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Simulation of the material removal rate and tool wear to improve 5-axis automatic polishing operations

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Abstract: In plastic injection mould and prosthesis industries, “mirror-effect” polished surfaces are required for obtaining transparent parts or surfaces without scratches. Traditionally done manually, we have proposed to automate polishing on 5-axis machining centre. One of the main advantages of automatic polishing is the repeatability of the machine movements in order to achieve confined form deviations. However, the material removal rate (*MRR*) during polishing depends on parameters such as contact pressure, velocity, tool path and tool wear. We have thus developed a virtual tool to model the effective *MRR* and choose the correct polishing parameters before any machining regarding the specified form deviation. After a brief review of *MRR* modeling in the literature, we present our approach to polish surfaces on 5-axis milling centers as well as the simulation tool we have developed to predict the material removal rate. Our process has been tested on a part made of X38CrMoV5 steel (53 HRC) and measurements using a noncontact sensor allow us to compare the differences between our prediction and the polished surface.

Key words: Polishing, Material Removal Rate, Tool wear, Numerical simulation, Form deviation

1- Introduction

The development of High Speed Machining (HSM) has dramatically modified the organization of plastic injection molds and tooling manufacturers. HSM in particular has made it possible to reduce mold manufacturing cycle times by replacing spark machining in many cases. In spite of these evolutions, HSM does not enable to remove the polishing operations from the process. In this paper, we deal with the realization of surfaces with high quality of surface finishing and mirror effect behavior. As the usual polishing process is expensive in terms of price and downtime of the mold, we have developed an automatic polishing process on 5-axis machine tool [PT1] [PT2]. Our approach consists in using the same tools as those used in manual polishing for pre-polishing and finishing polishing (figure 1). Pre-polishing is performed with abrasive discs mounted on a carrier. This carrier is a deformable part made in an elastomer material fixed on a steel shaft that allows mounting in the spindle. Hence, we do not have a force feedback control but we manage the polishing force with the length of the tool introduced in the numerical controller. The polishing strategies are for the most part issued from previous experiences as for trochoidal tool paths (figure 1) computed on fractal trajectories coming from robotized polishing or cycloidal weaving paths representative of manual polishing [MS1] [TH1] [TL1].

The main advantage of this process is the repeatability of the machine movements to respect the specified form deviation. Indeed, in manual polishing the material removal rate (*MRR*) depends on the polishing tool velocity and on the polishing pressure applied by the operator. An adequate polishing force facilitates the removal of cusps and stripes left on the part during milling or previous polishing operations. Nevertheless, the contact stress has to be as constant as possible to avoid over-polishing and respect form deviation tolerances. Furthermore, even if the effective *MRR* is quit constant, the polishing time spent in every area of the part as to be as constant as possible. This means that the polishing velocity along the tool path as to be constant and the distribution of the tool path has to be consistent.

The aim of the paper is thus to propose a tool to simulate the material removal rate during polishing. In the next section several models of the material removal rate from the literature are presented. Then in section 3 we will present our simulation tool based on contact pressure, tool velocity and abrasive wear. Applications of the simulation tool are proposed in the following section and the conclusions and future works end the paper.

