Research Article

Peter Ižol, Miroslav Tomáš*, and Jozef Beňo

Milling strategies evaluation when simulating the forming dies’ functional surfaces production

DOI 10.1515/eng-2016-0013
Received Dec 09, 2015; accepted Jan 23, 2016

Abstract: The paper deals with selection and evaluation of milling strategies, available in CAM systems and applicable when complicated shape parts are produced, such as forming dies. A method to obtain samples is proposed and this stems from real forming die surface machined by proper strategies. The strategy applicability for the whole part – forming die – is reviewed by the particular specimen evaluation. The presented methodology has been verified by machining model die and comparing it to the production procedure proposed in other CAM systems.

Keywords: 3-axis CNC milling; milling strategy; forging die; CAD/CAM

1 Introduction

CAD/CAM/CAE systems, used when realizing production requirements, are focused on product development and design, motion and structural analysis, as well as computer aided manufacturing, including production systems numerical control [1]. One of their biggest contributions is the possibility to design and produce complicated shapes, such as forming dies: plastic moulds, stamping and bulk forming dies, EDM electrodes, extrusion dies etc. [2].

Using CAM systems is considered the most rapid and effective way to propose and realize technology for serial production. The part model is designed in the CAD system and then imported into the CAM module. Here, the necessary production process parameters and tools for each operation are set, followed by simulations when the tool path suitability is verified. Then, after corrections when needed, NC-code can be generated [2].

It is commonly known the NC code creation sequence is given by the following steps [1]. First, the CAD model is imported and placed in the required position, in conjunction with the CNC machine coordinate system. The workpiece definition (importing or designing), machine parameters setting and fixtures exploitation are also part of this step. Machining operations are defined in the second step. Each operation defines tool (type, geometry, size), cutting conditions (cutting speed, feed, cutting depth) and tool motion parameters. CLData (Cutter Location Data) are generated in the third step, i.e. the file with tool paths and cutting conditions information. This file can’t be used for CNC machine directly, but it has to be transformed onto the layout depending on CNC machine control system. The CLData transformation is performed by specialized software – ‘postprocessor’. Consequently, this data after post-processing represents NC-code and it can be used for CNC machine control system.

Material removing on the tool machine is graphically simulated in order to check collision and tool path kinematics. Virtual simulation of material removing and tool machine operation are commonly used by industry. When NC code fails, a loop of parameters change – tools and tool paths – runs until an adequate result is reached. The virtual machining objective is to reduce or eliminate physical tests. The evolution of virtual machining reached the cutting forces simulation and feed optimisation along tool paths [3].

The tool-workpiece geometry changes when surfaces complicated in shape are machined. It causes the cutting depth and cutting width to not be constant. Different modelling techniques are presented by authors [4–6], describing tool-workpiece contact variability. Nevertheless, tool path selection is one of the critical parameters when machining processes are designed. Tool paths are usually selected from standard path libraries in commercial CAM systems and they have to be chosen whilst considering machined surface geometry [3].
Each strategy used in common has its advantages and these are shown when some surface types are machined. When the complex shaped surface is created from many types, the way is splitting the surface to the regions and applying proper strategy for the surface type prevailing in each region. The procedure is time consuming and such algorithm appears being a solution that generates tool paths by combination of tool paths from several standard strategies [7]. Also in [8] is stated that, based on shape types analysis, forging dies are created from some cavities with very different shapes and depths. Therefore, in many cases, not only one strategy is used for cavity machining, and topographic analysis is necessary before strategy selection for each particular region.

Many different comparative analyses have to be done when determining the strategy fitness for machining certain surface types. One way to evaluate milling strategies is presented in [9]. Three finishing strategies are compared when machining the shaped surface and the same cutting conditions are used. The surface texture and roughness, dimensional accuracy and machining time have been evaluated. Strategy selection, evaluation and optimisation are also presented in [10]. The author evaluates roughing and finishing strategies separately. Another study [11] also analysed and evaluated milling strategies. These are classified in three groups: the first group involves “offset” strategies when tool paths are derived from machined surface contours; the second group involves “zig-zag” strategies and its advantage lies in simple tool paths derived and its simple calculation; the third group involves “parallel-lining” strategies.

