CHAPTER 6

RESULTS AND DISCUSSION

6.1 INTRODUCTION – CASE STUDIES

The developed web-enabled knowledge base system has been uploaded on www.selectntm.com for the users to access the system and perform the selection of most suitable Non-Traditional Machining Processes (NTMPs) for a given machining problem. Provision is also made for administrator to access and modify the knowledge base through login window on www.selectntm.com/admin, by inputting the proper user Id and password (User Id: examiner; Password: ntmps). Several case studies (more than 25) have been taken from local manufacturing industries dealing with NTMPs in order to assess the performance of the developed system. The problem statement, input limiting requirements, a detailed analysis, and observation for ten selected case studies are presented in this Chapter. Remaining case studies are enclosed in Appendix 2. The results for the case studies given in Appendix 2 can be verified through online by accessing the web page: www.selectntm.com and inputting the limiting requirements for the respective case studies. The input web page screen shot showing the limiting requirements and output web page screen shot showing the list of most suitable NTMPs for the selected case studies are also presented in this Chapter in order to demonstrate the performance of the present approach.
6.2 CASE STUDY 1

6.2.1 Problem Statement

The small scale industry currently employs EDM to produce a die block made of Oil Hardened Nitride Steel (OHNS). The part $80 \times 100 \times 37.5$ mm has six complex blind cavities. In one application, a quality control check on the tolerance and surface finish achieved were within $\pm 0.03$ mm and $0.5$ $\mu$m Ra respectively. The depth of cut and corner radii of the part are $23$ mm and $0.25$ mm respectively. Minimum taper is $0.001$ mm/mm (Lucas 2008).

6.2.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.1 are as follows:

- Material : Tool Steel
- Shape Application : Pocketing (shallow)
- Min. Surface finish : $0.5$ $\mu$m Ra
- Min. Tolerance : $\pm 30$ $\mu$m
- Min. Taper : $0.001$ mm/mm
- Depth of Cut : $23$ mm
- Min. Corner radii of the part : $0.25$ mm.

6.2.3 Analysis

From the sample result of the program shown in Figure 6.2, it is observed that only EDM is found to be the most suitable NTMP for the given part. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMPs eliminated on the basis of the Shape Applications are EBM, PAM, and WEDM (Table 5.3). WJM, AJM, CHM, ECM, ECG,
USM, and ECH (Table 5.5) are eliminated due to process capability attributes such as tolerance, surface finish, width of cut, corner radii, taper etc. The important attributes used in ranking are Pocketing (shallow), Min.Tolerance, Min.Surface finish and Min.Taper. For this case study EDM is recommended for the application described. The developed procedure is highly sensitive to the grade values assigned to the various attributes. For an inexperienced NTMP user, it is very difficult to make decisions on the comparison of grade values between different NTMPs. In this case study, no information is given about Min. width of cut, Min.Over cut, Max. depth to diameter ratio and Max.Surface damage, hence these factors may influence the ranking score, if considered.

6.2.4 Observation

It is observed that only EDM is found to be the most suitable NTMP for the given part. In this Case study, if Tolerance is considered as the important attribute then USM would have had the highest ranking score owing to its capability in achieving close tolerance values. It is also observed from the output of the programme that EDM secured a very high Total grade (Total Grade: 16) (Table 5.1) securing maximum grades on all the individual grades such as Material Grade (good: 3), Shape Grade (good: 3) and Process Grade (fairly good in providing the given tolerance, surface finish and corner radii: 10). This reiterates the fact from the literature that EDM is found extremely good in pocketing applications particularly on Steel Products and can very easily achieve a tolerance of 30 µm.
Figure 6.1 Screen shot of the input web page for Case study 1
Figure 6.2 Screen shot of the output web page for Case study 1
6.3 CASE STUDY 2

6.3.1 Problem Statement

The automotive ancillary unit currently employs WEDM for several years to produce a commutator inner profile forming punch made of OHNS hardened to 60 HRC. The part Ø45 × 140 mm has 23 teeth. The tolerance and surface finish achieved are ± 0.0075 mm and 0.3 µm Ra, respectively (Lucas 2008).

6.3.2 Limiting requirements

Limiting requirements for this example as shown in Figure 6.3 are as follows:

- Material : Tool Steel (OHNS)
- Shape Application : Through Cutting (Shallow)
- Min. Tolerance : ± 7.5 µm
- Min. Surface finish : 0.3 µm Ra
- Min. Width of cut : 0 (i.e., not given)
- Min. Taper : 0 (i.e. not given)

6.3.3 Analysis

From the sample result of the program shown in Figure 6.4, it is observed that WEDM is found to be the most suitable NTMP for the given part. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMPs eliminated on the basis of the Shape Applications are EBM, ECG, and ECH (Table 5.3). WJM, CHM, ECM, EDM, ECG, AJM, USM, and ECH (Table 5.5) are eliminated due to process capability attributes. The important attributes used in ranking are Through Cutting (Shallow),
Min.Tolerance and Min.Surface finish. For this case study WEDM is recommended for the application described.

