ABSTRACT
The CNC milling work and the spark erosion work are the tasks that require more time in the mould construction. In some situations, it can reach more than 50% of the total time of the mould manufacture. The optimization of this task is very important in order to reduce mould construction costs. This dissertation aims to create a software application to optimize the cutting parameters in CNC milling work.
From a database with specifications of CNC machines, machining materials and tools, with an indication by the user of the desired cutting parameters, the application orders the tools that are in the database in descending order of the material removal rate and indicate the tools which are compatible and incompatible with the cutting parameters defined by the user. It will also indicate the causes of incompatibility and allow the selection of compatible tools to be added to a historic registry. To this historic registry, besides adding the necessary tools and their geometrical characteristics, also adds the calculated cutting parameters and the data of machining operation. After running the milling process, it is possible to make some remarks in order to be saved in the historic registry.
The goal of the historical registry is for the tools and parameters used in machining to be subsequently improved, and on this way can achieve quality and productivity of work.
As the data are saved on a database, the optimization process follows a criterion from the company and not from the worker.

KEYWORDS
Optimization of cutting parameters; Milling; Material removal rate in milling; Average thickness of chip in milling.

INTRODUCTION
The moulds industry is embedded in a global market and rapid technological change, facing many competitive markets, mostly in the automobile sector. Therefore, it has to be at the forefront of technology, requiring the milling machines to be in constant technological updating.
The decrease of production costs is a goal that must be always present in any mold building operation. In the milling operations, machining time is the main factor that influences the cost of the operation.
With the appearance of the 5 axis machines, flexibility of the milling machines increased, reducing time in labour preparation.
The tools had to follow the evolution of the milling machines and their choice must be carefully performed. With the software application developed on this dissertation it is possible to select the compatible tool from a database and reduce the machining time by optimizing the cutting parameters.
**TYPE OF MILLING CUTTERS**

The types of milling cutters used in the industry of moulds are the cutters with a straight cutting edge inserts or with round cutting edge inserts and solid carbide cutters. Typically, the straight cutting edge inserts and the solid carbide tools have radius in the corner.

The following table shows the milling cutters used in various typical operations in the industry of moulds.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Milling Cutter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face milling</td>
<td>Cutters with straight cutting edge inserts, with a 90° angle</td>
</tr>
<tr>
<td></td>
<td>Cutters with straight cutting edge inserts, with a 45° angle</td>
</tr>
<tr>
<td>Chamfering</td>
<td>Cutters with straight cutting edge inserts, with a 45° angle</td>
</tr>
<tr>
<td>Holes and cavities milling</td>
<td>Cutters with straight cutting edge inserts, with a 90° angle</td>
</tr>
<tr>
<td></td>
<td>Cutters with a round cutting edge inserts</td>
</tr>
<tr>
<td>Threading</td>
<td>Milling cutters for thread opening</td>
</tr>
<tr>
<td>Milling profiles</td>
<td>Cutters with straight cutting edge inserts</td>
</tr>
<tr>
<td></td>
<td>Cutters with a round cutting edge inserts</td>
</tr>
<tr>
<td></td>
<td>Solid carbide cutters</td>
</tr>
</tbody>
</table>

Table 1 - Typical cutters for milling operation
CUTTING PARAMETERS
The main cutting parameters that are calculated on the software are the following:

Outside Cutting diameter

\[ D_{ec} = D_c + \frac{2 \times a_p}{\tan \kappa} \text{ [mm]} \]  
(1) - for straight cutting edge (mm)

- \( \kappa \) - position angle; \( a_p \) - depth of cut (mm); \( D_c \) - cutting diameter of milling cutters (mm)

\[ D_{ec} = D_c + 2 \sqrt{\left(\frac{d}{2}\right)^2 - \left(\frac{d}{2} - a_p\right)^2} \text{ [mm]} \]  
(2) - for round cutting edge

d - diameter of the round insert (mm)

Cutting Speed

\[ V_c = \frac{\pi D_{ec} N}{1000} \text{ [m/min]} \]  
(3)

N – speed spindle milling machine (rpm)

Material removal rate

\[ Q = a_e a_p v_a \times \frac{10^3}{60} \text{ (mm}^3/\text{s}) \]  
(4)
a_e – width of cut (mm); \( V_a \) – feed rate (m/min.)

