A Study on the Material Removal Mechanisms in Ball Polishing

G. Savio[1], R. Meneghello[1], G. Concheri[1], A. Cerardi[1]
[1]*Laboratory of Design Tools and Methods in Industrial Engineering – DAUR – University of Padova, Italy*
gianpaolo.savio@unipd.it

Abstract

The manufacturing process of freeform glass components for precision optics is usually based on contour CNC grinding and polishing operations. To predict the geometrical precision of the production process, a correlation between the geometrical error and the process parameters is required. This is even more important in the polishing operation which is the final stage of the process.

In this work a model for material removal estimation in deterministic polishing of glass moulds is proposed and validated. The model is developed for CNC ball polishing of free-form surfaces, where the pad, made of a polyurethane layer superimposed to a rubber bulk, moves along a scanning path, in a suspension of cerium oxide. As many models in literature the removed material can be estimated by pressure and sliding velocity between polishing pad and workpiece. Adopting the Hertz theory these physical characteristics can be related to the CAD-CAM-CNC parameters, e.g. tool and workpiece shape, dimension and modulus of elasticity, feed rate, feed step, tool rotational speed and radial tool deformation.

The model validation was performed on ground glass flat samples polished with different process parameters, measuring the removed material by a contact probe profilometer. The developed model shows a satisfactory estimation of removal material as a function of the process parameters.

1 Introduction

As it is known the mechanisms of the polishing process (mechanical and chemical) are complex and not yet well understood: several parameters such as pressure, velocity, temperature, work-piece material, slurry material, shape and dimension of abrasive, pad material etc. influence the material removal (MR) in chemical mechanical polishing process (CMP). Moreover recent research showed that pad roughness [1], ceria concentration [2], CNC path [3] affect MR.

In this work the material removal MR in the ball polishing process of freeform surface of ground optical components is related to CAD-CAM-CNC parameters.

2 Material Removal evaluation

Reye’s theory assumes that the volume of removed material is proportional to the energy dissipated in the process, i.e. the work due to the friction force. This mean, in the differential form:

$$dh = k \cdot p \cdot v \cdot dt \tag{1}$$

where p is the pressure, v is the sliding velocity between the polishing pad and the workpiece, dh is the removal material per unit area in the time dt.

A similar conclusion is obtained by Preston [4] in the study of the chemical mechanical polishing process of glass. In literature a generalization of this equation can be found:

$$MR = \int k \cdot p^{\alpha} \cdot v^{\beta} \cdot dt \tag{2}$$

where α e β are two parameters to get better fit of the experimental data [5].

2.1 Kinematics and pressure distribution in polishing

The polishing machine used in the present study is equipped with a workpiece spindle, which moves along the x and z axes, and a wheel spindle, which rotates at angular velocity w and translates along the y-axis (Fig. 1a) [6]. Moving over the mould surface, the tool follows a scanning path [3] with feed rate v_{av} along the y-axis and feed step p_a in the x-direction (Fig. 1b). A radial deformation Δ is induced when the tool is kept in contact with the mould surface, generating a pressure distribution in the contact area which can be estimated according to the Hertz theory, disregarding the friction contribution [6]. The tool consists of a rubber ball where a polyurethane layer was superimposed and the abrasive slurry is a suspension of cerium oxide (CeO2) in water.

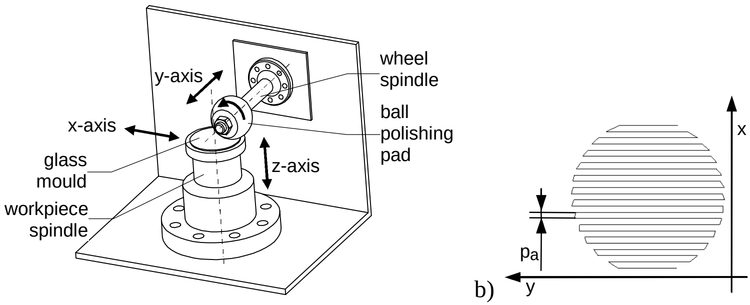

Figure 1: Scheme of the polishing CNC a) and tool path on a flat sample b).

