CHAPTER - 7
MACHINABILITY RATING USING THERMOCURRENT

One of the major problems of the manufacturer is to deliver the components to the customer according to their specific quality and in scheduled time. This in turn governs the production rate and minimum cost of production within the specified limits of quality. Hence the capability of the workmaterial to be machined needs to be stressed upon. This capability of the workmaterial is nothing but the machinability of the material. There are innumerable factors which impart their influence on the machinability or the ease of cutting. Hence exact evaluation of the machinability value is impossible. That is why machinability rated by one method may not conform to the rating by the other method.

In this chapter author wishes to study the machinability value with a reference to the thermocurrent. Since thermocurrent is related with tool life, surface finish etc. and affected by machining variables, it can be effectively used to rate the machinability of the workmaterial.

7.1. Machinability and Peltier Coefficient

Peltier coefficient as described in the Chapter 2 can be defined as the energy absorbed as liberated when unit charge passes through the hot junction. This Peltier
coefficient, \( \alpha \), will dictate the generation of the thermocurrent arising out of machining. Hence it will give the measure of the capability of the workmaterial prone to the generation of thermocurrent. From the Chapter 2 we can write

\[ Q = \alpha \cdot I \]  

Eqn. (7.1)

where,

- \( Q \) - Heat flux at tool-chip interface.
- \( \alpha \) - Peltier coefficient.
- \( I \) - Thermocurrent.

From the above equation if \( Q \) and \( I \) are known, Peltier coefficient can be evaluated. Quantity of heat generated at the tool-chip interface poses to be difficult to evaluate exactly. Of course, the expression for this have been given in Chapter 2 under thermal analysis of the tool.

Heat generated, \( Q \) also can be expressed as

\[ Q = F_w \cdot \frac{V}{J} \text{ CHW/min.} \]  

Eqn. (7.2)

where,

- \( F_w \) - Friction force, kg.
- \( V \) - Cutting force, m/min.
- \( J \) - Mechanical equivalent of heat (194 kgm/CHU).

Now friction force can be written as

\[ F_w = F_c \sin \alpha + F_t \cos \alpha \]  

Eqn. (7.3)

where,

- \( F_c \) - Cutting force, kg.
- \( F_t \) - Lateral force, kg.
- \( \alpha \) - Rake angle of the tool.
To calculate the friction force, author took the help of his previous work. From that cutting force obtained given below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting force $F_c$</th>
<th>Lateral force $F_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel with carbon - 0.11%</td>
<td>87 kg</td>
<td>18.4 kg</td>
</tr>
<tr>
<td>- 0.20%</td>
<td>90 &quot;</td>
<td>15 &quot;</td>
</tr>
<tr>
<td>- 0.29%</td>
<td>95 &quot;</td>
<td>22.6 &quot;</td>
</tr>
<tr>
<td>- 0.40%</td>
<td>100 &quot;</td>
<td>21 &quot;</td>
</tr>
<tr>
<td>- 0.51%</td>
<td>110 &quot;</td>
<td>23.2 &quot;</td>
</tr>
</tbody>
</table>

For the above values of $F_c$ and $F_t$, cutting speed 60 m/min., feed = 0.2 mm/rev., depth of cut = 1 mm. Tool used was carbide of rake angle 6°. So friction force can be calculated as

For steel with carbon - 0.11%  

$$F_w = 37 \sin 6^\circ + 18.4 \cos 6^\circ$$

$$= 27.2 \text{ kg.}$$

Similarly,

for steel with carbon 0.2% - $F_w = 23.1 \text{ kg.}$

0.29% - $F_w = 32.3 \text{ kg.}$

0.4% - $F_w = 31.2 \text{ kg.}$

0.51% - $F_w = 34.1 \text{ kg.}$
Heat generated $Q$ can be written as

$$Q = \frac{F_w \times V}{J}$$

For steel with carbon $- 0.11\%$

$$Q = \frac{27.2 \times 60}{194} = 8.4 \text{ CHU/Min.}$$

Similarly,

for steel with carbon $- 0.2\%$ $- Q = 7.15 \text{ CHU/Min.}$

$- 0.29\%$ $- Q = 10 \text{ CHU/Min.}$

for steel with carbon $- 0.4\%$ $- Q = 9.68 \text{ CHU/Min.}$

$- 0.51\%$ $- Q = 10.6 \text{ CHU/Min.}$

Now the thermocurrents noted during the experiment after 1 min. of cutting in each case have been tabulated in Table 7.1.