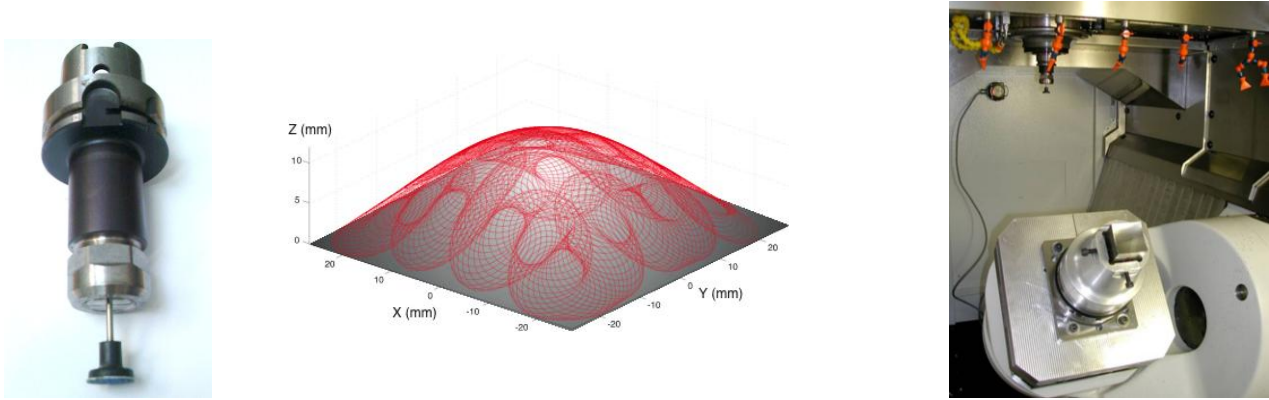


Figure 1: Polishing tool and tool paths in 5-axis automatic polishing

2- Related works

Regarding to the literature, the measurement or quantification of abrasion is most frequently given by the material removal rate (*MRR*), that is to say, the thickness of material removed per time unit. We can find two different approaches to model the *MRR*, the analytical models and the experimental models [NB1][R1].

The analytical models are based on modeling the interaction between the tool and the workpiece at the level of the abrasive particle [BZ1] [JZ1] [OS1]. We find these approaches in the electronics industry in particular for wafer polishing. The proposed models give an estimate of the material removal rate from all material characteristics (Young's modulus, hardness, Poisson's ratio), shape of the surface (type, size, distribution of asperities and particles) and the operating conditions (pressure, relative velocity, the effect of a chemical or fluid). There is no comparable model for the realization of mechanical parts, i.e. parts in steel, stainless steel or aluminum. The models used for polishing of these materials are rather experimental models. The experimental models are derived from the analysis of many polishing trials. The model of Preston [P1], developed within the context of glass polishing, is probably the one that remains today the most used (eq.1). The material removal rate (cutting depth z per time unit) in polishing is proportional to the average pressure of contact, P , and to the tool/part relative velocity V :

$$MRR = dz/dt = K \cdot P \cdot V \quad (1)$$

The coefficient of proportionality also called "Preston coefficient" (K) is determined experimentally and depends on process parameters (part material, abrasive, lubrication, etc.).

In their work, Luo *et al.* [LR1] studied the influence of the fluid for copper polishing. In addition to mechanical mechanisms, they highlight the fact that there are chemical mechanisms involved in abrasion. The proposed model is a slight evolution of the Preston model:

$$MRR = (K_1 \cdot P + B) V + R_c \quad (2)$$

where K_1 , B and R_c are three constants to be determined experimentally. R_c is the rate of material removal of the chemical mechanism.

Wang *et al.* [WL1] also proposed an extension of the Preston model for the manufacture of storage disk made of aluminum and magnesium alloy or glass-ceramic material:

$$MRR = K_2 \cdot P^{n/2} \cdot V^{1-n/2} \quad (3)$$

K_2 and n are two constants to be determined experimentally. This model seems to give good results for different materials.

Finally, analytical models have the advantage of predicting the removal material rate from all process data, which can also be a drawback because the knowing of all the physicochemical properties of the polishing components is mandatory. The experimental models are used for diverse materials. Preston's equation was originally used for polishing glass, but is now used for metal or semiconductor polishing. Whatever the model, the *MRR* always depends on pressure and relative velocity between the tool and the part.

However, literature models do not take into account the wear of the abrasive tool. Furthermore, these models have been developed for planar polishing on automatic machines (Figure 3). Thus, the contact area between the abrasive disk and the part is always a plane so that the contact pressure is uniform over the part. The relative velocity between the part and the tool is a combination of the tool (w_1) and part (w_2) rotation speed (figure 3). In automatic polishing, the cutting speed V_c of the tool is one hundred larger than the tool feedrate V_f , and V_f is not constant when polishing on a 5-axis machine tool [LT1].

Our simulation tool is thus based on the Preston model to compute the cutting depth per time unit and includes the wear of the polishing disk over the time. It also takes into account the contact area between the part and the tool along the tool path as well as the tool/part relative velocity, V_c and V_f .

