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Evaluating the roughness according to the tool path strategy when milling free form surfaces for mold application

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The mold manufacture has a direct influence on the lead time, costs and quality of plastic products. Milling is the most important machining process in this industry. Due to some limitations on the milling operations, the surface roughness required for a mold is frequently only achieved by hand finishing. Even using updated technologies such as High Speed Milling, which improves the machined surface quality, the hand finishing is still required and it brings some drawbacks such as costs, time and geometrical errors. Today, any CAM software offers some different tool path strategies to milling free form geometries. However, the users must have the know-how to choose the strategies according to geometry complexity, cutting tool geometry and its contact on the machined surface. Choosing an optimum strategy is a rather difficult task to do on the shop floor. This topic is still not very well explored. The current work investigates different tool path strategies for milling a mold cavity during finishing operation. A mold cavity was manufactured and the results show that the tool path strategies have a great influence on the real milling time, surface roughness and hand finishing time and also show that the traditional roughness parameters are not adequate to measure the roughness in such applications

Keywords: CAM software, tool path strategies, mold manufacturing.

1. Introduction

The mold industry represents a key position on the whole manufacturing chain, affecting the costs, quality and lead-time of a product. Besides, in order to filling the market demand, designers have been using free form geometries in the product shape, to be more attractive for marketing. This fact increases the product manufacture complexity. BOUJELBENE et al. [1] investigated the costs of plastic products, and concluded that 30% of these product costs is related to the mold manufacturing, 25% related to the injection process, 25% to the plastic material, 10% to design and simulation, 5% mold steel and 5% is related to other costs. Therefore, mold manufacturing is the most represented item in the cost of a plastic product.

According to FALLBÖHMER [2], the automotive industry is the greatest consumer of molds, followed by the electronic industry. 60% of the mold manufacturing time can be attributed to manufacturing the mold functional parts, the cavities. There are several inconveniencies on the mold manufacturing phase as cited in literature, from technological limitations of the equipment and machines [3], up to the lack of manufacturing process development [4].

The mold is not usually ready to go to production line after the milling operation due to the difficulties of getting a good surface roughness [1]. Therefore the mold core has to be finished by hand operation, polishing. Even when a very skilled hand-finishing professional does the task the geometric

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accuracy, time and costs are compromised. According to RIGBY [5], the hand finishing operation of mold for automotive industries is responsible for about 38% of total labour costs and the product lead time is deeply influenced by this process limitation. FALLBÖHMER [6] affirms that 2/3 of the manufacturing costs go to milling and hand finishing operation and about 20% to 30% of the time to manufacture the mold is spent in hand finishing. This is a huge drawback for the industry.

Unlike traditional milling, when milling free-form shapes, the contact between the cutting tool and the machined surface changes constantly. Furthermore, the center of the ball-end tool, which has a zero cutting speed, can take part in the material removal process. This condition was investigated by SOUZA et al. [7]. The tool path is also responsible for such circumstances and although many papers can be found about the theme, the influences of the finishing tool path on the roughness of the machined surface are not stated yet, especially focusing on costs and time.

Therefore the current work aims to increase the knowledge about the relationship of the surface roughness, tool path strategies, hand polishing, time consumption, and dimensional accuracy for manufacturing molds.

2. Tool paths for free form milling

According to RAMOS et al. [8] the adequate choice of a tool path to milling a specific geometry can propitiate a reduction on the production costs and improve the surface roughness. Besides, the tool path can influence the real machining time due to the amount of acceleration and deceleration involved and direction alteration of the movements on the machine [9].

Any commercial CAM software today offers several possibilities of strategies of distributing the tool path in the domain of the designed part. The commonly used tool path distribution strategies are [10-11].

1. Zig-zag or raster curves.
2. Contour curves.
3. Spiral curves.
4. Space filling curves.
5. Sequential generated curves.
6. Radial curves.

