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Mold manufacturing optimization: a global approach of milling and polishing processes

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Abstract

Within the context of molds and dies production, frequent changes in design and increased competitiveness require an overall optimized manufacturing process. The finishing process is typically composed of an accurate milling stage to manage shape deviations, followed by polishing operations to reach required surface roughness. Local improvements of milling and polishing set independently do not necessarily lead to an optimal manufacturing process planning. This study aims to propose a method to improve the whole sequence of milling and polishing considering constraints from polishing process and machine tool. The turning point between milling and polishing operations consists in linking them by the evaluation of the surface topography obtained after milling. From there, thanks to a predictive model of surface roughness, the design of polishing operations can be performed, and polishing time evaluated. On the other hand, for a given machine tool and a desired intermediate surface topography, milling parameters for finishing can also be modified and actual machining time predicted. Thus the whole process is evaluated balancing the milling and polishing times to reduce the total manufacturing time. Experiments are carried out on an aluminum mold for blowing process of plastic bottles.

Keywords: Mold ; Finishing ; Manufacturing process ; Milling ; Polishing ; Predictive model ; Topography

1. Introduction

The design and the production of molds have a decisive role on the final products quality and cost [1]. With the increasing competitiveness and frequent changes in molds design, it is very useful to estimate precisely the production costs to improve the manufacturing process.

The process of mold manufacturing is generally composed of two successive stages: mold machining then surface polishing. Indeed, starting from a raw piece, the CAM process leads to a final shape close to the CAD model. Nevertheless, the surface topography produced after milling (especially roughness criteria) are not reached. It is thus impossible to directly use the mold for injection: for a mold used for blowing process of plastic bottles, a "mirror" surface quality is needed in order to give the required bottle transparency. Hence, the abrasion process is used to polish the machined surfaces and reduce the scallop height to achieve a "mirror" aspect.

In literature, one can find numerous studies to improve each one of these two processes independently. Concerning milling, several models are developed to improve the actual surface quality. The aim is to get the best surface quality in terms of surface criteria with a given chordal deviation [2]. With a machining strategy point of view, different tool path have been developed, such as iso-scallop height, in order to obtain the desired surface roughness in a shorter tool path

[3]. Studies are also carried out to reduce the machining time. Feedrate planning of tool path for freeform surfaces is often improved taking into account machine kinematics (maximum axis velocities, accelerations and jerks) [4]. Thanks to the optimization of the tool path geometry and its interpolation for real-time execution, the surface quality can be improved, avoiding deviations from CAD design and avoiding marks caused by feedrate slowdowns. As the actual feedrate differs from the programmed one, the prediction of the velocity profile along the tool path is a real issue to predict machining time and can be used to estimate the actual machining productivity and costs.

Regarding polishing, modeling the abrasion process for freeform surfaces remain a scientific and technical obstacle towards an optimized and automated process [5]. The quantification of abrasion is most frequently given by the material removal rate (MRR) which corresponds to the thickness of material removed per time unit. To model the MRR, two different approaches can be distinguished: analytical models and experimental models [6]. The analytical models are based on the modeling of the interaction between the tool and the workpiece at the level of the abrasive particle [7]. Within the context of mechanical parts such as blowing mold, the models used are rather the experimental ones derived from the analysis of many polishing trials. The model developed by Preston within the context of glass polishing is probably the one that is today the most used [8]. For other materials, Klocke et al. propose a

more generic model involving three constants to be determined [9]. In these models, the MRR depends on the polishing tool velocity and on the polishing pressure. Most of these models don't take into account the geometric characteristics of the surface to be polished.

However, considering the whole manufacturing process of molds and its optimization, the milling and polishing stages cannot be improved independently. They are strongly linked by texture and deviations left on the surface by milling. Indeed, polishing range depends on the surface topography after milling. These two processes are then strongly interlinked. Few papers try to characterize this link between milling and polishing. Souza et al. evaluate the roughness according to the tool path strategy and determine polishing time according to the roughness [10]. Boujelbene shows the impact of tolerances and interpolation on polishing time which follow milling [11]. Although these studies provide predictive models for polishing time and the interaction with the milling operation, various machining strategy parameters that generates the finish surface are not investigated. In particular, the feed per tooth and the radius of the tool are not considered for the surface topography. The polishing range should also depend on the finish operation in milling. It is therefore necessary to study more in detail the relationship between machining strategy and range of polishing to optimize the overall process.