6.3.4 Observation

It is observed that WEDM is found to be the most suitable NTMP for the given part. It is worth mentioning that the company’s experts approved the system selection and they declare that they are using WEDM based on availability and cost. From the output of the programme it is clear that WEDM secured very high scores in Material application (good: 3), Shape application (good: 3) and a moderate score in Process grade (grade value secured: 8). It is also observed from the output of the programme that WEDM is the best among all the NTMPs for process available for shallow through cutting operation on Oil Hardened Nitride Steel and a close tolerance of 7.5 µm can be achieved using WEDM with ease. The NTMPs in the list next to WEDM could be EDM, WJM, and AJM etc., if a tolerance value of 50 µm is considered.
Figure 6.3 Screen shot of the input web page for Case study 2
Figure 6.4 Screen shot of the output web page for Case study 2
6.4 CASE STUDY 3

6.4.1 Problem Statement

The Die making industry currently employs EDM to produce a die block made of OHNS which is used to manufacture Deoball (made of plastics) by injection moulding. The part 110 × 100 × 36 mm has a complicated hemi-spherical blind cavity as shown in Figure 6.5. The tolerance and surface finish achieved were within ± 0.03 mm and 0.5 µm Ra respectively. The corner radius maintained is 0.1mm (Nutech 2008).

Figure 6.5 Part drawing of the die block used to manufacture deoball
6.4.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.6 are as follows:

Material : Steel
Shape Application : Pocketing Shallow
Tolerance : ± 0.03 mm
Surface finish : 0.5 µm Ra
Taper : 0 (not given)
Corner radii of the part : 0.1 mm.

6.4.3 Analysis

From the sample result of the program shown in Figure 6.7, it is observed that ECH, EDM, and USM are found to be the most suitable NTMPs for the given part with the stated requirements. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMPs eliminated on the basis of the Shape Applications are PAM, and WEDM (Table 5.3). WJM, CHM, ECM, AJM, EBM, LBM, and ECG (Table 5.5) are eliminated due to process capability attributes. The important attributes used in ranking are Shallow Pocketing, Min. Tolerance, Min. Surface finish and Min. Corner radii. In this case study ECH obtained the highest ranking score (Figure 6.7). In this case study, no information is given about Min. width of cut, Min. Over cut, Max. depth to diameter ratio and Max. Surface damage, and Min. Taper and hence these factors may influence the ranking score, if considered.
6.4.4 Observation

It is observed that the process grade for ECH is maximum (Process Grade: 12) and hence the overall ranking score of ECH is the highest (Total Grade: 18) of all the three most suitable NTMPs in the final list. The shape application grade (poor: 1) and material application grade (fair: 2) obtained for USM is the least of all the three NTMPs selected in the list and hence USM is ranked last in the list. Even though USM is good in achieving close tolerance values, the shape and material application parameters influenced the decision there by bringing USM to the last position. If materials like refractories and glass are considered then USM could be the best choice. Because of poor process grade, EDM is found second in the list even though EDM is very good in pocketing operations on OHNS material. In this case study, it is evident that the better process capability of ECH influenced on EDM and USM (inspite of their good application and shape capabilities) to be ranked first among the list of most suitable NTMPs. In this case study, there is every possibility that EDM or USM may take the first position, if the process capability attributes are slightly relaxed.
Figure 6.6 Screen shot of the input web page for Case study 3
**Figure 6.7 Screen shot of the output web page for Case study 3**

### Considering factors

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape Application</td>
<td>Pocketing/Shallow</td>
</tr>
<tr>
<td>Process Economy</td>
<td></td>
</tr>
<tr>
<td>Process Capabilities</td>
<td>Tolerance (μm): 30</td>
</tr>
<tr>
<td>Minimum Surface Finish (μm Ra): 0.5</td>
<td></td>
</tr>
<tr>
<td>Minimum Corner Radius (mm): 1.1</td>
<td></td>
</tr>
</tbody>
</table>