Some requisites for having an efficient tool path for high speed milling free form shapes are:

- Repeatability efficiency: Using Zig-zag tool path, the trajectory many times represent several parallel swipes of a profile. This item identifies the tool paths efficiency according to how similar the paths are along the workpiece.
- Tolerance efficiency: It includes three issues. First, the path must guarantee that the geometrical and dimensional tolerances are inside of the designed range. Second the software must use all extremes of the tolerance range, in order to calculate the fewest possible number of points following the tool path. Third, the distribution of the points must be as homogeneous as possible.
- Geometry compatibility: The calculus algorithms must ensure compatibility of path for any free form geometry, concave or convex forms.
- Efficiency for working with external geometry: The software must be also efficient when external geometries, from other formats (as IGES, VDA-FS, Step) are used to calculate the tool path.
- Tool path efficiency: It is evaluated according to the path trajectory, considering over milling and non-milling times, tool approaches, departures and rapid transversal.

3. Experimental procedure

The proposed work investigates the efficiency of the different tool path strategy for finishing milling of complex geometries, usually faced in the mold industries. To do so, a mold containing a representative workpiece was designed and manufactured for this project. By exchanging knowledge with the industry's technicians, geometry of a refrigerator's eggs-receipt was chosen, in which 5 (five) cavities were designed symmetrically (Fig. 1).

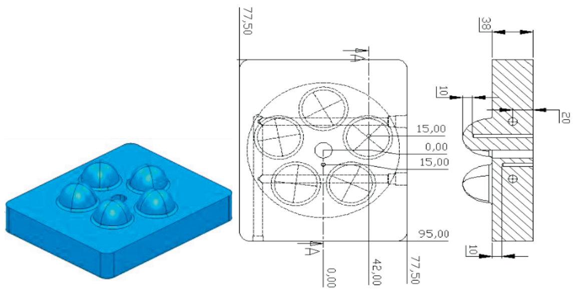


Fig. 1: Workpiece geometry.

Due to its symmetrical complexity, this geometry propitiates a possible way to investigate the manufacturing process of a plastic product.

The 5 cavities were roughened in the same manner, by 2 ½ axis milling, leaving an uniform amount of material of 0.2 mm, to be removed by the finishing milling, which was the focus of this study.

Each of the 5 cavities was finished by a different tool path strategy. The CAM software Powermill V8 from Delcam was used to calculate the tool path under the tolerance band of 0.01 mm.

The tool paths evaluated were (Figure 2):

1- Contour curves (*3D offset*). The trajectory is a composition of offset passes from the geometry, in a specified level horizontally. Several passes are formed, according to each level (step over) and connected to each other by a link connection on the surface (cavity 1).
2- Spiral curves (*Spiral*). The trajectory is only one segment following the geometry in a horizontal way; the tool engages on the material at the beginning and leaves only at the end. It looks like an offset; however there is no link between the passes once an offset is formed (cavity 2).
3- Radial curves (*Radial path*). The paths are calculated vertically on the surface. The center of a circumference and its border are the limits of each path. The cavity 3 uses the center of the geometry as the beginning of the path (from top to floor) and the cavity 4 uses the border as the beginning of the path (from floor to top). This condition

represents different contact between tool and machined surface. The paths are distanced by an angular step over and they are linked by movements without removing material (G00).

4- Zig-zag curves (*Raster*). In this technique parallel-linear paths are calculated laying on the desired surface. The step over distance the paths equality in a parametric plane, but on the surface, it depends on the surface topography (cavity 5).

The evaluation was carried out according to: i) surface quality after milling; ii) surface quality after hand finishing; iii) real machining time and a simple analyses on costs for manufacturing each cavity.

The tool path strategy was the only cutting parameter varied to milling the five cavities. However, after the first investigation, it was concluded that the cutting parameter step-over (a_e) could not be kept constant in all of the cases. It is because the options of finishing milling strategies change from horizontal, vertical and also radial trajectories as presented by Fig. 2. Therefore, keeping the step-over constant for all the cases will distinguish drastically the machining time and then mask the results. Therefore, in order to make sense the machining time should be the same for each of the 5 cases investigated. To do so, the machining time estimated by the CAM software was used to identify the step-over value (a_e) for each case, in order to keep the same time to machine the parts. It was set 6 minutes and 18 seconds to machine each part, according to estimative done by the CAM. Fig. 2 shows the step-over identified for each case and a detailed description of each tool path strategy.

A carbide ball end mill of 6 mm of diameter coated with titanium aluminum nitride (TiAlN) was used to perform the finishing operation with a spindle frequency of 18.000 rpm. The experiments were accomplished in a High Speed machine Deckel Maho DMU 60.