3- The simulation method

As mentioned in the previous section, there are many abrasion models, but in mechanical and particularly for the polishing of molds and dies, the easiest model to use is based on the Preston equation (eq.1). Using this equation for a little element of surface that can be assumed to be a plane of normal z , it is equivalent to write during a little time Δt :

$$MRR = dz/dt = K \cdot P \cdot V_c \quad (4)$$

$$\Delta z = K \cdot P \cdot V_c \cdot \Delta t \quad (5)$$

The cutting depth Δz is proportional to the polishing time spent on an area of the part, which is in contact with the disk. If the pressure and the velocity are kept constant during polishing, one can think that the MRR will be constant. Actually, the disk efficiency is different over the time because it wears. So the Preston coefficient K depends of time and it will be decompose by the product of the initial Preston coefficient $K_0=K(t=0)$ and a decreasing time function representative of the efficiency of the abrasive disk (wear law) $w(t)$. This function starts from 1 for a new disk and, according to the supplier of the abrasive, the wear law is similar to the one described in figure 2. The Preston coefficient $K(t)$ can be expressed as follow:

$$K(t) = K_0 \cdot w(t) \quad (6)$$

Hence the Preston equation becomes:

$$\Delta z = K_0 \cdot w(t) \cdot P \cdot V_c \cdot \Delta t \quad (7)$$

If we consider a constant velocity and a constant pressure, we can define a nominal material removal rate MRR_0 :

$$MRR_0 = K_0 \cdot P \cdot V_c = cst \quad (8)$$

$$\Delta z = MRR_0 \cdot w(t) \cdot \Delta t \quad (9)$$

Finally, the simulation consists in computing the polishing time spent at each point of the surface and weighting this time by an experimental wear law issued from previous experimentations. The wear law can also provide the value of MRR_0 (eq.8) since the experimental set-up must be identical, i.e., pressure, cutting speed and lubricification.

The contact area and the pressure distribution could be determined by finite element computation, taking into account the tool material behavior, inclination and position of the tool and the local geometry of the surface to polish. In a first approach, we consider that the pressure distribution in the contact area is uniform and the form and size of the contact area are supposed constant. These hypotheses are verified if the considered surface is a plane or a slender surface. The contact area contour is modeled by an ellipse with a demi-minor axis a and a demi-major axis b (Figure 3).

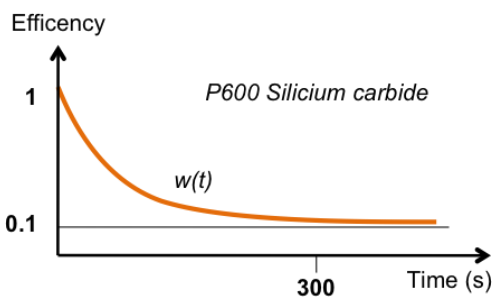


Figure 2: General abrasive disk efficiency $w(t)$

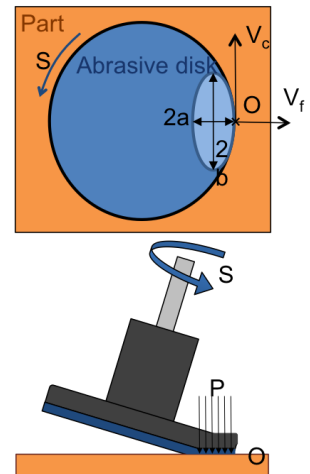
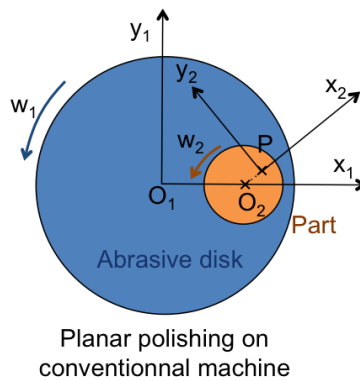


Figure 3: Polishing configurations

The first step of the method consists in meshing the surface to polish. Then, the following step is the sampling of the tool path according to a maximum length between points dl , initially fixed by the user (figure 4). The result is a list of n points M such as $|M(i+1)-M(i)| < dl$. Then for each point $M(i)$ of the tool path, the contact area is positioned such as the point O corresponds to the point $M(i)$ and oriented along the inclination direction, ie, $+y$ on figure 4. When the contact area is in place, any node j among the m nodes of the mesh is marked in a (n,m) dimension matrix $Inside(i,j)$. Any point included in the contact area (red points) takes the logical value 1 and all others take the logical value 0.

