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Abrasive finishing of surface structures with diamond-coated foams

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A B S T R A C T

Finishing of structured surfaces is a challenging task in the manufacturing of functional surfaces. This is due to the aim of reducing the overlaying surface roughness while preserving the general surface structure. Therefore, there is the need for tailored tool concepts concerning the abrasive finishing. In this case, diamond-coated foams are used for the application of finishing surfaces, structured by high-feed milling. The quantitative evaluation by means of area-based roughness parameters and the qualitative observation of the changes in the surface profiles emphasise the capability to smoothen the surface without affecting the functional structure.

1. Introduction and motivation

The properties of functional surfaces are of decisive importance concerning the functionality and wear behaviour of highly loaded components. Thus, tailored surfaces, for instance those defined by specific structures, are a central element concerning the design of complex components such as forming [1] or cutting tools [2]. Moreover, surface structures are used to adjust the tribological properties in diverse contact situations [3]. Besides the different functions of structured surfaces, there are various manufacturing processes for the structuring process [4]. Using the example of forming tools for sheet-bulk metal forming, which has been chosen as the example application for the research conducted with regard to abrasive finishing, the aim of using structured surfaces is to control the material flow [1]. These surface structures can be machined by high-feed milling processes [1]. In contact, the components show a running-in behaviour with a slight alteration of the surface topography [5]. Moreover, the high-feed milling process can lead to surface imperfections such as micro burrs. Those imperfections may cause negative effects on the functional properties of the components [6]. Additionally, a finished surface topography can be advantageous for a subsequent coating of the surfaces [7]. For these reasons, the necessity of finishing operations for structured surfaces is motivated. In order to prepare structured surfaces, finishing operations are required, which are capable of reducing the surface roughness and imperfections without affecting the functional structure.

Abrasive finishing techniques can be divided with regard to bonded and unbonded grains [8]. The use of bonded abrasives for finishing tools allows a local surface preparation and can be realised on common machine tools [9]. Moreover, flexible and compliant abrasive tools show the ability to adapt to the shape of surfaces [10]. This is a key requirement for the finishing of structured surfaces with fixed abrasives. Thus, flexible and soft tools, such as diamond-coated foams, are promising for the application of finishing surface structures.

Cho et al. introduce a tool concept in which the abrasives are fixed to a polyurethane elastomer main body by means of an adhesive [11]. With respect to the finishing of freeform surfaces, *Zhu* et al. examine the shape adaptive grinding with compliant grinding tools, which have a tool body consisting of solid rubber [12]. The finishing of surfaces with specific grooves using a polishing process with loose abrasives is investigated by *Brinksmeier et al.* In this context, tools with a specific shape are used [13].

In this research work, the finishing of structured surfaces using mounted points with diamond-coated foams is investigated. The aim is to utilise the elastic deformability of the abrasive layer in order to realise a sensitive finishing of milled surface structures using a basic cylindrical tool geometry. With regard to future applications, the surface topography should be modified according to the running-in behaviour [5] in order to decrease the initial wear. Hence, the surface topography and shape modification of the structure depending on the process variables and tool specifications are the focus of the research conducted.

2. Experimental setup

For the finishing of structured surfaces, mounted points with diamond-coated foams of different characteristics (Powder and Surface GmbH) as abrasive layer were used within the scope of this work. The carrier material of the diamonds and therefore the basis of the abrasive layer is soft and elastic polyurethane foam with varying degrees of flexibility. The behaviour of three different diamond-coated foams for finishing structured surfaces was investigated. The specifications of the carrier material can be distinguished by the compression hardness H under 10 % deformation according to the manufacturer's specifications (Fig. 1). Diamonds of grain size D12 were

