I. Introduction

Manufacturing costs increase exponentially with both target surface quality and workpiece complexity. Up to 50% of manufacturing costs of ceramic products are attributed to the finishing processes such as grinding and polishing. Therefore, new finishing processes are required for the growing share of complex-shaped ceramic components in the optical technology, mold and die production and medical technology sectors. For multiple curved surfaces used in these products, the currently existing finishing processes are very costly. In the area of medical technology, the need for a new finishing technique is even greater owing to the replacement of conventional implant materials such as cobalt-chromium or titanium alloys by advanced high-strength bioceramics like zirconia-toughened alumina.

To reduce wear of joint implants, one possibility is the replacement of metal components by hard, wear-resistant bioceramics used in hip implants. The shape of the articulating surfaces of a hip implant roughly corresponds to a ball joint. Such implants are manufactured in up to 60 individual steps. The manufacturing of the geometry of a knee joint implant with free-form surfaces is more difficult. This would lead to high rates of rejected parts and uneconomical manufacturing chains. Furthermore, there are no uniform standards for the requirements of surface and shape quality of ceramic knee implants. The current target values are based on experiences with ceramic hip prostheses.

International standards for design and manufacturing of implants describe and specify the tests for ceramics in different applications. They classify and dimension the knee prostheses made of different materials, but the given information is not sufficient for characterizing knee implants. In the literature, surface quality is primarily quantified using the 2D average roughness parameter, $R_a$. The $R_a$ is an arithmetic average value of the absolute values of the surface profile sections from 3D measured surfaces (160 μm x 160 μm) are described.

To finish precision-ground all-ceramic knee implants, a polishing process is needed which works according to the requirements of such a ceramic implant. This means the ability to smooth the roughness peaks of free-formed ceramic surfaces without changing the pre-ground macro-geometry of an implant, the avoidance of polishing suspensions, and the use of the tools in one CNC-machine tool leads to the reduction of the manufacturing steps.

Keywords: Biomedical ceramics, processing by polishing and fine grinding, elastic tool, surface topography, knee implant.
In dental applications ceramic free-form surfaces have been machined manually with elastic pin tools for many years. For shape machining, the ceramic component is treated by means of fine-grinding pins with hard resin bonds. In the following finishing steps, resilient tools with grains in polyurethane or silicone bonds are used. As final manufacturing step, lapping with multiple felt polishing steps and loose abrasive elements (suspension or paste) is performed to achieve the typical dental surface. The post-shaping steps are known collectively as ‘polishing’.

However, polishing is not conceptually and technologically standardized in DIN 8589 (manufacturing processes) as a manufacturing technology. Depending on the application required, different processes have been established. Regardless, high surface qualities are always required after the polishing step, preferably in the nanometer range. In the outdated DIN 4766-T2 (processes for roughness of surfaces; achievable arithmetic average roughness Ra), surface roughnesses of $Ra = 12 – 400 \, \text{nm}$ are realized by polishing. ISO 1302 (geometric product specifications (GPS) – Indication of surface texture in technical documentation) defines surfaces of $Ra = 7.5 – 60 \, \text{nm}$ by polishing, lapping, or superfinishing.

An appropriate classification of the application-specific polishing processes is sub-division in accordance with the principle of material removal and chipping, such as those described by Gessenharter:

(i) Physical-mechanical processes;
(ii) Physical, but not mechanical, processes;
(iii) Chemical removal processes.

Resiliently or elastically bonded grains are allocated to category (i). In polishing with elastic-bonded grains, material removal is achieved by means of an abrasive procedure where, typically, the hard abrasive penetrates the softer workpiece surface. This resembles fine grinding processes. Here, physical-mechanical polishing is defined by the type of grain integration:

(i) **Polishing with loose abrasive**: Grains are located between the workpiece surface and the polishing tool. Therefore, grains mainly roll in between the surfaces, generating 3-body abrasion. This mechanism is called micro-cracking. Examples: CMP, lapping.

(ii) **Polishing with rigidly bonded abrasive**: A ductile removal is achieved by a scratching grain corresponding to grinding wheels. This is called 2-body abrasion and results in a micro-cutting mechanism. Examples: precision grinding, honing.

