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Procedia CIRP 78 (2018) 313–317

www.elsevier.com/locate/procedia

6th CIRP Global Web Conference
"Envisaging the future manufacturing, design, technologies and systems in innovation era"

Technological CAD/CAM chain for automated polishing of geometrically complex workpieces

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Abstract

Despite recent advances in automation technology, geometrically complex workpieces are still often finished manually. An example for this is the post-processing of dental prostheses, which display exceptionally high surface requirements. Aiming for an improved quality assurance, this article presents a methodology for an adaptive tool path planning for polishing of geometrically complex workpieces. For this purpose, the initial roughness of the workpiece is determined using a machine-integrated measuring system. Next, suitable process parameters are selected based on machine knowledge and the adapted NC code of the polishing process is generated and simulated. The results of the simulation and the actual polishing process are compared afterwards and transformed into process knowledge. Thus, the adaption of the process parameters and the quality of the simulation are continuously improved. The article highlights the implementation of the methodology with special emphasis on the selection of the process parameters.

Keywords: Polishing; Computer aided manufacturing (CAM); Machine learning

1. Introduction

Polishing is a part of the finishing process within the process chain of manufacturing products with high surface quality requirements. Depending on the application, various machining processes have been established. All processes aim to achieve high surface qualities by eliminating minor scratches and reducing the surface roughness of the machined part. Fields of application can therefore be found in various industrial sectors, such as in microelectronics, in tool and mold making or in manufacturing of optical components [1]. In addition, polishing is a common process in the medical industry. Here, load-bearing implants and joint implants as well as dental prostheses are polished using a wide variety of techniques and tools [2]. The polishing process is usually carried out with flexible tools. Due to their design, complex geometries can be machined very closely to the contour with small material removal.

Despite a trend towards intelligent machine tools and novel process planning concepts, finishing of complex parts, e.g. dental implants, is still done manually to meet the high surface requirements [3] (compare Fig. 1). Thus, polishing is time and cost-intensive. Moreover, polishing is often carried out in an iterative manner. The result of the polishing process depends on the tool, the process parameters, the workpiece contour to be machined and the expertise of the worker. Therefore, automated processes offer high potential to increase the economic

10.1016/j.procir.2018.09.049

efficiency of the polishing process as well as the stability of the product quality.

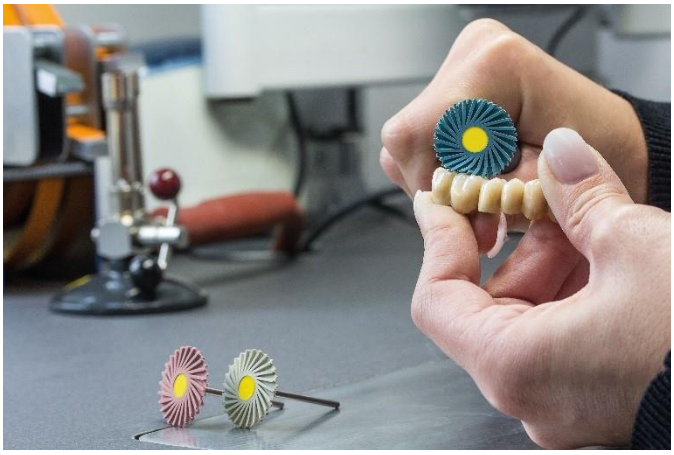

Fig. 1. Manual polishing with flexible polishing tools (EVE Ernst Vetter GmbH)

First approaches to automate the process using machine tools and robots can be found in the literature [4,5]. However, it becomes clear that the sense of touch and the experience of a technician are hard to substitute by a machine tool so far. Machine tools do not have sensors like human fingers that can adapt to the changing conditions of the polished surface. Process knowledge and experience is established over several years by technicians and usually not documented systematically. Consequently, there is a lack of machine-interpretable data about the influence of process parameters and the initial surface on the resulting surface quality after polishing, although some experimental studies were published in this area [6].

