Modern Machining Processes for the Manufacturing of Screw Machine Components

Priv.-Doz. Dr.-Ing. Dipl.-Inform. Andreas Zabel, Institute of Machining Technology (ISF), TU Dortmund University, Dortmund

Abstract

This contribution covers different modern machining processes, namely milling and grinding/polishing, which can be applied to the manufacturing of screw machine components in order to achieve high quality parts in an efficient manner. The first process discussed is simulation based five-axis milling for the generation of complex free-formed surfaces. Here it is shown that nearly arbitrary geometries can be milled. The second part deals with NC-based free-form grinding processes and their application to coated and uncoated surfaces. Then some new developments with respect to the cutting of difficult to machine workpiece materials, such as special steel alloys are presented. Here the question of machinability and process efficiency arises as these materials are well-suited for application in screw machines. At the end of the paper, micromilling processes that add specific structures to workpiece surfaces in order to fulfil functional purposes are proposed and finally polishing steps, carried out by flexible grinding wheels in order to achieve very high surface qualities are addressed.

Simulation based milling of free formed surfaces

Screw rotor machines are used in various industrial applications due to their capability to work with different kinds of fluids like gases, fluids or multi-phase mixtures. Their deployment ranges from super chargers in automobiles, heat pumps or air compressors to extruder barrels [1]. The essential parts of the machines are the male and female screw rotors that are significant for the performance and endurance. The key factor is the clearance between both rotors. To attain the best performance, it is necessary to keep the sealing gap as low as possible but high enough to retain sufficient clearance during high loads [2]. Therefore the production of the free-formed rotor-surfaces need to attain low deviations for the designed contour. Complex surfaces and high tolerances need to be machined with special tools and additional finishing processes which usually cause high production times and costs. In most cases the rotors are cast to a preform with rough tolerances and subsequently machined to the desired final shape by conventional milling and grinding processes [3]. The machining is mostly done using shaped milling cutters and grinding wheels and is performed on gear cutting or hobbing machines to achieve a fast and economic series production. For very large screw rotors and small batches or prototypes multi-axis CNC-milling processes are employed because of their high flexibility.

The standard processes and machines are not capable of manufacturing screw rotors with variable pitch or similar special geometries, so the use of five axis milling processes with ball- and torus-cutters becomes necessary. When it comes to complex shapes with free formed surfaces, like the surface of the rotors, CAM-Systems (Computer Aided Manufacturing) are used to generate the NC-paths based on different available five axis cycles. Depending on the details of the workpiece geometry and the required form accuracy, roughing, pre-finishing and finishing operations with different tool geometries, cutting depths and path distances are employed (Fig 1).

