

MODELING THE POLISHING PROCESS WITH RESILIENT DIAMOND TOOLS FOR MANUFACTURING OF COMPLEX SHAPED CERAMIC IMPLANTS

Berend Denkena¹, Jens Köhler¹, and Anke Turger¹
¹Institute of Production Engineering and Machine Tools,
 Leibniz Universität, Hannover, Germany

INTRODUCTION

Artificial joint implants create high demands on the manufacturing technology concerning surface quality and shape accuracy. With the application of brittle, hard, and wear resistant bioceramics (Al_2O_3 and ZrO_2) an increase in life span of hip implants up to more than 20 years could be achieved [1]. To get an economical process for more complex implants made from ceramic materials, e.g. a knee implant, new manufacturing strategies are required. Due to its material properties, grinding with diamond tools is the only way to machine oxide bioceramics with appropriate material removal rates [2]. To achieve high surface qualities, different precision machining processes were developed. Nonetheless, neither of these processes is appropriate for machining free form geometries such as knee implants; due to high influences on form accuracy [3].

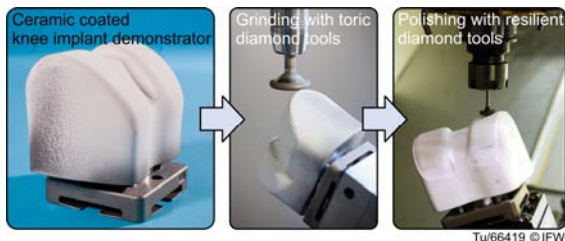


FIGURE 1. Developed processes for fully ceramic knee implants.

Therefore, a simplified process chain was developed which allows processing ceramic knee implants via one clamping on one machine tool (Figure 1). Firstly, the near net shape sintered and hiped ceramic body will be ground by toric diamond tools on a multi-axis machine tool to achieve high geometrical form accuracy [3]. In a second step, a resilient bond diamond tool is used to smoothen the roughness peaks of the ground surface. The tool path and force controlled polishing method keeps the influence on the shape accuracy at a minimum along with

lowest surface roughnesses ($S_a < 20 \text{ nm}$) (Figure 2).

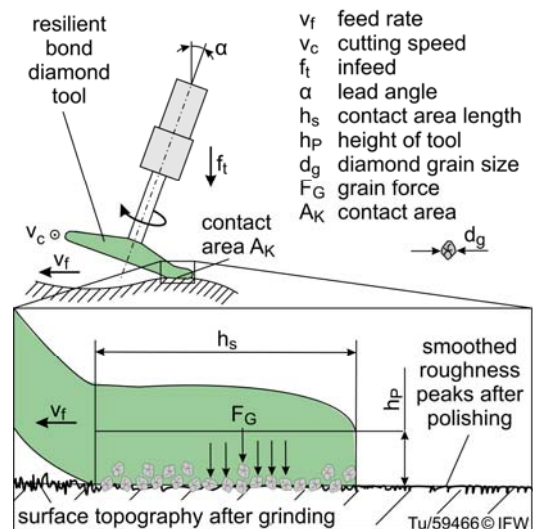


FIGURE 2. Geometric and kinematic parameters for the polishing process with resilient tools.

This paper follows up to the presented method from ASPE 2009 where the material removal mechanisms during polishing of ceramic as well as a basic modeling approach to determine the number of active grains were presented [4]. This approach is now expanded by calculation of the number of grains and verified by several experiments.

MODELLING THE POLISHING PROCESS

During polishing the removal of the roughness peaks depends on the number of grains N_{KP} sliding over a surface unit during a specific time unit and on the single grain force F_G (Figure 2). The number of active grains is governed by system parameters tool geometry and specification as well as process parameters feed rate v_f , cutting speed v_c , pressure/infeed f_t , tool path distance f_p and inclination α of the tool. All characters can be ascribed to the number of active grains and the grain force (Table 1, step 1). Assuming a regular grain distribution (2)

in the tool bonding and a contact area A_K between the tool and the surface the number of grains in the bonding volume over the supported area $N''_{KP,sec}$ can be calculated. Considering various grain distributions and grain shapes the number of active grains in the contact area N''_{KP} can be calculated (3). The model is specified by means of the process parameters cutting speed, tool path distance and the area which should be polished (4/5).