In order to imitate the sense of touch, some approaches use force control. Feng et al. developed an algorithm for planning a polishing process by controlling the contact force. Based on previously determined contact points of the tool and its inclination angle, the position angle of the tool with respect to the surface is calculated. The application of the algorithm on flat and curved surfaces shows that intensive shiny surfaces can be produced [7]. Chaves-Jacob et al. developed a force-controlled system for surface finishing with a polishing pen. It was determined experimentally that the radial engagement of the tool significantly influences the radial force to be controlled [8]. A different control approach was presented by Ahn et al. They showed that the surface roughness during mechanical polishing can be estimated indirectly from acoustic emission measurements. The experiments were performed with different diamond abrasive pads on a 5-axis polishing machine. The polishing sequence was modified online according to the monitored status [9]. Aiming to optimize the process planning of surface finishing by belt grinding of dies and molds, Tönshoff et al. investigated an algorithm to create tool paths automatically. The algorithm uses locally defined criteria to incrementally fill areas to be machined. Curvatures were also considered in the approach [10].

However, the mentioned studies consider the process conditions rather than the outcome for process control. In order to integrate the obtained surface quality into the control loop, sophisticated in-line measuring systems are required. With respect to polishing dental implants, the measuring system must be able to detect the workpiece contour as well as the topography. Moreover, the system should be easy to integrate into a machine tool.

Based on industrial requirements and the reviewed literature this article proposes a novel adaptive planning approach for polishing operations. The presented approach aims to fully integrate the polishing process into the CAD/CAM chain. The required technological knowledge is derived from a comparison of the expected and the actually achieved surface quality.

2. Conceptual design

Fig. 2 summarizes the concept of the presented approach. In order to automatically plan and execute tool paths for the polishing process, the workpiece surface is measured prior to machining. Based on the initial local roughness, a planning algorithm identifies the first processing steps for the different areas on the surface of the workpiece. Using a roughness model, appropriate process parameters for machining are selected depending on the current surface roughness. These processing steps are combined to a tool path including locally optimized process parameters. Subsequently, the planned process is tested in a machining simulation and transferred to the machine tool for the actual polishing operation.

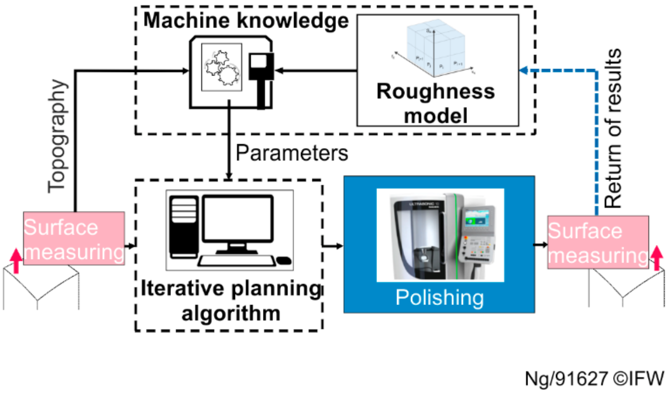

Fig. 2. Adaptive planning of the polishing process

The planning algorithm is embedded in a simulation environment for geometric process simulation developed at the IFW called IFW CutS [11]. The software uses a dexel model, which allows a geometric assessment of the tool path and, thus, the interaction of the tool and the workpiece. In combination with empirical models, the prognosis of technology-based aspects, like the surface roughness, is possible [12]. In order to estimate the roughness after the polishing process the initial local roughness and the corresponding cutting conditions are required. For that purpose, the initial roughness is stored in the dexel's structure and the cutting conditions are calculated by the geometric process simulation.

After machining the achieved roughness is measured again and compared to the simulated roughness. The result is fed back into the planning algorithm and an additional polishing step is planned, if the measured roughness does not agree with the aimed roughness. Consequently, the entire system is able to adapt the process parameters to the current situation and an iterative processing is initiated automatically.

Since the quality of the planned process and the number of required processing steps depends strongly on the accuracy of the roughness model, the proposed concept includes a feedback loop for updating the empirical model based on the actual process results. Thereby it is possible to establish a self-learning roughness model for continuous improvement of the polishing process.