(iii) **Polishing with elastically bonded grain**: Initially, a grain is fixed to the bond; it scratches the surface by micro-cutting (2-body abrasion). Owing to cutting forces higher than the bond retention forces, the grain is pulled off. Then, the grain rolls between the tool and the surface (micro-cracking, chipping, 3-body abrasion). Examples: belt polishing, dental tools.

First results on the mechanisms and the principle process behavior in polishing of ceramic materials with elastically bonded diamond tools were presented by the authors in 2009 and 2010. Previous studies by Ahn in 2002 used for 5-axis polishing of cold working steel a silicone-base body which was adapted to a pneumatically working spindle head. He shows that the change in roughness is proportionally dependent on the polishing pressure and the polishing grain radius and inversely proportional to the hardness of the steel – similar to the results of loose polishing found by Luo. Thereby, the minimally achievable roughness is limited by the indent depth of the grain.

Brinksmeier et al. found out that steel can be work-hardened by grinding with elastically bonded tools. He uses polyurethane-bonded corundum tools in plunge grinding. The tool engagement conditions are different to polishing pins used in this paper (Fig. 1), but he measured specific process forces between 5 and 8 N/mm² during the finishing step. They describe the tool mechanisms in three steps: Firstly the tool stiffens, secondly the tool engages in the material and thirdly plastic deformation occurs. During polishing and grinding with elastically bonded tools heat is generated and can be used for grind hardening. An increase in the hardness of the bonding increases the compressive stresses in the subsurface of steel. A comparison of the roughness after polishing with these tools is lacking. Compared to the tools used here, he uses very hard elastic bonds measured with a Grindosonic system. Hahmann described that the hardness of the elastic bonding will not considerably influence the roughness, however, the grain’s size will. She showed a significant influence of the infeed and whereas the velocity quotient had a minor effect on the roughness.

The literature review comes to the partially controversial conclusion concerning the effects of the process parameter in polishing depending on the tool used and tool kinematics. Furthermore, important process parameters
are not included in the published results. No further literature on polishing of ceramics with elastically bonded diamond tools exists. A defined process design based on the polishing forces of a single grain and the number of active grains in process is lacking.

Therefore, in the present study the tool performance of elastically bonded polishing tools has been investigated in order to polish biomedical oxide ceramics by the targeted reduction of the roughness peaks. To enable economical and automated polish machining of ceramic implants, it is clear that an increased understanding of the process and key parameters is essential.

II. Material and Methods

(1) Process and system parameters in fine grinding with elastic tools

Elastic tools are available as wheels or pins (Fig. 1). Regardless of the shape and size of the tool, the bond stiffness is influential and can be described by the shore hardness or Young’s modulus \( E \). The grain types, sizes and concentrations influence the Young's modulus \( E \) of the bond. Furthermore, the tool-workpiece contact is influenced predominantly by its use in processing. The pressure is adjustable based on the infeed \( f_t \). The cutting speed \( v_c \), the feed rate \( v_f \), the tool path distance \( a_p \) and the angle \( \alpha \) mainly influence the time for material removal. Tool path distance and feed rate also determine the polishing time. Beyond this, the surface quality of a ceramic workpiece is highly dependent on the ceramic characteristics: hardness \( H \), fracture toughness \( K_{IC} \), the material combination, and the particle grain size and porosity after the sintering step. At present, there is limited understanding of this comparatively young technology of defined machining with resilient bond.