The aim of this paper is to propose a method to predict the time necessary of the whole process (milling, polishing), taking actual milling and polishing conditions. Hence, by tuning different parameters, it is possible to find an optimized operating point between milling and polishing. Unlike the above mentioned papers, tool path strategy and tolerances don't vary. A parallel planes tool path strategy and confined error are used ; only tangential and transverse scallop heights are studied for their interactions with polishing.

The paper is organized as follows: Section 2 deals with the relations between surface topography achieve by the finishing operation and the actual milling time. Then, this surface topography is linked in section 3 to the polishing time according to the first abrasive disk used. In section 4, a method to choose the values of influent parameters in order to minimize the whole process time is detailed. Last section is dedicated to the experimental validation of the proposed method on an aluminum blowing mold used to product plastic bottles.

2. Relation between surface topography and milling time

2.1. Surface topography modeling

Surface topography models depend on machining strategy parameters. Two standpoints can be adopted: the experimental standpoint and the theoretical one. Based on surface topography measurements, most experimental methods attempt to establish the link between feedrates, machining direction, tool orientation and 3D topographies [12]. Unfortunately, these results are only qualitative and the relationship between the machining strategy parameters and the surface topography is not formalized. With the theoretical standpoint, it is possible to describe the texture obtained in ball-end milling [13] from numerical simulations. Recent works have shown that the surface to-

pography can be simulated by taking into account cutting conditions (transversal step and the feedrate) [14] but also the evolution of the tool axis orientation in 5-axis milling [15]. Fig. 1 represents a typical surface topography achieve after ball-end milling where one can easily recognize the effects of the machining parameters.

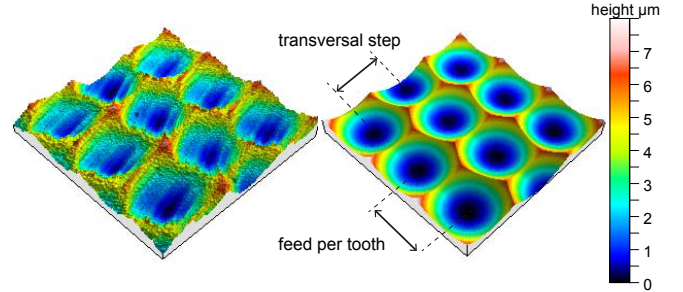


Fig. 1. Surface topography measurement and simulation

Quinsat et al. proposed a simple way to determine surface topography in ball-end milling [16]. Each tooth revolution can be locally modeled by a sphere, which radius corresponds to the tool radius. The pattern generated by the teeth revolutions and the tool displacement is thus the juxtaposition of several spherical cups (Fig. 2). This pattern depends only on the feed per tooth (f_z), the transverse step (p) and the radius of the tool (R_o). In order to characterize polishing after milling, the evaluation of the remaining volume to be removed is modeled. Such a macro-geometric model seems sufficient; studying the geometry at lower scale (including cutting edge wear for instance) is not necessary.

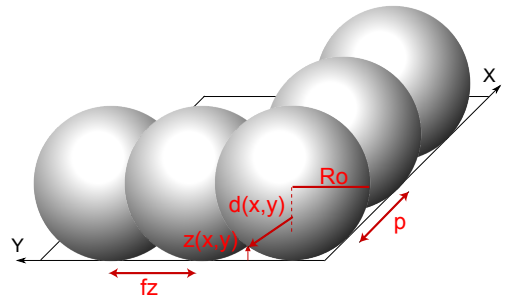


Fig. 2. Surface topography model

The volume V left after milling can thus be evaluated considering the height between the local plane and the spheres. Supposing that the juxtaposition of the spheres is symmetric, the remaining volume can be expressed on a pattern of size (f_z, p) by Eq. (1):

$$V = \int_{-\frac{f_z}{2}}^{\frac{f_z}{2}} \int_{-\frac{p}{2}}^{\frac{p}{2}} z(x, y) dx dy \quad (1)$$

where the height can be directly expressed as a function of the distance to the projection of the sphere center on the plane