### RESULT: Most Suitable Process

<table>
<thead>
<tr>
<th>Rank</th>
<th>Process name</th>
<th>Material Grade:3</th>
<th>Process Grade:12</th>
<th>Shape Grade:3</th>
<th>Total Grade:16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ECH</td>
<td>Material Grade:3</td>
<td>Process Grade:12</td>
<td>Shape Grade:3</td>
<td>Total Grade:16</td>
</tr>
<tr>
<td>2</td>
<td>EDM</td>
<td>Material Grade:3</td>
<td>Process Grade:5</td>
<td>Shape Grade:3</td>
<td>Total Grade:11</td>
</tr>
<tr>
<td>3</td>
<td>USM</td>
<td>Material Grade:2</td>
<td>Process Grade:7</td>
<td>Shape Grade:1</td>
<td>Total Grade:10</td>
</tr>
</tbody>
</table>


6.5 CASE STUDY 4

6.5.1 Problem Statement

A Die Block 120 × 120 × 120 mm with HRc 35 made of P20 Steel has a complicated conical blind cavity for Ø87.5 × 92.5 mm with half taper angle 26.26° located at its centre. The Conical cavity is machined using Vertical Machining Centre (VMC). Only the bottom part of the conical cavity with Ø35 × 37 mm has been performed using EDM for several years. The tolerance and the surface finish maintained are ± 0.03 mm and 5 µm Ra respectively. The Min.Taper is 0.05 mm/mm (Jeytech 2008).

6.5.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.8 are as follows:

Material : Steel
Shape Application : Blind conical cavity
Min. Surface finish : 10 µm Ra
Min. Tolerance : ± 30 µm
Min. Taper : 0.05 mm/mm
Min. Corner radii of the part : 0.1 mm.

6.5.3 Analysis

From the sample result of the program shown in Figure 6.9, it is observed that EDM and USM are found to be the most suitable NTMPs for the given part with the stated requirements. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMPs eliminated on the basis of the Shape Applications are ECH, and PAM (Table 5.3). WJM, CHM, ECM, AJM, EBM, LBM, WEDM and ECG (Table 5.5) are eliminated due to
process capability attributes. The important attributes used in ranking are Conical blind cavity (shallow), Min. Tolerance, Min. Surface finish and Min. Corner radii. In this case study, no information is given about Min. width of cut, Min. Over cut, Max. depth to diameter ratio and Min. Surface damage, and Min. Taper and hence these factors may influence the ranking score, if considered.

6.5.4 Observation

It is observed that EDM and USM are found to be the most suitable NTMPs for the given part with the stated requirements. It is also observed that the shape application (good: 3), material application grade (good: 3), process grade (fair: 10) and Total grade (fair: 16) obtained for EDM is the highest of the two NTMPs selected in the list and hence USM is ranked 1st among the two most suitable NTMPs. It is worth mentioning that the company’s experts approved the system selection and they declare that they are using EDM based on availability and cost. In this case study process capabilities and shape application grades influenced the selection that EDM obtained the highest ranking score owing to its good process capability and shape application. USM obtained a reasonable process grade (fair: 8) but because of poor shape (poor: 1) and material grade (fair: 2), the Total grade (fair: 11) is reduced and hence USM secured the 2nd position only. USM may secure the 1st position, if close tolerance values are considered.
Figure 6.8 Screen shot of the input web page for Case study 4
Figure 6.9 Screen shot of the output web page for Case study 4
6.6 CASE STUDY 5

6.6.1 Problem Statement

An American automobile manufacturer has need trepanning for drilling lubrication holes in an internal gear used in transmission. The gear is fabricated from hot forged powder steel 4662 alloy hardened to HRC 60. The requirements for the holes included a diameter of $1.2 \pm 0.15$ mm, taper not to exceed $0.05$ mm/mm and a hole length of $7.6$ mm (Johnson 1984).

6.6.2 Limiting Requirements

Limiting requirements for this example as shown in 6.10 are as follows:

- **Material**: Steel
- **Min. Surface finish**: 0 (i.e. not given)
- **Min. Tolerance**: $\pm 150$ µm
- **Min. Width of cut**: 0 (i.e., not given)
- **Min. Taper**: 0.05 mm/mm
- **Hole Length**: 7.6 mm
- **Hole diameter**: 1.52
- **L/D ratio**: 5.0 (=7.6/1.52).

6.6.3 Analysis

From the sample result of the program shown in Figures 6.11, it is observed that WEDM, EDM, ECM, USM, AJM, WJM, EBM, and LBM are the most suitable for the given part. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). No NTMPs eliminated on the basis of the Shape Application as well (Table 5.3). ECG and ECH and CHM (Table 5.5) are eliminated due to process capability attributes. The important
attributes used in ranking are Hole L/D < 20, Min.Tolerance and Min.Surface finish and Min.Taper.