3. Implementation of the adaptive planning process

3.1. Modelling of the surface roughness

Aiming to identify a suitable roughness model, an experimental study on polishing of flat surfaces was conducted. Different two-dimensional roughness parameters were measured (Ra, Rq, Rmax and Rz as standard roughness parameters; Rp and Rv to consider the peaks and valleys separately; Rk, Rpk and Rvk to examine the shape of the surface profile more closely) [13]. It was found that Ra is best suited due to its low scattering. For the subsequent evaluation, the roughness difference between the measured roughness after the polishing process and the initial roughness of the sample before the polishing process was calculated. The tests were carried out on ground brass since it exhibits a similar machinability with respect to polishing than that of materials such as gold or some stainless steel alloys used in the dental sector.

In order to limit the number of parameters to the polishing process, the main influencing variables were determined in the first step. For that purpose, a screening experimental design was carried out to identify which of these parameters had a significant effect on the roughness of the surface. Two stages were defined for each parameter: For the feed velocity v_f = 100 mm/min and v_f = 600 mm/min, for the cutting speed v_c = 5 m/s and v_c = 15 m/s, for the inclination angle α = 30° and α = 60°, for the depth of cut f_t = 0.5 mm and f_t = 2 mm.

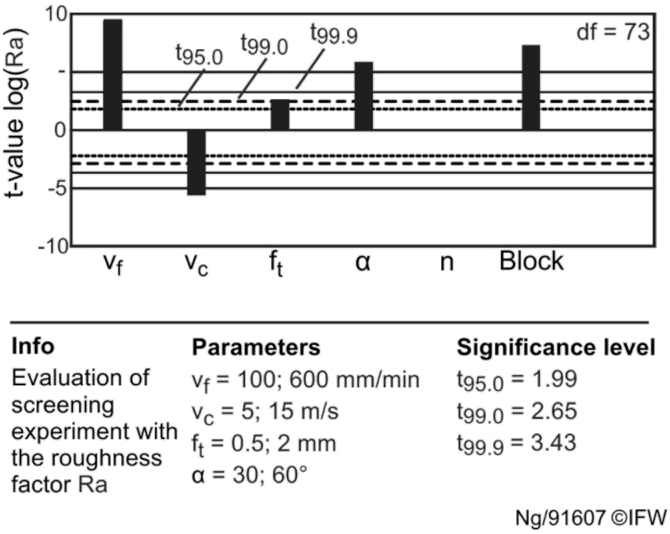

Fig. 3. Effect diagram of the screening experiment for Ra

The variable n is the number of times polished over the same spot, which were considered here for one and three times. Block is the effect of using different polishing tools of the same type, whereby two tools were used in one run. With df the degree of freedom for linear regression models is represented. The experiments were repeated up to three times.

Fig. 3 summarizes the identified effects for the roughness parameter Ra. In following, those parameters that exceed the confidence level of 99% were considered significant. Over all roughness measures, the screening experiment showed that the feed velocity and the cutting speed were significant parameters. The inclination angle and the depth of cut were also significant for some, but not all roughness parameters, e.g. both parameters did not affect Rmax and Rv substantially. Further, the depth of cut had no significant effect on Rq and Rz.

Based on the results, further experiments were carried out to define a suitable roughness function. For this purpose, a centrally composed experimental design was used to determine the quantitative dependence between the main influencing parameters and the roughness in detail. The experiments showed that process combinations of a low feed velocity, a high cutting speed and a high depth of cut lead to a strong levelling of roughness peaks. However, a roughness function could not be determined due to the strong scattering of the measurement results. Difficulties arose due to the inconsistent behavior of the polishing tool, whose wear condition influences the result. Instead of a roughness function, discrete polishing cases were therefore selected. The process parameters leading to a high, medium and low reduction of the roughness are summarized in Table 1. The parameter Δ Ra represents the difference between the Ra before and after polishing.

Table 1. Parameters of the polishing cases.

Polishing case	v_f [mm/min]	v_c [m/s]	f_t [mm]	α [°]	Δ Ra [µm]
High	50	15	2	30	-0,24
Medium	150	15	2	30	-0,11
Low	450	15	2	30	-0,07

3.2. Roughness measurement and workpiece representation

The in-line measuring was carried out with a system by Akcurate (Crocodile S2), which allows to determine the roughness as well as the topography. A chromatic-confocal distance measurement sensor was used to record measurement data at different speeds and measuring frequencies. The data sets indicate not only the local surface roughness but also the position and orientation of the individual measurement points.