Copying cutter is used in many cases when shaped surfaces are finished by milling. The tool leaves redundant material in the form of cusps between adjacent tool paths. The cusp height determines surface roughness and influences the dimensional accuracy as well. Therefore, it is necessary to reach the lowest values [9, 12]. The cusp height can be decreased by higher of either tool path density or tool diameter. The tool diameter is chosen by the machined surface dimensions and space between these surfaces. Consequently, the maximum tool diameter is chosen when NC code is programmed, so cusp height decreasing by choosing larger tool diameter is not possible. Tool path density increasing makes machining time consuming and increases production costs. The objective is to reach such a tool paths density to make production time and costs as minimal as possible [13]. The solution is such tool paths that generate cusp height constant, called iso-cusped tool paths. Some approaches are presented in [14], where the way to reach these paths is presented and the cusp height is derived from machined surface tolerances.

Advantages of using torus milling cutter in such cases is presented in [15].

2 Methods and experiments

The objective of experimental work has been to propose method for milling strategies evaluation when shaped surfaces of different tools are machined. Strategies evaluation through the specimens as a result of surface splitting to the regions do not always bring the desired results as carefully prepared specimens cannot involve all shaped features existing on tools [16]. Machining of shaped tool models is time-consuming, difficult and also verifies only one of the proposed production procedures. The presented methodology combines both these methods. Surface fragments are chosen before machining design and these are included into the specimens. On these specimens, machined by different strategies, its suitability for defined shape type is evaluated [17].

Connection rod has been chosen as a model of part and it is produced by closed-die forging in common. Distance of holes in pin and crank ends has been 100 mm and maximal thickness 22 mm. Cavities of upper and lower forging dies have been derived from the CAD model and some ways are described in [18]. Connecting rod, upper and lower forging dies are shown in Fig. 1.

![Figure 1: Upper and lower forging die with connecting rod – CAD models.](image-url)
Figure 2: Specimens extracted from forging die cavity.

dimensions. Specimen dimensions has been 50 × 50 × 20 mm. Virtual specimens 60 × 60 × 20 mm have been designed when NC programming due to tool paths generation over the specimen edges. So, the surface at the edges will not be influenced by tool lead-in and lead-out gaps. Specimens materials were aluminium alloy 42401 (AlCu4Mg) and Ebaboard L, known as a board material (synthetic, post-cured material on polyurethane base) – see Tab. 1.

Table 1: Selected properties of experimental materials.

<table>
<thead>
<tr>
<th></th>
<th>Ebaboard L</th>
<th>Aluminium alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg·dm⁻³]</td>
<td>0.45</td>
<td>2.8</td>
</tr>
<tr>
<td>E modulus [GPa]</td>
<td>0.570</td>
<td>72.4</td>
</tr>
<tr>
<td>Strength [MPa]</td>
<td>13 (bending)</td>
<td>380 (tensile)</td>
</tr>
<tr>
<td></td>
<td>11 (compression)</td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>45 (Shore)</td>
<td>105 (HB)</td>
</tr>
<tr>
<td>Thermal expansion coefficient [K⁻¹]</td>
<td>66 × 10⁻⁶</td>
<td>23.5 × 10⁻⁶</td>
</tr>
</tbody>
</table>

When machine the specimens, a three step production process has been designed – roughing, semi-finishing and finishing. Roughing and semi-finishing strategies have been the same for all specimens so the same initial conditions have been reached for finishing strategies. Roughing has used Contour strategy with tool path overlapping \( a_p = 0.65 \) mm and cutting depth \( a_p = 1 \) mm. Allowance \( h = 1 \) mm for finishing has been left for all surfaces.

Semi-finishing has used Constant Z strategy with variable cutting depth within \( a_p = 0.2–0.5 \) mm. It is defined by CAM system in dependence on surface orientation to reach the scallop height \( SH = 0.5 \) mm. After semi-finishing allowance \( h = 0.1 \) mm has been left for all surfaces.

Combined constant Z, Spiral and Parallel lining strategies have been used when finishing. Two values of side step \( a_e = 0.25 \) and \( 0.35 \) mm have been set in order to investigate its influence to the surface roughness and appearance.

Cutting conditions for aluminium alloy machining have been chosen, according to the tools producers’ recommendations and the same ones have been used for Ebaboard L:

- Roughing – end mill \( D = 18 \) mm by Korloy AMS 2018S, 2 replaceable uncoated carbide inserts, cutting speed \( v_c = 230 \) m·min⁻¹, feed \( f_z = 0.1 \) mm.
- Semi-finishing – end mill \( D = 10 \) mm by ZPS-FN, 4 teeth, material HSS Co8, cutting speed \( v_c = 160 \) m·min⁻¹, feed \( f_z = 0.035 \) mm.
- Finishing – ball mill \( D = 8 \) mm by ZPS-FN, 4 teeth, material HSS Co8, cutting speed \( v_c = 125 \) m·min⁻¹, feed \( f_z = 0.028 \) mm.