(2) Theory

All used parameters and variables described in this paper are listed in the Appendices, Table A1. The majority of the process and system variables of an elastic polishing system can be attributed to two characteristics defined by the authors: grain number \( N_{III,A} \) and grain force \( F_G \). The number of grains \( N_{III,A} \) includes all abrasive grains present in a bonding material and is given in \( 1/\text{mm}^3 \). The force \( F_G \) defines the part of the process forces acting on one single abrasive grain in normal direction during polishing. The system variables are described by grain concentration \( C \) (4.4 ct/cm\(^3\) = 0.88 g/cm\(^3\) \( \equiv C_{100} \)) and grain volume \( V_g \) as well as the density of diamond \( \rho_d \). All together they can be used as grain density \( \gamma_o \) in a bond \( \gamma_o = N_{III,A} \). The bond volume connected with the area of contact \( A_C \), the grain distribution and the grain shape are represented by the number of grains in the contact area \( N_{II,Ac} \). The process is characterized by cutting speed \( v_c \) and feed rate \( v_f \) defining the number of grains which slide over the surface during one rotation of the tool. The tool path distance \( a_p \) and the surface area to be polished \( A_p \) determine the number of grains \( N_{II,Ac,vc} \) which slide over this surface in the time interval. The stiffness/hardness of the tool bond, the infeed and the number of grains in contact define the single grain force \( F_G \).

Consequently, our hypothesis is that surface quality is determined by the number of grains sliding over the surface and the force with which the grains are treating the surface. This paper describes the calculation of the characterizing variables and an experimental assessment of this hypothesis.

In a first step, the aim is to describe the active grain number depending on the tool specification (system variables). In the second step, the process parameters are included. Table 1 gives an overview of the calculation procedure.

Table 1: Simulated bond types and their mechanical characteristics.

<table>
<thead>
<tr>
<th>Step of calculation</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>concentration ( C ) grain volume ( V_g ) grain density ( \gamma_o )</td>
<td>( N_{III,A} = \gamma_o )</td>
<td>grain density in the bond material per cm(^3)</td>
</tr>
<tr>
<td>System parameters</td>
<td>volume of bond ( V_{bond} ) contact area ( A_c ) height of bond ( h_p ) distribution of grains grain shape</td>
<td>( N_{II,Ac} )</td>
<td>number of grains in the contact area</td>
</tr>
<tr>
<td></td>
<td>cutting speed ( v_c ) feed rate ( v_f )</td>
<td>( N_{II,A} )</td>
<td>number of grains contacting the surface</td>
</tr>
<tr>
<td></td>
<td>tool path distance ( a_p ) size of surface to be polished ( l_p,w ) hardness and elasticity of bond ( H, E ) numbers of grains ( N_{II,Ac} )</td>
<td>( N_{II,Ac,vc} )</td>
<td>number of grains sliding over the surface per tool rotation</td>
</tr>
<tr>
<td>Process parameters</td>
<td></td>
<td>( N_{process} )</td>
<td>number of grains sliding over surface in the process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( F_G )</td>
<td>single grain force</td>
</tr>
</tbody>
</table>
Calculating the number of active grains in contact $N_{IIA_c}$

At this point, the conceptual model of cubic unit cells is used to describe the grain distribution in the bond material. The bond material is subdivided into cube elements (CE). Each cube is equivalent to one cubic unit cell. Assuming that the grains and CEs are isotropic, the edge length of the cube is constant and can be calculated. The number of grains in one CE is given by the CE structure (e.g., primitive, hexagonal close packed (HCP), face-centered cubic (FCC) or diamond lattice). The number of grains in the tool bond is constant, thus the grain density $\gamma_o$ is described equivalently to grinding (Eq. 1).

$$N_{IIA_c} = \frac{c}{V_g \cdot \rho_g} = \gamma_o$$

Assuming a constant grain density $\gamma_o$, the number of grains contacting the surface $N_{IIA_c}$ varies only by the given CE structure (Fig. 2). The number of CEs $N_{CE}$ is calculated by the quotient of the number of grains in the volume $N_{III,A}$ and the number of grains per CE $N_{g,CE}$.

$$N_{CE} = \frac{N_{III,A}}{N_{g,CE}}$$

The number of stacked CE-layers $N_{layer}$ is calculated based on the edge length of the cube element $a_c$. The height of the overlying bond height is $h_p$ and the cube volume $V_{CE}$ (Eq. 3). The cube volume is calculated based on the surface-contacting bond $V_{bond}$ and the number of CE $N_{g,CE}$ (Eq. 4).

