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# Tool wear modelling for constant removal rate in two-bodies automated polishing

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**Abstract**

Complex shapes such as medical implants or injection moulds require the use of super-finishing operations to minimize geometrical defects, down to mirror effect finish. These pre-polishing and polishing operations are still regularly performed manually by skilled workers. In spite of advantages in terms of repeatability, productivity and geometrical quality, automatic polishing methods are not widely used because they require systematic and significant developments. One of the main issues is the modification of the abrasive tool efficiency during the process. It evolves over time due to abrasive grains tearing and transfer onto the abrasive tool surface of workpiece microchips. Thus a model of tool wear is proposed and compensation strategies are elaborated to ensure a constant material removal rate on the surface. Compensations are performed by optimizing the spindle speed and/or the feedrate along the tool path and are validated through experimental investigations.

*Keywords:* Automatic polishing, Tool wear, Material Removal Rate, Feedrate compensation, 5-axis machine tool

**Notation**

$MMR$ : Material Removal Rate
$K$ : Preston's coefficient
$P$ : Abrasion pression
$V$ : Abrasion velocity
$dh$ : Depth of material remove during $dt$
$dh_i$ : Initial depth of material remove
$dh_f$ : Final depth of material remove
$\Delta h$ : Depth of material remove during $\Delta t$
$\gamma$ : Efficiency law
$\gamma_f$ : Final efficiency
$\tau$ : Efficiency law basetime
$V_f$ : Feedrate
$N$ : Spindle speed

## 1. Introduction

The development of High Speed Machining (HSM) has dramatically modified the organization of plastic injection moulds and tooling manufacturers. HSM in particular reduces mould manufacturing cycle times by replacing spark machining, but does not enable to remove the polishing operations from the process. As the usual polishing process is expensive in terms of price and downtime of the mould, specific methods have been developed to replace manual polishing by automatic polishing. Among those approaches, an automatic polishing process on 5-axis machine tool has been presented in Pessoles and Tournier (2009) and more recently in Feng et al. (2014). The main advantage is to be able to machine the part from rough cutting to polishing on the same machine-tool. The proposed approach consists in using the same tools as those used in manual polishing for pre-polishing and finishing polishing (Fig. 1). Pre-polishing is performed with abrasive discs fixed on a carrier. This carrier is a deformable part made in an elastomer material fixed on a steel shaft that allows mounting in the CNC machine tool spindle (Fig. 2). Hence, there is no force feedback control but the polishing force is managed thanks to the length of the tool introduced in the numerical controller. 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 pressure has to be as constant as possible to avoid over-polishing and respect form deviation tolerances.

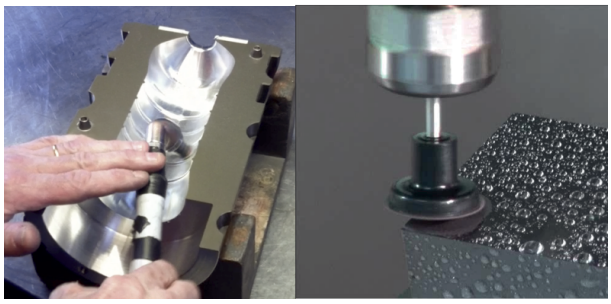


Figure 1: Comparison between manual and automated polishing

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. As mentioned by Nasri and Bolmsjö (1994), two different approaches to model the MRR can be distinguished, the analytical models and the experimental models. The analytical models are based on the modelling of the interaction between the tool and the work piece at the level of the abrasive particle. Bai et al. (2007) assumed that all the molecules in contact with a particle during the action of the latter are disengaged from the work piece. From FEM simulations, Jiang et al. (2008) deduce the removal of material caused by the action of a particle. Oh and Seok (2009) studied polishing of silicon dioxide $SiO_2$ assuming that the removed material corresponds to the scrape marks made by the particle on the part. These approaches are used in the electronics industry for wafer polishing for instance. The proposed models give an estimate of the material removal rate based on material characteristics, shape of the surface and operating conditions. The models used for mechanical parts polishing are rather experimental models. They are derived from the analysis of many polishing trials. The model developed by Preston (1927) within the context of glass polishing is probably the one that remains today the most used (eq. 1) and states that the material removal rate is proportional to the average pressure of contact, $P$, and to the tool/part relative velocity $V$. The coefficient of proportionality $K$ is determined experimentally and depends on process parameters (part material, abrasive grade, lubrification, etc.).

$$MRR = \frac{dh}{dt} = K \cdot P \cdot V \tag{1}$$

In their work, Luo et al. (1998) 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 where $K$, $B$ are two constants to be determined experimentally and $R_c$ is the rate of material removal due to the chemical mechanism. The coefficient B is used to model a non-null MMR even for very low pressure as the authors observe that the removal rate has a greater dependence on the velocity compared to the pressure when pressure drops.