Along all segment i included between points $M(i)$ and $M(i+1)$, the feedrate V_f and wear law $w(t)$ are supposed constant. Thus the segment i travel time can be approximated by $\Delta t(i) = |M(i+1)-M(i)|/V_f(i)$. Taking dl small enough allows to make the assumption that the points in contact for the position $M(i)$ still in contact during the entire segment i .

Now it is simple to obtain the abrasion time $T(j)$ for each node of the mesh:

$$T(j) = \sum_{i=1}^n \Delta t(i) \cdot Inside(i,j) \quad (10)$$

The cutting depth is computed using the Preston equation and wear law (eq.9).

We first define the local abrasion time for each node $T_w(j)$ weighted by the tool wear :

$$T_w(j) = \sum_{i=1}^n w(t_i) \cdot \Delta t(i) \cdot Inside(i,j) \quad (11)$$

Finally, the cutting depth $D(j)$ at the node j is obtained by the relation:

$$D(j) = MRR_0 \cdot \sum_{i=1}^n w(t_i) \cdot \Delta t(i) \cdot Inside(i,j) \quad (12)$$

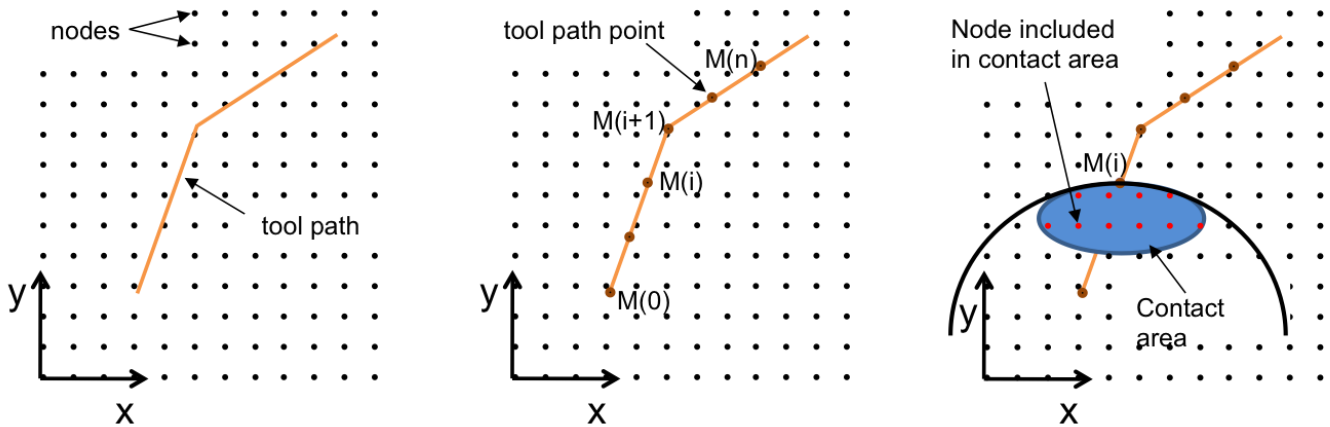


Figure 4: (left) Mesh and tool path ; (centre) Tool path discretized ; (right) Contact area positioned and oriented

4- Experimental investigations

The experiment allows us to show correlations and differences obtained between simulation and geometrical deviation. The test surface is a planar face the section of which is 50 mm x 50 mm machined in a stock made of X35CrMoV5 (Hrc 53) steel. We choose a planar surface because our topography measuring system only provides a measuring range of 110 μm . The different machining and pre polishing operations are defined as follows (figure 5):