$$N_{layer} = \frac{h_p}{a_c} = \frac{h_p}{\sqrt[V_{CE}]{V_{CE}}}$$

$$V_{CE} = \frac{V_{bond}}{N_{CE}}$$

with

$$V_{bond} = A_c \cdot h_p$$

Thus, the number of CEs in the contacting surface $N_{CE,layer}$ is determined by the number of CEs $N_{CE}$ and the number of stacked layers $N_{layer}$.

$$N_{CE,layer} = \frac{N_{CE}}{N_{layer}} = \frac{A_c}{a_c}$$

Depending on the cubic cell structure (number of grain planes in one cubic element $N_{CE,planes}$) and the number of grains in one CE $N_{g,CE}$, a different number of active grains is calculated. Therefore, these grains penetrate the bottom layer of the bond and take an active part in the fine-grinding process.

$$N_{IIA_c} = \frac{N_{CE,layer}}{N_{CE,planes}}$$

Assuming a constant grain density (Eq. 1), only system parameters resulting from tool specification influence this number of grains $N_{IIA_c}$. The average grain size $d_g$ belongs to the diameter of the grain shape (e.g., ball, double taper, double pyramid, double frustum of pyramid) (Fig. 3).

Inserting Eq. 7 in Eq. 8 the numbers of grains per unit of area $N_{IIA_c}$, where $N_{g,plane}$ is the number of grains in one cube element plane:

$$N_{IIA_c} = \frac{\gamma_o}{A_c} = \frac{N_{g,layer}}{N_{g,planes}}$$

If the Eq. 2–6 and 1 are inserted in Eq. 9, the number of grains per unit of area $N_{IIA_c}$ is calculated by Eq. 10.

$$N_{IIA_c} = \frac{\gamma_o \cdot V_{CE}^{1/3}}{A_c} = \frac{N_{g,layer}}{N_{g,CE}} \cdot h_p \cdot N_{g,planes}$$

$$\gamma_o = \frac{A_c^{4/3} \cdot h_p^{2/3}}{N_{g,planes}} \cdot N_{IIA_c}$$

Fig. 2: Grain distribution, definition of cube elements, layers and planes.

Figs. 4 a-c present the results for the number of grains in the surface-contacting bond layer $N_{IIA_c}$ (Eq. 10) for three different grain sizes $d_g$ varying bond material (polyurethane and silicone) and diamond grain concentration C. For this calculation a diamond lattice and a ball shape were used. SEM images were made of the bond to count the number of grains. The SEM images were divided in $0.1 \times 0.1 \text{mm}^2$ areas. Each tool was counted eight times and of each tool type three tools were counted. The standard deviation in counting was 4.8 grains at maximum. The ball shape is the form with the lowest differences to the counted amount of grains.

The highest deviation was found for a polyurethane tool (C115) and a silicone tool (C100) with the grain size $d_g = 30 \mu m – 40 \mu m$ (Fig. 4c). This results from the grain size distribution of the diamond powder. According to the manufacturer's instructions of type RVM-N a diamond grain type of $15 \mu m – 25 \mu m$ contains 7.5 % of grains smaller than $15 \mu m$ and coincidently only 2 % of grains bigger than...
25 μm (Fig. 4b). However, the distribution of PDA type $d_p = 30 \mu m - 40 \mu m$ contains only 50% of grains between 33.5 μm and 36.5 μm.

To establish a link between $N_{II,A}$ and the process parameters tool path distance $a_p$, feed rate $v_f$, cutting speed $v_c$, and the size of the surface that has to be machined, the number of active grains in the complete polishing process $N_{process}$ can be calculated by means of two different solutions. On the one hand the number of grains in the contact area per tool rotation $N_{II,A}$ can be multiplied with the number of tool rotations in the complete process $n_{process}$. On the other hand, the process time $t_{process}$ can be multiplied with the amount of grains per time unit $N_{II,A_c}$. Both solutions have the same result.