$$MRR = (KP + B)\,V + R_c \tag{2}$$

Wang et al. (2002) also proposed an extension of the Preston model for the manufacture of storage disk made of aluminum and magnesium alloy or glass-ceramic material. $K$ and $n$ are two constants to be determined experimentally. This model seems to give good results for different materials.

$$MRR = K \cdot P^{\frac{n}{2}} \cdot V^{1-\frac{n}{2}} \tag{3}$$

Some polishing tests of silicon nitride with cerium oxide abrasive particles with different pressures and abrasion speeds showed that the Preston's model is not suitable. Indeed, the effect of pressure is much greater than the speed on the MRR. Klocke et al. (2011) proposed a model even more generic than Wang's one involving three constants ($K$, $\alpha$, $\beta$) to determine experimentally.

$$MRR = K \cdot P^{\alpha} \cdot V^{\beta} \tag{4}$$

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 glass polishing, but is now used for metal or semiconductor polishing.

Even if the effective MRR is quit constant, the polishing time spent in every area of the part and consequently the polishing velocity along the tool path has to be constant and the distribution of the tool path has to be consistent. The polishing strategies are for the most part issued from previous experiences as for trochoidal tool paths (Fig. 2). They must ensure good coverage of the surface. Tam et al. (1999) use deformed zigzag tool path to facilitate the realization of continuous polishing. Polishing strategies must also avoid repetition of patterns. Mizugaki and Sakamoto (1992) propose tool path computed on fractal trajectories coming from robotised polishing. Tam and Cheng (2010) compare Peano path used by Mizugaki and Sakamoto (1992) and Hilbert path for polishing automation. Tsai and Huang (2006) use cycloidal weaving paths representative of manual polishing. More recently Chaves-Jacob et al. (2013) have proposed a 3D polishing tool path of free-form surfaces introducing optimized patterns to ensure regular covering of the surface.

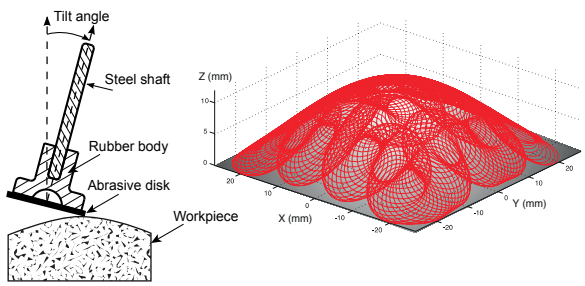



FIGURE 2: Trochoidal tool path (Pessoles and Tournier (2009))

Tool wear is also an important issue to ensure a constant removal rate. Many abrasion models assume that the material removal rate is not a function of time, that is to say that the loss of efficiency is negligible. In fact, abrasive efficiency evolves over time due to loaded tool and abrasive grains tearing. Within the grinding context, it is possible to dress the grinding wheel in order to preserve its shape to maintain accuracy. Furthermore, the use of the lubricant contributes to the elimination of micro chips. Regarding fixed abrasive discs, they are discarded and replaced when they have lost their efficiency. Abrasive discs used in this study have dimensions of 18 or 30 mm in diameter. They are therefore under heavy use, in particular on the periphery of their surface, which increases the ratio between

the useful abrasive surface of the disk and the surface area to polish. The difficulty is to determine the wear from which they must be replaced. Lacharnay et al. (2012) investigated this efficiency and more particularly the best moment to change the abrasive disk from one grade to another. While it is recognized that efficiency decreases with the abrasion time, the literature does not provide analytical model. It is therefore necessary to conduct experimentations to identify and take into account this behaviour.

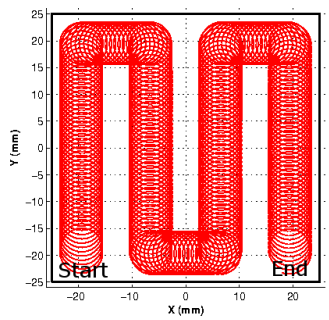
Thus, this article deals with the prediction of macroscopic defects and process parameters optimisation in order to improve the automation of the polishing process on CNC machine tool. In particular, the presented work provides solution to model tool wear in order to establish a compensation strategy to ensure a constant material removal rate. The paper is organised as follows : in the first section, an analysis of the tool wear is proposed to illustrate the problem. Then, the modeling of the tool wear through a design of expriment is carried out in the second section. In the third section, several strategies are proposed to compensate tool wear and maintain a constant material removal rate over the surface. Finally, experimental investigations are carried out to assess the proposed compensation method.

