in spiral pattern under 12 V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate. This is 28.11 % lower when compared to the results of straight jet in circular pattern tool. At minimum surface roughness, a corresponding MRR of 337.949 mm³/min is observed, which is 20.55 % lower when compared to maximum MRR of 425.385 mm³/min. However, 27.77 % improved surface roughness is achieved.

Non-rotating tool with straight jet in spiral pattern shows its performance consistency in AISI 202 also by yielding better MRR and surface roughness while using NaCl aqua electrolyte solution.

4.2.2.2 Rotating tool experiments with NaCl electrolyte

Similarly, experiments were conducted on AISI 202 using rotating tool with different electrolyte jet patterns and 15 % NaCl aqua electrolyte. The effect of influencing parameters on MRR is shown in Figure 4.11. Variation in MRR under different speeds is meager at 18 V. The maximum MRR of 382.393 mm³/min has been achieved by rotating tool with straight jet in spiral pattern under 18V, 0.54 mm/min feed rate and 100 RPM, which is 5.81 % higher when compared to straight jet in circular pattern. The effect of voltage on MRR is significant at all speeds. The MRR on AISI 202 is lower when compared to HCHC die steel while using rotating tools. At maximum MRR, a corresponding surface roughness of 1.22 µm Ra is obtained.
Figure 4.9 MRR on AISI 202 while using non-rotating tool with different jet patterns and NaCl electrolyte
Figure 4.10 Surface roughness on AISI 202 while using non-rotating tool with different jet patterns and NaCl electrolyte
Figure 4.12 shows the effect of influencing parameters on surface roughness in AISI 202 while using rotating tool with NaCl aqua electrolyte. Surface roughness on AISI 202 using rotating tool is lower when compared to that of non-rotating tool and decreases with increase in voltage which is clearly identified with straight jet in spiral pattern under 200 RPM. A minimum surface roughness of 1.12 µm Ra is achieved by rotating tool with straight jet in spiral pattern under 15 V, 0.54 mm/min feed rate and 150 RPM. This is 42.86 % lower than that of straight jet in circular pattern. The minimum surface roughness is improved by 15.79 % when compared to that of non-rotating tool. At minimum surface roughness, a corresponding MRR of 348.444 mm$^3$/min is observed, which is 8.87 % lower when compared to maximum MRR. However, 8.2 % improved surface roughness is achieved.

Rotating tool with straight jet in spiral pattern shows significant improvement on MRR and surface roughness under all working conditions.

4.2.2.3 Non-rotating tool experiments with NaNO$_3$ electrolyte

Figure 4.13 shows the effect of feed rate on MRR in AISI 202 while using NaNO$_3$ aqua electrolyte solution. The MRR increases with increase in feed rate which is clearly exhibited by inclined jet in spiral pattern under all voltage conditions. Effect of voltage on MRR is similar to that of HCHC die steel. The MRR increases with increase in electrolyte discharge rate under all voltage conditions except at 12 V. The maximum MRR of 345.231 mm$^3$/min is achieved by non-rotating tool with inclined jet in spiral pattern under 18 V, 0.54 mm/min and 12 l/min electrolyte discharge rate. This is higher by 5.81 % when compared to MRR of straight jet in circular pattern. At maximum MRR, the surface roughness was 0.45 µm Ra.
Figure 4.11 MRR on AISI 202 while using rotating tool with different jet patterns and NaCl electrolyte
Figure 4.12 Surface roughness on AISI 202 while using rotating tool with different jet patterns and NaCl electrolyte
Figure 4.14 shows the effect of influencing parameters on surface roughness in AISI 202 while using non-rotating tool with 15 % NaNO₃ aqua electrolyte solution. Aqua electrolyte of NaNO₃ shows remarkable performance on AISI 202 which has been identified through the achieved results of surface roughness. Variation in surface roughness for different jet patterns is meager at 8 l/min electrolyte discharge rate. The variation of surface roughness with feed rate is similar to that in HCHC die steel. A minimum surface roughness of 0.34 µm Ra is achieved by non-rotating tool with inclined jet in spiral pattern under 12V, 0.54 mm/min feed rate and 10 l/min electrolyte discharge rate, which is better by 42.86 %, when compared to straight jet in circular pattern. At minimum surface roughness, a corresponding MRR of 202.353 mm³/min is obtained, which is 41.38 % lower when compared to the maximum MRR. However, 24.44 % improved surface roughness has been obtained.