The number of rotations $n_{process}$ is defined by the process time $t_{process}$ and the time needed for one tool rotation $t_r$.

$$n_{process} = \frac{t_{process}}{t_r} = \frac{t_{path} \cdot n_{path}}{t_r} = \frac{l_p}{v_f} \cdot \frac{w_p}{a_p} \cdot \frac{1}{t_r} \quad (11)$$

Thus, the number of grains in the complete polishing process of an area $(l_p \cdot w_p)$ is computable with Eq. 12 and the tool diameter $d_p$.

$$N_{process} = n_{process} \cdot N_{II,A_c} = t_{process} \cdot N_{II,A} \cdot A_c \cdot v_c \quad (12)$$

All variables of Eq. 12 are known or can be determined with simple methods. Therefore, a calculation of the active number of grains in process is possible.

(4) Determination of polishing force per grain $F_G$

During fine grinding with elastic polishing tools, the bond is deformed when contacting the workpiece surface. The theoretical model for the contact surface can only be calculated based on the assumption of an ideal deformation of the tool. From a mechanical point of view the deformation of the tool bond can be considered as a bending of a disc. But the theory of disc bending presupposes that the bending is small compared to disc thickness and the deflection is much smaller than the disc thickness to avoid distortion. Both conditions are not met for the application of the elastic polishing pin. Hence, the contact area $A_c$ is computed here with help of finite element methods. For determining the contact area and contact forces of the bond with the surface for different tool bond types (Table 2) as well as different infeeds $f_t$, Ansys 14.5 was used.

The bond can be interpreted as an elastomer, which is simulated as linear-elastic material. Since the tool is not loaded until failure, hyperelasticity can be neglected. The shank is firmly connected to the bond. On the shank of the tool a shift $f_t$ is applied. The friction coefficient $\mu$ is 0.5 and the Poisson ratio $\nu$ is 0.477. The simulated contact area $A_c$ and the acting normal force are as an example shown for silicone bond in Figs. 5 and 6.

The contact force $F_N$ increases with the Young’s modulus $E$ and with infeed $f_t$. The inclination angle $\alpha$ shows a lesser influence. $F_N$ can be described by a quadratic regression model. The correlation coefficient for $F_N$ is given in Table 3. Parameters are significant for $p < 0.1$ (student distribution, confidence interval 99%, $t$-value = |2.423| for significance for 40 degrees of freedom). $F_N$ can be calculated in Eq. 13 with the coefficient of determination of 0.99.

$$F_N = b \cdot E + c \cdot f_t \cdot \alpha + d \cdot f_t^2 + e \cdot E \cdot f_t \quad (13)$$

With regression coefficient $b = -0.002$; $c = -0.236$, $d = 0.208$ and $e = 0.054$. Fig. 7 shows the results of the regression model in accordance with measured and computed forces. Forces were measured in process with a rotational force dynamometer Kistler HS-RCD 9125 A. Eq. 13 allows calculation of the contact force without additional numerical methods. Dividing $F_N$ by the active number of grains in contact $N_{II,A_c}$ the single-grain force $F_G$ is computable.
Table 2: Simulated bond types and their mechanical characteristics.

<table>
<thead>
<tr>
<th>Type of bond</th>
<th>Grain concentration C</th>
<th>Grain size $d_g$ in μm</th>
<th>Shore A hardness of bonds</th>
<th>Young’s modulus $E$ in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>silicone</td>
<td>50</td>
<td>20</td>
<td>78.0</td>
<td>11.07</td>
</tr>
<tr>
<td>silicone</td>
<td>100</td>
<td>20</td>
<td>81.0</td>
<td>13.27</td>
</tr>
<tr>
<td>silicone</td>
<td>200</td>
<td>20</td>
<td>95.0</td>
<td>58.40</td>
</tr>
<tr>
<td>polyurethane</td>
<td>100</td>
<td>20</td>
<td>90.3</td>
<td>28.56</td>
</tr>
</tbody>
</table>

Table 3: Correlation coefficient matrix for $F_N$.