**Table 7.1**

Machinability Rating Using Peltier Coefficient

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Steel with carbon per cent</th>
<th>Q on CHU</th>
<th>Thermocurrent, $I$ (amp $\times 10^5$)</th>
<th>Peltier coefficient</th>
<th>Machinability Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.11</td>
<td>8.4</td>
<td>12</td>
<td>0.70</td>
<td>86</td>
</tr>
<tr>
<td>2.</td>
<td>0.2</td>
<td>7.15</td>
<td>12</td>
<td>0.6</td>
<td>100</td>
</tr>
<tr>
<td>3.</td>
<td>0.29</td>
<td>10</td>
<td>13</td>
<td>0.78</td>
<td>77</td>
</tr>
<tr>
<td>4.</td>
<td>0.4</td>
<td>9.68</td>
<td>13.5</td>
<td>0.715</td>
<td>34</td>
</tr>
<tr>
<td>5.</td>
<td>0.51</td>
<td>10.6</td>
<td>14</td>
<td>0.76</td>
<td>49</td>
</tr>
</tbody>
</table>
Lower value of Peltier coefficient will indicate lower heat generation and hence good machinability.

From the Table 7.1, steel containing carbon percentage 0.2 gives the highest machinability value. From the trend of the results obtained in Table 7.1, it seems machinability value decreases with the carbon content increment in the material with specific reference to Peltier coefficient.

7.2. Machinability and Burn-out Voltage

Machinability value can also be evaluated with the 'burn-out' voltage as described by Billet\textsuperscript{12}. Relationship between the e.m.f. produced during turning and speed of cutting may be given as\textsuperscript{12}

\[ E = KV^m \] ... Eqn. (7.4)

where,

- \( E \) - e.m.f. generated in cutting.
- \( V \) - Speed.
- \( K \) - Constant of proportionality.
- \( m \) - Exponent.

After that Billet\textsuperscript{12} modified the above equation as:

\[ E = E_m (1-e^{-KV}) \] ... Eqn. (7.5)

where,

- \( E_m \) - 'Burn-out' voltage.
This 'burn-out' voltage depends on the set of tool and workmaterial. This $E_m$ can be found out from the graph of speed vs. e.m.f. Fig. 7.1 shows the 'burn-out' voltage estimation from the speed - e.m.f. graph. General form of the speed - e.m.f. graph shows a decreasing slope up to a relatively high value of $E$. After that if there is an increase in slope, it will be followed up by rapid tool wear, failure or 'burn-out'. Hence this 'burn-out' voltage will dictate the point from which rapid wear starts. Speed at which the 'burn-out' voltage occurs will give the machinability value for the workmaterial.

For different material the starting point will be different. Hence the 'burn-out' voltage will give an idea of the machinability value. Table 7.2 shows the machinability rating of the different materials considering burn-out voltage.

**Table 7.2**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Workmaterial</th>
<th>Speed m/min.</th>
<th>Machinability rating %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>EN 24 steel</td>
<td>196</td>
<td>79</td>
</tr>
<tr>
<td>2.</td>
<td>M.S.</td>
<td>242</td>
<td>97.2</td>
</tr>
<tr>
<td>3.</td>
<td>0.29% Carbon Steel</td>
<td>226</td>
<td>91</td>
</tr>
<tr>
<td>4.</td>
<td>0.2% Carbon Steel</td>
<td>239</td>
<td>96</td>
</tr>
<tr>
<td>5.</td>
<td>0.11% Carbon Steel</td>
<td>243</td>
<td>100</td>
</tr>
</tbody>
</table>
FIG. 7.1 'BURN-OUT' VOLTAGE FROM SPEED-EMF PLOT
High value in machinability rating shows good machinable properties of the workmaterial.

7.3. Machinability and Performance Index

Sometimes it is desirable to have the x assessment of the machinability or a quick test of machinability over on-line processing. In this respect performance index can play an important role in evaluating the machinability value. Let us analyse the performance index.

Let

\[ K_1 \text{ - direct labour cost + over head.} \]
\[ K_2 \text{ - tool cost + tool grinding cost.} \]
\[ T \text{ - tool life, min.} \]
\[ t_c \text{ - tool change time, min.} \]

Then

\[ \text{Cost} = K_1 T + K_1 t_c + K_2 \quad \text{... Eqn. (7.7)} \]

Average cost per unit volume of cut

\[ C_{\text{avg}} = \frac{K_1 T + K_1 t_c + K_2}{1000 \int_0^T V.f.t. d\gamma} \quad \text{... Eqn. (7.7)} \]

Where

\[ V \text{ - Speed, m/min.} \]
\[ f \text{ - feed, mm/rev.} \]
\[ t \text{ - depth of cut, mm.} \]
\[ t \text{ - time of cut, min.} \]
\[ T \text{ - tool life, min.} \]
\[
W^* = \int_0^T \frac{dw}{d\gamma} d\gamma 
\quad \text{... Eqn. (7.8)}
\]

where

\[
w \quad \text{flank wear}
\]

\[
W^* \quad \text{flank wear for tool life criterion}
\]