4.2.2.4 Rotating tool experiments with NaNO₃ electrolyte

The experiments were conducted on AISI 202 using rotating tool with NaNO₃ aqua electrolyte solution and results obtained are given in Figure 4.15. The MRR is better at 200 RPM, compared to 100 RPM under 18 V. The performance consistency of inclined jet in spiral pattern is ascertained through achieving better MRR on AISI 202. A maximum MRR of 230.769 mm³/min is yielded by rotating tool with inclined jet in spiral pattern under 18 V, 0.54 mm/min feed rate and 200 RPM. This is 57.62 % higher, when compared to straight jet in circular pattern. The maximum MRR is 33.15 % lower than the MRR with non-rotating tool. At maximum MRR, a corresponding surface roughness of 0.13 µm Ra is observed.
Figure 4.13 MRR on AISI 202 while using non-rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.14 Surface roughness on AISI 202 while using non-rotating tool with different jet patterns and NaNO$_3$ electrolyte
Figure 4.16 shows the improved performance of ECM while using rotating tool with different electrolyte jet patterns. Surface roughness on AISI 202 is much lower for rotating tool with NaNO₃ aqua electrolyte in comparison with NaCl aqua electrolyte. Most of the surface roughness values lie between 0.54 µm Ra and 0.1 µm Ra. Among all jet patterns, inclined jet in spiral pattern is consistent under all working conditions. The best surface roughness of 0.1 µm Ra is achieved by rotating tool with inclined jet in spiral pattern under 18V, 0.54 mm/min feed rate and 100 RPM. It is an improvement by 64.29 % when compared to straight jet in circular pattern. At minimum surface roughness, a corresponding MRR of 115.224 mm³/min is observed, which is 50 % lower than that with maximum MRR, but the surface roughness is improved by 23.07 %.

Experiments reveal that rotating tool with inclined jet in spiral pattern performs satisfactorily for obtaining better MRR and surface roughness on AISI 202. The summary of maximum MRR and minimum surface roughness on AISI 202 is presented in Table 4.2.

### 4.2.3 AISI 1035 Medium Carbon Steel

Experimental MRR and surface roughness on AISI 1035 are found and the effects of influencing parameters discussed.

#### 4.2.3.1 Non-rotating tool experiments with NaCl electrolyte

In the same way, experiments were conducted on AISI 1035 under different working conditions in order to analyze the performance consistency, of different electrolyte jet patterns on MRR using 15 % NaCl aqua electrolyte.

Figure 4.17 shows the pattern of MRR on AISI 1035 under different working conditions. It is noted that MRR increases with increasing feed rate under all voltage conditions. The effect of electrolyte discharge rate is significant on
Figure 4.15 MRR on AISI 202 while using rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.16 Surface roughness on AISI 202 while using rotating tool with different jet patterns and NaNO₃ electrolyte
Table 4.2 Summary of maximum MRR and minimum surface roughness in AISI 202

<table>
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<tr>
<th>S.No</th>
<th>Tool jet pattern</th>
<th>Conditions of tool</th>
<th>Electrolyte solution</th>
<th>Voltage (V)</th>
<th>Feed rate (mm/min)</th>
<th>Electrolyte discharge rate (l/min)</th>
<th>Rotary speed (RPM)</th>
<th>Maximum MRR (mm$^3$/min) and surface roughness (Ra)</th>
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<th>% of improvement</th>
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<td>382.393 and 1.22</td>
<td>--</td>
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<td>0.54</td>
<td>10</td>
<td>NA</td>
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<td>0.34 and 202.353</td>
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<td>15 % NaNO$_3$</td>
<td>18</td>
<td>0.54</td>
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<td>230.769 and 0.13</td>
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<td>0.1 and 115.224</td>
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</table>