TABLE 1. Modeling steps.

	Parameter	Symbol	Description	Step
System parameter	concentration, grain volume, grain density	$N'''_{KP} = C_0$	grain density in bonding	(1)
	bonding vol., contact area, height of tool	$N''_{KP,sec}$	no. of grains in volume over supported area	(2)
	distribution, grain shape	$N''_{KP,A} / N''_{KP}$	no. of grains in contact area/ referred to area unit	(3)
Process parameter	cutting speed, feed rate	$N''_{KP,v}$	no. of grains per tool rotation	(4)
	path distance, polish area	$N''_{process}$	no. of grains polishing a spec. area in spec. time	(5)
	stiffness, number of grains (3)	F_G	single grain force	(6)
Work-piece	indentation depth and single grain force (6)	h_{cu}	chip thickness	(7)

The force acting in the contact zone can be determined by stiffness investigations. Using the number of active grains N''_{KP} and assuming that the normal force predominantly acts on the active grain contact, the single grain force F_G can then be calculated (6). The chip thickness can be determined by the material specific indentation depth (7).

MODEL VERIFICATION AND RESULTS

In order to develop a modeling approach to predict the material removal during the polishing process, the modeling steps 1-7 have to be verified. Conclusions about the grain distribution and shape (3) are evaluated by μ -CT (x-ray computer-tomography), SEM (scanning electron microscopy) and video-microscopy of the bonding structure (Figure 3). Figure 3a shows a voxel-based morphometry of the tool body. In contrast Figure 3b illustrates an x-ray photograph of the tool and its particles. The voxel-picture suggests a reinforcement of the diamond concentration C in the outside volumes of the bonding, especially for C200. A

quantification of the number of grains by the voxel-method is impossible due to low resolution of the μ CT ($15 \mu\text{m} - 20 \mu\text{m}$). However, the x-ray picture allows a nearly constant distribution of the grains. The percentage of white picture points increases with the number of grains (Figure 3b, bottom). The SEM- and video-photographs in Figure 3c and 3d were used to identify the grain shape of the diamond (type RVM-N, Diamond Innovations) and assign them to a calculable geometrical object. The typical, blocky grain can be matched to a double truncated pyramid.

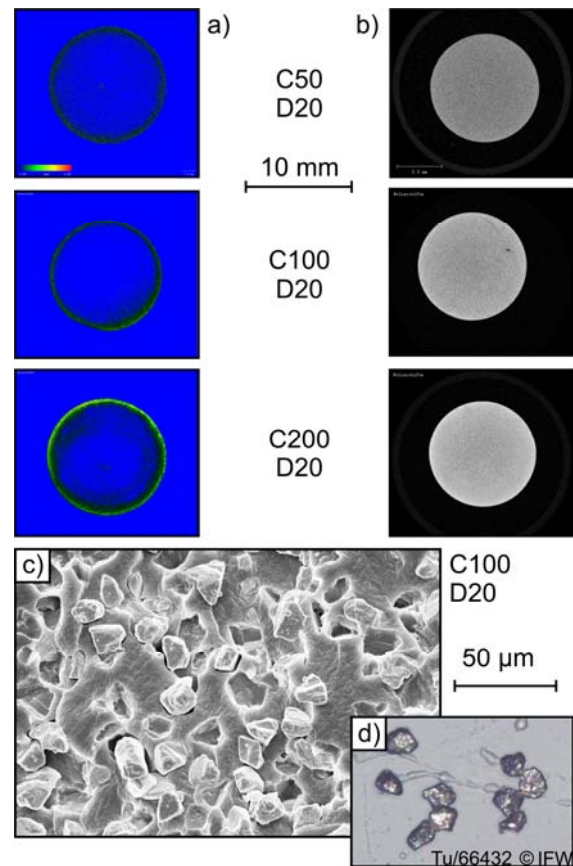


FIGURE 3. μ CT (a), x-ray (b), SEM (c) and video-microscope (d) of bonding structure and grain shape.