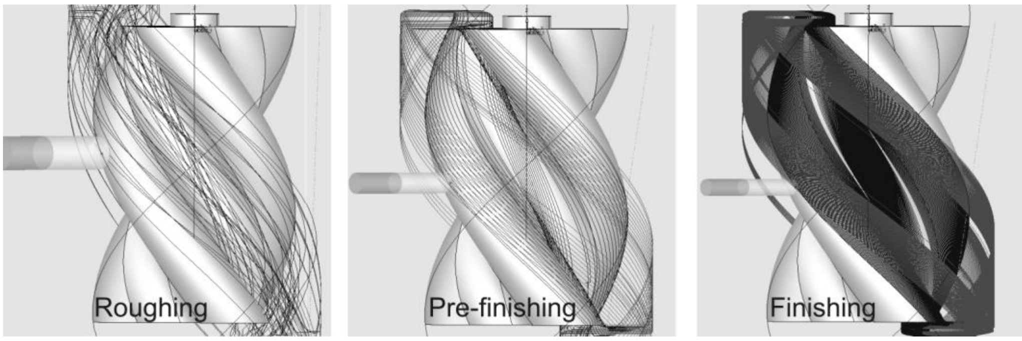

Fig. 1: Disparity of generated NC-paths for different operation steps

Most of the modern CAM-systems have integrated material removal simulations which use geometrical models like Dexel or CSG (Constructive Solid Geometry) to detect and avoid collisions and in some cases to estimate the tool load and engagement conditions for a feed rate optimization. An extension of the simulation systems includes the kinematics of the machine tools into the collision detection algorithm to achieve a better process reliability. For a more detailed simulation of the real process it is required to integrate the kinematics of the machine tool e. g. the acceleration of the machine axes and especially the behaviour of the NC-controller to calculate the motion of each machine axis and the current feed along the programmed tool path resulting from limitations imposed by the controller and the feed-drives. These features can be used in a Virtual Machine which is based on the original setup and behaviour of the original machine tool. In addition to e. g. collision detection the run-time of the milling processes can be calculated very precisely, including for example the tool changes, which is important e. g. to benchmark different machining strategies and to support process planning and optimization (Fig 2).

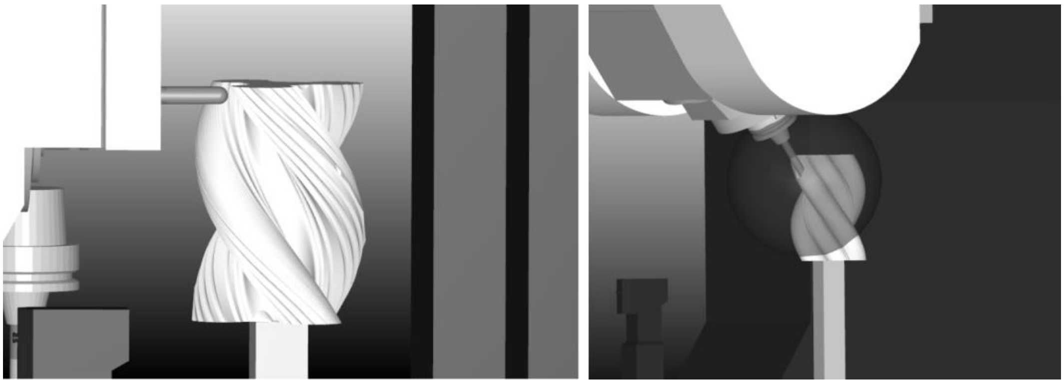

Fig. 2: Virtual Machine with removed material (left) and detected surface collision (right)

While these CAM- or virtual machine-based simulation systems cover a variety of geometric process features of milling processes it cannot detect effects like chatter or tool deflections because they lack a detailed and efficient material removal simulation at cutting edge level and an appropriate cutting force model. In the Institute of Machining Technology (ISF) an efficient geometric-physical milling simulation based on dexel- and CSG-models has been developed. The cutting operation between tool and workpiece is modelled for each tooth feed along the NC-path with high geometric accuracy and high resolution in time, so that the engagement conditions can be fed into a cutting force model. For simulating the dynamic behaviour of the tool, the machine tool and the spindle system experimental parameters (modal mass, damping, and eigenfrequency) need to be determined precedently and are interpolated by a set of uncoupled harmonic oscillators to allow for a fast, mathematical efficient integration into the simulation system. The updated tool deflection can be simulated by calculating the cutting forces for each simulated time step and apply them to the dynamic model of the milling tool at the current deflection state. The deflected tool positions are used for modelling the chip shape and to calculate the process forces instead of the original NC positions to incorporate the complete dynamic behaviour along the tool path [4].

NC grinding of sculptured surfaces

For the grinding of screw rotors shaped cubic boron nitride (CBN) grinding wheels are commonly used [5]. These tools provide high shape accuracy and wear resistance which allows the grinding of complete screw rotors without intermittent dressing processes. Additionally, an excellent grinding performance can be achieved without defects like burn or cracks in the surface [6]. In comparison to the conventional profile grinding of 2D-extruded screw rotor profiles, NC grinding on machining centres using abrasive mounted points enables the machinability of irregular free formed surfaces [7]. Using the five-axis-grinding process workpieces with multiple curved surfaces like forming dies, turbine blades or knee implants can be machined [8] and this process is also applicable to the rotors of screw machines.