## 2. Tool wear issues

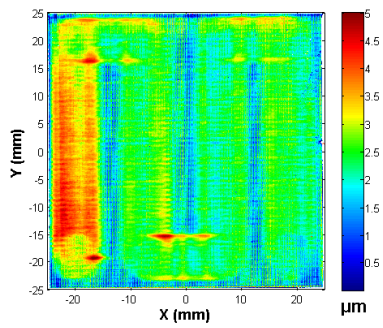
In order to illustrate the tool wear issue, the study of a pre polishing operation (P600) of a milled plane surface of 50 $mm \times 50$ $mm$ is proposed. The material is a 52 HRC hardness steel (X38CrMoV5-1). The tool path is a trochoidal curve represented in figure 3(a). A feedrate of 2m/min is chosen, the tool displacement and the tilt angle are respectively equal to 0.5mm and 15° and the spindle speed is fixed to 2000 rpm. The polished surface is measured with a chromatic confocal sensor (Fig. 3(b)).

In this example, the abrasion depth decreases over time from approximately 2.7 $\mu m$ to 1.5 $\mu m$ at the end of the operation. The efficiency of abrasion is almost divided by two after three minutes of pre polishing and the decrease of efficiency is more important at the beginning of the operation. At the end of the first strip, after 30 seconds of pre polishing, the depth of abrasion decreases by 30 percent. However, on the next three bands, the abrasive efficiency is almost constant, the abrasion depth decreases by an average of 10 percent.

The initial geometry of a P600 abrasive disk has been compared to the final geometry after 6 min of polishing. Images of the figure 4 are resulting from an electronic measurement with a scanning electron microscope and from optical measurements with a 3D optical measurement device based on focus variation technology. On the initial area, the density of abrasive particles is high and the geometry of the particles is sharp while in the worn area, the particle density decreases strongly, most of the particles initially present have disappear from the disk. Only the most embedded particles in the substrate could withstand the grinding operation. Initially, the range between the highest peaks and the lowest valleys is about 90 $\mu m$ and the particles are homogeneously and randomly distributed. In the worn area,




(a) Tool path used




(b) Measured depth ($\mu m$)

FIGURE 3: Surface depth measurement along the tool path

| | New abrasive disk | Worn abrasive disk |
|---|---|---|
| $S_a$ ($\mu m$) | 12,2 | 4,39 |
| $S_k$ ($\mu m$) | 37,2 | 10,6 |
| $S_{pk}$ ($\mu m$) | 16,3 | 4,95 |
| $S_{vk}$ ($\mu m$) | 13,4 | 11,2 |
| $SP_c$ ($pics/mm^2$) | 92 | 4 |

TABLE 1: Roughness parameters for new and worn abrasive disks

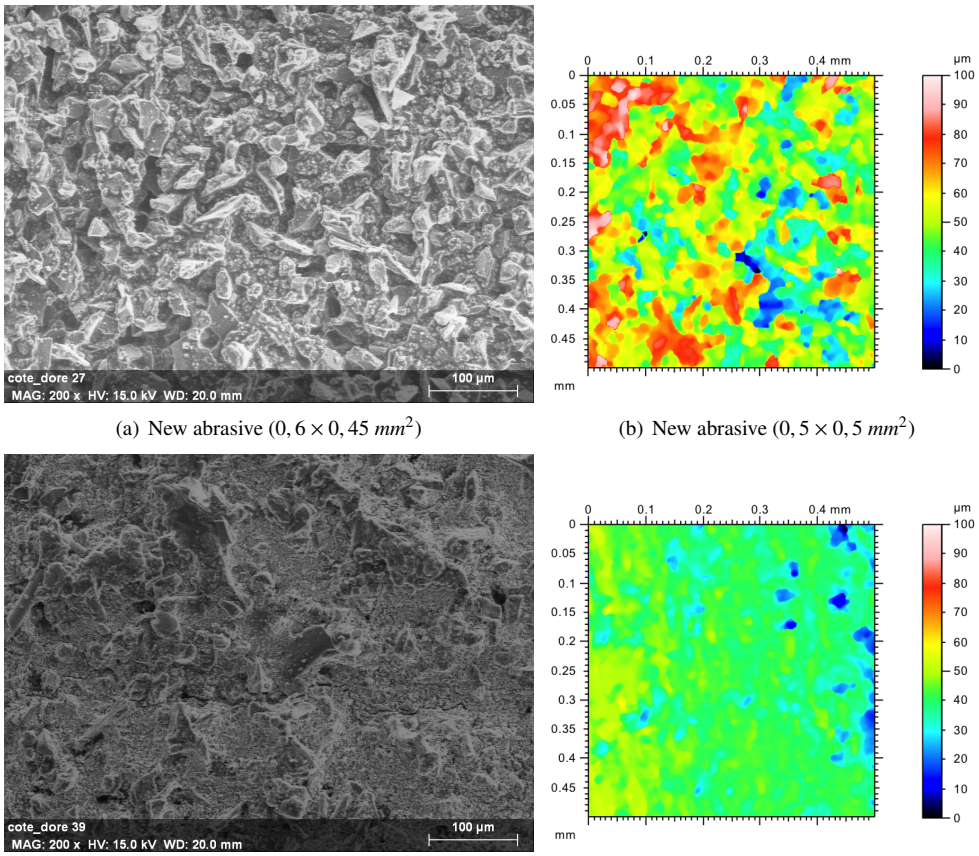
the range of heights has also greatly decreases and the surface appears as a plane with some irregularities.