The surface roughness has been measured on the specimens after machining. Besides, Ebaboard L suitability to verification of cutting conditions and strategies was verified. Based on reached knowledge, model die has been machined.

Specimens and model die machining was done on 3-axis Emco Concept mill 155 with Heidenhein control system. SolidCAM was used as a programming software and CL data were transformed onto NC code by postprocessor.

3 Results

Fig. 3 and Fig. 4 show roughness comparison (arithmetic mean surface roughness Ra and surface roughness depth Rz) for specimens machined by three different strategies – Spiral, Combined constant Z and Parallel lining. The side step was \( a_e = 0.25 \) mm. The arithmetic mean surface roughness Ra for aluminium specimens reaches values within 1.68 to 2.02 \( \mu m \) and for Ebaboard L specimens within 3.59 to 4.19 \( \mu m \). The surface roughness depth Rz for aluminium specimens reaches values within 9.68 to 11.37 \( \mu m \) and for Ebaboard L specimens within 22 to 26.87 \( \mu m \).

Fig. 5 and Fig. 6 show roughness Ra and Rz comparison for specimens machined by the same strategies when the side step was \( a_e = 0.35 \) mm. The arithmetic mean surface roughness Ra for aluminium specimens reaches values within 1.84 to 2.04 \( \mu m \) and for Ebaboard L specimens within 3.94 to 4.26 \( \mu m \). The surface roughness depth Rz for aluminium specimens reaches values within 10.06
Figure 3: The arithmetic mean surface roughness Ra comparison when side step $a_e = 0.25$ mm.

Figure 4: The surface roughness depth Rz comparison when side step $a_e = 0.25$ mm.

Figure 5: The arithmetic mean surface roughness Ra comparison when side step $a_e = 0.35$ mm.

Figure 6: The surface roughness depth Rz comparison when side step $a_e = 0.35$ mm.

to 11.65 $\mu$m and for Ebaboard L specimens within 22.37 to 28.21 $\mu$m.

Based on the roughness values presented, the arithmetic mean surface roughness Ra for Ebaboard L material has been 2.2× higher than measured for aluminium alloy and 2.3× higher when the surface roughness depth Rz has been measured. Consequently, the board material Ebaboard L can be used for experiments to evaluate production processes due to good machinability. Otherwise, its usability to evaluate qualitative characteristics of machined surface is poor.

The surface roughness does not get worse from certain values of the side step. It is given by the allowance left after semi-finishing. The allowance determines the scallop height of the surface and the side step increases only the span of the scallops – Fig. 7. The allowance value left by semi-finishing operation should not be defined considering the side step value for finishing.
4 Knowledge application

The first step when model of forging die machining has been roughing with the same tool paths as they were applied for samples machining – Contour strategy. Programming system generates tool paths according to contours of final surface with allowance specified. The tool size – end mill D = 6 mm – do not allow to access whole cavity, so post-roughing has been needed with tool diameter D = 3 mm. Tool path generation only in desired regions have been provided by machining of residual material.

Constant Z strategy has been applied when semi-finishing. The end mill tool D = 3 mm has been used to make the allowance uniform before finishing. Uniform allowance makes the tool movement stable and it positively influences the final surface quality.

Die cavity finishing has been done with Combined constant Z strategy and ball mill D = 3 mm. The following tools and cutting conditions have been used:

- Roughing – end mill D = 6 mm by ZPD-FN, 4 teeth, material HSS Co8, cutting speed \( v_c = 94 \text{ m-min}^{-1} \), feed \( f_z = 0.022 \text{ mm} \).

- Post-roughing and semi-finishing – end mill D = 3 mm by ZPD-FN, 4 teeth, material HSS Co8, cutting speed \( v_c = 47 \text{ m-min}^{-1} \), feed \( f_z = 0.009 \text{ mm} \).

- Finishing – ball mill D = 3 mm by ZPD-FN, 4 teeth, material HSS Co8, cutting speed \( v_c = 47 \text{ m-min}^{-1} \), feed \( f_z = 0.008 \text{ mm} \).

