FLEXIBLE POLISHING WITH BOUNDED GRAINS FOR COMPLEX CERAMIC ENDOPROSTHESES

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INTRODUCTION
Worldwide, the knee is the most medically treated joint. The complication rate amounts to about 26% on the whole. The main reason for the failure of the interconnection between bone and prosthesis is the agglomeration of wear debris of the polyethylene part [1].

Inspired by the successfully employed ceramic hip joint prostheses, the trend in the development of implant material pairings goes towards the use of ceramics [2-3]. So the objective of this project within the scope of the Collaborative Research Center 599 sponsored by the DFG is to improve the durability of complex implants, like knee implants, by means of new machining technologies for ceramics [4].

The objective is to realize automated high-precision machining processes using one single machine, so that the low-wear ceramic also gets the upper hand for other complex joint replacements. Two promising polishing methods using flexible tools with bound abrasives are presented. On the one hand, rubber bond diamond tools are applied with special focus on the modeling of the influencing parameters. On the other hand, a polishing belt apparatus is introduced including first experimental results.

MATERIAL REMOVAL MECHANISMS

In general, ceramic materials are machined using abrasive processes with diamond particles. For controlling the surface properties, the involved material removal mechanisms have to be characterized. In the most commonly applied machining processes with geometrically non-defined cutting edges like grinding, honing, lapping and polishing, the material is removed by the penetration of separate diamond cutting edges into the working material.

Zum Gahr [5] classified the mechanisms involved in the wear of the material. Two of these mechanisms are relevant for the polishing of ceramics using flexible tools with bound grains (FIG. 1). The penetration of the grains mostly causes plasticizing and a ductile removal of ceramic particles, but unbound grains, which are rolling between the flexible bonding and the workpiece, can cause micro-cracks and brittle outbursts.

FIGURE 1. Polishing mechanisms.

The superposition of different scratching motions of the abrasive grains parallel to the workpiece surface is characteristic for abrasive processes. Taking this into consideration, a hypothesis can be put forward for polishing processes using flexible tools with bound grains (FIG. 2).

FIGURE 2. Hypothesis and relevant parameters.

The removal of the roughness peaks depends on the number of grains which slide over the workpiece in a fixed period of time and on the contact pressure of the grains on the workpiece. A higher number of grains leads to decreased surface roughness and a higher contact pressure of the polishing grains on the workpiece leads to an increased smoothening up to a certain degree. If the pressure is increased beyond this certain point, the material removal rate also increases. This means that not only the surface roughness, but also the shape accuracy are
reduced with an increase in the contact pressure or the polishing time.

In the left of FIG. 2, the relevant actuating variables and system variables are summed up; the evaluation criteria are listed in the right. The modeling procedure presented in the following will point out the relationship between the influencing variables and the evaluation variables. The knowledge of this relationship is necessary to predict the work piece quality.

**MODELING**

The first focus in the modeling process is on the number of polishing grains which slide over one unit of the work piece.

**FIGURE 3. Variables of a flexible polishing tool.**

With an infeed depth $f$, of the flexible polishing tool into the work piece, a specific forming of the tool is achieved by means of the contact pressure $p_A$ depending on the feed angle $\beta$ (FIG. 3). If we assume that the tool is ideally elastic, the tool contour is linear up to the point where the tool bends at the edge of the contact area. However in combination with the softness resp. rigidity $c_p$ of the tool, the real deformation differs from the ideal one. The work piece contour is nonlinear from the middle of the tool and passes tangentially into the contact area. This also affects the ideal resp. real contact areas $A_{\text{ideal}}$ and $A_{\text{actual}}$, which have to be defined by experiments. The number of polishing grains can be determined as follows: First, the number of grains per unit of volume $N'''_{Kp}$ is defined for the concentration $C$, the single grain volume $V_{ge}$ and the density of the polishing material $\rho_g$,

$$N'''_{Kp} = \frac{C}{(V_{ge} \cdot \rho_g)}$$

whereas $\rho_g = 3.52 \cdot \frac{g}{cm^3}$ for diamond material and

$$V_{ge} = q_e \cdot \frac{1}{6} \cdot \pi \cdot d_g^3$$

whereas $q_e = 1$ the grain shape factor for round grains.

**FIGURE 4. Grains in the contact area.**

The number of grains in the overlying section of the disk $N'''_{Kp,ges}$ (FIG. 4) is

$$N'''_{Kp,ges} = N'''_{Kp} \cdot V_{p,\text{Abschnitt}}$$

with a polishing tool volume in the overlying section $V_{p,\text{section}}$ of:

$$V_{p,\text{Abschnitt}} = \frac{1}{2} \cdot h_p \cdot s \cdot (r_p - h_s)$$

whereas $h_p$ = height of the polishing tool, $h_s$ = height of the circle segment, $r_p$ = radius of the polishing tool and $s$ = length of the circle segment chord (Fig. 3 and 4). The number of grains in the overlying area $N''''_{Kp}$ is calculated by dividing $N'''_{Kp,ges}$ by the grain size $d_g$:

$$N''''_{Kp} = \frac{N'''_{Kp,ges}}{d_g}$$

Taking into account the cutting speed $v_{cp}$, the number of grains sliding over the contact area $N''''_{Kp,v}$ is

$$N''''_{Kp,v} = N''''_{Kp} \cdot \frac{v_{cp}}{\pi \cdot d_p}$$

whereas $d_p$ = diameter of the polishing tool.