(Eq. (2)):

$$z(x, y) = Ro - \sqrt{Ro^2 - d(x, y)^2} \text{ with } d(x, y) = \sqrt{x^2 + y^2} \quad (2)$$

This volume V left after milling is the volume which has to be removed during polishing. It has an impact on the polishing time considering a constant MRR defined for each abrasive papers (see section 3). This volume can be obviously decreased by reducing machining strategy parameters (f_z and p) but this leads to an increasing milling time.

So it is necessary to establish a relationship between remaining volume V and milling time t to further investigate an overall optimization.

2.2. Milling time estimation

Milling time depends on machining strategy, cutting parameters like the feed per tooth (f_z), the transversal step (p) but also depends on the machine-tool kinematics. Indeed, the mechanical components (motors, axis, machine tool structure...) limit the machine-tool performances. As a consequence, manufacturers limit the kinematics by defining maximum parameters for each machine-tool axis. Maximum velocity, acceleration and jerk of each axis are thus reducing the programmed feedrate during the feedrate planning. Considering these kinematical limits, the tool path geometry, especially discontinuities or high curvatures, will cause slowdowns of the actual feedrate during the execution of the trajectory.

Milling time t is given by the evolution of the actual feedrate \dot{s} along the path (Eq. (3)):

$$t_{milling} = \int_{s=0}^L \frac{1}{\dot{s}} ds \quad (3)$$

By noting \mathbf{q} the axes position, for a path displacement s , the velocity of the axes $\dot{\mathbf{q}}$ can be expressed as a function of the geometry \mathbf{q}_s multiplied by a function of the motion \dot{s} (Eq. (4)). This formula is valid for each axis of the machine (X, Y, Z).

The acceleration $\ddot{\mathbf{q}}$ and jerk $\dddot{\mathbf{q}}$ of the axes are obtained in the same manner (Eq. (5) and Eq. (6)).

$$\dot{\mathbf{q}} = \frac{d\mathbf{q}}{dt} = \frac{d\mathbf{q}(s)}{ds} \cdot \frac{ds}{dt} = \mathbf{q}_s(s) \cdot \dot{s} \quad (4)$$

$$\ddot{\mathbf{q}} = \mathbf{q}_{ss}(s) \cdot \dot{s}^2 + \mathbf{q}_s(s) \cdot \ddot{s} \quad (5)$$

$$\dddot{\mathbf{q}} = \mathbf{q}_{sss}(s) \cdot \dot{s}^3 + 3\mathbf{q}_{ss}(s) \cdot \dot{s} \cdot \ddot{s} + \mathbf{q}_s(s) \cdot \dddot{s} \quad (6)$$

Focusing on feedrate slowdowns, to estimate the lowest speed, tangential velocity and tangential acceleration along the tool path are locally null ($\ddot{s} = 0$ and $\ddot{s} = 0$). Hence an approximation of the actual feedrate respecting the kinematics is given

by Eq. (7). Further details can be found in [17].

$$\dot{s} \leq \min_{i=\{X,Y,Z\}} \left(F_{prog}, \frac{\dot{q}_{max}^i}{|q_s^i|}, \sqrt{\frac{\ddot{q}_{max}^i}{|q_{ss}^i|}}, \sqrt[3]{\frac{\dddot{q}_{max}^i}{|q_{sss}^i|}} \right) \quad (7)$$

where

- i represents each axis X, Y and Z
- F_{prog} : programmed feedrate
- $\dot{q}_{max}, \ddot{q}_{max}, \dddot{q}_{max}$: maximum axis velocity, acceleration and jerk
- q_s, q_{ss}, q_{sss} : geometrical derivatives

Once the relationship is established between milling time $t_{milling}$ and remaining volume V , it is possible to study the influence of the machining strategy parameters f_z, p and Ro on the following stage of the process. For that purpose, a characterization of the abrasion process between the material of the mold and the abrasive paper has to be performed first.