<table>
<thead>
<tr>
<th></th>
<th>$E$</th>
<th>$f_t \cdot \alpha$</th>
<th>$f_t^2$</th>
<th>$E \cdot f_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>1.000</td>
<td>-0.347</td>
<td>0.439</td>
<td>-0.743</td>
</tr>
<tr>
<td>$f_t \cdot \alpha$</td>
<td>1.000</td>
<td>-0.767</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>$f_t^2$</td>
<td>1.000</td>
<td></td>
<td>-0.446</td>
<td></td>
</tr>
<tr>
<td>$E \cdot f_t$</td>
<td></td>
<td></td>
<td></td>
<td>1.000</td>
</tr>
</tbody>
</table>

Fig. 5: Contact area $A_C$ dependent on infeed $f_t$ and inclination angle $\alpha$.

Fig. 6: Normal $F_N$ dependent on infeed $f_t$ and inclination angle $\alpha$. 
III. Machine Tools, Workpieces and Measurement Equipment

Fine-grinding experiments were done with elastic polishing pins (Fig. 1) on a 5-axis machine tool (Röders RFM 600 DS). In the machine tool, a laser length measuring system is integrated. No cooling lubricant was used. The investigations were conducted on sintered, HIP-ed and pre-ground biomedical alumina oxide ceramic workpieces with an average grain size of 1.75 μm, a density of 3.97 g/cm³, a hardness of 2040 HV1, a Young’s modulus E of 407 GPa and a fracture toughness KIc of 3.2 MPa m⁻¹/₂.

The process parameters cutting speed \( v_c \), feed rate \( v_f \) and tool path distance \( a_p \), the infeed \( f_t \) and the inclination angle \( \alpha \) were varied in five steps in a central composite design of experiments. Repetitions were done twice for the central point, which are shown as a range in the result graphs. The bond type, the grain size and the grain concentration were varied at the central point, too.

Roughness was measured with an optical white light microscope (Nanofocus, μSurf). The lens has a magnification of 100. Thus, a measuring field of 160 x 160 μm² was possible. The vertical measuring range is 0.08 mm with a vertical resolution of 1.5 nm. In the investigations the average roughness value \( S_a \) was determined based on EUR 15178 N. \( R_p \) was calculated based on DIN EN ISO 4287 as an average value of 512 profile sections. A Gaussian filter of 0.08 mm was used.

\( R_p \) means the shift of initial roughness to roughness after polishing \( \Delta R_p = R_p - R_{p1} \). \( \Delta R_p \) is used owing to the fact that the initial roughness from pre-grinding on different specimen cannot be kept constant.

IV. Results

Owing to that fact that the number of grains \( N_{\text{process}} \) and the single grain force \( F_G \) cannot be directly varied as a parameter during polishing, in the investigation the process parameters cutting speed \( v_c \), feed rate \( v_f \), tool path distance \( a_p \), the infeed \( f_t \), inclination angle \( \alpha \) and the system parameters bond type, grain size \( d_g \) and grain concentration \( C \) were systematically examined.

In this paper, the results will be split up by the influence of the number of grains \( N_{\text{process}} \) (See section IV. (1)) and the influence of the force per grain \( F_G \) (section IV. (2)) on the refinement of the roughness (peak height \( R_p \)). The shift of \( R_p (\Delta R_p) \) is always plotted on the Y-axis. The number of grains is influenced by the process parameters cutting velocity \( v_c \), feed rate \( v_f \), tool path distance/overlap \( a_p \) and the system parameters grain size \( d_g \) and grain concentration \( C \). The force per grain is affected by the infeed \( f_t \), inclination angle \( \alpha \), the number of grains and the Young’s modulus E of the bond. Process and system parameters are plotted on the x-axis. On the 2nd axis of diagrams the related number of grains \( N_{\text{process}} \) or the force per grain \( F_G \) is given. More detailed results were described by the authors31.

Fig. 8: Influence of the number of grains \( N_{\text{process}} \) and relating parameter.

(1) Influence of number of grains on roughness

The cutting speed \( v_c \) has a considerable influence on the number of active grains (Fig. 8a). However, in case of increasing cutting speed no significant impact could be found. On average a slight decrease could be found for in-
creasing cutting speeds and thus with increasing number of grains. The effect of increasing cutting speeds is overlapped by the tool wear behavior. If the cutting speed is increased, the friction between bond and workpiece surface and therefore, the contact temperature rises. Elastic silicone bonds are not wear-resistant at temperatures over 200 °C. The grains break out owing to a burned bond. In the case of low cutting speed fewer grains are active. So, the normal force $F_N$ is transmitted to the workpiece by a lower number of grains. This increases the force per active grain. If the polishing force exceeds the bond retention forces, the grain will break out of the bond.