*With reference to straight jet in circular pattern
MRR under all voltage conditions. Here too, non-rotating tool with straight jet in spiral pattern performs significantly good. A maximum MRR of 400.641 mm$^3$/min is achieved by non-rotating tool with straight jet in spiral pattern under 18V, 0.54 mm/min and 12 l/min electrolyte discharge rate. This is 7.22 % higher than MRR of straight jet in circular pattern. 3-8 % of improved MRR is achieved by the same pattern due to increase in electrolyte discharge rates. This in turn, facilitates to flush out the residues causing high current density at IEG, resulting in improved MRR. At maximum MRR, a corresponding surface roughness of 1.47 µm Ra is observed.

Figure 4.18 shows the effect of feed rate on surface roughness of AISI 1035 when using non-rotating tool with NaCl aqua electrolyte solution, which is similar to the effects on HCHC die steel and AISI 202. The variation in surface roughness is meager under all jet patterns at 12 V and 0.54 mm/min feed rate. Non-rotating tool with straight jet in spiral pattern performs satisfactorily to achieve better surface roughness in AISI 1035. A minimum surface roughness of 1.38 µm Ra is achieved by the same pattern under 18 V, 0.54 mm/min feed rate and 10 l/min electrolyte discharge rate.

It is lower by 7.38 % when compared to the results of straight jet in circular pattern tool. At minimum surface roughness, a corresponding MRR of 366.197 mm$^3$/min is achieved, which is 8.59 % low when compared to maximum MRR. However, surface roughness is improved by 6.12 %.

Experiments show that better MRR and surface roughness are achieved by non-rotating tool with straight jet in spiral pattern while using NaCl aqua electrolyte solution.
Figure 4.17 MRR on AISI 1035 while using non-rotating tool with different jet patterns and NaCl electrolyte
Figure 4.18 Surface roughness on AISI 1035 while using non-rotating tool with different jet patterns and NaCl electrolyte.
4.2.3.2  Rotating tool experiments with NaCl electrolyte

Figure 4.19 shows the improved performance of ECM in terms of MRR when machining AISI 1035 using 15 % NaCl aqua electrolyte. The pattern of MRR with respect to feed rate is similar to HCHC die steel and AISI 202 under both conditions of tool. It is clearly observed that MRR increases with increase in feed rate. Among all jet patterns, straight jet pattern yields better MRR on AISI 1035 which has already been recognized in HCHC die steel and AISI 202 with NaCl electrolyte solution.

A maximum MRR of 457.65 mm$^3$/min is achieved by rotating tool with straight jet in spiral pattern under 18 V, 0.54 mm/min feed rate and 100 RPM which is 30.69 % higher when compared to the results of straight jet in circular pattern. The maximum MRR of AISI 1035 is 14.22 % higher when compared to that of non-rotating tool with straight jet in spiral pattern.

Non-rotating tool yields better MRR than rotating tool. Rotating tool with straight jet in spiral pattern and NaCl aqua electrolyte is preferred for machining of AISI 1035. The improved MRR is observed at all speeds in straight jet in spiral pattern. At 100 RPM, MRR observed at 18 V is 34 % higher compared to that at 12 V. It is concluded that lower speeds is preferred for yielding better MRR on AISI 1035 by rotating tool with straight jet in spiral pattern. At maximum MRR, a corresponding surface roughness of 1.49 µm Ra is observed.

Figure 4.20 shows the effect of feed rate on surface roughness in AISI 1035 when using rotating tool with 15 % NaCl aqua electrolyte solution. Most of surface roughness values lie between 2.84 µm Ra and 1.12 µm Ra. Improvement in surface roughness achieved by rotating tool is more, compared to non-rotating tool results of AISI 1035. Surface roughness
decreases with increase in feed rate which is similar to non-rotating tool results.