3. Characterization of the disks abrasiveness

The characterization of the polishing process with the Material Removal Rate is highly dependent on the couple {tool-material}. Within the context of the blowing mold manufacturing, disks with Al_2O_3 abrasive particles and the aluminum 7000 series are often used. The experimental set-up used by Lacharnay et al. [18] is implemented. Various papers are used on an automatic polishing machine to polish surfaces with different topographies. The choice of the pressure and the cutting speed is made according to Lee et al. in order to be closed to the actual conditions used by operators [19]. For the experiments, three different grades are used (150, 240, 400). For each experiment, the automatic polishing is interrupted every two seconds to measure the arithmetic surface roughness S_a (ISO 25178-2). Fig. 3 represents the decrease of S_a over time. It allows determining the finest S_a that can be reached for each grade, and the corresponding time for the area of the sample.

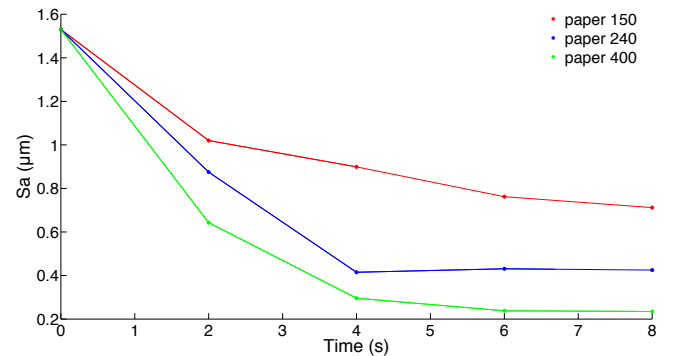


Fig. 3. S_a versus time

Whatever the paper used, S_a decreases in a rather similar way until a limit value is reached for the considered couple tool-material. However, although the limit value of each paper is reached after 8 seconds, the surface topography is not the same. Indeed, Fig. 4 shows that all milling marks have not disappeared for paper 400. When the scallop height is too high, the small

abrasive particules of the paper 400 can not succeed to remove quickly all undesired marks.

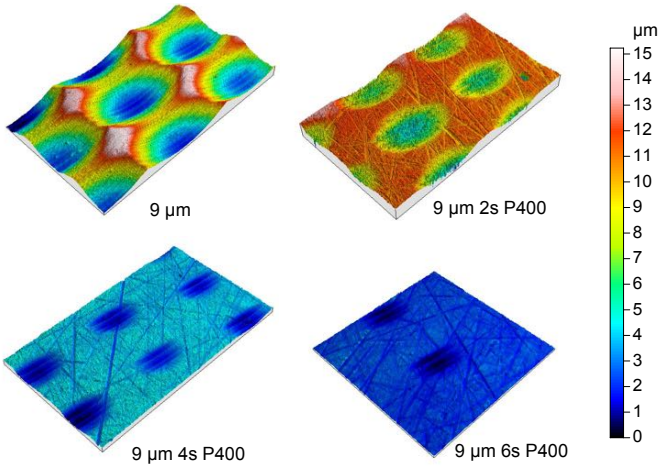


Fig. 4. Milling marks after polishing with paper 400 for $h_s = 9\mu\text{m}$

The evolution of S_a is linked to the time and it can be fitted by a decrease exponential function during polishing with the first paper. In the Eq. (8), B is the acceptable limit of S_a and $A + B$ is the initial value of S_a . This model does not take into account soiling and the consequence of wear and tear.

$$S_a = A \cdot \exp\left(\frac{-t}{\tau}\right) + B \quad (8)$$

As the "mirror" quality on the surface cannot be achieved with a two bodies polishing process, it is necessary to add a three bodies polishing operation with diamond paste. However, this last operation is not studied in this work. Hence, with various scallop heights, it is possible to estimate the impact of a volume V change on polishing time for the first paper. Experimental results are shown in Fig. 5 for several initial S_a for one paper. Fig. 5 shows that for every scallop height programmed exper-