Average chip thickness

The chip thickness is the most important parameter in order to obtain a reliable and productive machining process, which will be the subject of further study. In the calculation of the cutting force, the value of the thickness of the chip used is the average value.

In the context of the application the side milling will only be considered, as shown in the following figure, since it is the type of milling normally used in the plastic mold industry.

\[ e_m = a_z \sin \kappa \frac{1 - \cos \phi}{\phi} \]  
(5)

Figure 1 – Side milling
\( \phi \) – angle contact between the cutter and the material.

\( \phi_e \) – initial angle contact between the cutter with the material. On the situation of side milling \( \phi_e = 0 \).

\( \phi_s \) – final angle contact between the cutter with the material. On the situation of figure 1 \( \phi_s = \phi \).

**Calculation of the average thickness of the chip on the cut with round edge**

![Figure 2 – Cutting section with round edge, for calculating the average thickness of the chip](image)

\[
e_n = \frac{a_r (1 - \cos \phi) (1 - \cos \theta)}{\phi \theta}
\] (6)

- \( l \) - length of the cutting edge in contact with the material (mm)
- \( a_r \) - radial feed (mm)
- \( e \) - chip thickness at a given point. In the figure, the point is defined by the angle \( \theta \) on the edge (mm)
- \( s \) - section of the chip. In the case of the figure 2, it is defined by the trajectory of 2 successive cutting teeth (mm²)

**Calculation of the average thickness of the chip on the cut with mixed edge**

In the cut with mixed edges, there are cuts with the 2 types referred to in the previous points: the cut with a straight edge and cut with a round edge, as shown in the following figure:

![Figure 3 – Cutting section with mixed edge](image)
Figure 4 – Sections for calculating the average thickness of the chip, with mixed edge

\[ e_{m \text{ mixed}} = \frac{e_{m \text{ straight}} \times l_{\text{straight}} + e_{m \text{ round}} \times l_{\text{round}}}{l_{\text{straight}} + l_{\text{round}}} \]  

(7)

- \( e_{m \text{ mixed}} \) – average chip thickness on the cut with mixed edge (mm)
- \( e_{m \text{ straight}} \) – average chip thickness on the cut with straight edge (mm)
- \( e_{m \text{ round}} \) – average chip thickness on the cut with round edge (mm)
- \( l_{\text{straight}} \) – length of the cutting straight edge in contact with the material (mm)
- \( l_{\text{round}} \) – length of the cutting round edge in contact with the material (mm)

**Validation of the calculations of the average thickness of the chip**

To prove that the expressions (5), (6) and (7) for calculating the average thickness of the chip are valid for the entire width of the cutter cutting, spreadsheets were prepared varying the angle \( \phi \) of the cutting width, see figure 1, since \( \phi = 0^\circ \) until the full milling, where \( \phi = 180^\circ \).

For each angular value \( \phi \) the value calculated by expressions was compared with the average value calculated by angular increments of \( \phi \) \( \theta \) (if applicable).

This procedure was performed for one of the 8 bits of the application, each one with its typical cutting edge:

- Milling cutter with straight cutting edge insert
- Milling cutter with straight cutting edge insert with chamfer
- Milling cutter with straight cutting edge insert with radius
- Milling cutter with round cutting edge insert
- Solid carbide cutter
- Solid carbide cutter with chamfer
- Solid carbide cutter with radius
- Solid carbide cutter with ball end

The following graphics show the variation of the deviations between the calculations by the expression (5), (6) or (7) and the angular increments, with the radial angle of the milling cutter and the variation of the average thickness of the chip calculated by the same expressions, with the radial angle of the milling cutter, for the cutting edges situations above mentioned.
The following table shows the maximum values of the thickness of the chip and the values of the deviations between the calculations and the values of $\varphi$ where occur:

<table>
<thead>
<tr>
<th>Type of milling cutter</th>
<th>chip thickness</th>
<th>Deviations between calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>straight cutting edge insert</td>
<td>$\varphi = 133^\circ$ 0,180 mm</td>
<td>$\varphi = 180^\circ$ 0,56 %</td>
</tr>
<tr>
<td>straight cutt. edge insert w/ chamfer</td>
<td>$\varphi = 133^\circ$ 0,148 mm</td>
<td>$\varphi = 180^\circ$ 0,56 %</td>
</tr>
<tr>
<td>straight cutt. edge insert w/ radius</td>
<td>$\varphi = 133^\circ$ 0,117 mm</td>
<td>$\varphi = 180^\circ$ 0,62 %</td>
</tr>
<tr>
<td>round cutt. edge insert</td>
<td>$\varphi = 133^\circ$ 0,101 mm</td>
<td>$\varphi = 180^\circ$ 0,79 %</td>
</tr>
<tr>
<td>Solid carbide cutter</td>
<td>$\varphi = 133^\circ$ 0,180 mm</td>
<td>$\varphi = 180^\circ$ 0,56 %</td>
</tr>
<tr>
<td>Solid carbide cutter with chamfer</td>
<td>$\varphi = 133^\circ$ 0,150 mm</td>
<td>$\varphi = 180^\circ$ 0,56 %</td>
</tr>
<tr>
<td>Solid carbide cutter with radius</td>
<td>$\varphi = 133^\circ$ 0,129 mm</td>
<td>$\varphi = 180^\circ$ 0,72 %</td>
</tr>
</tbody>
</table>

Table 2 – Maximum values of the thickness of the chip and the deviations between calculations

The values of the average thickness occur all at the same angular value of $\varphi=133^\circ$ and are larger in cutting situations with solid carbide cutter. These values are greater than in the case of the cut with
straight edged insert because the cutters have the maximum value of the $\kappa=90^\circ$ and the thickness of the chip increases with the value of $\kappa$.

The minimum values occur in the case of cutting with round edge inserts. The round cutting edge decreases the average thickness of the chip as it can be seen in the case of cutters that have radius.

The deviations between the calculations by expressions, and by increments all occur at the maximum value of $\phi$ and are larger in the case of the round edge.

From what has been shown, the deviations are perfectly acceptable, validating the expressions (5), (6) and (7) for the purpose of calculating the average thickness of the chip in the application.

**Cutting Force and Materials**

Cutting force is calculated using the expression:

$$F_C = K_s e_m I Z_a (N) \quad (8)$$

$Z_a$ - number of effective teeth; $K_s$ - specific pressure of the cut (Ks) is a constant that depends on the material to be machined.

The most common materials used in the moulds industry are grouped in the application database in the following classes and with the following orders of magnitude for $K_s$, according to the catalogue of Seco [13]:

<table>
<thead>
<tr>
<th>Class</th>
<th>Materials</th>
<th>$K_s$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>construction and pre-treated steels</td>
<td>1700</td>
</tr>
<tr>
<td>M</td>
<td>stainless steels</td>
<td>1900</td>
</tr>
<tr>
<td>K</td>
<td>cast irons</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>non-ferrous materials (copper-beryllium, graphite and aluminum)</td>
<td>700</td>
</tr>
<tr>
<td>S</td>
<td>Super-alloys</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>hardened steel</td>
<td>1900-2000</td>
</tr>
</tbody>
</table>

Table 3 – Reference values for $K_s$ depending on the class of materials

**Power and Torque**

By calculating the cutting power ($P_c$) and the cutting torque ($B_c$) required for the operation, it is possible to verify if the machine supports or not the desired milling operation. The expressions are calculated, as following.

$$B_c = \frac{F_C R}{1000} \quad (Nm) \quad (9) \quad R – \text{milling cutter radius}$$

$$P_c = \frac{2 \pi N B_c}{60} \quad (W) \quad (10)$$
PRACTICAL MILLING SITUATIONS

On the following table it is possible to compare time and feed rates values calculated by the software with real milling times and feeds rates.