The process kinematics of NC grinding using spherically shaped mounted points for the machining of wear-resistant coated forming tools is shown in Fig. 3. Tungsten carbide in a cobalt matrix, deposited by means of a high velocity oxy-fuel (HVOF) flame spraying process, was applied in order to increase the lifetime of the deep drawing tool. Due to the inhomogeneous coating thickness and the high surface roughness after the spraying process, the coatings have to be machined prior to their industrial application. As a result of the small contact zone between grinding tool and workpiece surface the process forces and the thermal load remain at a low level. In order to reduce the machining time, the shape of the grinding tools can be adjusted to the curvature of the workpiece by the dressing process.

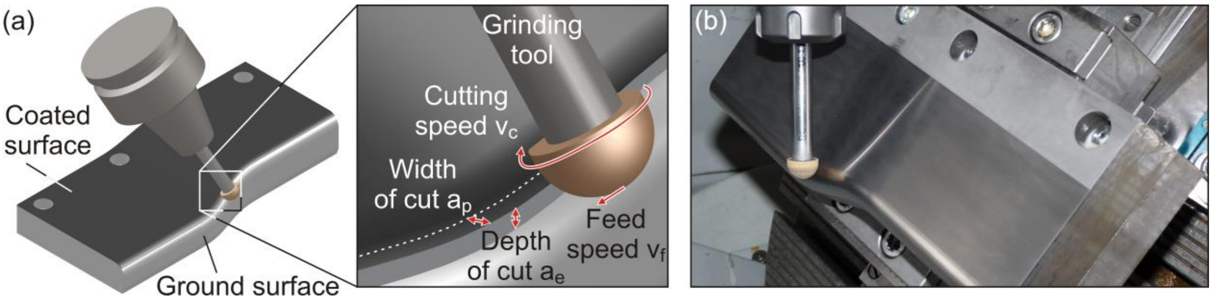

Fig. 3: NC grinding on machining centres using spherically shaped mounted points. (a) Process kinematics and (b) picture of the grinding process

The NC grinding process can also be used to generate good surface qualities and to achieve high shape accuracy of free formed surfaces of screw rotors without using new profiled grinding wheels. Hence, this process is mainly recommended for prototyping because of the relatively long machining time. The material usually used for the production of such rotor workpieces poses no further challenges to the machining process. The application of cavitation wear-resistant coatings might be also a suitable solution to increase the life time of screw rotors. In analogy to the milling process, the NC paths for the grinding process can be generated by using the same CAM-systems under the assumption of ball- or torus end-mills.

Machining of difficult to cut materials

Besides the general process design, a focus has to be placed on the workpiece material. Screw rotors often are made of high-alloy steel. Especially for cases of application where the components are exposed to a corrosive environment, stainless steels are used [9]. Alongside their high resistance against chemicals and corrosion resulting from a self-induced passivation layer, versatile mechanical properties can be named as advantages. This leads to a widespread use of stainless steels which even outperforms the usage of plastics [10]. By using varying alloy compositions, different microstructures can be obtained. These cause varying mechanical, physical and corrosion-preventing material properties. Thus, stainless steels can be directly adapted to requirements arising from different areas of application. Besides those advantages, machining of stainless steels can represent a major challenge. The tendencies to strain-hardening, adhesion of workpiece material on the tools or low ductility are examples of such challenges for machining stainless steels. For cutting, a high tendency the formation of a built-up edge and a low heat conductivity can also have a negative impact. Due to these different problems arising from varying material properties, universal recommendations for machining of stainless steels cannot be made. The cutting process has to be designed depending on the material to deduce machining parameters under consideration of the aspects productivity and workpiece quality. Extensive experiments conducted at the Institute of Machining Technology for miscellaneous machining operations showed that due to the microstructure of stainless steels, different tool lifetimes result. For identical microstructures, an impact of the alloys and mechanical properties on the highest possible material removal rate was observed (Fig. 4).

