ABSTRACT. High Speed Machining (HSM) has been discovered as one of the most promising technology for reducing production times and to improve surface finish in the machining of precision moulds and dies. However there are several factors that are critical for a good performance: cutting tool, cutting parameters and mainly the cutting strategy used in the process.

This paper will focus in this area, presenting the advances achieved in the development of new cutting strategies for HSM of hardened steels and how these strategies can improve significantly the result, both from the tool life point of view and also in the geometrical accuracy and surface finish of the machined workpiece.

The results described in this paper are the proposed solutions for the HSM of real parts in hardened steels in four different mould and die application sectors like forging, stamping, injection of aluminium and plastic injection.

KEY WORDS: High speed machining, Rough cutting strategies, Mould and die manufacturing.
0. Introduction

This article intends to summarise the work done in a basque ambit project [TEK 99] by some Technological Research Centres and Universities with the direct implication of machine-tool manufacturing companies, and mould and die manufacturers. The project, financed by the Basque Government during 3 years, has allowed to develop the high speed process in machines of our own machine-tool sector, to machine real pieces of users and to compare them to the current processes. A technological data base about the process (cutting tools, cutting conditions, strategies, CAD/CAM, characteristics of machines) has been generated and the objective of the formation of a wide nucleus of work teams that guaranty the generalised development of the high speed processes in the wide basque sector of the mechanical manufacturing has also been accomplished.

As a particular contribution we will mention the development of the “circular” strategy and its application to any tool trajectory, strategy that allows to carry out rough cutting operations with small diameter tools and HSM machines of limited power.

Finally, just to mention that with the background generated during the project, the partners have collaborated in the edition of a monographic about high speed machining and its applications [LOP 99].

1. Experimental set-up

The figure 1 shows the High Speed Machine employed by Tekniker. The machine, type Kondia HS 1000, is equipped with a spindle of 24000 rpm, power of 17 Kw and a maximum feed speed of 24 m/min. A similar machine has been utilised in the laboratories of UPV. In the programme of machining tests Rambaudi and Fidia High Speed milling machines have also intervened, as well other milling machines reconverted with electrospindles.

The next commercial CAD/CAM software packages have been used:

<table>
<thead>
<tr>
<th>CAD</th>
<th>EUKLID, IDEAS, INTERGRAPH, UNIGRAPHICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM</td>
<td>EUKLID, WORK NC, UNIGRAPHICS, POWER MILL</td>
</tr>
</tbody>
</table>

The next materials have been used in the machining tests.

<table>
<thead>
<tr>
<th>Work piece material</th>
<th>Application field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron GG25</td>
<td>Sheet forming</td>
</tr>
<tr>
<td>54NiCrVMo6 (40-41 HRc)</td>
<td>Forge and plastic injection</td>
</tr>
<tr>
<td>X40CrMoV5 1 (46-48 HRc)</td>
<td>Forge and plastic and aluminium injection</td>
</tr>
<tr>
<td>34CrMo4 (38-42 HRc)</td>
<td>Aluminium injection</td>
</tr>
</tbody>
</table>
Figure 1. Kondia HS1000 High Speed Machine used in Tekniker.

Tools of different geometry and from different suppliers have been used. In the same way, specific tools for some operations have been manufactured. The next table summarises the characteristics of the ones most utilised during the project.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cutter</th>
<th>Diameter (mm)</th>
<th>Number of teeth</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough cutting</td>
<td>Cylindrical</td>
<td>6,8,10</td>
<td>4</td>
<td>TiAlN</td>
</tr>
<tr>
<td>Finish cutting</td>
<td>Spherical</td>
<td>2,4,6,8,10</td>
<td>2,4</td>
<td>TiAlN</td>
</tr>
</tbody>
</table>

The machining tests programme has combined systematic tests on specimens, with the machining of real workpieces with complex surfaces. As result it has been obtained, on one hand a data base that contains the utilised cutting conditions, the tools employed and the obtained performances, and on the other hand, a relation of real cases where the current manufacturing processes of these pieces and the alternative of high speed milling processes are compared in terms of time. In the next points, the mentioned aspects are detailed.