In order to quantify the geometrical differences between a new and a worn disk, several roughness parameters (ISO 25178-2 (2012),ISO 13565-2 (1996)) have been computed from the measurements. Parameters are defined hereafter and the numerical values are provided in table **??**.

— $S_a$ : Arithmetic mean of the absolute height.
— $SP_c$ : Number of peaks per unit area.
— $S_k$ : Kernel roughness (roughness depth of the core).
— $S_{vk}$ : Reduced valley depth (roughness of the valleys)
— $S_{pk}$ : Reduced peak height (roughness depth of the peaks).

Parameters $S_k$, $S_{vk}$ and $S_{pk}$ are defined as functional parameters and based on the linear material ratio curve (Abbott-Firestone curve).

The flattening observed on the abrasive topography measurements can be found in the evolution of various roughness parameters ($S_a, S_k, S_{pk}$) that decrease a factor of three. These




(a) New abrasive ($0,6 \times 0,45\ mm^2$)

(b) New abrasive ($0,5 \times 0,5\ mm^2$)

(c) Worn abrasive ($0,6 \times 0,45\ mm^2$)

(d) Worn abrasive ($0,5 \times 0,5\ mm^2$)

FIGURE 4: P600 abrasive disk measurements : SEM images (left) and 3D optical measurement (right)

variations indicate that the geometry evolution and therefore the wear of abrasive are important. On the other hand, the roughness parameter $S_{vk}$ is only reduced by 20%, which may correspond to the filling of the valley by particles dissociated from the abrasive disk or the workpiece. The peaks density $SP_c$ is reduced more than 95%, hence the number of particles allowing to remove material is strongly reduced. Thus, the decrease of the abrasive wear during polishing process is well correlated with the evolution of abrasive surface topography. This evolution corresponds to a clogging of the abrasive as well as a decrease in the number and size of the active particles. Hence, in order to be able to modelize the form deviation of the polished surface, this tool wear must be predicted according to the polishing parameters.

## 3. Tool wear modeling

The evolution of the abrasive wear has to be determined in order to model the polishing operation and evaluate the geometrical deviations. This evolution depends on the grade of the fixed abrasive, on the work piece material and also on the operating parameters. It evolves over time due to abrasive grains arrachement and transfer onto the abrasive tool surface of workpiece microchips. Thus, a model of the abrasive tool efficiency is mandatory to obtain a constant MRR during a polishing operation.

A model of this evolution according to the operating parameters is proposed based on a design of experiments for a P600 tool grade and a X38CrMoV5-1 hard steel workpiece material. These tests (Fig. 5) consist in polishing straight bands and measuring the resulting depth which is equivalent to $dh(t)$ (Fig. 6). To facilitate the realization of these bands on a 5-axis machine tool, the tool path used is designed in a zig-zag mode, the tool displacement and the tilt angle are respectively equal to 0.5 mm and 15$^\circ$ . As the polishing conditions are different in the corners (contact surfaces, low-speed), these areas are not measured but their completion time is taken into account in the construction of the curves shown in figure 6. In order to reduce disparities between abrasive disk, the first strip is used as a running-in cycle to prepare each new abrasive disk. Running-in parameters are the same for each experimentation : the feedrate is set to 120 $mm/min$ and the spindle speed to 2000 $rpm$. A design of experiment is realized as described in table 2. The tool paths used are straight lines rather than trochoidal curves. The feedrates are thus chosen in order to have equivalent local abrasion time between the two strategies.

The resulting curves present an initial rapid evolution and then stabilize towards an asymptotic value (Fig. 6). This form is

| **Test** | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $V_f$ $mm/min$ | 90 | 90 | 180 | 180 |
| $N$ $rpm$ | 2000 | 4000 | 2000 | 4000 |