The tests have shown that machining processes need to be designed specifically for the material to be cut and this applies in particular to machining of new steel grades. High strength steels with a bainitic microstructure can be mentioned as an innovative material for manufacturing hydraulic components and screw machine rotors also. Bainite is a microstructure that can be obtained by isothermal transformation in a temperature range between those of martensitic and perlitic transformation. This microstructure is characterised by a high strength in combination with favourable ductility values and can therefore be used for components exposed to high pressures and with long component lifetimes. For machining high strength steels, a considerable influence on the process behaviour and the resulting workpieces are expected. Comparative tests with a quenched and tempered steel used for similar applications showed a higher tool load over cutting time when machining the bainitic steel and therefore a clear reduction of the tool life time (Fig. 4). Based on the comparative tests conducted a tool optimisation was executed, which led to a comparable tool life time when machining the high strength bainitic steel without the loss of productivity [11]. In summary it can be said that the material chosen for manufacturing hydraulic components has a significant influence on the machining process and thereby on economic efficiency of the complete production process.

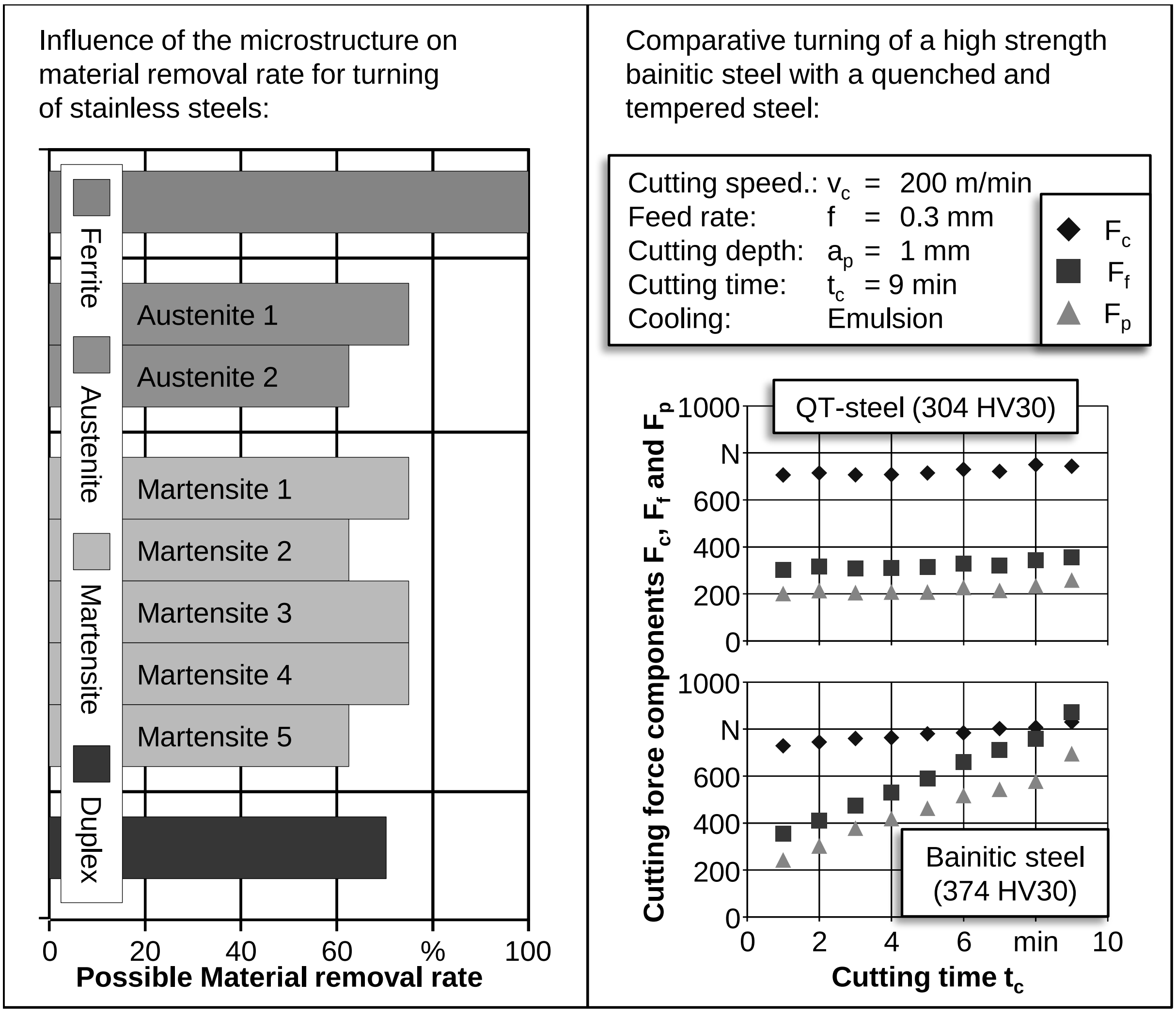

Fig. 4: Examples of material influence for machining of difficult to cut steels (F_c=cutting force, F_f=feed force, F_p=passive force)