6.6.4 Observation

It is observed that the process grade (good: 10) for ECM the highest among the most suitable NTMPs in the selection list. It is also seen from the output of the programme that the process grades for WEDM (process grade: 8) and EDM (process grade: 8) are the second highest and hence the overall ranking score of WEDM and EDM secured 2nd position (with equal Total grade: 11 each) among the most suitable NTMPs in the selection list. The WJM and USM obtained a reasonable process grade but because of poor material grade and shape grade, they could secure only third position (with equal Total Grade: 8 each). The process grade obtained for AJM, EBM and LBM is the least of all the seven NTMPs selected and hence their overall ranking score is very low. The procedure proposed by Cogun (1994) displays EDM, ECM, EBM and LBM as candidate NTMPs selected for the production of the part. It is observed that the most suitable NTMPs displayed by the developed system accommodate all the four NTMPs selected as candidates by the procedure proposed by Cogun (1994). Since the list of most suitable NTMPs obtained is very lengthy with 8 out of 12 NTMPs available in the selection list (because of loose design requirements in this case study), the selection procedure developed is unable to give a short listed NTMPs and hence certain other important selection parameters such as machining cost, machining time, and MRR can be included in the selection procedure and a refined and meaningful selection can be made.
Figure 6.10 Screen shot of the input web page for Case study 5
**Figure 6.11** Screen shot of the output web page for Case study 5 (Continued)
**RESULT: Most Suitable Process**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Process Name</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ECM</td>
<td>Material Grade: 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 13</td>
</tr>
<tr>
<td>2</td>
<td>WEDM</td>
<td>Material Grade: 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 11</td>
</tr>
<tr>
<td>3</td>
<td>EDM</td>
<td>Material Grade: 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 11</td>
</tr>
<tr>
<td>4</td>
<td>WJM</td>
<td>Material Grade: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 8</td>
</tr>
<tr>
<td>5</td>
<td>USM</td>
<td>Material Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 8</td>
</tr>
<tr>
<td>6</td>
<td>ESM</td>
<td>Material Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 4</td>
</tr>
<tr>
<td>7</td>
<td>AJM</td>
<td>Material Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 4</td>
</tr>
<tr>
<td>8</td>
<td>LSM</td>
<td>Material Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process Grade: 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Grade: 4</td>
</tr>
</tbody>
</table>

**Figure 6.11** Screen shot of the output web page for Case study 5
6.7 CASE STUDY 6

6.7.1 Problem Statement

As reported by Rutan (1994) special USM tools are used to produce multitude of holes simultaneously in precise patterns. A 0.64 mm thick, non-conductive, ceramic substrate (made of aluminium oxide) is used by the electronics industry. USM was used to simultaneously drill 930 holes of diameter 0.112 mm. The entire operation was performed in 8.5 min using array stainless steel hypodermic needles as tools and 320 grit boron carbide as the abrasive. The process time equates to approximately 0.5 s/hole.

6.7.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.12 are as follows:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ceramic (non-conductive)</td>
</tr>
<tr>
<td>Shape Application</td>
<td>Cylindrical through hole drilling</td>
</tr>
<tr>
<td>Min. Surface finish</td>
<td>0 (i.e. not given)</td>
</tr>
<tr>
<td>Min. Tolerance</td>
<td>± 250 µm</td>
</tr>
<tr>
<td>Min. Width of cut</td>
<td>0 (i.e., not given)</td>
</tr>
<tr>
<td>Min. Taper</td>
<td>0 (i.e., not given)</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>0.64</td>
</tr>
<tr>
<td>L/D ratio</td>
<td>5.7 (=0.64/0.112)</td>
</tr>
</tbody>
</table>

6.7.3 Analysis

From the sample result of the program shown in Figure 6.13, it is observed that USM, LBM, EBM, AJM and WJM are the most suitable NTMPs for the given part. The NTMPs eliminated on the basis of Work material (non-conductive) (Table 5.2) are ECM, ECG, ECH, EDM, WEDM,
and PAM. NTMPs are eliminated on the basis of shape application is CHM (Table 5.3). No NTMPs are eliminated on the basis of process capabilities (Table 5.5). The important attributes used for ranking include Min.Tolerance, Min.Surface finish, and L/D Ratio.