2. Data base

An application developed in visual Basic V5 for a Access data base is available in CD format for users. It is not an exhaustive data base, thereby it does not pretend gathering all the possible casuistry of materials, cutting tools, cutting conditions and strategies. It presents in a friendly way the tests and successful machining operations carried out in different high speed milling machines by the different partners.
involved in the project. It pursues the objective of being useful, as starting point, for any new user of the high speed machining process. It also facilitates the personalisation of the software to the needs of the user.

The figure 2 shows the main screen of the programme with fields defined for the material, tool, conditions, strategy employed and performance of the milling operations in those conditions. The performance is expressed in terms of tool life and obtained surface quality. The current database has information available about 6 materials of hardness from 20 to 60HRc, 25 cutting tools (geometry of cylindrical and spherical tip, of 2,3 and 4 flutes, of diameters between 1 and 20 mm, most of them coated with TiAlN) and 40 successful machining tests with different roughing, semifinishing and finishing conditions.

Figure 2. Main screen of the data base that includes information about workpiece materials, milling tools and HSM process conditions.

3. Machining of real mould and die pieces

In this project, different reference pieces from different mould and die sectors have been undertaken. Dies for warm forging and sheet stamping, and moulds for injection of plastic and aluminium have been machined. Each of these sectors represents different casuistry that can be briefly summarised in the next aspects: Forging is the less exigent sector as for tolerances and required surface quality; sheet stamping uses cast-iron dies which facilitates the machining process; aluminium injection treats with deep cavities, which makes it difficult the high speed machining
process in 3 axes machines; finally the plastic injection, may be the most exigent sector as for tolerances and a good surface finishing necessities.

Different machining tests have been carried out in which it has been tried to optimise progressively the manufacturing HSM process of the considered reference mould and dies. Likewise, an evaluation of the 4 studied cases, comparing the current processes to the ones developed during the project, has been carried out.

The figure 3 summarises the most significant data of the studied cases. In all of them the advantage contributed by the high speed machining processes can be seen in a notable reduction of manufacturing time.

In all the analysed cases, a reduction of time of the cycle of manufacturing of the piece applying high speed milling process has been observed, time reduction depending on the characteristics of the pieces.

It is confirmed, as it is known, that the HSM processes avoid or substitute the EDM process, with which avoids the manufacturing of the electrode, and the EDM process itself, considered a slow manufacturing process.

The drastic reduction of polishing time is other important advantage, due to the good surface quality obtained with the HSM processes. We remind that the polishing, frequently, is revealed as the critical operation in the mould manufacturing.

Among the disadvantages of the HSM is identified the major CAM required time, justified by the major difficulty that presents the definition of the machining strategies to be employed.

Although it is not evaluated in time, another advantage that the HSM users appreciate is that when working with treated material a lot of mould movements, for their heat treatment after the preliminary rough cutting operations, are eliminated. Also that the worn moulds can pass directly to be machined with a new trace, reducing in this way the time for its reuse.
<table>
<thead>
<tr>
<th>Process</th>
<th>Conventional</th>
<th>CAD/CAM</th>
<th>By HSM</th>
<th>CAD/CAM</th>
<th>By HSM</th>
<th>CAD/CAM</th>
<th>By HSM</th>
<th>CAD/CAM</th>
<th>By HSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forging die</td>
<td>26 Hours</td>
<td>10.5 Hrs</td>
<td>98.5 Hrs</td>
<td>53 Hrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic injection mould</td>
<td>24 Hours</td>
<td>20 Hrs</td>
<td>45 Hrs</td>
<td>21 Hrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.** Comparison of the conventional manufacturing cycles with those using High speed machining, in the production of 4 moulds and dies from different fields like the forge, the sheet forming and the injection of plastic and aluminium.
4. New cutting strategies

In different machine tool exhibitions [JIN 98] [MAQ 98], several high speed machine manufacturers are offering interesting strategies that however are hardly available in CAD/CAM commercial programmes. Strategies as the ones called “trochoidal” [ENH 98] or “epicycloidal” achieve to machine slots with tools of diameter lower than the width of the slot, with really amazing performance in terms of the metal removal rate and the tool life.