The effect of voltage is significant at higher speeds. A minimum surface roughness of 1.12 µm Ra is achieved by rotating tool with straight jet in spiral pattern under 12 V, 0.54 mm/min feed rate and 150 RPM. This is 33.73 % low when compared to straight jet in circular pattern result and also the minimum surface roughness is 18.84 % low when compared to non-rotating tool with NaCl result. At minimum surface roughness, a corresponding MRR of 284.15 mm³/min is observed, which is 37.91 % lower than maximum MRR. However, the minimum surface roughness on AISI 1035 is improved by 24.83 %.

It is concluded that rotating tool with straight jet in spiral pattern performs satisfactorily for obtaining better MRR and surface roughness on AISI 1035. In general, NaCl electrolyte is preferred for getting better MRR. AISI 1035 experimental results also show that NaCl electrolyte is preferred to produce better surface roughness while using rotating tool with straight jet in spiral pattern.

4.2.3.3 Non-rotating tool experiments with NaNO₃ electrolyte

Figure 4.21 shows the trend of MRR on AISI 1035 while using non-rotating tool with NaNO₃ aqua electrolyte solution. As mentioned earlier, the performance consistency of selected electrolyte jet patterns is evaluated by machining different materials. The effect of feed rate on MRR is clearly noticed which is similar to HCHC die steel and AISI 202. Inclined jet in spiral pattern achieves better MRR under all working conditions. A maximum MRR of 374.872 mm³/min is achieved by non-rotating tool with inclined jet in spiral pattern under 18 V, 0.54 mm/min feed rate and 10 l/min electrolyte discharge rate. This is 99.73 % higher than that of straight jet in circular
Figure 4.19 MRR on AISI 1035 while using rotating tool with different jet patterns and NaCl electrolyte
Figure 4.20 Surface roughness on AISI 1035 while using rotating tool with different jet patterns and NaCl electrolyte
pattern tool. Under 10 l/min electrolyte discharge rate, MRR is 24% higher at 18 V when compared to that at 12 V. It is evident that MRR increases with increase in voltage (Hocheng 2003) and the corresponding surface roughness of 1.44 µm Ra is observed under maximum MRR.

Figure 4.22 shows AISI 1035 surface roughness results when using non-rotating tool with 15 % NaNO₃ aqua electrolyte solution. The effect of NaNO₃ electrolyte aqua solution on surface roughness in AISI 1035 is insignificant, because surface roughness values are slightly lower than NaCl result. Surface roughness decreases with increase in electrolyte discharge rate which is established in HCHC die steel and AISI 202. A minimum surface roughness of 1.31 µm Ra is achieved by non-rotating tool with inclined jet in spiral pattern under 12 V, 0.54 mm/min feed rate and 10 l/min electrolyte discharge rate, which is 31.41 % lower than that of straight jet in circular pattern tool. At minimum surface roughness, a corresponding MRR of 285.897 mm³/min is observed, which is 23.73 % lower than that with maximum MRR, but surface roughness is improved by 9 %.

Hence, it is concluded that non-rotating tool with inclined jet in spiral pattern shows performance consistency on MRR and surface roughness, while using NaNO₃ aqua electrolyte solution.

4.2.3.4 Rotating tool experiments with NaNO₃ electrolyte

Figure 4.23 shows the effect of influencing parameters on MRR in AISI 1035 while using rotating tool with different jet patterns and 15 % NaNO₃ aqua electrolyte solution. Among all jet patterns, inclined jet in spiral pattern performs satisfactorily by yielding better MRR. Improved MRR is observed at 200 RPM due to increase of voltage from 12 V to 18 V. A maximum MRR of 292.684 mm³/min is achieved by rotating tool with
Figure 4.21 MRR on AISI 1035 while using non-rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.22 Surface roughness on AISI 1035 while using non-rotating tool with different jet patterns and NaNO₃ electrolyte
inclined jet in spiral pattern under 18 V, 0.54 mm/min feed rate and 200 RPM. This is higher than straight jet in circular pattern result by 31.22 %. At maximum MRR, a corresponding surface roughness of 1.37 µm Ra is observed. Thus, the effect of inclined jet in spiral pattern on MRR is notable with NaNO₃ aqua electrolyte solution under both conditions of tool.