6.7.4 Observation

The developed approach recommends USM for the application described. In the case study, NTMPs that are very good in producing cylindrical through holes such as ECM and EDM are eliminated on account of use of the non-conductive workmaterial. The highest ranking score of USM is expected result since tolerance is the most important process capability attribute which influence the process grade and USM has the best Tolerance value (Figure 6.13). Also the material grade is equal for all the selected NTMPs. In this case study, WJM is found last in the list of most suitable NTMPs, since the material grade (poor: 1), process grade (poor: 0) and overall grade (Total Grade: 3) obtained by USM is very low. In this application the shape capability of USM is better than LBM and hence LBM secured 2nd position in the selection list. It is worth mentioning that the USM solution obtained from the developed approach is consistent with the solution introduced by both Rutan (1994) and Yurdakul et al (2003).
Figure 6.12 Screen shot of the input web page for Case study 6
### Considering factors

<table>
<thead>
<tr>
<th>Material</th>
<th>Ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape Application</td>
<td>Hole LD Ratio Less than 20</td>
</tr>
<tr>
<td>Process Economy</td>
<td>Tolerance (um): 150</td>
</tr>
</tbody>
</table>

### RESULT: Most Suitable Process

<table>
<thead>
<tr>
<th>Rank</th>
<th>Process Name</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1    | USM          | Material Grade: 3  
Process Grade: 2  
Shape Grade: 3  
Total Grade: 8 |
| 2    | LSM          | Material Grade: 3  
Process Grade: 1  
Shape Grade: 2  
Total Grade: 6 |
| 3    | EBM          | Material Grade: 3  
Process Grade: 1  
Shape Grade: 2  
Total Grade: 6 |
| 4    | AMI          | Material Grade: 3  
Process Grade: 0  
Shape Grade: 2  
Total Grade: 5 |
| 5    | WUM          | Material Grade: 1  
Process Grade: 0  
Shape Grade: 2  
Total Grade: 3 |

---

Figure 6.13 Screen shot of the output web page for Case study 6
6.8 CASE STUDY 7

6.8.1 Problem Statement

An automotive industry employed EDM drilling to produce precision injector nozzle holes. Varying numbers of holes are drilled in a precise pattern around the tip of the injector. In one application, a quality control check on the hole diameters achieved for 800 consecutive holes showed that holes were within ± 0.02 mm of the target diameter of 0.1753 mm machined on 1 mm thick plate made of 52100 steel hardened to HRc 65 (Gettelman 1983).

6.8.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.14 are as follows:

- **Material**: 52100 Steel
- **Shape Application**: Cylindrical through hole drilling
- **Min. Surface finish**: 0 (i.e. not given)
- **Min. Tolerance**: ± 20 µm
- **Min. Width of cut**: 0 (i.e., not given)
- **Min. Taper**: 0 (i.e., not given)
- **Plate Thickness**: 1 mm
- **Hole diameter**: 0.1753 mm
- **L/D ratio**: 5.7 (=1.0/0.1753).

6.8.3 Analysis

From the sample result of the program shown in Figure 6.15, it is observed that only WEDM (Total Grade: 13), ECH (Total Grade: 8) and USM (Total Grade: 7) are found to be the most suitable NTMPs for the given
part. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMP eliminated on the basis of the Shape Applications is PAM (Table 5.3). WJM, AJM, EBM, CHM, ECM, ECG, and EDM (Table 5.5) are eliminated due to process capability attributes. The important attributes used in ranking are Material Application, Min.Tolerance and L/D ratio. For this case study WEDM is recommended for the application described.

6.8.4 Observation

It is observed that only WEDM, ECH, and USM in order of preference are found to be the most suitable NTMP for the given part. In this application, WEDM secured the highest overall (Total Grade: 13) and individual ranking score (material grade: 3; process grade: 7; shape grade: 3) and hence secured the 1st position in the selection list. USM is well known for its shape capability (shape grade: 3) but because of poor material and process grade it comes last in the list of most suitable NTMPs. ECH secured 2nd position, because of its good material and shape capability (material grade: 3; shape grade: 3) and also the material grade obtained by ECH (material grade: 3) is higher than USM (material grade: 2). In this Case study, if Tolerance is considered as the important attribute then USM would have had the highest ranking score owing to its capability in achieving close tolerance values.
Figure 6.14 Screen shot of the input web page for Case study 7
Figure 6.15 Screen shot of the output web page for Case study 7
6.9 CASE STUDY 8

6.9.1 Problem Statement

The drilling of turbine engine combustor domes made of CrNiCoMoW steel (HRc 35) has been performed for several years using EBM. The part has a wall thickness of 1.1 mm and is perforated with 3748 holes that are 0.9 ± 0.05 mm in diameter. Each part is drilled for 60 min for a drilling rate of approximately one hole every second.

6.9.2 Limiting requirements

Limiting requirements for this example as shown in Figure 6.16 are as follows:

- Material : CrNiCoMoW Steel
- Shape Application : Cylindrical through hole drilling
- Min.Surface finish : 0 (i.e. not given)
- Min.Tolerance : ± 50 µm
- Min.Width of cut : 0 (i.e., not given)
- Min.Taper : 0 (i.e., not given)
- Wall Thickness : 1.1 mm
- Hole diameter : 0.9 mm
- L/D ratio : 1.2 (=1.1/0.9).