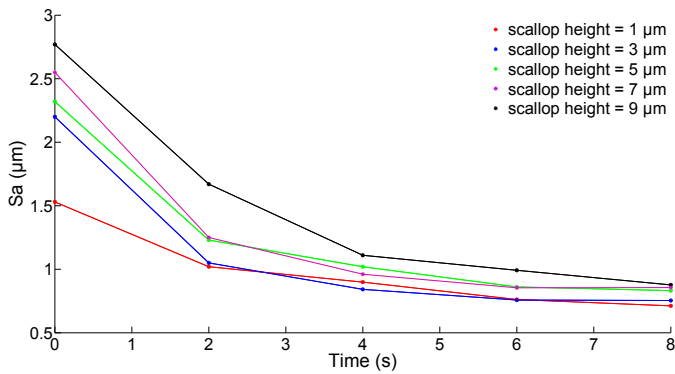


Fig. 5. S_a versus time for paper 150

imentally, the same final value is obtained for a given paper but different values of τ are obtained. Fig. 6 allows to determine the evolution of τ depending on the volume V left after milling. For every papers, τ depends on the volume to remove and its evolution can be fitted by a polynomial equation of degree 2. Nevertheless, this approximation is not correct near a very small volume V near 0 because polishing time is not null.

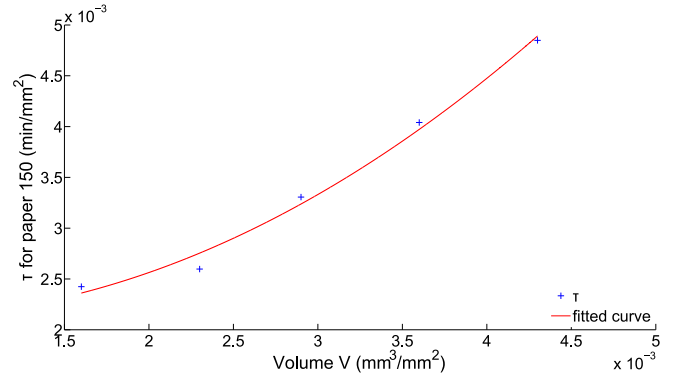


Fig. 6. Evolution of τ versus volume V

To sum up, depending on the paper used and the material volume left by the milling operation, the evolution of S_a is modeled by Eq. (9). Finally Eq. (10) gives polishing time.

$$S_a = (S_a^{ini} - S_a^{paper}) \cdot \exp\left(\frac{-t}{a.V^2 + b.V + c}\right) + S_a^{paper} \quad (9)$$

$$t = -\ln\left(\frac{S_a^{desired} - S_a^{paper}}{S_a^{ini} - S_a^{paper}}\right) \cdot (a.V^2 + b.V + c) \quad (10)$$

This section allows to show a method to estimate polishing time for the first paper used in the polishing process. This time is linked to the volume V left after the last milling operation. Besides, the section 2 allows to link the volume V to an estimation of milling time.

4. Implementation on an operating point between milling and polishing

The two previous sections presented the dependance of the milling time and polishing time to parameters (feed per tooth f_z , transverse step p and tool radius R_o). From these results, the link between the milling time and polishing time can be highlighted. The method to estimate this two times is sum up in Fig. 7.

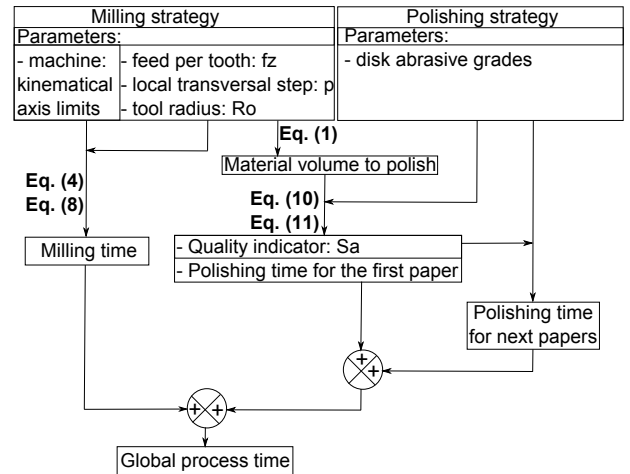


Fig. 7. Summary of the method to estimate milling time and polishing time

5. Application to a mold

Within the context of molds production, the increase of competitiveness requires an overall manufacturing process composed of milling and polishing. For this reason, the methodology presented above is applied to a mold for blowing plastic bottles which is presented on Fig. 8.