Structuring of free formed surfaces

In general, the aim of the manufacturing process is to get the best surface quality that means the lowest possible roughness values, which may involve the additional grinding or polishing operations. An alternative approach can be to produce a specific surface structure with positive properties during the milling process (s. above). Nature shows that specific structures can lead to essential advantages in fauna and flora. Due to evolutionary processes, forms of life adapted to their environment, perfectly. One example is a sandfish (Fig. 5 a). This reptile, which is to be found in the Sahara desert, has developed its scales to minimize friction and abrasion during movements in the sand [12]. The sand flows like water over the skin of this reptile, making its movement similar to a fish movement in the water. The structures of the sandfish are shown in Fig. 5 b. Another example is the skin of a shark (Fig. 5 c). Inspired by this structure, NASA Riblets and DLR Riblets (German Centre for Aerospace - Deutsches Zentrum für Luft- und Raumfahrt) (Fig. 5 d) were developed and successfully tested [13, 14]. The structures of the shark and also the Riblet structures are arranged parallel to the flow direction of the water and prevent the formation of turbulent flows at a high movement speed. According to the research at the Institute of Propulsion Technology in Berlin, the results show that using a Riblet structure a reduction of frictional resistance of 10 % can be achieved compared to the non-textured surfaces [15], and this might also be an interesting application for screw rotors.