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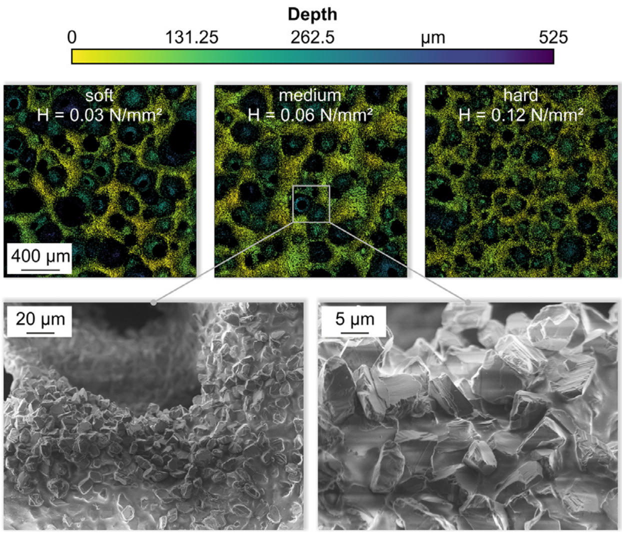
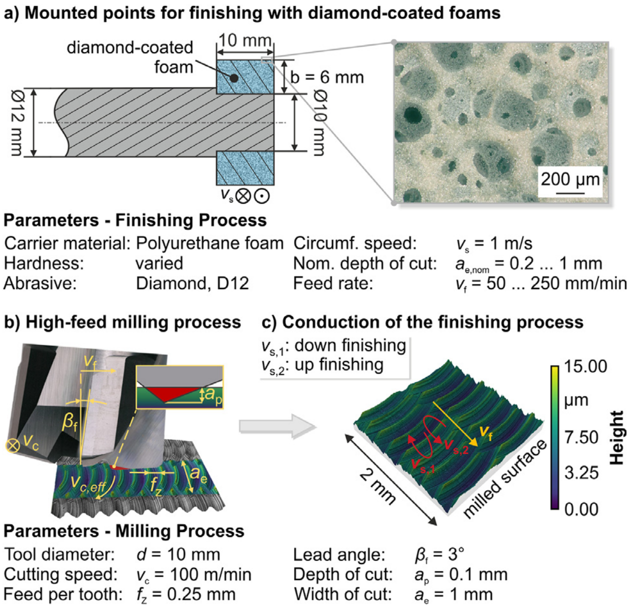


Fig. 1. Topography of the diamond-coated foams with different flexibility.

utilised as abrasive, which are embedded directly into the surface of the polyurethane foam [14]. Owing to the characteristics of the abrasive tool, this is a finishing process with fixed abrasives. In addition to the high flexibility and elastic deformability, the diamond-coated foams are characterised by a high number of pores. The images of the topography of the different diamond-coated foams shown in Fig. 1 reveal a change in the pore structure with varying flexibility. There is the tendency of an increasing area of pores on the surface of the diamond-coated foams with decreasing compression hardness of the carrier material. Moreover, the scanning electron microscope (SEM) images show that the surface of the polyurethane foam is nearly completely covered with diamond grains, which are homogeneously distributed and strongly bonded to the polyurethane foam.

In order to use the diamond-coated foams for a finishing operation on a five-axis machine tool (DMU 50 eVolution, Deckel Maho), mounted points with cemented carbide shafts and abrasive layers of 6 mm thickness were prepared (Fig. 2). In this case, the circumference of the polyurethane foam rings was coated with diamonds. As a basis for the finishing process, the structured surface was produced by applying a high-feed milling process according to [5]. Tool steel (1.2379) with a hardness of about 62 HRC was utilised as the workpiece material. The surface structure is characterised by pronounced valleys and peaks. Moreover, the initial topography shows grooves and burrs as a result of the contact conditions in milling. Therefore, the chosen structure offers the opportunity to evaluate the finishing process with diamond-coated foams according to the alteration of the structure with regard to contour deviations, i.e. the change of peaks. In addition, the reduction of imperfections such as burrs can be considered as well.