6.9.3 Analysis

From the sample result of the program shown in Figure 6.17, it is observed that WEDM, ECH, USM, ECG, EDM, ECM, LBM, EBM, AJM, and WJM are found to be list of the most suitable NTMPs for the given part in the order of preference. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMP eliminated on the basis of the Shape
Applications is PAM (Table 5.3). CHM (Table 5.5) is eliminated due to process capability attributes. The important attributes used in ranking are Material Application, L/D ratio, and Min.Tolerance. For this case study WEDM is recommended for the application described since it secures the 1st position.

6.9.4 Observation

It is observed that WEDM is found to be the NTMP available on top of the list most suitable NTMPs for the given part. In this case study ECG, ECG and EDM secure equal overall score (Total grade: 7 each) and hence appear 3rd in the list. Since the list is so lengthy, only the NTMPs that occupy the first three positions (WEDM, ECH, USM, ECG, and EDM) can be taken and cost comparison can be made in order to select the final competitive NTMP for the given application problem. It is worth mentioning that the selection list accommodates all the NTMPs listed in the selection suggested by Cogun (1994). However, USM is very unlikely to be applicable since the workpiece materials softer than HRc 40 result in prohibitively long cycles. The best machining rates can be obtained on materials harder than HRc 60. Also, EDM and ECM should be reconsidered taking into account the possible dielectric and electrolyte flow problems through the gap, high cost of tooling and low material removal rates for this specified case.
Figure 6.16 Screen shot of the input web page for Case study 8
Figure 6.17 Screen shot of the output web page for Case study 8 (Continued)
6.10 CASE STUDY 9

6.10.1 Problem Statement

Electro-chemical machining can be used simultaneously to machine multiple pockets in blind cavities in a fraction of the time required by conventional milling. The example part has 16 equally spaced pockets electro-chemically machined into a hardened bearing surface. The pocket measures approximately 16.5 × 8.9 mm and penetrates 2.3 mm deep. All dimensions are maintained within a tolerance of 0.13 mm. All pockets are machined burr free by ECM in one operation lasting less than 6 min. The material is assumed as 4140 die steel.

6.10.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.18 are as follows:
Material: Steel
Shape Application: Pocketing Shallow
Tolerance: ±50 µm
Surface finish: 2.5 µm Ra
Taper: 0 (not given)
Corner radii of the part: 0 (not given)

6.10.3 Analysis

From the sample result of the program shown in Figure 6.19, it is observed that ECH, ECG, ECM, EDM, USM and CHM are found to be the most suitable NTMPs for the given part with the stated requirements. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2). The NTMPs eliminated on the basis of the Shape Applications are AJM, EBM, LBM, PAM, and WEDM (Table 5.3). WJM (Table 5.5) is eliminated due to process capability attributes. The important attributes used in ranking are Material Application, Shape application, Min.Tolerance and Min.Surface finish. In this case study ECH obtained the highest ranking score (Figure 6.19). It is observed that the process grade for ECH is high and hence the overall ranking score of ECH is the highest of all the three most suitable NTMPs. The shape application and material application grade obtained for USM is the least of all the three NTMPs selected and hence USM is ranked three among the most suitable NTMPs even though the process grade for USM is comparatively higher than the processes ranked better than USM.

6.10.4 Observation

It is observed that ECH, ECG, ECM, EDM, USM and CHM are found to be the most suitable NTMPs for the given part in order of preference with the stated requirements. Among the listed most suitable NTMPs, ECH obtained highest individual ranking score on Material Grade, Process Grade,
and Shape Grade and hence obtained the highest overall ranking score. EDM scored maximum in material grade and shape grade but because of poor process grade, EDM is found fourth among the six NTMPs listed. In this case study, ECH, ECG, EDM and ECM secured equal shape grade (good: 3) and material grade (good: 3) but the variation in their ranking position is mainly due to their individual score in process grade. The individual grade values for USM and CHM are totally different but their Total Grade remains equal. CHM enjoys superior material and shape grades but USM because of good process grade when compared to CHM, without good material and shape grade managed to equal the total grade obtained by CHM. Hence it is advisable to analyse the individual scores before making the final decision on selection of most suitable NTMPs. Total Grade alone is not sufficient enough to complete the selection.
**Figure 6.18** Screen shot of the input web page for Case study 9

![Screen shot of the input web page for Case study 9](image)