TABLE 2: Design of experimentations definition

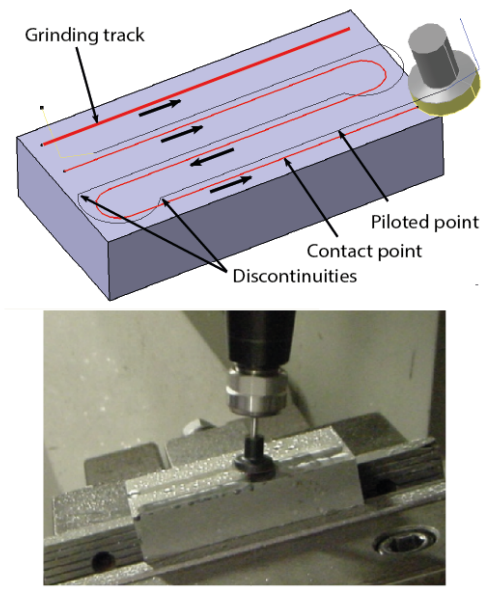



FIGURE 5: Experiment tool path to model abrasive wear

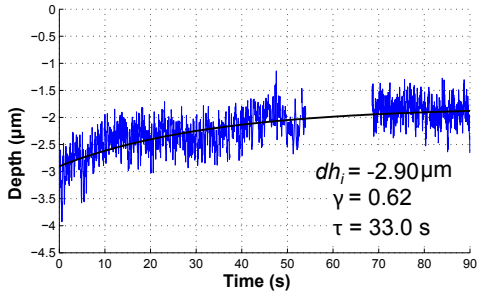
typical of exponential curves and a model of the depth evolution along the bands is proposed in the form of equation 5 and 6. Hence, the evolution of the depth $dh(t)$ over time is expressed in terms of the initial depth $dh_i$ and abrasive efficiency over time $\gamma(t)$. The evolution of the abrasive efficiency $\gamma(t)$ depends on the time constant $\tau$ and the final efficiency $\gamma_f$.

$$dh(t) = dh_f + (dh_i - dh_f) * e^{\frac{-t}{\tau}} \tag{5}$$

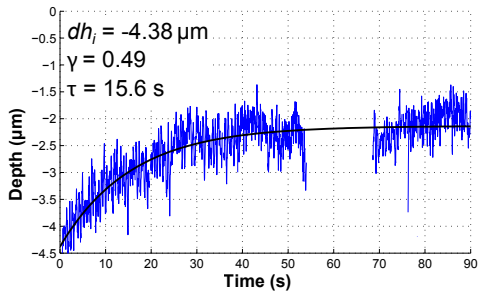
$$dh(t) = dh_i \cdot \gamma(t) = dh_i \cdot \left(\gamma_f + (1 - \gamma_f) * e^{\frac{-t}{\tau}}\right) \tag{6}$$

— The initial depth $dh_i$ represent the initial abrasive wear.
— The final efficiency $\gamma_f$ characterize the tool wear of the disc at the end of the tool path.
— The constant $\tau$ allows to appreciate how fast the efficiency decreases.
— The final depth $dh_f$ is expressed as the product of the initial depth and the final efficiency.

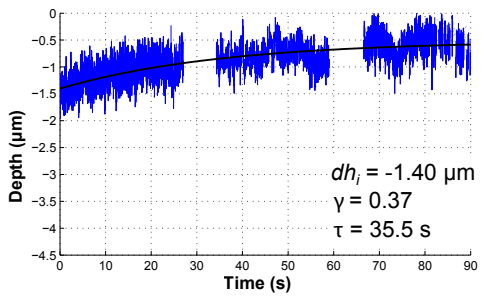
For each test, the three constants ($dh_i$, $\gamma_f$, $\tau$) are determined by a least square minimisation between the measured points and the modeled curve. Only the first 90 seconds, corresponding to the total time of the shortest tests, are taken into account for the identification of the model. The missing portions on the graphics are circular portions that are not taken into account because of slowdowns during the operation. The depths of the four tests and the models identified by the least squares criterion are shown in figure 6. Thanks to the three constants determination for each test defined in table 2, it is possible to determine their mean value and the effect of the polishing parameters. The effect of a parameter is calculated using Taguchy's methodology. The mean value of all the collected data is subtracted from the average value of the collected data at the high level of the factor. Assuming a linear model, the abrasive wear could be interpolated from the data presented in table 3.



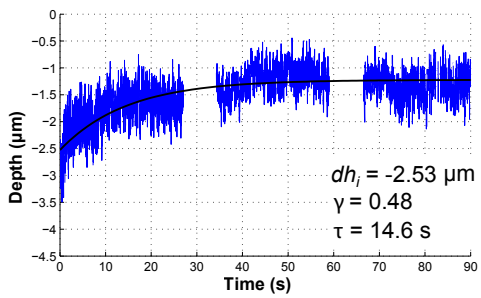

(a) 90 $mm/min$-2000 $rpm$




(b) 90 $mm/min$- 4000 $rpm$




(c) 180 $mm/min$-2000 $rpm$




(d) 180 $mm/min$- 4000 $rpm$

FIGURE 6: Depth measurement and identified model

One of the shortcomings of the proposed model, defined as

| Parameter | mean | $V_f$ effect | $N$ effect |
|---|---|---|---|
| $dh_i$ $(mm)$ | 2.802 | 0.837 | -0.652 |
| $\tau$ $(s)$ | 24.675 | 0,375 | -9,575 |
| $\gamma_f$ | 0.490 | -0.065 | -0,005 |

TABLE 3: DOE Results

a single exponential decay, is its inability to model the thermal effects during polishing. Indeed, due to viscoplasticity of the polymer and the cyclic loading of the rubber body, any changes of temperature in the tool can affect the contact area and the pressure distribution. In order to illustrate this behaviour, the temperature of the tool's external surface is measured using a thermal imaging camera while polishing the same point during 360 secondes (Fig. 7).