The first thing that attracts attention with these strategies is that the axial depth of cut increases 10 or 20 times, that is, we pass from working with axial engagements of ~0.1*D to work with values of ~1.5*D (being D the diameter of the tool). Regardless other considerations these strategies allows a more rational use of the cutting tool, no limiting this exclusively to the tip of the tool.

In the project, in view of the commercial unavailability of this kind strategy, we have developed the “circular” called strategy (see figure 4). An specific developed utility allows the use of this strategy on any programmed tool path.

Designed for rough cutting operations, the advantageous performance of this approach has been proved in different cases that are commented later on. At the same time the reasons of such good behaviour will be explained. The acquisition of cutting forces and the analysis of its distribution over the cycle defined by the mentioned strategy will help us, comparing it to rectilinear cycles, to argument the obtained advantages.

![Tool path trajectory generated for the "circular" strategy.](image)

Figure 4. Tool path trajectory generated for the "circular" strategy.
The tool path follows a semicircular trajectory that after each cycle moves the value of the lateral feed (\(Ae\)).

In the machining tests carried out with this trajectory, it has been noticed that practically the total amount of the heat generated during the cutting is eliminated with the chip (red-hot chip) and that the tool remains cold, which favours the prolongation of the tool life.

Respecting to a rectilinear trajectory the differences can be summarised in the next points:

- The contact time tool/piece is cut practically by half, which allows its cooling.
- The tool, submitted to nominal cutting forces, happens to be only during a short moment, which represents a drastic reduction of the solicitations of the tool.

**Figure 5.** Evolution of cutting forces in the orthogonal directions X-Y of the measuring table, during a cycle of the circular tool path trajectory, when machining a slot of 16 mm width with a 10 mm. diameter tool. (\(Y=\) tool progression axis)

**Figure 6** shows the relative magnitude of the cutting forces of the figure 5, made his radial (\(Fr\)) and tangential components (\(Ft\)), and distributed on the circular trajectory of a cycle. \(FR\) represents the resultant force. From the tangential force will be extracted the Torque and consumed spindle power.

Figure 5 shows the registered efforts with a Kistler dynamometric table in the X-Y orthogonal axis (\(Y=\) axis of the radial advance of the tool) during a machining cycle with the circular strategy. Nominal spindle rotation and radial feed are 10,000 RPM and 4 m/min, respectively.
Intervening geometric transformation tangential and radial components are calculated (see figure 6). It can be observed that efforts are minimum to the beginning and end of circular trajectory and they pass by maximum values in the central part, position in which $F_t$ attempt a value of 187 N. In these terms, and for a diameter of tool of 10 mm, the Torque value is 0.93 N.m. and the consumed power 1 KW. Like say in the introduction, it is demonstrated that it is possible to accomplish operations of rough cutting with little power consumption.

5. Generalisation of the circular strategy to any tool path trajectory

This option has been activated to apply the circular strategy to any programmed tool path trajectory. The figure 7 represents the idea of the mentioned generalisation. This option has not been found in any of the CAM software used by the different partners of the project. The developed utility asks for the input file name (file that contains the basic trajectory), the output file name (file that will contain the new trajectory), and the values of the basic parameters required by the circular strategy.

Figure 7. The figure present, on the left the trajectory on the one it is tried to apply the circular strategy (its code is contains in a file), and on the right the result of the developed application in which it can be observed how the tool describes circles centered in the initial tool trajectory. The tool penetration cycle, consisting in an helicoidal descendent strategy can also be observed in the figure.

5.1. Application of the circular strategy in pocket machining

To apply it in interior zones, previously it is need to deepen with a descendent circular cycle until the desired depth is reached (see figure 7).

To carry out slots it will be enough to define the desired width of the slot, the diameter of the available tool and the nominal feed per revolution.
It is fundamental, in any event in HSM processes, that at every opportunity it pertain to use the "down milling" strategy (see figure 8).

With this strategy the tool begin machining the maximum thickness for progressively go reducing until to the exit where the thickness of cutting is zero.

![Figure 8. Down milling strategy.](image)

As an example of application we present the rough cutting operation carried out on the workpiece shown in the figure 9. It is a forging die with a depth of cavity of 70 mm, and a removal chip volume of 40 cm$^3$.