All cases investigated were machined by 3 axes milling, down cutting, without coolant. The tool holder was a shrink fit. The AISI P20 steel was the material used as a workpiece with approximately 30 HRc and it was fixed direct on the machine table.

The time that the tool is engaged on the material as well as its contact position with the machined surface alters according to the tool path strategy, what may influence tool wear. But, for finishing milling operation, the cost of the tool is not significant and, therefore, this point was not analyzed in this paper.

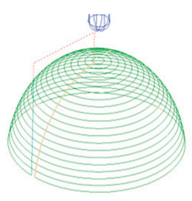
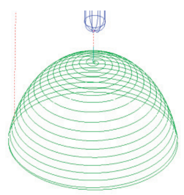
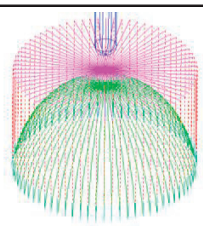
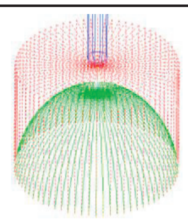
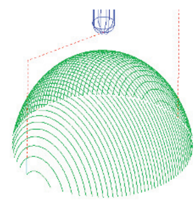
	Cavity				
	Cav. 1	**Cav. 2**	**Cav. 3**	**Cav. 4**	**Cav. 5**
Tool Path					
	Paths in a 3D offset Starting from the floor.	Spiral path. From the top to the floor.	Radial path From the floor to the top.	Radial path From the top to the floor.	Parallels paths. One way.
Step over	0.15 mm	0.14 mm	0.81 degree	0.81 degree	0.135 mm

Fig.2: Tool path and step over (ae) for finishing the five cavities.

The roughness of the finished surface was measured using a Taylor Hobson roughness equipment. The parameters Ra, Rz and Rt were accessed, perpendicular to the tool paths. The resultant values correspond to a median value of 3 (three) data acquisitions. The cut-off value was selected as recommended by ISO 4288 (1998).

With the help of an industry which offers services for polishing molds for many years, the evaluation of the surface roughness after milling was added by a feed-back of the polishing process required to finish each cavity (the 5 cases). In all cases, the hand polishing was done by the same worker who is an expert on it.

Even considering the nature constrains of evaluating the hand finishing, it is very important to accomplish the proposed investigation because reflects the real practice. Due to costs and time, it does not justify having more than one worker to polish to have statistic validation. It because considering the possibility to have some differences from one polisher to another, such difference will not have great significance, either because the deviation would be much smaller than the basic value and/or because all the 5 cases was polished by the same worker. Thus, the difference among polishers (faster/slower) would be for all cases, and the cases which are compared with the others. Therefore, for a comparative evaluation among the cases, this analysis fits reasonably.

All the steps required to do this process for each of the 5 cavities was documented.

4. Results and discussion

This work presents the results of the male part of the mold as follows.

4.1. Surface quality

The surface roughness was evaluated by the parameters Ra, Rz, Rt after milling and later by the time required to polish each cavity. Fig. 3 shows the machined surface of each case and its roughness parameters. Table 1 presents the sequence of operations required to hand finish each cavity and the time to do so. For hand finishing process, first abrasive files were used and after sand paper, both with different grain size, as presented on Tab. 1. The roughness parameters are the median of 3 acquisitions with a confidence interval of 95%.

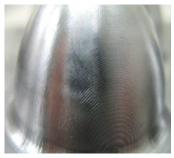
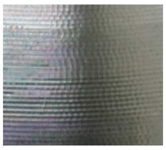
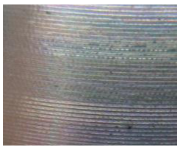
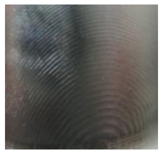
	Cav. 1	**Cav. 2**	**Cav. 3**	**Cav. 4**	**Cav. 5**
Cavity					
Amplified view					
Ra (μm)	0,81	0,77	0,67	4,25	2,18
Rt (μm)	5,42	6,27	4,11	21,54	15,31
Rz (μm)	5,25	6,09	3,84	20,84	10,39

Fig.3: The machined parts and its respective roughness parameters.

Analyzing the surface after milling, there can be observed an expressive difference of the roughness among the 5 cases. It shows that the surface roughness is not only affected by the cutting parameters, such as cutting speed and feed per teeth, but it is also strongly influenced by the tool path strategy.