The slower the tool moves, the more frequently the grains grab into the material. Thus, if the feed rate is reduced, the roughness peaks are significantly reduced (Fig. 8b). However, decreasing the feed rate means the reduction of the process productivity. In addition, the tool path distance $a_p$ contributes to the productivity of the process. A smaller tool path distance significantly increases the number of active grains. The same behavior is shown for $\Delta R_p$ (Fig. 8c). In case of $a_p < 0.1$ mm, the tool wear strongly increases.

(2) Influence of force per grain on roughness

The infeed $f_t$ causes an increase in the axial forces during fine grinding. This was shown in Eq. 13. In Fig. 10 the acting grain force is shown for increasing $f_t$. If $f_t$ increases from 0.1 mm to 0.8 mm $R_p$ was shifted by 0.9 $\mu$m in the same way. If the inclination angle $\alpha$ rises, the acting grain forces rise too, owing to a decreasing contact area of the bond. In this case the roughness decreases, which was shown by the shift of $\Delta R_p$ by 0.5 $\mu$m.

Concerning the tool behavior under the influence of a variable inclination angle, it was possible to show, that the influence of the grain force on $\Delta R_p$ is higher than for the active number of grains. For changing the angle from 15° to 45° $\Delta R_p$ is shifted by 0.5 $\mu$m. In this case the active number of grains in process $N_{\text{process}}$ falls from $6.32 \times 10^9$ to $0.28 \times 10^9$ grains. However, the acting single grain force rises from 2.5 mN to 46 mN.

Fig. 9: Influence of grain concentration and grain size.

As described before, the grain size (Fig. 9a) and the diamond grain concentration (Fig. 9b) influence the number of grains in the bond. The tendency that the roughness is influenced more with increasing grain size $d_g$ can be confirmed for both types of bond. In case of constant concentration, the grain size also affects the number of grains due to a constant diamond weight in the bond. If the grain size is constant (Fig. 9b), the roughness changes more if the grain concentration and the Young’s modulus rises. This confirms the effect of a higher number of grains. The ability to change the roughness is higher for the tool with polyurethane, which has higher bond stiffness/Young’s modulus (Table 1).