The milling of the mold is conducted on 4-axis machine-tool with 3 different orientations and based on a parallel planes strategy. The geometry of the mold is very intricate (many grooves), therefore the proposed method is first applied on the central area before being applied on the complete half mold.

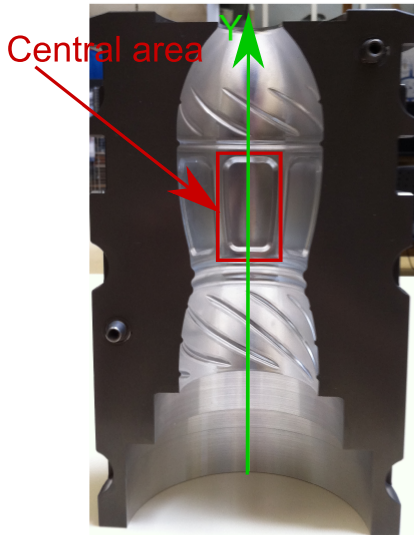


Fig. 8. Mold for blowing plastic bottles

5.1. Central area 1

Milling time estimation

The previous sections allowed to construct a method to determine milling time depending on 4 parameters: the feedrate per tooth (fz), the local transverse step (p), the radius of the tool (Ro) and the kinematical axis limits. According to Eq. (7), Fig. 9 shows the prediction of the maximal feedrate thanks to knowledge of the surface geometry and the machine-tool kinematical limits. The results represented in Fig. 9 is evaluated for one pass along the Y axis. The area 1 is framed.

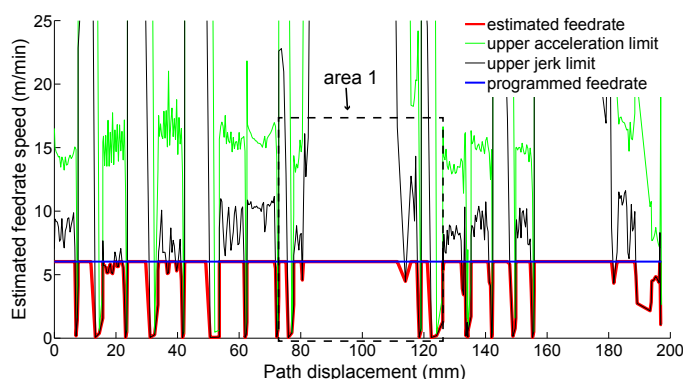


Fig. 9. Feedrate estimation by upper kinematical limits

By using this method, it is possible to estimate milling time for the following parameters:

- feed per tooth: $fz = 0.35/2$ mm/tooth
- transverse step: $p = 0.4$ mm
- tool radius: $Ro = 4$ mm
- axes characteristics (speed, acceleration, jerk)

The lower estimation of the milling time to cover the central area is about 2.69 min with the model. In order to validate the model used, the tool path has been executed on the considered machine tool (DMG HSV 75V linear) and the resulting milling time is 2.31 min. Thus, the proposed estimation seems to be correct. s

Polishing time estimation

From the above parameters, the polishing time for the first paper (P150) is estimated to 0.47 min. This result is consistent with polishing time currently.

Choice of an turning point between milling and polishing

To find the global manufacturing process planning, milling time and polishing time can be estimated for various parameters ($p = 0.1$ to 0.5 mm with a step of 0.1 , $Ro = 2$ to 6 mm with a step of 1 , $fz = 2.Ro/45$, machine-tool, and abrasive papers).