a) Mounted points for finishing with diamond-coated foams

Parameters - Finishing Process

Carrier material: Polyurethane foam
Hardness: varied
Abrasive: Diamond, D12
Circumf. speed: v_s = 1 m/s
Nom. depth of cut: $a_{e,nom}$ = 0.2 ... 1 mm
Feed rate: v_f = 50 ... 250 mm/min

b) High-feed milling process

c) Conduction of the finishing process

Parameters - Milling Process

Tool diameter: d = 10 mm
Cutting speed: v_c = 100 m/min
Feed per tooth: f_z = 0.25 mm
Lead angle: β_f = 3°
Depth of cut: a_p = 0.1 mm
Width of cut: a_e = 1 mm

Fig. 2. Tool concept and structured surface for the finishing experiments.

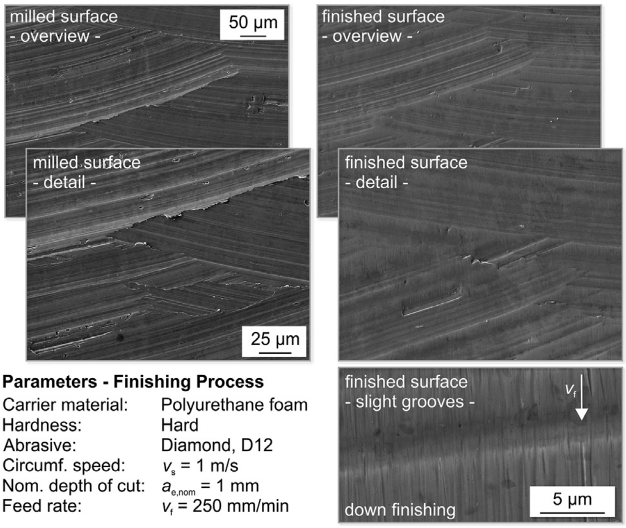
During the abrasive finishing process, the whole width (10 mm) of the abrasive layer was in contact with the flat but structured workpiece surface. The finishing process was realised in different process kinematics. Due to the change in the direction of rotation of the tool, up and down finishing are differentiated. Whereas the milling process was conducted under dry conditions, emulsion was used as a cooling lubricant for the finishing operation. In addition to the specification of the diamond-coated foams, the nominal depth of cut $a_{e,nom}$ and the feed rate v_f were considered as variables. These are well-known as relevant parameters for the use of elastically bonded grinding tools [15]. The value ranges for the process parameters are derived from previous investigations with the tools. The experimental procedure was to carry out the resulting 18 test points with one tool, followed by a repetition of the test plan with another tool. In order to avoid influences through tool wear, the sequence of the test points was randomised and the topography of the tools was monitored. Due to the shape of the mounted points and the deformation capability of the foam, the maximum depth of cut was raised to $a_{e,nom}$ = 1 mm.

3. Results and discussion

The aim of the finishing process is to modify the structured surfaces by reducing imperfections such as burrs and the micro roughness. Simultaneously, the preservation of the initial surface structure is the overall target, focussing on the avoidance of shape deviations. Therefore, the qualitative and quantitative analysis before and after finishing has been conducted on similar surface sections of each specimen.

3.1. Alteration of the surface roughness

In Fig. 3 the topography of the initially milled surface, structured by high-feed milling, is compared to the finished surface based on SEM images.



Parameters - Finishing Process

Carrier material: Polyurethane foam
Hardness: Hard
Abrasive: Diamond, D12
Circumf. speed: v_s = 1 m/s
Nom. depth of cut: $a_{e,nom}$ = 1 mm
Feed rate: v_f = 250 mm/min

Fig. 3. Reduction of micro burrs as a result of the finishing process.