**WEB-ENABLED KNOWLEDGE BASE SYSTEM FOR SELECTION OF NON-TRADITIONAL MACHINING PROCESSES**

<table>
<thead>
<tr>
<th>User Module</th>
<th>Process Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Tolerance(±)</td>
</tr>
<tr>
<td></td>
<td>50µm</td>
</tr>
<tr>
<td></td>
<td>Minimum Surface Finish</td>
</tr>
<tr>
<td></td>
<td>Above 2µm</td>
</tr>
<tr>
<td></td>
<td>Minimum Surface Damage</td>
</tr>
<tr>
<td></td>
<td>Minimum Cone Rad</td>
</tr>
<tr>
<td></td>
<td>Minimum Taper</td>
</tr>
<tr>
<td></td>
<td>Minimum Width of Cut</td>
</tr>
<tr>
<td></td>
<td>Minimum Overcut</td>
</tr>
<tr>
<td></td>
<td>Minimum Depth to Dia Ratio</td>
</tr>
</tbody>
</table>

**User Module**

- **Material:** Steel

**Selection Criteria**

- **Operation:**
  - Precision
  - Standard
- **Hole LO Ratio:**
  - Less than 20
  - Greater than 20
- **Through Cavities:**
  - Precision
  - Standard
- **Puckeling:**
  - Shallow
  - Deep
- **Surfacing:**
  - Double Contour
  - Surface of Revolution
- **Through Cutting:**
  - Shallow
  - Deep

**Process Economy**

- Capital Investment
- Tooling and Fixtures
- Power Requirement
- Efficiency
- Tool Consumption

**Clear**  |  **Perform Selection**
### Case Study 9

#### Process Details
- **Material:** Steel
- **Shape Application:** Pocketing Shallow
- **Process Economy**
- **Process Capabilities**
  - Tolerance (μm): 50
  - Minimum Surface Finish (μm Ra): 2.5

#### RESULT: Most Suitable Process

<table>
<thead>
<tr>
<th>Rank</th>
<th>Process Name</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1    | ECH          | Material Grade 3  
|      |              | Process Grade 6  
|      |              | Shape Grade 3    
|      |              | Total Grade 13   |
| 2    | ECG          | Material Grade 3  
|      |              | Process Grade 6  
|      |              | Shape Grade 3    
|      |              | Total Grade 12   |
| 3    | ECM          | Material Grade 3  
|      |              | Process Grade 5  
|      |              | Shape Grade 3    
|      |              | Total Grade 11   |
| 4    | EDM          | Material Grade 3  
|      |              | Process Grade 3  
|      |              | Shape Grade 3    
|      |              | Total Grade 9    |
| 5    | USM          | Material Grade 2  
|      |              | Process Grade 5  
|      |              | Shape Grade 1    
|      |              | Total Grade 8    |
| 6    | CHM          | Material Grade 3  
|      |              | Process Grade 2  
|      |              | Shape Grade 3    
|      |              | Total Grade 8    |

**Figure 6.19 Screen shot of the output web page for Case study 9**
6.11 CASE STUDY 10

6.11.1 Problem Statement

A stamping die for Instron tensile test specimen is shown in Figure 6.20. The die is machined from 10 mm thick mild steel plate and the tolerance required is ± 0.025 mm.

![Stamping die for Instron test specimen](image)

Figure 6.20 Stamping die for Instron test specimen

6.11.2 Limiting Requirements

Limiting requirements for this example as shown in Figure 6.21 are as follows:

- **Material**: Mild Steel
- **Shape Application**: Through cutting Shallow
- **Min. Surface finish**: 0 (not given)
- **Min. Tolerance**: ± 0.025 μm
- **Min. Taper**: 0 (not given)
- **Min. Corner radii of the part**: 0 (not given).

6.11.3 Analysis

From the sample result of the program shown in Figure 6.22, it is observed that WEDM, ECH, ECG, CHM, LBM, USM and EDM are found to
the most suitable NTMPs in order of preference for the given part. No NTMPs are eliminated on the basis of the Material Applications (Table 5.2) and Shape Applications is (Table 5.3). WJM, AJM, ECM, EBM and PAM (Table 5.5) are eliminated due to process capability attributes.