Assuming a regular distribution of the diamond grains, a predictable distribution structure has to be determined to describe the location of the grains in the bonding. This is required to calculate the number of grains $N''_{KP,A}$ (3). For this purpose, the crystal structures "cubic primitive lattice pcc", "body-centered cubic lattice bcc", "face-centered cubic lattice fcc", "cubic-diamond fcc" and the model by Yegenoglu [5] were compared. For each type of tool 108

surfaces of bonding with a size of 0.0625 mm^2 were counted by three different persons under video-microscope. Figure 4 shows the calculated and the counted numbers of grains. The best concurrence was found with “cubic-diamond fcc” structure and the double truncated pyramid.

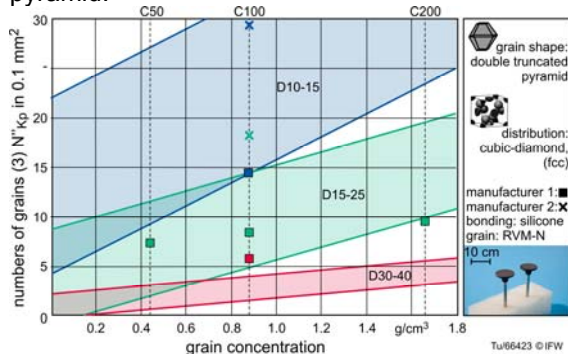


FIGURE 4. Number of grains in 0.1 mm^2 of bonding surface.

Furthermore, the knowledge of the resilience of the tools is required to estimate the single grain force during the polishing process. To evaluate the dynamic stiffness, a rotational cutting force dynamometer is applied to measure the normal force in process. The stiffness c is calculated by the quotient of force and change in length (f_t). The reciprocal $1/c$ is the resilience. In Figure 5 the resilience is plotted against variable diamond concentrations C , inclination angle α , and infeeds f_t . The lower the ratio of diamond, the more resilient is the tool and the smaller is the resulting single grain force F_G . The expected rise of the stiffness with the inclination could not be

confirmed. The differences are lower than 1 N and vary in the range of repeatability. In case of small infeeds f_t the high deviations can lead back to the increasing influence of the tool wear and the difficulty to detect the first tool-workpiece contact. It can be assumed that the stiffness depends significantly on the concentration and the grain size but not on the inclination of the tool.

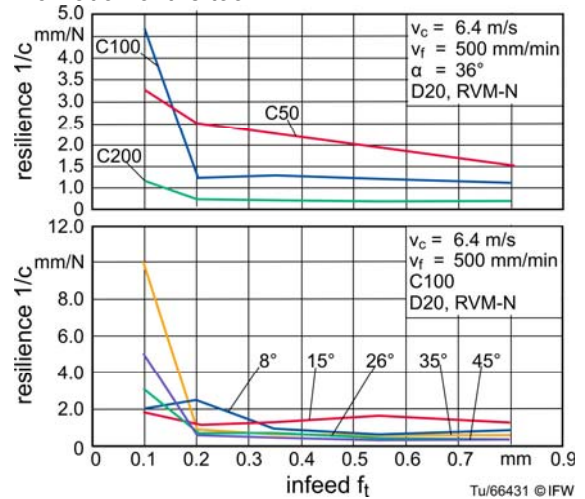
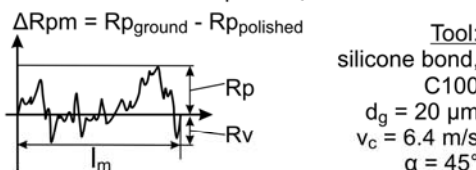


FIGURE 5. Resilience of polishing tools of different concentration and bonding.