In order to consider the initial roughness in the simulation of the polishing process, it is necessary to implement the roughness measurements, which are available in CSV format, into the workpiece model. For that purpose, the roughness values are stored in the dexel's extender of the workpiece model. Thus, a certain roughness value can be assigned to each dexel of the workpiece. This approach is well suited for the polishing process, because the contour does not change significantly in this process. Fig. 4 shows an example of a point cloud of a measured surface in IFW CutS. The differently colored points represent the different roughness values in the extenders.

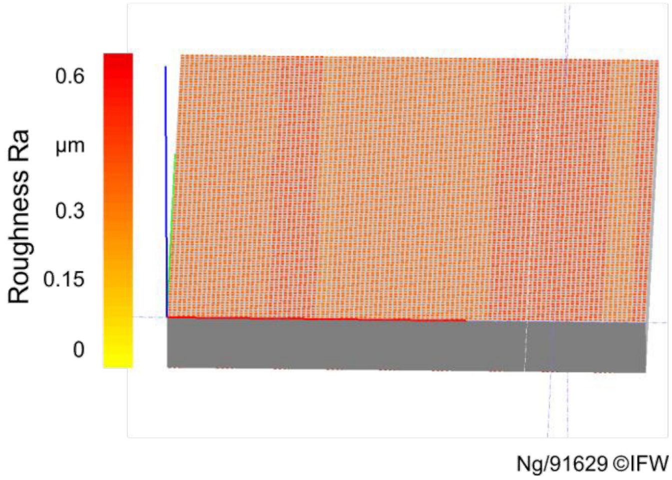

Fig. 4. Roughness representation in IFW CutS

3.3. Simulation of the polishing process

Fig. 5 summarizes the procedure for adapting the NC code. A challenge arising for the application is the modelling and mapping of the flexible polishing tool in the simulation, because the penetrated positions from the simulation are not equal to those in reality. This can be explained by the flexible behavior of the tool, which is not accounted for in the simulation. One possibility for taking this into account is to consider the width of the resulting path of the polishing process in the simulation model. This was chosen as the approach for process planning at the plane.

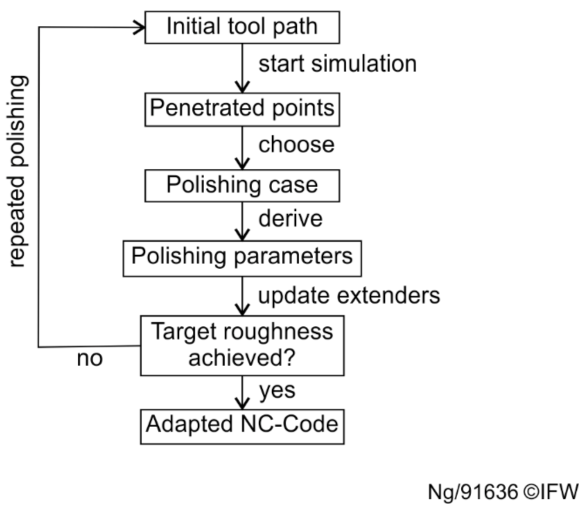

Fig. 5. Flow chart of generating an adapted NC code for the polishing process

At the beginning of each simulation step, the penetrated points are determined and stored in a list. The list represents the points of the workpiece that are potentially changed in the simulation step. The mean roughness of the listed points determines which polishing case is chosen (compare section 3.1). Next, the distance from the tool center point (TCP) to each point penetrated by the tool is calculated. This step is necessary to consider just the points, which are affected in the step of the polishing process. The points in the simulation that are within this experimentally determined range are modified according to the roughness model. The new roughness values are stored again in the extender of the respective dexels.