6.11.4 Observation

It is observed that WEDM, ECH, ECG, CHM, LBM, USM and EDM are found to be the most suitable NTMPs in order of preference for the given part with the stated requirements. It is also observed that the shape application grade obtained for LBM is maximum but because of least Process Grade, it could secure only 5th rank among seven NTMPs in the list of most suitable NTMPs for the given test specimen. In this case study process capabilities and shape application grades influenced the selection that EDM obtained the highest ranking score owing to its good material application, EDM comes last in list of most suitable NTMPs. It was found that the WEDM and the LBM are both capable of producing the stamping die. Thus, the decision on selecting the most appropriate process lies on the machining cost incurred in producing the stamping die to its required accuracy for each process. Based on the process models determined by Yeo et al (1997) for a specified tolerance of 0.025 mm, LBM is the preferred process owing to its lower machining costs. But on the contrary to the above stated fact that WEDM is listed in the top of the list and LBM comes almost last in the list. It is worth mentioning that both WEDM and LBM considered for research on cost-tolerance relationship by Yeo et al (1997) are accommodated in the list of most suitable NTMPs and ensures the correctness of data used in the developed selection procedure.
Figure 6.21 Screen shot of the input web page for Case study 10
**Figure 6.22** Screen shot of the output web page for Case study 10

<table>
<thead>
<tr>
<th>Rank</th>
<th>Process Name</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1    | WEDMI        | Material Grade: 3  
                   Process Grade: 7  
                   Shape Grade: 3  
                   Total Grade: 13 |
| 2    | ECH          | Material Grade: 3  
                   Process Grade: 2  
                   Shape Grade: 3  
                   Total Grade: 8  |
| 3    | ECG          | Material Grade: 3  
                   Process Grade: 1  
                   Shape Grade: 3  
                   Total Grade: 7  |
| 4    | CHM          | Material Grade: 3  
                   Process Grade: 1  
                   Shape Grade: 3  
                   Total Grade: 7  |
| 5    | LBM          | Material Grade: 2  
                   Process Grade: 1  
                   Shape Grade: 3  
                   Total Grade: 6  |
| 6    | USM          | Material Grade: 2  
                   Process Grade: 2  
                   Shape Grade: 1  
                   Total Grade: 5  |
| 7    | EDM          | Material Grade: 3  
                   Process Grade: 1  
                   Shape Grade: 1  
                   Total Grade: 5  |
6.12 DISCUSSION

The conducted case studies (more than 25) indicated that correct ranking of NTMPs by the developed approach depends strongly on the following issues:

1. The shape application and process capability information of NTMPs in Tables 5.3 and 5.5 have great importance in the ranking of NTMPs. If the information given in these tables is not valid, then the elimination of unsuitable NTMPs will be mistaken. Moreover, values of the attributes given in the process economy table (Table 5.4) are also used in ranking of the most suitable NTMPs. Mistakes in Table 5.2 will result in incorrect ranking of NTMPs. In the present work, a large number of published studies and the researcher’s experience with NTMPs have been used in preparation of these critical tables. A large number of case studies have been applied to the developed approach. The consistency of the selected NTMPs with the industrial applications proves the correctness of the information given in the tables. The NTMPs introduced in this study are in ongoing development. The shape application and process capability information should be updated continually in order to ensure correct selection and ranking of the processes in future.

2. The present online approach can produce a clear preference order of a set of alternative NTMPs. However, the success of the selection procedure is sensitive to the grades of the important attributes. These grades may only be subjectively evaluated, and hence their accuracies always depend on the
decision-makers’ knowledge and familiarity with the special application.

3. In the developed approach, the ranking of the NTMPs is very sensitive to variations in the grade values. If the grade value is not made correctly, then it affects the ranking of the NTMPs. The exhaustive research studies showed that the technical information available in the case studies, which is taken from real life industrial applications, is generally insufficient for accurate selection. In many cases the experience of the researcher is used in answering the question as to which attribute is more important and at what magnitude. The detailed study on important attributes should be made independently for every case study by considering the requirements of the particular application.

4. The present web enabled SQL based selection approach brings a structure and uniformity to the calculation of individual grade for material, shape application, process capabilities, process economy, and the total grade for the most suitable NTMPs. Decision-makers are more comfortable offering relative rather than absolute preference information. Web enabled SQL approach is likely to be more reliable than simple rating methods because it is able to prevent decision-makers from responding arbitrarily by employing the consistency check.

5. The workpiece material suitability (Table 5.2) and shape application capability limitations (Table 5.3) of the NTMPs are used directly in narrowing down the list of feasible NTMPs. It is clear that the workpiece material limitation is not
a powerful tool in eliminating the NTMPs since only a very limited number of engineering materials (such as ceramics) cannot be machined by many NTMPs.

6.13 SUMMARY

The case studies have shown that the program selects the candidate NTMPs correctly in the sense that the selection conforms to field experience. However in each example more than one process is selected as most suitable NTMPs. This is due to the relatively loose design requirements. Sometimes the list of most suitable NTMPs could be too long for practical use. Usually, the optimum selection can be obtained by evaluating the cost of production between the competitive NTMPs.