2.2 Model for Material Removal estimation

From the kinematics of the polishing CNC and the pressure distribution [6], assuming that p_a is less than one-tenth of the radius of contact area, the MR can be derived from eq. 2, as:

$$MR \cong k \frac{2\pi}{2+\alpha}\left(\frac{2 \cdot E_{eq}}{\pi}\right)^{\alpha} \frac{\left(v_{tr}^{\ 2} + v_{av}^{\ 2}\right)^{\beta/2}}{p_a} \frac{R_{eq}^{\ 1-\alpha/2} \cdot \Delta^{1+\alpha/2}}{v_{av}} \tag{3}$$

where E_{eq} is the equivalent modulus of elasticity and R_{eq} is the equivalent curvature radius which are related to modulus of elasticity, Poisson's ratio and radius of tool and workpiece. R_{eq} is equal to the polishing pad radius when the workpiece is flat.

2.3 Material Removal measurement

The actual MR (MR_A) was assessed on ground flat samples which were polished only over half the surface, by measuring a transverse profile (parallel to x-axis) partially in the ground portion and partially in the polished area. The MR_A value was derived by the difference between the height of the ground portion and the depth of the polished surface (fig.2).

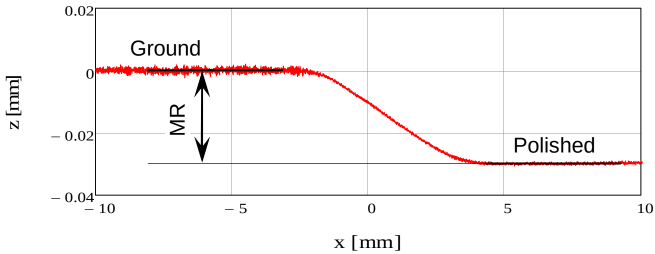

Figure 2: Profile measured with contact probe profilometer and MR_A measurement.

3 Results and discussion

In order to evaluate the performance of the model the actual MR_A was measured on 7 flat glass samples (Schott UV-W 76) by a Carl Zeiss-TSK Surfcom 1800D profilometer. The parameters p_a, v_{av} and v_{tr} of the samples assume different values as in table 1. The other parameters are: R_{eq}=34.79 mm, Δ=0.5 mm, E_{eq}=12 MPa, CeO_2 density 1150 kg/m^3 and temperature 30°C.

Theoretical MR_{Th1} was determined assuming $\alpha=\beta=1$; in this way $k=5.535\cdot10^{-13}$ Pa^{-1} has been found by fitting. The model predict the MR with an error less then 9% and the coefficient k is similar to the Preston coefficient available in literature (e.g. [7]). Theoretical MR_{Th2} was calculated supposing $\alpha=1$; subsequently, by fitting, $k=6.322\cdot10^{-13}$ and $\beta=0.885$ were found. In this case the model predicts the MR with an error less then 7%. The case with $\alpha\neq1$ can not be studied because samples with different value of R_{eq} or Δ are not available.

Table1: Experimental assessment and results

Sample ID	p_a [mm]	v_{tr} (rpm) [m/sec]	v_{av} [m/sec]	RM_A [μm]	RM_{Th1} [μm]	ε_1%	RM_{Th2} [μm]	ε_2%
T1	0.16	3.64 (1000)	0.005	46.1	44.8	-2.8	44.2	-4.3
T2	0.3	3.64 (1000)	0.005	26.4	26.9	1.7	26.5	0.1
T3	0.5	3.64 (1000)	0.005	78.8	84.0	6.7	82.7	5.0
T4	0.3	1.82 (500)	0.005	24.6	22.4	-8.9	23.9	-2.9
T5	0.3	2.73 (750)	0.005	32.2	33.6	4.3	34.2	6.2
T6	0.3	3.64 (1000)	0.0024	91.0	93.4	2.6	91.9	1.0
T7	0.3	3.64 (1000)	0.009	26.4	24.9	-5.5	24.5	-7.0

4 Conclusion

In this work a model is proposed which is able to calculate the material removal as a function of the CAD-CAM-CNC process parameters in the ball polishing process of freeform precision glass components. Moreover the influence of feed step, feed rate and tangential velocity of the tool have been investigated. Experimental measurements have shown that the model predicts the material removal with an error less then 9%.

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