This temperature measurement shows that the time constants of the temperature fluctuation is around 45 seconds which is significant considering that the expected lifetime of the abrasive discs is around 180 seconds. An improvement to our model could be made by combining not one but two exponentials to take into account respectively the wear and the thermal effect as described in figure 8. Furthermore, it demonstrates that it is preferable to use tool paths that maintain a permanent contact between the tool and the workpiece.

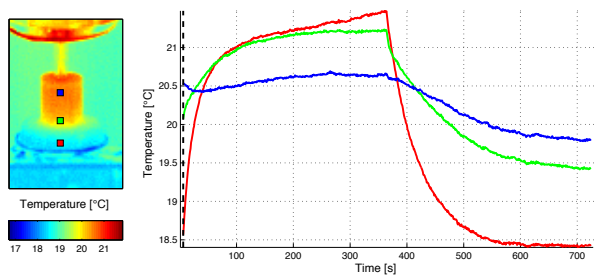



FIGURE 7: Temperature measurement (15° - 1500 rpm- 0.5 mm tool displacement)

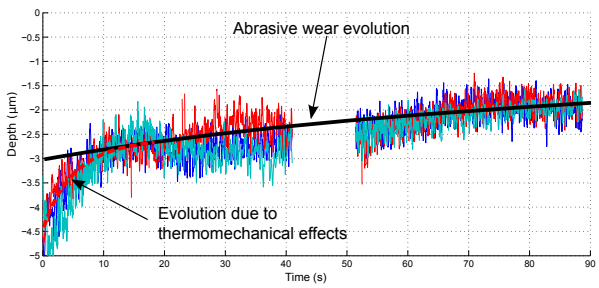



FIGURE 8: Two exponentials model with thermal effect

Nevertheless, the results show that it is possible to establish a model of abrasive tool wear evolution in the form of equation 6. The abrasion efficiency over time is modeled as a decreasing function denoted $\gamma(t)$. As the $MRR$ is defined by $MMR = dh/dt$, "Preston coefficient" $K$ ( Eq. 1) is assumed to be proportional to the abrasion efficiency $K(t) = K \cdot \gamma(t)$. Based on polishing tests, this model is sufficiently robust to be used to control the geometrical deviation of polished surfaces. The next section shows how this model can be inserted into a compensation method in order to ensure a constant material removal rate.

## 4. Optimisation of the material removal

The aim of this section is to optimize the polishing parameters to obtain a constant MRR along the tool path despite the tool wear variations. The material removal rate is defined by equation 7.

$$MRR(t) = K \cdot P \cdot V \cdot \left(\gamma_f + (1 - \gamma_f) * e^{\frac{-t}{\tau}}\right) \tag{7}$$

The most significant parameters on MRR which are easily controllable on machine tool are the pressure $P$, the relative velocity $V$ and the local abrasion time. They can be respectively adjusted by the imposed displacement and the angle between the tool and the part, the spindle speed and the feedrate $V_f$. According to the proposed abrasion model (eq. 7), the MRR is proportional to the spindle speed and inversely proportional to the feedrate. As these parameters are easily controlled on a machine-tool, their are used to compensate the reduction of efficiency and obtain a constant material removal. Three different methods are now presented to achieve a constant MRR.

### 4.1. Feedrate compensation

To obtain a constant material removal rate, all parameters are fixed excepted the feedrate. The pressure distribution is assumed to be constant choosing a planar geometry and imposing a constant tool inclination and position. The constant spindle speed allows a constant abrasion velocity and a fixed abrasive efficiency model. Hence, with these pressure conditions and constant abrasion velocity, at every contact point, the removal rate is written hereafter where $MRR_0$ is a constant.

$$MRR(t) = K \cdot P \cdot V \cdot \gamma(t) = MRR_0 \cdot \gamma(t) \tag{8}$$

The depth variation $\Delta h$ corresponding to a small displacement $\Delta l_0$ is expressed as follow :

$$\Delta h(t) = MRR(t) \cdot \Delta t = (MRR_0 \cdot \gamma(t)) \cdot \left(\frac{\Delta l_0}{V_f(t)}\right) \tag{9}$$