Fig. 10: Influence of single grain force $F_G$ and related parameters.
Table A.1: Symbols used in calculation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_c$</td>
<td>Edge length of one CE</td>
<td>$N_{II, \text{process}}$</td>
<td>Number of active grains in process (in area)</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Contact area</td>
<td>$N_{III, A} = \gamma_o$</td>
<td>Number of grains in bonding volume = grain density</td>
</tr>
<tr>
<td>$a_p$</td>
<td>Tool path distance</td>
<td>$N_{layer}$</td>
<td>Number of stacked layers in the tool bond height</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Area to be polished</td>
<td>$n_{path}$</td>
<td>Number of tool paths in area $A_p$</td>
</tr>
<tr>
<td>$C$</td>
<td>Grain concentration</td>
<td>$N_{process}$</td>
<td>Number of grains in complete process</td>
</tr>
<tr>
<td>$d_g$</td>
<td>Grain size</td>
<td>$n_{process}$</td>
<td>Number of tool rotations in complete process</td>
</tr>
<tr>
<td>$E$</td>
<td>Young's modulus</td>
<td>$t_{path}$</td>
<td>Time needed for one tool path</td>
</tr>
<tr>
<td>$F_G$</td>
<td>Active grain force</td>
<td>$t_{process}$</td>
<td>Process time</td>
</tr>
<tr>
<td>$F_N$</td>
<td>Normal force</td>
<td>$t_r$</td>
<td>Time needed for one tool rotation</td>
</tr>
<tr>
<td>$f_t$</td>
<td>Infeed</td>
<td>$V_{bond}$</td>
<td>Volume of bond</td>
</tr>
<tr>
<td>$h_p$</td>
<td>Height of polishing tool</td>
<td>$v_c$</td>
<td>Cutting speed</td>
</tr>
<tr>
<td>$l_p$</td>
<td>Length of area $A_p$</td>
<td>$V_{CE}$</td>
<td>Volume of one CE</td>
</tr>
<tr>
<td>$N_{CE}$</td>
<td>Number of CEs</td>
<td>$V_g$</td>
<td>Volume of grains</td>
</tr>
<tr>
<td>$N_{CE, \text{layer}}$</td>
<td>Number of CEs in the contacting surface layer</td>
<td>$v_f$</td>
<td>Feed rate</td>
</tr>
<tr>
<td>$N_{CE, \text{planes}}$</td>
<td>Number pf planes in one CE</td>
<td>$w_p$</td>
<td>Width of area $A_p$</td>
</tr>
<tr>
<td>$N_g, CE$</td>
<td>Number of grains in one CE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_g, \text{plane}$</td>
<td>Number of grains per CE plane</td>
<td>$\alpha$</td>
<td>Inclination angle</td>
</tr>
<tr>
<td>$N_g, \text{plane}$</td>
<td>Number of grains in one CE plane</td>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$N_{II, A}$</td>
<td>Number of active grains per area $a_g$ unit</td>
<td>$\mu$</td>
<td>Friction coefficient</td>
</tr>
<tr>
<td>$N_{II, Ac}$</td>
<td>Number of active grains in the contact area</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.2: Additional Abbreviations.

<table>
<thead>
<tr>
<th>Abb.</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE</td>
<td>Cube element</td>
<td>PVA</td>
<td>Grain type of Element Six Ltd.</td>
</tr>
<tr>
<td>FCC</td>
<td>Face centered cubic</td>
<td>RVM-N</td>
<td>Grain type of Diamond Innovations, Inc.</td>
</tr>
<tr>
<td>HCP</td>
<td>Hexagonal close packed</td>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

V. Conclusions

The application of ceramics in complex implants, e.g. knee joint implants, exhibits an altered stress situation compared to conventional implants made of steel and polyethylene. Ceramics can withstand these stresses owing to very high compressive strength. However, they break brittle under tensile loads. The mechanical characteristics of an implant are not only determined by design, but by flaws in the microstructure of the ceramic substrate. Chemical properties, different phases, microstructure and surface behaviour affect the prospects for selling an implant. These properties in turn are dependent on the manufacturing process, which is determined by the raw material, the sintering process and the particularly with the finish machining.

To achieve defined surface characteristics a polishing tool was needed to precisely machine free-formed ceramic implants. A polishing process with elastic tools that is able to meet the given requirements on surface finish and shape accuracy has been identified. To use elastic tools in automatic machining, the process know-how must be gained in order to estimate the needed surface finish. This know-how is based on the acting grain force and the number of active grains in process.
The results confirm the hypothesis that the increase of the single grain force results in the reduction of the surface roughness peaks while taking into account the bond characteristics. In case of higher forces, a single grain grabs easily into the material, smooths the roughness peaks and thus, roughness is refined. As shown in section IV (1) the number of grains shows a considerable influence on roughness, too. The influence of the cutting speed is not significant owing to an overlap with the bond characteristics. Decreasing feed rate and tool path distance, increasing grain concentration, rising infed and inclination angle lead to an improvement of the ceramic surface quality.

Now, a transfer of process knowledge from the small elastic polishing pins to larger, in actual machining processes usable tools must be carried out. There is enormous potential for the development of elastic polishing tools. For automated use as machine tools for the finishing of all-ceramic implants the following challenges have to be solved: wear detection and compensation, by e.g. force-controlled polishing, and the temperature stability of the bonds.

Acknowledgements

The investigations described in this paper have been conducted with the support of the German Research Foundation (DFG) within the framework of the collaborative research center CRC 599 “Sustainable Bioreabsorbable and Permanent Implants of Metallic and Ceramic Materials”.

References