Figure 4.24 shows the effect of influencing parameters on surface roughness in AISI 1035 when using rotating tool with 15 % NaNO₃ aqua electrolyte solution. The effect of NaNO₃ aqua electrolyte solution on surface roughness in AISI 1035 is insignificant. Feed rate effect on surface roughness is similar to AISI 202 and HCHC die steel results. There is no significant effect of rotary tool speed on surface roughness. A minimum surface roughness of 1.38 µm Ra is obtained by rotating tool with inclined jet in spiral pattern under 18 V, 0.54 mm/min feed rate and 100 RPM. This is 26.2 % higher than the results of straight jet in circular pattern. At minimum surface roughness, a corresponding MRR of 278.632 mm³/min is observed, which is 4.81 % lower when compared to maximum MRR. The summary of maximum MRR and minimum surface roughness on AISI 1035 is presented in Table 4.3.

But the minimum surface roughness is only 1 % lower compared to that at the maximum MRR. It is concluded that rotating tool with inclined jet in spiral pattern performs satisfactorily for obtaining better MRR and surface roughness on AISI 1035 while using NaNO₃ aqua electrolyte solution.
Figure 4.23 MRR on AISI 1035 while using rotating tool with different jet patterns and NaNO₃ electrolyte
Figure 4.24 Surface roughness on AISI 1035 while using rotating tool with different jet patterns and NaNO$_3$ electrolyte
Table 4.3 Summary of maximum MRR and minimum surface roughness in AISI 1035

<table>
<thead>
<tr>
<th>S.No</th>
<th>Tool jet pattern</th>
<th>Conditions of tool</th>
<th>Electrolyte solution</th>
<th>Voltage (V)</th>
<th>Feed rate (mm/min)</th>
<th>Electrolyte discharge rate (l/min)</th>
<th>Rotary speed (RPM)</th>
<th>Maximum MRR (mm³/min) and surface roughness (Ra)</th>
<th>Minimum surface roughness (Ra) and MRR (mm³/min)</th>
<th>% of improvement</th>
<th>MRR</th>
<th>Surface roughness</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Straight jet in spiral</td>
<td>Non-rotating</td>
<td>15 % NaCl</td>
<td>18</td>
<td>0.54</td>
<td>12</td>
<td>NA</td>
<td>400.641 and 1.47</td>
<td>--</td>
<td>7.22</td>
<td>11.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>0.54</td>
<td>10</td>
<td></td>
<td>--</td>
<td>1.38 and 366.197</td>
<td>11.14</td>
<td>7.38</td>
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<td>Rotating</td>
<td>15 % NaCl</td>
<td>18</td>
<td>0.54</td>
<td>NA</td>
<td>100</td>
<td>457.65 and 1.49</td>
<td>--</td>
<td>30.69</td>
<td>8.59</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.54</td>
<td>150</td>
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<td>--</td>
<td>1.12 and 284.145</td>
<td>3.63</td>
<td>33.73</td>
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<td>3</td>
<td>Inclined jet in spiral</td>
<td>Non-rotating</td>
<td>15 % NaNO₃</td>
<td>18</td>
<td>0.54</td>
<td>10</td>
<td>NA</td>
<td>374.872 and 1.44</td>
<td>--</td>
<td>99.73</td>
<td>20.44</td>
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<td>12</td>
<td>0.54</td>
<td>10</td>
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<td>1.31 and 285.897</td>
<td>14.74</td>
<td>31.41</td>
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<tr>
<td>4</td>
<td>Inclined jet in spiral</td>
<td>Rotating</td>
<td>15 % NaNO₃</td>
<td>18</td>
<td>0.54</td>
<td>NA</td>
<td>200</td>
<td>292.684 and 1.37</td>
<td>--</td>
<td>31.22</td>
<td>15.95</td>
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<td></td>
<td>18</td>
<td>0.54</td>
<td>100</td>
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<td>--</td>
<td>1.38 and 278.632</td>
<td>9.05</td>
<td>26.2</td>
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</table>

*With reference to straight jet in circular pattern*
4.3 SUMMARY

Experiments have been conducted on HCHC die steel, AISI 202 and AISI 1035 using non-rotating and rotating tools with different jet patterns and the effects of influencing parameters on MRR and surface roughness are presented. The salient results of experimentation are presented in Table 4.4.