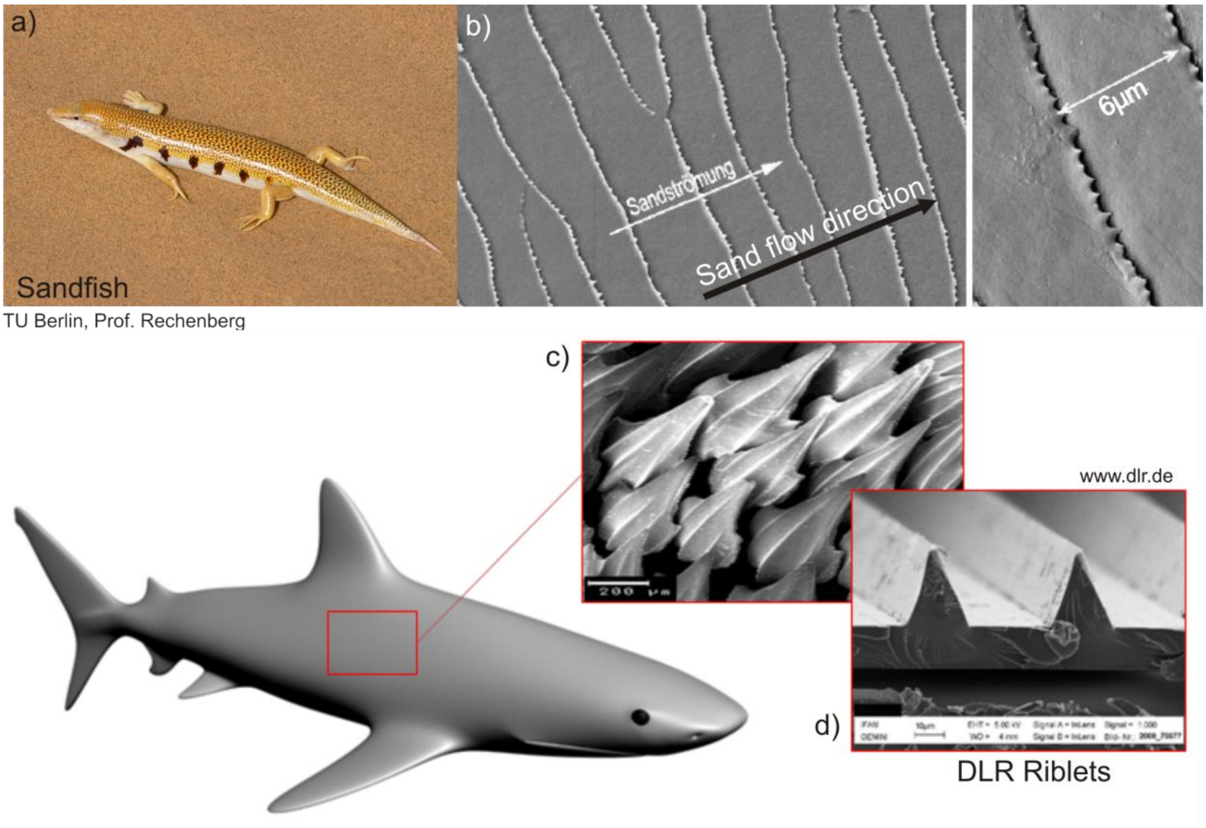

Fig. 5: Scanning electron microscope recordings of sandfish skin (b) [12], sharp skin structures and the DLR Riblets [15]

At the ISF the manufacturing of such surface structures using milling processes is investigated. The aim of current projects in the DFG supported TR73 is e.g. the manufacturing surface structures on forming tools to influence the friction behavior and also the material flow [16]. For this purpose, further developments were achieved in the micromilling of hardened tool steels (> 60 HRC). Now, complex structures, even in the field of bionics, can be produced process-reliably using tool with diameters down to d = 0.2 mm. Based on the results of a detailed analysis of the machining process, suitable cutting parameters, tool configurations and process conditions can be defined, which enable a high manufacturing quality and a rework-free production with roughness values down to $R_a = 0.04$ when milling the aforementioned difficult to machine materials. In addition, structures can be locally manufactured on free-formed surfaces. Fig. 6 shows an example of some manufactured surface structures of a Scarab beetle and a Dung Beetle [17]. As it can be seen, the quality of these structures is on a very high level. Before such structures can be produced, first, the real structures from the beetles had to be analyzed. After that 3D CAD models can be constructed for the purpose of NC-paths calculation in a CAM system. According to the description in the above paragraph on simulation based milling, the NC program for surface structuring can be calculated at the same step of the overall procedure. If the machining center fulfils the requirements of the structuring process, i.e. a high production accuracy and acceleration of machine tools axes, the production of complete components with surface structures can be accomplished in one setup.