Applying the “circular” strategy the rough cutting operation has been carried out in 5 steps of 10 mm of depth of cut (1 time the tool diameter, D=10 mm). Machining time was 1.5 hours, which means a chip removal rate of 0.44 cm$^3$/min.

With the "conventional" HSM strategy, using an spherical end mill and cuts of 1 mm depth (0.1*D), and 1 mm of lateral feed, the machining time was 6 hours, which means a chip removal rate of 0.11 cm$^3$/min, being this chip flow 4 times lower than the one obtained with the “circular” strategy.

Certain is that the rough cutting with the circular strategy requires of a semifinishing work, in which 2 hours more were employed. Even so the time of process with the circular strategy result favourable (3. 5 hours versus 6 hours).

It is also important to mention that while the tool used in "conventional" conditions had to be substituted to the ending of this operation, the tool employed with the circular strategy machined a second workpiece.
Figure 9. Final aspect of the forging die.

Figure 10. Rough cutting process using the circular strategy, carried out in 5 cuts. In conventional strategy conditions 30 cuts were required.

The high metal removal rate using the “circular” strategy allows considering it as strategy for rough cutting operations. Being performed with small diameter tools, lets us obtain the important conclusion that it is not necessary to have high power HSM machines to carry out Rough cutting operations.

5.2. Application of the circular strategy in contouring machining

The performance of the HSM processes can be improved applying the “circular” strategy also to the contouring machining.
In this paragraph two aspects will be analysed. On the one hand the performance of the circular strategy in front of the conventional rectilinear strategy used for contour operations, and in the other hand, the influence of the internal of the own circular strategy parameters (basically the radio of the described circles) on the cycle time, on cutting forces and on the tool behaviour.

To use this proposed strategy it will be enough to apply it on the contour of the piece, adjusting the values of two parameters as the arc of circumference, \( \alpha \), slightly higher to the arc defined by the tool engagement (to the object of clearing it), and the radio \( R \) of the circumference, circumference on the tool progress with its rotational movement (see figure 11).

**Figure 11.a.** Schemes shows the geometric process conditions with the circular strategy for the radios of \( R1 = 15 \text{ mm} \) and \( R2 = 50 \text{ mm} \). The magnitudes of radial and tangential forces, shown to scale, can be compared.

**Figure 11.b.** Evolution in time of cutting forces for both circles radios. Influence of the radio on terms of the tool/workpiece contact time and the magnitude of the cutting forces can be observed.

Figure 11 shows the results of two machining tests in those the influence of the radio in the application of the circular strategy has been compared. A “small” radio of 15 mm. and a “big” radio of 50 mm. have been chosen. The other basic cutting
parameters were: S: 10,000rpm, F: 4 m/min, depth of cut: 10 mm. and a tool diameter: 10 mm. Workpiece material: UNE F1250 (42 HRc).

Results are summarised in the table 1:

<table>
<thead>
<tr>
<th>Radio of the circular strategy:</th>
<th>R1= 15 mm.</th>
<th>R2= 50 mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool/piece contact time/ cycle</td>
<td>0.2 sec.</td>
<td>0.4 sec.</td>
</tr>
<tr>
<td>Radial force (N):</td>
<td>570</td>
<td>450</td>
</tr>
<tr>
<td>Tangential force (N):</td>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>Torque (N.m.):</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Spindle Consumed power (Kw):</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Metal Removal rate:</td>
<td>45 mm³/cycle, the same in both cases (lateral engagement* Ae * Ap)</td>
<td></td>
</tr>
<tr>
<td>Machining observations:</td>
<td>Case R=15: - Incandescent chip, cold tool, inappreciable wear of the tool. Case R=50: - Premature tool damage. Excessive tool flank wear</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of the influence of the radio on the circular strategy.

For the observations during machining, we realise that it is preferable a little radio to a big radio. Priority must be given to the reduction of the tool/piece contact time, even in spite of the fact that the cutting forces grow larger.