Although \(dw/d\gamma\) is usually time dependent, numerous experiments have revealed that flank wear \(w\) can be linearized with regard to time by introducing the concept of initial wear \(W_o\). Thus referring to Takeyama \(^{50}\), following equation can be written

\[
W^* - W_o = \frac{dw}{d\gamma} \int_0^T d\gamma 
\quad = \frac{dw}{d\gamma} \cdot T 
\quad \text{... Eqn. (7.9)}
\]

In on-line process, it is difficult to measure the wear of the tool; this necessitates picking up in an on-line fashion another measurable signal which will substitute for the tool-wear. In this respect, thermocurrent is best suited to replace tool wear. As seen in Fig. 5.4, thermocurrent varies almost linearly with time of cut, and hence it can be viewed in a manner very similar to tool wear.

Taking thermocurrent as the tool life criterion and \(I^*\) representing the thermocurrent corresponding to tool life and \(I_o\) as the initial thermocurrent, we get

\[
I^* - I_o = \frac{dI}{dT} \cdot T 
\text{... Eqn. (7.10)}
\]
If \( C_1 \) = instantaneous cost

then \( C_{\text{avg}} = \frac{1}{T} \int_0^T c_1 \, dt \)  

... Eqn. (7.11)

Now equating eqn. (7.7) and (7.11)

\[
\frac{1}{T} \int_0^T c_1 \, dt = \frac{K_1 T + K_1 t_c + K_2}{1000 \int_0^T \text{v.f.t.} \, dt}  
\]

... Eqn. (7.12)

Using \( T = (I^* - I_o) \frac{dt}{dI} \)

\[
\frac{1}{T} \int_0^T c_1 \, dt = \frac{K_1 + \frac{dI}{dt} - \frac{1}{(I^* - I_o)} \left[ K_1 t_c + K_2 \right]}{1000 \int_0^T \text{v.f.t.} \, dt}  
\]

... Eqn. (7.13)

\[
c_1 = \lim_{T \to 0} \frac{1}{T} \int_0^T c_1 \, dt = \frac{K_1 + \left[ K_1 t_c + K_2 \right] - \frac{1}{(I^* - I_o)} \frac{dI}{dt}}{1000 \text{v.f.t.}}  
\]

... Eqn. (7.14)

Taking reciprocal of \( c_1 \) as performance index \( P \)

\[
P = \frac{1000 \text{v.f.t.}}{K_1 + \left[ K_1 t_c + K_2 \right] - \frac{1}{(I^* - I_o)} \frac{dI}{dt}}  
\]

Taking \( I^* - I_o = \Delta I \) and\n
If \( v, f \) and \( t \) are kept constant then

\[
P \propto \frac{\Delta I}{K_1 + \left[ K_1 t_c + K_2 \right] \frac{dI}{dt}}  
\]

... Eqn. (7.15)
Using the above performance index as a measure of machinability since $\Delta I$ and $\frac{dI}{dt}$ depends on the characteristics of the workmaterial, machinability rating has been shown in Table 7.3. A sample calculation has been shown in Appendix 7.1.

**Table 7.3**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Workmaterial</th>
<th>$\Delta I$ (amp x $10^5$)</th>
<th>$\frac{dI}{dt}$</th>
<th>Performance index</th>
<th>Machinability%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Steel - 0.11% C</td>
<td>15</td>
<td>0.16</td>
<td>9.0</td>
<td>100</td>
</tr>
<tr>
<td>2.</td>
<td>Steel - 0.2 % C</td>
<td>14</td>
<td>0.17</td>
<td>8.86</td>
<td>98.5</td>
</tr>
<tr>
<td>3.</td>
<td>Mild Steel</td>
<td>13</td>
<td>0.20</td>
<td>8.55</td>
<td>95</td>
</tr>
<tr>
<td>4.</td>
<td>Steel - 0.4% C</td>
<td>11</td>
<td>0.24</td>
<td>8.05</td>
<td>89.5</td>
</tr>
<tr>
<td>5.</td>
<td>Steel EN 24</td>
<td>10</td>
<td>0.27</td>
<td>7.2</td>
<td>80</td>
</tr>
</tbody>
</table>

It has been seen that steel with 0.11% carbon gives best machinability and EN 24 steel gives worst machinability among the five varieties of steel. From the Table 7.1, it has been seen that 0.2% carbon steel gives best machinability properties. So the machinability value may be changed depending upon the set of conditions and situation imparted on the experiment and that the value of machinability will hold good conforming to that set only.