Based on the experimental results, the following conclusions are drawn.

1. Electrolyte jet patterns have an impact on the MRR and surface roughness.
2. **Straight jet in spiral pattern** under non-rotating and rotating tool conditions performs satisfactorily yielding better MRR and surface roughness when NaCl aqua electrolyte solution is used.
3. **Inclined jet in spiral pattern** under non-rotating and rotating tool conditions performs satisfactorily yielding better MRR and surface roughness when NaNO₃ aqua electrolyte solution is used.
4. **Non-rotating tool** yields a maximum MRR when compared to that of rotating tool, when NaCl aqua solution for the selected materials is used.
5. At lower speeds, NaCl aqua electrolyte solution helps the rotating tools to achieve better MRR, whereas at higher speeds similar results are obtained if NaNO₃ aqua electrolyte solution is used.
6. Better **surface roughness** has been achieved by **rotating tool** when NaNO₃ aqua electrolyte solution is used for the selected materials.
7. A maximum MRR of 462.863 mm$^3$/min has been achieved in HCHC die steel by non-rotating tool with straight jet in spiral pattern when NaCl electrolyte at 18V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate is used. A minimum surface roughness of 0.2 µm Ra has been achieved by rotating tool with inclined jet in spiral pattern when NaNO$_3$ aqua electrolyte solution under 12 V, 0.54 mm/min feed rate and 200 RPM is used.

8. A maximum MRR of 425.385 mm$^3$/min has been achieved in AISI 202 Austenitic stainless steel by non-rotating tool with straight jet in spiral pattern when NaCl electrolyte at 18V, 0.54 mm/min feed rate and 12 l/min electrolyte discharge rate is used. A minimum surface roughness of 0.1 µm Ra has been achieved by rotating tool with inclined jet in spiral pattern when NaNO$_3$ aqua electrolyte under 12 V, 0.54 mm/min feed rate and 100 RPM is used.

9. A maximum MRR of 457.65 mm$^3$/min has been achieved in AISI 1035 Medium carbon steel by rotating tool with straight jet in spiral pattern when NaCl electrolyte at 18V, 0.54 mm/min feed rate and 100 RPM is used. A minimum surface roughness of 1.12 µm Ra has been achieved by rotating tool with straight jet in spiral pattern when NaCl aqua electrolyte under 12 V, 0.54 mm/min feed rate and 150 RPM is used.
Table 4.4 Summary of Experimental results

<table>
<thead>
<tr>
<th>S. No</th>
<th>Material</th>
<th>Tool electrolyte jet pattern</th>
<th>Maximum MRR obtained condition</th>
<th>Electrolyte</th>
<th>Tool condition</th>
<th>Minimum Surface roughness obtained condition</th>
<th>Electrolyte</th>
<th>Tool condition</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>MRR (mm^3/min)</td>
<td>Surface roughness (Ra)</td>
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<td>MRR (mm^3/min)</td>
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<tr>
<td>1</td>
<td>HCHC die steel</td>
<td>Straight jet in circular pattern</td>
<td>384.017</td>
<td>2.99</td>
<td>NaCl</td>
<td>Non-rotating</td>
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<td>Rotating</td>
<td>0.36</td>
<td>113.761</td>
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<td>Inclined jet in square pattern</td>
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<td>Non-rotating</td>
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<td>257.65</td>
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<td>1.92</td>
<td>NaCl</td>
<td>Non-rotating</td>
<td>1.24</td>
<td>276.538</td>
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<td>NaCl</td>
<td>Rotating</td>
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<td>NaCl</td>
<td>Non-rotating</td>
<td>1.39</td>
<td>280.684</td>
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