Considering small dimensions of die cavity, small tool diameters for each operation have been chosen. It is generally understood in machining praxis, small tool dimensions are considered from 1 to 10 mm. So, because of the radii at the die bottom is 2 mm, the tool diameter must not exceed 4 mm. Thus, the ball end mill D = 3 mm has been chosen based on the rule: the tool diameter has to be lower than the inner radii; limit value is 0.9 \times inner radii. Cutting speeds recommended by tool producers haven’t been used due to low maximum spindle speed of 3-axis milling machine used for machining. Consequently, the feed rate has been decreased and production time became longer. If recommended cutting speed of ball mill D = 3 mm would be used, feed rate would reach \( v_f = 540 \text{ mm-min}^{-1} \), compared to \( v_f = 160 \text{ mm-min}^{-1} \) used when machining. Production time for finishing would reduce 3.4 times.

Fig. 8 and Fig. 9 show machined die details in small and crank end regions. There is shown on hemisphere in
pin end the surface fragmentation due to inadequate tolerance when substituted its shape by linear tool paths. The tolerance is the parameter when strategy definition in the CAM software. This has not been significant for the forging accuracy, so the finding was not important for author’s intention.

To verify knowledge gained when model die machining on CAM system SolidCAM to another CAM system, model die production also have been programmed in Creo CAD/CAM system. The objective was to use as many settings as possible for each operation. Tool paths generated for crank end region of connecting rod are compared on Fig. 10 and Fig. 11. Fig. 12 and Fig. 13 show tool paths for pin end region of the connecting rod. The difference has been found in tool path density mainly on vertical and sloped walls of die cavity, which would influence the surface roughness. Positions of tool lead-in and lead-out also differ as well as interconnection of adjacent tool paths.

When strategies are selected for specimens machining, not all problems are considered, because some would occur when these are selected for entire surface to be machined. Such as solution, partially, is the production process working out – selection of operations, tools and strategies – and then specimens selection.

Knowledge gained at specimen machining does not have to be fully applicable when the whole surface is machined. Thus, they allow in short time to review the strategy at virtual machining and when some problem are found, the strategy would not be suitable for the whole surface.

One global strategy designed for all surfaces is not always appropriate to use. Setting for some surfaces (e.g. sloped, vertical) are not applicable to others (e.g. sphere). Therefore, surface splitting onto groups is a solution (sloped and vertical, curved, horizontal, shaped etc.) and use different strategies for each group. In the example pre-
sented in previous, model die finished operation by universal Combined constant Z strategy would split onto two different strategies – Constant Z and Plains. The first one would use ball mill and the second one end mill. Extended programing time will compensate number of faults and time for corrections.

Stock removal splitting onto some operations is sometimes necessary due to other reasons. Narrow regions may occur on machined parts, so it is not possible to use tools with large diameters. In such cases, small tool diameter is chosen and production time becomes longer and effectiveness decreases. Small tool diameter requires denser tool paths and total cutting path elongates, together with lower feed values and machining time elongation. Consequently, tool or insert cutting life problems occurs. The solution is to split allowance removing onto some operations with different tool diameters – from larger to smaller. Longer time machining also will compensate by faster production and tooling costs.

Experience and knowledge reached using one CAM system are not fully applicable to another one. Detail control of CAM system selected for programming is necessary to achieve good results.

5 Conclusion

Results of the verification of the strategy selection when milling complex shaped surfaces have shown the importance of selection regions from shaped surface. Specimens have to be chosen to characterise all main shape marks entirely. In the example presented in this study, the places where two or more shape types join were not included enough into the specimens. Strategies that present good results on simple specimens (combination of flat-sloped surface or flat-basic shaped surface such as cylinder, cone and sphere) do not have to be applicable on when complex shapes are machined (basic shaped surface combination, parametric or free-form surface). The model die chosen as an example has allowed knowledge transfer from simple specimens.

Acknowledgement: This work was supported by the project VEGA 1/0360/15 Research on Active Surface Preparation For Advanced Tooling Produced by CNC Form Milling and VEGA 1/0434/15 Research on Process Dependent Interface when Milling with Small Diameter of End Mill Cutters granted by Scientific grant agency VEGA of Ministry of Education, Science, Research and Sport. Authors express also their thanks Slovak Research and Development Agency under Contract No. D07RP–0014–09.

References

[13] Schornik V., Daňa M., Zetková l., The influence of the cutting conditions on the machined surface quality when the crfrp is machined, Procedia Engineering, 2015, 100, 1270–1276