Besides stiffness and contact area investigations, polishing experiments with variable tool specification (C , d_g , bonding) and different process parameter settings (v_c , v_f , f_t , f_p , α) have been carried out. Figure 6 shows the exemplarily influence of the feed rate v_f and the infeed f_t on the workpiece quality for a silicone

Roughness parameter:
 S_a EUR 15178N (RMS of 3D surface)
 R_{pm} DIN EN ISO 4287, ASME B46.1,
 mean of all profiles, cut-off 0.08 mm



Roughness modification by polishing:
 ground $S_a = 0.71 \text{ μm}$ polished $S_a = 0.37 \text{ μm}$

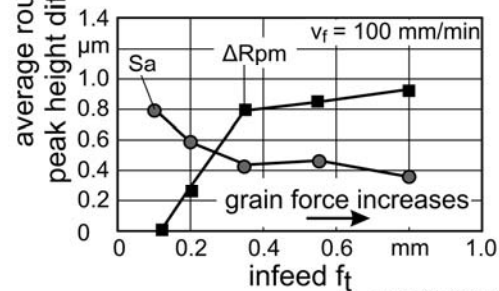
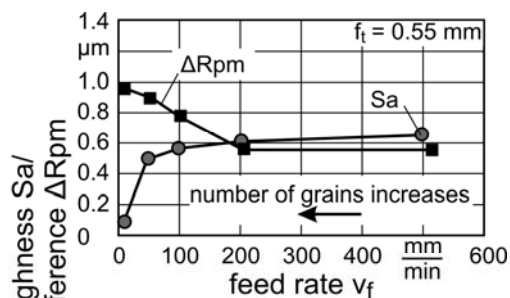
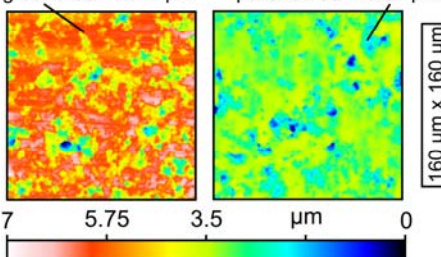


FIGURE 6. Surface roughness and peak height of polished surfaces for variable process parameter.

bond diamond tool with grain size D20 (15 - 25 μm) by concentration C100. This is described by the average surface roughness S_a and the reduction of roughness peaks (peak height R_p). The surfaces were measured by white light interferometry (μsurf , Nanofocus) and determined by EN15178 (S_a) and DIN EN 4287 (R_p).

In Figure 6 it turns out that the roughness S_a of polished surfaces decreases the slower the tool moves (low v_t) due to more grains sliding over the surface during a specific time unit. This also results in a higher peak height (ΔR_p). The situation is different with increasing infeed f_t of the tool to the surface (Figure 6, bottom). This mechanism can be described as follows. The more the tool is pressed onto the surface the higher the force which pushes the grains into the surface and the stronger the smoothing of the roughness peaks (Figure 7).

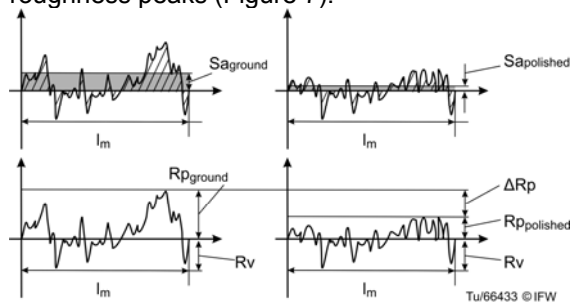


FIGURE 7. Change of roughness parameters during polishing process with resilient tools.

The results clearly indicate a relationship between the achievable roughness S_a , the number of active grains and the grain force. The roughness decreases progressively with an increasing number of diamond grains; while raising the single grain force. The influence of the grain force is 30 % lower than that of the number of grains due to very low process normal forces ($< 10 \text{ N}$).

CONCLUSION AND OUTLOOK

A theoretical model determining the active grains and the acting single grain force was developed. Thru polishing experiments, the resulting roughness has been evaluated. Further investigations will focus on the influence of the initial roughness after grinding, different bonding materials, the grain and pore size of the ceramic material, as well as the tool wear on the surface roughness to expand the process model. Prospectively, the impact of the grain force will be investigated by means of force controlled

scratch tests under real single grain loading to determine the single grain chip thickness during polishing. Finally, a complete process model to predict the surface quality after the grinding and polishing of ceramic knee implants will be generated.

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