For a constant material removal $\Delta h_0$ with a constant pressure and abrasion velocity, the feedrate should be proportional to the efficiency evolution.

$$V_f(t) = \left(\frac{MRR_0 \cdot \Delta l_0}{\Delta h_0}\right) \cdot \gamma(t) \tag{10}$$

### 4.2. Spindle speed compensation

Assuming that the feedrate could be neglected compared to the cutting speed, the abrasion velocity $V$ is expressed according to the spindle frequency $N$ and the distance $R$ between the contact area and the spindle axis (eq. 11).

$$V = \frac{2\pi \cdot N}{60} \cdot R \tag{11}$$

Thus, from the general form of the material removal equation (eq. 8 and eq. 9), the expression of the spindle speed may be expressed as follows :

$$N(t) = \frac{\Delta h_0 \cdot 60}{\Delta l_0 \cdot 2\pi \cdot K \cdot P} \cdot \frac{V_f(t)}{\gamma(t)} = \frac{N_0}{V_f 0} \cdot \frac{Vf(t)}{\gamma(t)} \tag{12}$$

To achieve a constant material removal $\Delta h_0$ with a constant pressure, the spindle speed must be proportional to the ratio between the feedrate $V_f(t)$ and the efficiency $\gamma(t)$. Thus, the efficiency compensation by the spindle speed method can be used directly to compensate the efficiency variation or the feedrate variation. This method presents two major difficulties.

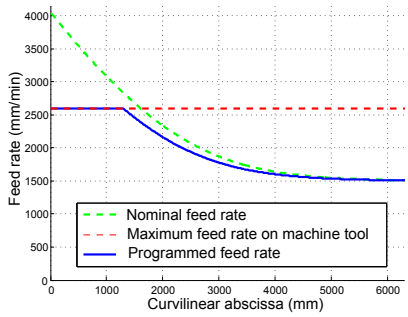
The first one concern the modelisation of the efficiency law. When the spindle speed is constant, the efficiently $\gamma(t)$ could be modeled as expressed in section 3 but the coefficient of the model are expressed as a function of the spindle speed. So, the conservation of a correct modelling of the efficiency requires a reduced spindle speed range. This would correspond to a particular use of the spindle speed variation to compensate feedrate variations.

The second difficulty is linked to the opportunities offered by the current CNC machine tools. Indeed, the axes movements are stopped until the spindle speed reaches the set point. Thus, it is necessary to change some standard features of the CNC that link the movement of the machine axes with respect to the spindle speed instruction.

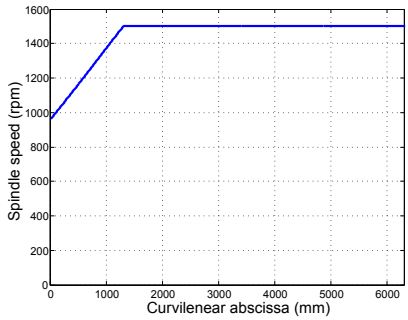
### 4.3. Mixed compensation

Two methods have been presented to control the MRR variation by driving the feedrate $V_f$ and the spindle speed $N$. Contrary to the spindle speed, the feedrate have a limited influence on the efficiency model and can be easily used to reduce the MRR variation. As the tool paths commonly used in polishing process contain low curvature radius, it is necessary to limit the initial feedrate according to the dynamic performance of the machine tool. To compensate the efficiency reduction, the feedrate at the end of the operation will be very slow and the machining time could be inconsistent with the production constraints. From a prediction of the actual feedrate during the execution of the tool path as developed by Beudaert et al. (2012), it is possible to modify the spindle speed in order to keep a constant material removal when the machine tool slows down. As an exemple, it is considered that the final feedrate must be greater than 1500 $mm/min$, the maximal feedrate is 2600 $mm/min$ and the nominal spindle speed is chosen equal to 1500 $rpm$. The initial feedrate is calculated from equation 13 and the theoretical feedrate as presented in section 4.1. The evolution of the desired feedrate along the tool path is illustrated in figure 9(a) according to the feedrate limitation. Then the spindle speed is calculated according to equation 12 in order to compensate the feedrate slow down (Fig. 9(b)).

$$Vf_0 = \frac{1500}{\gamma_f} = 4054\ mm/min \tag{13}$$




(a) Feedrate evolution




(b) Spindle speed evolution

FIGURE 9: Feedrate and spindle speed evolution for abrasive wear compensation

## 5. Experimental assessment with feedrate compensation

In this section the compensation methods presented previously are applied to an example. The selected surface to polish is a planar face in order to facilitate measurement with a chromatic confocal sensor and thus validate the proposed approach. Nevertheless polishing strategies would be identical on a complex surface.