For the same lateral feed for cycle (Ae), the thickness of cutting is minor when principal is the radio (as it can be seen comparing scheme of figure 11.a or can be read from the values of cutting forces (figure 11.b)).

In these terms, enlarging the tool/piece contact time, time machining almost nothing also increases putting the tool simply rubbing against to workpiece surface, under a considerable radial effort, what undoubtedly explains the exaggerated and premature deterioration of the cutting edges.

To emphasise that the metal removal volume do not vary with the "radio", being this volume calculated by the product of the lateral feed, the slot width and the depth of cut.

Radio values lower than 2 times the diameter of the tool can be recommended. For minimising the tool/workpiece contact time the slot width must be also limited to a maximum of 1.5 times the tool diameter.

In the following paragraphs will be mentioned the advantages shown by the application of the circular strategy in the "contourning” operation, comparing it with the conventional rectilinear strategy. Figures 13 and 14 summarises used conditions
and strategies, and obtained performances in terms of cycles times and cutting forces.

**Figure 13.a. Contouring with the circular strategy.**

**Figure 14.a. Conventional contouring.**

<table>
<thead>
<tr>
<th>CONDITIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S: 10,000 r.p.m. F: 4,000 mm/min. Ae: 0.3 mm. Ap: 10mm.</td>
<td></td>
</tr>
<tr>
<td>Width of the slot: 16 mm. Length of the slot: 10 mm.</td>
<td></td>
</tr>
<tr>
<td>Contact time: 0.3 sec.</td>
<td>Contact time: 0.4 sec.</td>
</tr>
<tr>
<td>Cycle time: 0.8 sec.</td>
<td>Cycle time: 1.2 sec.</td>
</tr>
<tr>
<td>Machining time: 26 sec.</td>
<td>Machining time: 64 sec.</td>
</tr>
</tbody>
</table>

Evolution of cutting forces during a cycle

**Figure 13.b. Evolution of the cutting forces corresponding with a cycle of the "circular" strategy.**

**Figure 14.b. Evolution of the cutting forces corresponding with a cycle of the "conventional rectilinear" strategy.**

From the presented example it can be concluded that removing the same chip volume, in the application of the circular strategy a series of advantages come together:

- Machining time is sensitively inferior (26 seconds vs. 64 seconds), 2.5 times faster.
- Lower Tool/workpiece contact time (0.3 seconds vs. 0.4 seconds). This favours the observed cooling of the tool.
- Lower cutting forces.

It has to be added that during the machining the carried out observations confirm that the tool works easily. It keeps colder and the chips present better aspect.

These characteristics show that the "contouring machining" with the circular strategy is preferable because of it combines higher metal removal rates with improved tool life.

6. Conclusions

- The realisation of the project during the last 3 years has allowed the training of 5 working teams in the Basque Country in HSM processes. Likewise, 5 companies from the moulds and dies sectors have been able to optimise their manufacturing processes identifying new manufacturing solutions.
- A database about HSM processes applied to mould and die machining has been developed, and it is available, with the aim of becoming a guide for beginners or a tool adaptable to the needs of the experimented user.
- The advantageous application of HSM comparing to the conventional processes has been demonstrated on different mould and dies (from the forging, plastic and aluminium injection sectors),
- The “circular” strategy has been developed, and applied successfully in rough cutting operations, proving its indubitable properties:
  - It favours the concentration of the heat generated on the chip, maintaining the tool cold.
  - It allows the use of big depths of cut (till $\approx 1*D$).
  - It reduces the machining time, increasing the metal removal rate.
  - By means of the reduction of the cutting forces and the tool/piece contact time, it is favoured the tool life improvement.
- The application of the circular strategy to any tool path trajectory has been developed.
- Future works: the obtaining of better surface finishing and the machining in 5 axes to achieve deeper cavities, avoiding vibration problems due to an excessive slenderness of the tools, are considered pending aspects.

7. Acknowledgements

The author wish to thank to the Industry Department of the Basque Government the financing of the project, without which it would not have been possible the development of the project. Last, but by no means least, I would like to acknowledge the significant contributions to all aspects of this work by the other 10 partners involved in this project: Mech. Dept. of the ETSII (UPV), Mech. Dept. of
8. References