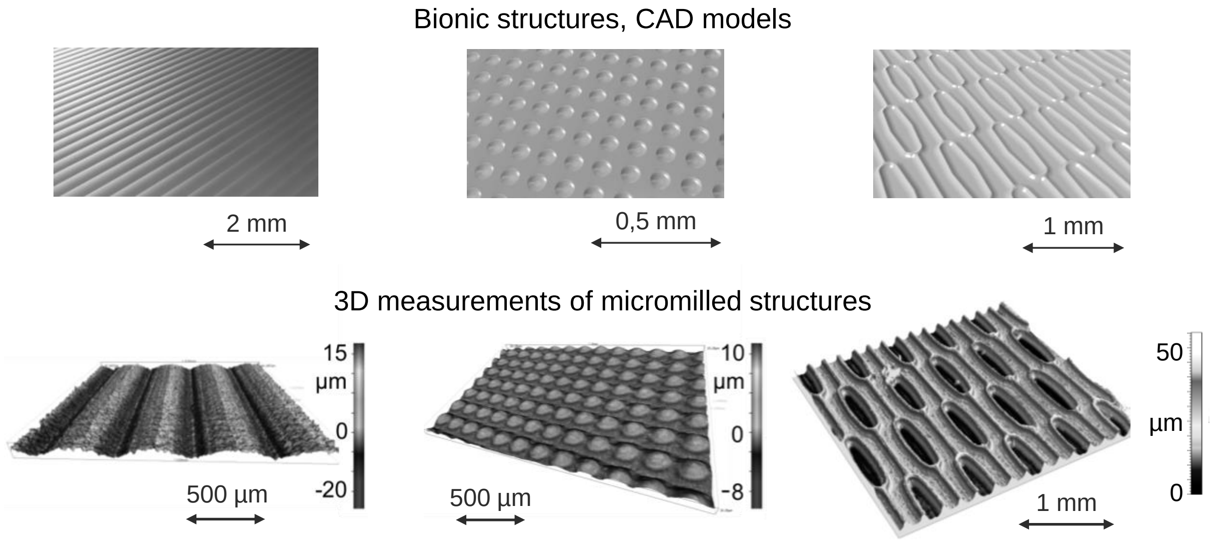

Fig. 6: Overview of some CAD models and machined surfaces from bionic structures (beetles)

With the regard to productivity, so called technological functional surface structures have also been developed. These structures are optimized concerning the micromilling process which allows producing 1000 structures in about six minutes. Despite the amazing results, the research and development of structuring different surfaces with the micromilling process is still at the beginning but there is a large potential for the application of such structures on the surfaces of screw machine rotors.

Polishing with flexible bonded grinding wheels

For the polishing of complex shaped surfaces such as screw rotors or flutes of cutting tools only few methods are available. A very effective and efficient way for processing such surfaces is the use of flexible bonded diamond grinding wheels. Within the available literature there are to date only a few sources that deal with the behavior of elastic bondend grinding wheels. Kacalak and Pluta were the first who dealt in their work with grinding wheels in porous polyurethane or rubber bond. They found out that these grinding wheels provide an effective way of smoothing flat and complex workpiece surfaces [18]. In the recent past, this process is advancing more and more for the finishing of steel materials and high precision glass surfaces as well. In addition to these classical applications, an attempt is made in using the elastic bonded grinding wheels to deal with complex surfaces, such as the flutes of solid carbide cutting tools in order to improve the surface quality significantly. The kinematics of the chip flute grinding process for cutting tool are in general similar to those which are applied in grinding of screw rotors. Fig. 7 shows the result of the polishing process for drill flutes.

Fig. 7: Comparison between ground and polished drill flute of a solid carbide tool

Especially for the machining of screw rotors, this method offers possibilities due to the flexible application. Moreover the processing result can be controlled be the specification of the grinding wheel as well as the process parameters. Other advantages that distinguish this method ate the universal applicability in different types of machine tools and the low investment costs. Due to their specific behavior during the machining process flexible bonded grinding wheels with different abrasive grains offer great opportunities to polish screw rotor surfaces. Depending on the hardness of the flexible bond the grinding wheel has the possibility to adapt to the component surface and thus generating a uniformly result with very good roughness values. Additionally polishing with flexible bonded grinding wheels is a process step which can enhance the workpiece quality and thus the durability of the screw rotor.

Conclusion and Outlook

The paper gives a brief overview on different modern machining processes which are or which can potentially be applied for the manufacturing of screw machine components, especially the rotors. The processes offer a great potential for the increase of productivity, the improvement of the rotor's lifetime and the performance of screw machines using the possibilities provides by the machining processes.

Future work should concentrate on the transformation of the already well-developed machining processes shown in the paper to the field of application of screw machines. Here the specific materials and geometries have to be considered.

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