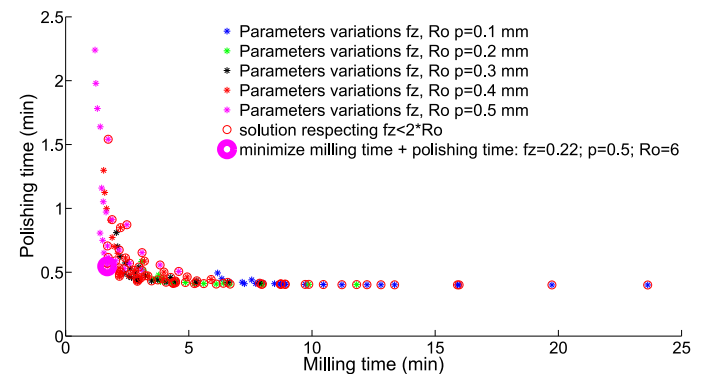


Fig. 10. Milling time versus polishing time by varying parameters: fz , p , Ro

All possibilities and possibilities respecting the constraint $fz < 2.Ro/45$, for a radius tool given (Ro), are plotted in Fig. 10. It is possible to determine parameters which minimize global time process.

The Pareto front gives solutions which minimize global time process without favoring milling time or polishing time. There are several parameters which give practically similar points, so operators can choose the best parameters.

5.2. Complete mold

Milling time estimation

The results presented on Fig. 9 are evaluated for one pass along with Y . By doing this estimation for all the half mold, milling time estimation is about 20min30s and experimentally, the time is about 21 min. So the estimation seems to be correct for all the mold. The results are given for $fz = 0.35/2$ mm/tooth, $p = 0.4$ mm and $Ro = 4$ mm.

Polishing time estimation

However, this mold is not a stretch surface and there are grooves (Fig. 8). As machining time does not take into account the dedicated operations to rework the grooves, the polishing operation is not considered as well. Besides, one of the hypothesis of the model should be taken into account for a large surface to polish. The normal wear and tear of the abrasive disks is not taken into account, and it is possible to add this time. Manual polishers change the disks every 50 seconds and it lasts about 10 seconds. Reflecting these comments, polishing time would last about 5.45 minutes with the abrasive paper 150.

Choice of an turning point between milling and polishing

By varying the different parameters (f_z, p, Ro), the repartition of milling time and polishing time is given in Fig. 11.

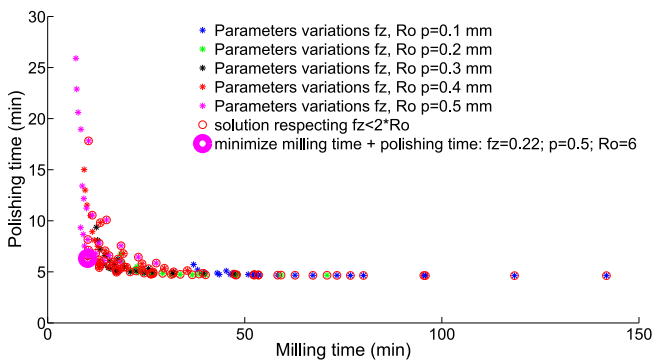


Fig. 11. Milling time versus polishing time for half mold

According to Fig. 11, it is possible to reduce milling time by 50% by changing cutting conditions and polishing time will increase very little. Polishing time and milling time have the same order of magnitude. However, the range of values is less important in polishing time. This behavior is due to the hypothesis regarding the constant wear and tear of the polishing tool with regards to the volume V . Furthermore, the time spent to polish a groove is also the same for all volume V . A further study could take into account the influence of V for both the polishing time and the tool wear.

6. Conclusion

The increase of competitiveness in molds and dies production requires an overall optimized manufacturing process including milling and polishing. Consequently, the aim of this article was to improve these two processes together by finding an optimal operating point. Indicators on milling time and polishing time have been proposed. As milling time and polishing time depend on the same parameters, it is possible to estimate their relative influence. Thanks to experimental measurements, a model to estimate polishing time has been set up for different abrasive papers. By varying these parameters it has been possible to estimate the different times and the global processing time. It could help to choose the most appropriate parameters for a company depending on the availability of equipment. This method has been implemented on a blowing mold, and time estimations are close to the reality, especially when there are not too many grooves. The method to estimate polishing time could be improved by taking into account grooves and the consequences of soiling, wear and tear.

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