- The plane is milled using a 12 mm diameter hemispherical tool along parallel planes. The distance between paths, in the X direction, is set to 0.3 mm in order to obtain a scallop height inferior to 2 μm . The tool is tilted to 20 degrees around X direction in order to avoid a zero cutting velocity at the tool tip and the feedrate is set to 0.5 $\text{m} \cdot \text{min}^{-1}$.
- The pre-polishing operations are performed with a 18 mm diameter abrasive disk made of silicium carbide (grit 600). The same disk is used for the two pre-polishing operations. Tool paths are trochoidal trajectories based on parallel planes in two orthogonal directions. The distance between planes is set to 5 mm, the trochoid diameter and step are set to 10 mm and 1 mm respectively. The imposed displacement is 0.5 mm leading to a contact force of 5N [PT1].

In order to avoid slowdowns along the pre polishing tool path, special functions of the Siemens Sinumerik 840D controller equipping the machine tool are activated: SOFT, COMPCAD, FFWON and G642 with a possible deviation of 0.05 mm on each axis. The programmed feedrate ($2 \text{ m} \cdot \text{min}^{-1}$) is then reach during most of the operation.

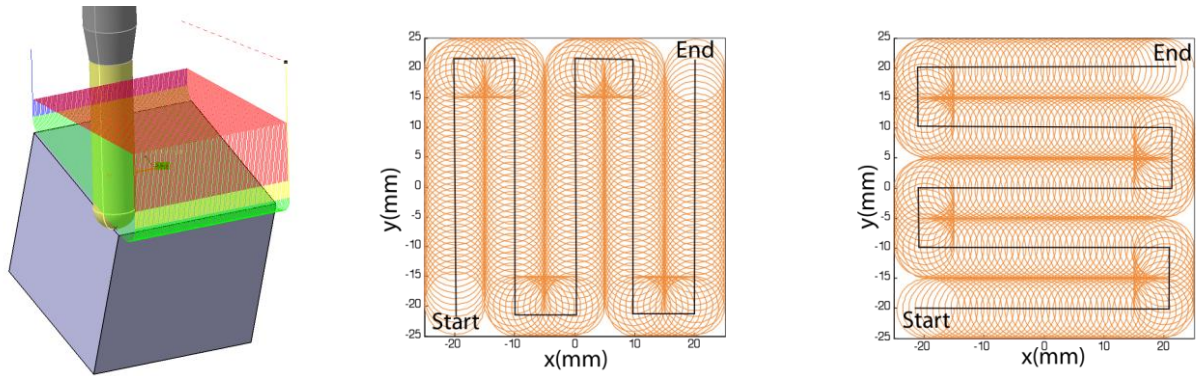


Figure 5: Milling (left) and pre polishing trajectories (centre and right)

The demi-minor axis a is determined by measuring the area of the disk soiled by chips and the demi-major axis b is determined by polishing a segment measuring approximately the width of the polished area. This leads to $a = 1$ mm and $b = 3.5$ mm. The size of the quadrangular mesh is set to 0.5 mm in both directions x and y .

Measurements are carried out with a non-contact sensor based on chromatic confocal technology (Figure 6). The profiles follow the x direction by measuring a point every 50 μm . The distance between two profiles, in the y direction, is also 50 μm . It can be observed that the material removal is greater where the tool path overlaps, leading to geometrical deviation values up to 10 μm . There are also areas in which scallops generated by the milling operation are still visible.

The first result extracted from the simulation is the polishing time $T(j)$ at each node of the mesh (figure 7). A perfect correlation between this graph and the geometry of the pre polishing tool paths (figure 5) can be observed due to the symmetry of the tool paths. If we focus on the circled areas on figure 6, this symmetrical behavior is not present because of the tool wear. At the beginning of the tool paths (figure 6, area 1), there is a red spot due to the slowdown during the approach of the tool along the z -axis. We can see that the simulation (figure 7) is able to reproduce this behavior by taking into account the programmed feedrate. The polishing time at each node of the mesh weighted by the wear law $T_w(j)$ is plotted figure 8. The wear law $w(t)$ was predicted on a first experiment based on the efficiency given by the tool supplier (figure 9). We can compute the nominal material removal rate MRR_0 (eq. 8) which is approximately equal to 6 $\mu\text{m.s}^{-1}$. The simulation gives an interesting result even if small differences persist between simulation (figure 8) and measurement (figure 6, area 2 and 3).