A reasonable relationship among the roughness parameters could be observed i.e.: cavity 3 had the lowest value for Ra, Rz and Rt, and the cavity 4 had the highest value for all 3 parameters. The strategies 4 and 5 are the much worse than the others and should not be used in similar cases.

Table 1. Sequence of the polishing process, abrasive files and sand papers and the time consumption.

Hand polishing task					
	Time (minutes)				
Appliance	**Cav. 1**	**Cav. 2**	**Cav. 3**	**Cav. 4**	**Cav. 5**
Abrasive file 150	-	-	-	40	30
Abrasive file 220	-	17	25	25	25
Abrasive file 320	15	15	15	20	20
Abrasive file 400	10	10	10	20	20
Abrasive file 600	15	15	15	20	25
Sand paper 320	15	15	15	15	15
Sand paper 400	10	10	10	10	10
Sand paper 600	7	7	7	7	7
Sand paper 800	7	7	7	7	7
Sand paper 1000	7	7	7	7	7
Sand paper 1500	10	10	10	10	10
Total time (minutes)	**96**	**113**	**121**	**181**	**176**

Analyzing the time required for polishing, it can be seen that cavity 3, which presented the lowest values of roughness for all parameters, demanded more time to polish than cavity 1 and cavity 2. Therefore, a relationship between roughness parameters and the polishing time could not be established, indicating that there are limits to apply the ordinary roughness parameters for evaluating roughness of a free form surface for molds applications. It also can be seen that cavities 4 and 5, which presented roughness values many times higher than cavities 1, 2 and 3, presented polishing time not more than twice as long as the time used to polish these last cavities. Furthermore, the roughness values of cavity 4 were much higher than the values obtained in cavity 5, but their polishing time was about the same.

4.2. Surface roughness after polishing

Fig. 4 shows the workpieces and Tab. 2 the values of the roughness parameters after the polishing operations.

Fig. 4: Mold after polishing

Tab. 2. Mold roughness after polishing.

Cavity	Ra	Rt	Rz
1	0.035	0.56	0.34
2	0.024	0.37	0.2
3	0.024	0.47	0.28
4	0.02	0.19	0.14
5	0.019	0.26	0.15

After hand polishing the measured value of the roughness become much similar for all the 5 cavities. However, to reach this result the geometric accuracy can be affected, as presented ahead.

4.3 Analysis of the dimensional accuracy

The geometric error after the polishing was accessed by a measure machine coordinates Mitutoyo, Beyong Crysta700. It was accessed diameters along the workpiece, on each of the 5 cases. Diameters on three heights above the mold base were analyzed: 10, 15 and 20 mm. The values of the diameter are presented on Tab. 3. It is the medium of 2 acquisitions in each high. A total of 40 points in each acquisition was obtained.

There is a significant variation of the values observed among the different cavities, up to 0.240 mm. That discrepancy shows that an amount of material should be removed to reach the polishing required. Therefore, besides time and costs, geometric inaccuracy can be expected after hand finishing.

Tab 3. Form error after polishing.

Position evaluated	Cavity 1	2	3	4	5
10 mm	37.215	37.083	37.022	37.071	37.068
15 mm	33.352	33.422	33.347	33.349	33.376
20 mm	27.611	27.493	27.431	27.371	27.438

4.4. Real machining time

Because of the limitation of the machine-CNC, the time prediction from CAM software to mill a free form shape is not usually achieved, once the CAM does not consider some machine limitation, such as acceleration and deceleration, and CNC block processing time. Commercial CAM software estimate the machining time simply by dividing the entire tool path length by the programmed feed rate. This estimation differs drastically from the real process time because the feed rate is not always constant, due to machine and CNC limitations [12].

Therefore, the real machining time was measured for the 5 tool paths analyzed. Fig. 5 shows the real time compared to the estimated one, reminding us that the time set on CAM should be 6 min. and 18 sec. (378 sec.) for all 5 cases.