The transformation with regard to the work piece is carried out by regarding one surface element and the grains sliding over it. Because the tool is symmetric, only one half is considered:

$$\frac{1}{2} \cdot A_K = \frac{1}{2} \cdot N''''_{Kp,v}$$

**FIGURE 5. Grains per work piece element.**
The ratio of the half contact area $A_K$ to the area of the work piece element $A_{WE,i}$ is similar to the ratio of half the number of grains sliding over the surface $N''_K_{AV}$ to the number of grains sliding over one work piece element $N''_{WE}$. $A_{WE,i}$ is the segment of the tool which is in contact with the work piece (FIG. 5).

The surface area of this segment can be determined using integration by parts. Three assumptions are made regarding the deformation of the contact area: in case of an ideal deformation, the area is a semi circle with the radius of the polishing tool $r_p$; the real deformation corresponds to a segment of a circle with a segment height $h_s$ or to a sickle.

For the semi-circular contact area (FIG. 5, left) follows

$$A_{WE} = \frac{x}{2} \cdot \left( r_p^2 - x^2 \right) + \frac{r_p}{2} \cdot \arcsin \left( \frac{x}{r_p} \right)$$

(8)

For the contact area in the form of a circle segment (FIG. 5, center), $A_{WE}$ has to be calculated by subtraction of the hatched rectangular area:

$$A_{WE} = [A_{WE1} - (x_1 - x_2) \cdot (r_p - h_s)] \cdot x_2$$

(9)

In the case of the sickle-shaped contact area (FIG. 5, right), $A_{WE1}$ is calculated as well as the surface area of a circular function which is translated by $z$ and if necessary provided with an increased radius $r_2$:

$$A_{WE} = [A_{WE1} - A_{WE2}] \cdot x_1$$

(10)

For the calculation of the grains sliding over the work piece $N''_{WE}$, $A_{WE1}$ has to be inserted into Equation 7.

The feed speed $v_{fp}$ also influences the number of grains sliding over a work piece unit of 1 mm² within a fixed period of time. This has to be taken into account by means of the following calculation:

$$N''_{WE,vf} = \frac{N''_{WE} \cdot v_{cp} \cdot (s + 1 \text{ mm})}{2 \cdot \pi \cdot r_p \cdot v_{fp}}$$

(11)

Whereas $s = r_p$ for an ideal contact area resp. $s = h_s$ for a real contact area or $s = z$ for a sickle-shaped contact area.

If the respective unit of the work piece is not located in the middle of the tool, the number of grains increases in the form of a circular function with a shifting of the unit towards the tool edge. The integration interval has to be adapted accordingly.

The modelling approach presented in this paper relates several variables to each other by means of their interdependencies. Thus the number of grains sliding over one work piece unit within a fixed period of time can be calculated. The assumptions which have been made for this calculation have been proven by means of experiments in which the numbers of grains and the contact pressure on the grains have been varied systematically.

**USE OF FLEXIBLE POLISHING TOOLS**

In order to verify the presented modeling approach, the machining parameters in the polishing process cutting speed $v_{cp}$, feed speed $v_{fp}$, path distance $f_p$, and infeed $a_{ep}$ have been varied and the effects of these variations have been evaluated (FIG. 6).

![FIGURE 6. Roughness values after machining by flexible polishing tools.](image)

The roughness values $R_a$ attained by the polishing process are contrasted with those of the initial ground surface with $R_a = 75$ nm and with the surface of conventional ceramic hip prostheses with $R_a = 20$ nm. With an increase in the feed speed $v_{fp}$, the surface roughness rises because less polishing grains are sliding over the surface per time unit. With a lower path distance $f_p$, i.e. in case of an increased overlapping, the surface quality improves because more polishing grains are sliding over each surface unit. The roughness can also be reduced by an increase in the infeed $a_{ep}$ because the contact area is enlarged and more grains are implied. It can be assumed that additionally, the force of each grain is enhanced, which again increases the smoothening effect. In regard to the cutting speed, the optimal results are attained using a moderate speed of $v_{cp} = 6.4$ m/s. For a target value of $R_a = 20$ nm, medium values are also sufficient for the feed speed $v_{fp}$, the path distance $f_p$, and the infeed $a_{ep}$.

Our hypothesis mainly complies with the experimental results. The normal force per grain is integrated into the presented model.
FIGURE 7. Results of the wear tests.

Several specimens have been subject to wear tests using the parameters and tool specifications presented in the bottom of FIG. 7. These specimens have been pre-machined by a front grinding process using a toric mounted point in order to attain high-quality components with $R_a < 10 \text{ nm}$ after the polishing process. The surfaces are also shown in SEM micrographs in the right of FIG. 7. The shape accuracy lies within the target tolerances of $\pm 1 \text{ µm}$.


For the testing of an alternative polishing method, a belt polishing system was developed (FIG. 8). Thanks to a flexible contact roll with a rubber surface and a flexible contact foot fixed by a spring, the machining process will not be purely force-controlled. Additionally, a long belt path was implemented using eight deflection pulleys providing a higher wear volume compared with that of the rubber bond flexible polishers. A standard diamond belt with a grain size of $d_g = 25 \text{ µm}$ was tested first. The cutting speed corresponding to the belt velocity and feed velocity were varied. The plane bioceramic specimens were pre-machined by peripheral grinding with an initial average roughness of $R_a = 0.6 \text{ µm}$. In analogy to the results attained with the rubber bond tools, the roughness values were decreased by lower feed speeds and higher cutting speeds. The mean surface roughness $R_a$ is developing similar to the roughness depth $R_z$. With a slower feed speed and a higher belt speed, more grains are penetrating into the ceramic surface. If more grains are engaged, more work piece material is removed and the surface is smoothed further.

OUTLOOK

In the present investigations, the rigidity, the corresponding real contact area and the influence of the forces per grain on the surface quality have been determined [6, 7]. The next step will be to validate the model for flexible polishing tools by means of experiments. At the same time, the belt apparatus will be examined further regarding the optimal belt specifications and contact rolls.

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REFERENCES