3.4. Toolpath generation and local adaptation of the NC code

The toolpath generation starts with an initial tool path that consists of parallel straight paths next to each other. The distance between two paths corresponds to half of the polishing width. Thus, the entire surface of the workpiece is covered. Next, a simulation run with the initial tool path is conducted. In the simulation, the individual points of the workpiece are penetrated by the tool, whereby the conceivable polished areas are detected (compare section 3.3). The locally measured roughness values stored in the extenders are read out at the points penetrated by the tool. Based on these values the polishing parameters are selected according to the aforementioned polishing cases (compare section 3.1). The polishing case with the highest roughness reduction will be selected if the roughness value is still high. For example, if the roughness value is close to the target roughness value, a polishing case will be selected which leads to a smaller reduction of the roughness. The roughness value is also adjusted in the extenders and the resulting width of the polished path for this polishing case is taken from the contact surface model. The resulting change of the polished part represent through the changing roughness values extenders of the simulation can be seen in Fig. 6.

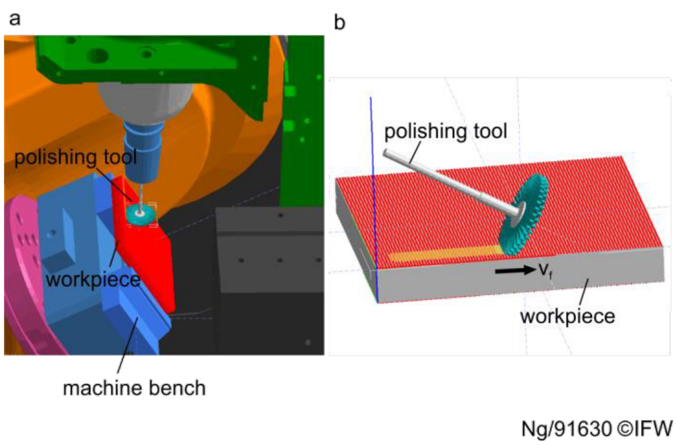

Fig. 6. Simulation of the polishing process in IFW CutS
(a) machining view; (b) detail process view

The NC code is then adapted with the selected parameters at the respective points. After completing the initial toolpath in the simulation, the complete initial NC code is generated based on the measured roughness on the workpiece. It is also taken into account if the target roughness has not yet been achieved during the first run. The planning algorithm generates the adapted NC code in such a way that it is repeatedly polished over the points at which the target roughness has not yet been reached. In a first test application for adapting the NC code on a flat surface, only the feed velocity was adjusted, since it has shown the highest effect on the roughness according to the screening experiment. In addition, the contact surface is kept constant by a firmly selected depth of cut and inclination angle.

After machining, the roughness is measured again and fed back into the planning algorithm. It is examined whether the target roughness is achieved yet or not. If it is still necessary to polish, the planning algorithm will start again from the beginning and the local adaption of the process parameters to the current situation will be executed. The iterative procedure of the polishing process will be validated experimentally in future research. In addition, it is planned to set up a database to store the results of both the simulation and the machine-polished surface roughness. Based on this data a machine learning model will improve continuously the roughness model and adjust the process parameters for the next polishing step.

4. Conclusion and outlook

This article presented an adaptive planning process for polishing. The approach contains in-line measurements of the surface roughness before and after machining, a dexel-based material removal simulation and a roughness model. Based on the measured surface roughness an initial tool path is derived and the corresponding process parameters are identified using the established roughness model. Within this study it was found that the cutting speed and the feed rate have the highest effect on the roughness. However, it was not possible to model the roughness as a function of these parameters due to the high variance of the process outcome. Instead, classes were defined to select suited process parameters. After the workpiece has been polished for the first time, it is measured again and the machine-polished surface is compared with the result of the simulation. This feedback enables the system to adjust the process parameters and to continuously improve the polishing process. Because the system learns from experience, it can process increasingly complex workpieces and meet the high surface requirements. The vision is to be able to process even unknown geometries automatically on this basis.

In future research it is planned to test the iterative behavior of the system. Moreover, the implementation of the feedback and the development of the knowledge database is intended. A self-optimizing roughness model using machine learning methods will be developed to take a step towards polishing of free-form surfaces.

Acknowledgements

These investigations were funded by the German Federal Ministry of Economics and Energy (ZF4078502) and carried out in cooperation with the companies Akcurate GmbH and EVE Ernst Vetter GmbH. The authors thank our cooperation partners for their support in the project.

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