![Figure 5 – Practical milling situations parts](image)

<table>
<thead>
<tr>
<th>Part / operation type / Milling cutter type</th>
<th>( V_a ) specified (m/min.)</th>
<th>( T ) theoretical (minutes)</th>
<th>SOFTWARE CALCULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHA 9893-3 / rough milling / Round cutting edge inserts</td>
<td>5,5</td>
<td>35</td>
<td>5,5</td>
</tr>
<tr>
<td>AHA 9893-3 / rough milling / Straight cutting edge inserts w/ rad.</td>
<td>9</td>
<td>153</td>
<td>9</td>
</tr>
<tr>
<td>AHA 9893-3 / finishing / Round cutting edge inserts</td>
<td>2,7</td>
<td>109</td>
<td>2,7</td>
</tr>
<tr>
<td>AHA 9893-3 / finishing / Solid carbide cutter with radius</td>
<td>0,25</td>
<td>12</td>
<td>0,25</td>
</tr>
<tr>
<td>EDI 6054-201 / rough milling / Straight cutting edge inserts w/ rad.</td>
<td>8</td>
<td>37</td>
<td>8</td>
</tr>
<tr>
<td>EDI 6054-202 / rough milling / Straight cutting edge inserts w/ rad.</td>
<td>6</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>EDI 6057-2 / rough milling / Straight cutting edge inserts w/ rad.</td>
<td>8</td>
<td>60,4</td>
<td>8</td>
</tr>
<tr>
<td>PRT 2247 - 101 / rough milling / Straight cutting edge inserts w/ rad.</td>
<td>2,2</td>
<td>52</td>
<td>2,2</td>
</tr>
<tr>
<td>PRT 2385 - 200 / finishing / Solid carbide cutter with radius</td>
<td>1,5</td>
<td>30,07</td>
<td>1,5</td>
</tr>
<tr>
<td>PRT 2385 - 200 / finishing / Solid carbide cutter with radius</td>
<td>0,65</td>
<td>24,5</td>
<td>0,65</td>
</tr>
</tbody>
</table>
Table 4 – Comparison between real milling values and calculated values by the software

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>Feed Rate</th>
<th>Milling Time</th>
<th>Fc</th>
<th>Bc</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRT 2385 – 81A</td>
<td>Rough milling / Straight cutting edge inserts w/ rad.</td>
<td>3,6</td>
<td>34,20</td>
<td>3,6</td>
<td>34</td>
</tr>
<tr>
<td>PRT 2399 – 200A</td>
<td>Rough milling / Straight cutting edge inserts w/ rad.</td>
<td>1,2</td>
<td>111</td>
<td>1,2</td>
<td>111</td>
</tr>
<tr>
<td>PRT 2399 – 81</td>
<td>Rough milling / Round cutting edge inserts</td>
<td>4</td>
<td>36</td>
<td>4</td>
<td>36</td>
</tr>
</tbody>
</table>

CONCLUSIONS

From what has been shown on the table 4, the real and the calculated values are nearly the same, validating the calculation of the feed rate and milling time by the software. Relating to the other parameters, they were not measured on real milling situations, but from what has been shown on the calculation of the average thickness of the chip, this calculation can be also validated and consequently the other parameters related to the thickness of the chip - Fc, Bc and Pc -. However these are theoretical values, they were not measured on real milling situations, like has been made to the feed rate and milling time.

The software has a database with tools optimized cutting conditions. This optimization is very important in order to reduce milling costs, because with this optimized cutting parameters the milling time is lower. However the optimization in some situations can reduce the tool lifetime. The calculation of the cost and benefit of the optimization has to be done.
REFERENCES