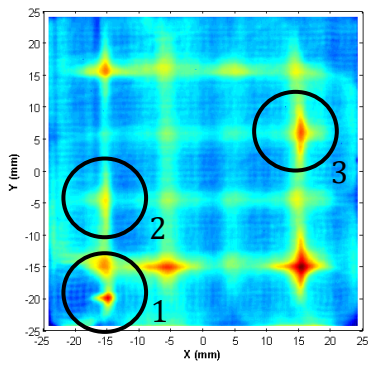


Figure 6: depth of polishing μm (measurement)

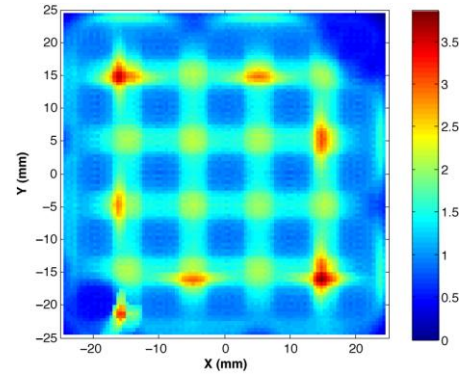


Figure 7: local polishing time (s)

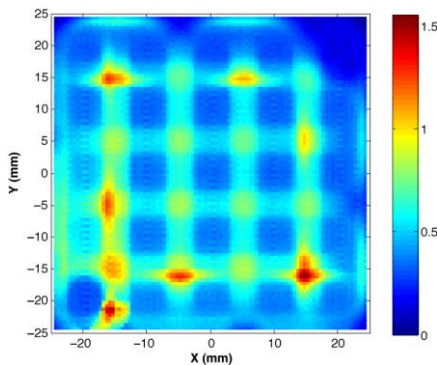


Figure 8: local weighted polishing time (s)

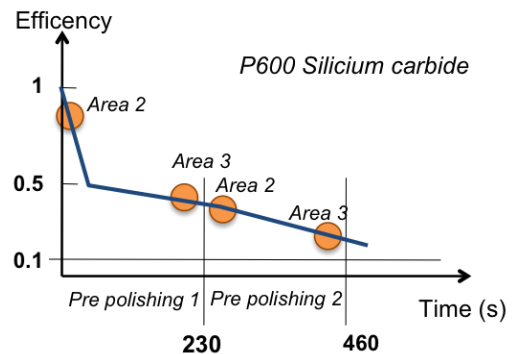


Figure 9: adapted abrasive disk efficiency $w(t)$

5- Conclusion and future works

In this article, we propose a method to predict the geometrical deviation due to an automatic pre-polishing operation. This method, based on the Preston model of the material removal rate takes into account the wear of the abrasive during the polishing operation. Our model also offers the possibility to include the effective feedrate instead of a constant value if the user can provide its evolution either by simulation [LT1] or by measurements.

Experimental investigation leads to a good correlation between simulations and experiments. We can observe that the tool path geometry has a great influence on the final geometrical deviation. Experimentation also shows that some improvements could be made in the modeling of the tool wear.

We prospect to improve this simulator by imposing a pressure repartition representative of the real contact area between the tool and the part. This will be possible by performing finite elements simulations of the contact on several characteristic surfaces based on their curvature properties. Hence, it will be possible to have a set of contact configurations depending on surface curvature characteristics and imposed tool displacements.

Since we already have tools to simulate the machined surface generated by end milling operations, the simulation of the pre polishing operation will help to determine the best milling and polishing parameters to respect form deviation. It is also an interesting tool to optimize both milling and pre polishing operations in order to minimize the machining time.

This work was carried out within the Manufacturing 21 working group, which comprises 16 French research laboratories. The topics covered are: modeling of the manufacturing process, virtual machining and emergence of new manufacturing methods.

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