The experimental conditions are equivalent to those described in section 2 excepted for the feedrate which is chosen proportional to the efficienty law (eq. 10).

Using this method, the feedrate is maximum at the beginning of the tool path, and then must decrease to compensate the efficiency variation. The initial velocity $Vf_0$ must be chosen in order to avoid excessive material removal and to respect the kinematical constraints of the machine tool. As the tool path is cyclic, the maximum feedrate that can reach the machine-tool leads to a 8 $mm$ trochoidal diameter and an initial feedrate $V_0$ equal to 2.6 $m/min$. The feedrate is calculated based on the curvilinear abscissa from the equation 10, which allows to define the desired velocity for each block of the machining program.

The calculated feedrate and the measured one are represented according to the curvilinear abscissa on figure 10. The measured depth map of the polished surface is shown in figure 11.

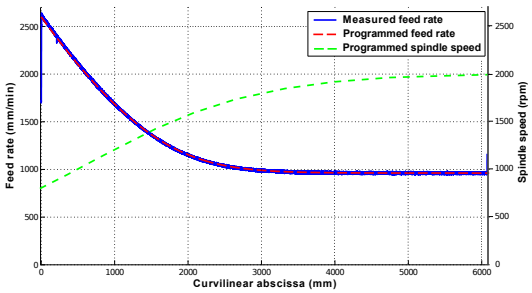



FIGURE 10: Feedrate and spindle speed evolution

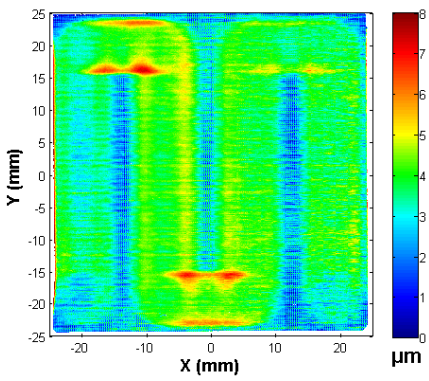



FIGURE 11: Measured depth ($\mu m$) with feedrate compensation

As for the first test, the vertical and horizontal portions of trochoid do not have the same depth as the contact area is larger in the X direction. In the corners of the trochoid, the depth is the most important because the path density is more important. We are only interested in trochoid's portions in the Y direction. On the experimental test, the abrasion depth is slightly lower on the start of the operation compared to the end. The feedrate is either too much fast at the beginning, or too slow at the end. This difference means that the final efficiency $\gamma_f$ was slightly underestimated in the efficiency law. However, the material removal is almost constant along the tool path with depth variation less than 20% (Fig. 11), compare to the polishing test without compensation where the depth variations are greater than 50% (Fig. 3(b)). As the correlation between simulation and experimental results is very good, it is possible to validate the proposed approach. Thus, this method allows to obtain a homogeneous abrasion on the polished surface and reduce the shape defect generated during polishing operations.

Although experimental validation tests haven't been performed, it is proposed to compare the previous polishing time to ones potentially achievable with the two compensation methods

| **Method** | **Vf init.** | **Vf final** | **Time** |
|---|---|---|---|
| | $mm/min$ | $mm/min$ | (s) |
| Feedrate | 2600 | 962 | 321 |
| Spindle | 2600 | 2600 | 141 |
| Mixed | 2600 | 1500 | 197 |

TABLE 4: Pre-polishing time according to chosen compensation

presented in section 4.2 and 4.3. The experimental conditions are identical to those previously used. From a desired feedrate, the programmed spindle speed is computed in function of the curvilinear abscissa (10). The experimental conditions for the mixed compensation are detailed in section 4.3.

A classification of the compensation methods is proposed in table 4 according to the theoretical polishing time. Compensation by the spindle speed reduces machining time because the maximum feedrate achievable on the machine can be chosen. On the other hand, the feedrate compensation method gives higher's machining time. Indeed, the final velocity depends on the maximum achievable velocity by the machine tool at the beginning of the operation.

From a quality point of view, the developed efficiency laws do not take into account the variation of spindle speed. Thus, the compensation method based on spindle speed variation may not provide entirely predictable results. A mixed compensation could be a good compromise between quality and productivity.

## 6. Conclusion

A complete approach has been presented in this paper to ensure a constant material removal rate in two bodies automated polishing. First of all, an analysis of the tool wear is carried out to emphasize the problem. Then an abrasive's wear model based on a design of experiment is built and an efficiency coefficient is introduced in the Preston's law. Although the established parameters are only valid for the material and the parameters range studied, the proposed method is general and the domain of validity can be easily extended.Three compensation strategies are proposed to integrate the efficiency of the abrasive and provide a constant material removal rate. The strategy based on feedrate variation has been validated through experimental investigation on a 5-axis machine tool. Spindle speed variation will be address in futur works by the the use of an open-CNC.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