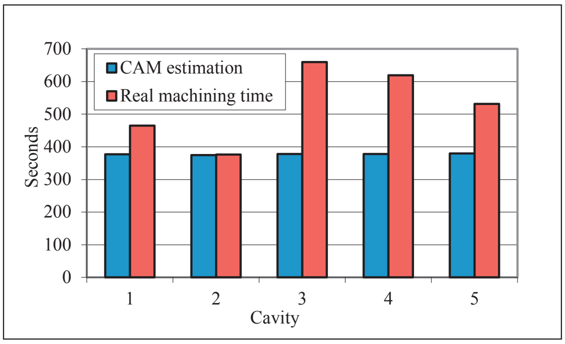


Fig.5: Machining time. Estimation from CAM and real.

Figure 5 shows that the real time to machine the cavities was higher than estimated by the CAM software for all cases evaluated and the highest error reached up to 78%. That happened due to limitation on the machine/CNC which cannot be predicted by the software, as discussed by COELHO et al. [13]. These results also show that there is no direct association between the machining time and surface quality. For instance, case 4, even taking the second longer time to machine the part it had the worst surface quality, considering all roughness parameters and polishing time. It took longer due to both, the number of engagements and retractions from the material during the machining and because the higher number of segments to describe the form by the tool path.

4.5. Evaluating the time to mill and polishing

Table 4 presents the total time required to finish each cavity; considering the real time to machine each cavity together with the time to polish.

Tab. 4. Time required to finishing each cavity

Tool path method	Real machining time [s]	Polishing time [s]	Total time [s]
1) 3D Offset	**960**	5760	**6720**
2) Spiral	1130	6780	7910
3) Radial ascendant	1210	7260	8470
4) Radial descendent	**1810**	10860	**12670**
5) Parallel passes	1760	10560	12320

Considering the total time, the longest method (case 4) took about 88% more time to be concluded than the fastest one (case 1).

4.6. A simple view about the costs

Just to propitiate a qualitative view about the costs involved, it was considered that polishing costs U$30.00 per hour and milling U$ 60.00 per hour. Fig. 6 shows this estimation.

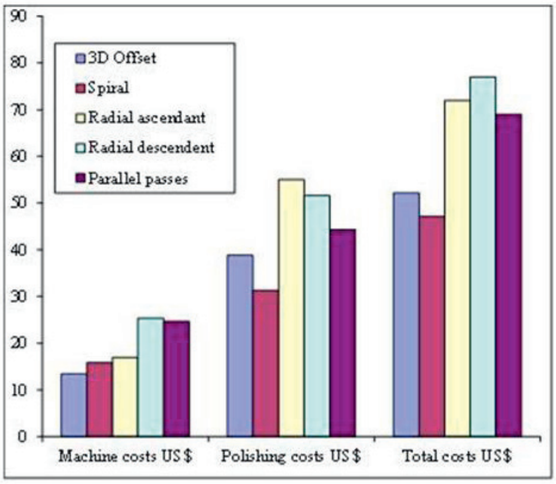


Fig.6: A qualitative evaluation about the costs according to path strategy.

In the cases investigated the tool path strategies had a quite significant impact on the production costs. A difference of about 40% was found.

5. Conclusions

This work investigates the influences of the tool path strategy on the surface roughness for die and mold application. It was assessed by the real machining time according to tool path strategy, the roughness parameters and the time required for polishing the samples, as usually required by mold application. The results demonstrate that the roughness of free form geometry after milling is much influenced by the tool path strategy. The path strategy influences real machining time, polishing time and costs. The results show that the right choice of the tool path can save 88% of the time and 40% of the costs for finishing the mold evaluated, if compared to the less appropriate option.

Both tool path strategies which slice the part in a horizontal manner (*3D offset* and *Spiral,* case 1 and 2, respectively) got the best results. It is suggested that these differences came from the orientation from start to the end of the path. In case 2 (spiral path) the tool starts milling at the top and goes down to the bottom surface to end the machining. In case 1 (*3D offset*) the machining starts at the bottom and goes to the top. This feature implicates directly the contact between tool-surface. And it propitiates better surface roughness when the tool starts at the bottom and goes to the top. Therefore, the tool path has a great impact on the contact tool-surface and it will be investigated in future work.

Analyzing the results of the hand polishing the work demonstrates that the ordinary parameters to evaluate surface roughness are not appropriate for mold application due to the surface complexity and the high level of polishing required. A method to qualify properly such surfaces is still missing. For future work, some mechanisms can be proposed and evaluated.

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