In the initial stadium, the surface topography shows irregularities and the occurrence of burrs. The finishing process with diamond-coated foams enables the deburring, while the transitions between the marks are smoothened as well. Nonetheless, the grooves resulting from the milling process are still recognisable. This shows the sensitivity of the finishing process conducted. Moreover, the detailed

SEM images of the finished surface reveal slight and small grooves caused by the finishing process. These point in the vertical direction, according to the feed direction of the finishing process. This indicates abrasive material removal caused by the use of diamond-coated foams, similar to finishing processes with common bonded abrasives.

For the quantitative analysis of the surface roughness, confocal microscopy (TOOLinspect, confovis GmbH) was used. The roughness parameters of the milled and prepared surface were determined and the reduction in the roughness was calculated as the difference between these two stadiums for each test point. Due to the slight alteration of the surface topography by finishing and in order to avoid macroscopic influences of the structure on the roughness parameters, the filtered surface topography (2 mm x 2 mm, λc = 0.080 mm) was used as a basis. The results concerning the reduction of the average square height ΔSq due to the finishing operation are shown in Fig. 4. In the milled initial stadium, the average square height is Sq_{init} = 0.47 µm, calculated as the mean of all specimens.

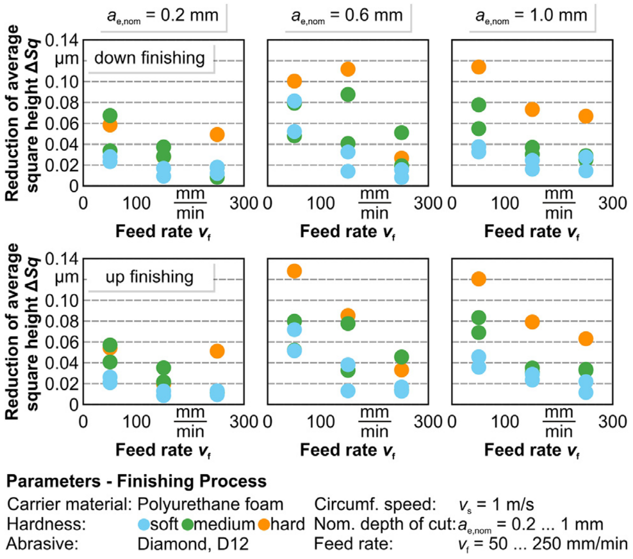


Fig. 4. Alteration of the surface roughness depending on the process circumstances.

The quantitative data reveal a clear influence of the feed rate on the alteration of the surface roughness. A higher feed rate leads to a smaller reduction in the surface roughness. This corresponds to a reduced process time of the finishing process with increasing feed rate. Moreover, the highest alteration of the surface roughness is achieved with the lowest deformability of the diamond-coated foams. This can be attributed to a higher surface pressure with lower deformability of the carrier materials for a constant nominal depth of cut. The influences of the process variables on the roughness parameters are similar for up and down finishing. The quantitative data on surface roughness indicate that there is no substantial change in the functional surface structure. Mainly micro defects are reduced.

3.2. Preservation of the surface structure

The analysis of the surface profiles, which were determined on the basis of the optical measurements of the topography, reveals detailed information on the alteration of the structure (Fig. 5). The direct comparison of the milled and finished profiles is possible because of the deterministic surface structure. Thus, the milled surface stadium was measured on a reference surface area for each specimen.

Finishing with diamond-coated foams generates only a slight alteration of the profile. This depends on the process parameters and specifications of the diamond-coated foams. For parameter combinations with low impact ($a_{e,\text{nom}}$ = 0.2 mm, v_f = 250 mm/min), no significant change in the profile can be observed. It can be assumed that the diamond grains are mainly pressed into the polyurethane foam, whereas the carrier material is compressed as well. This can be compared to the mechanisms in polishing with loose abrasives [16]. In combination with a short contact time, there is no relevant substantial modification of the profile. Nonetheless, additional SEM images reveal that the contact conditions lead to the reduction in micro burrs, especially regarding the peaks of the structure (Fig. 6).

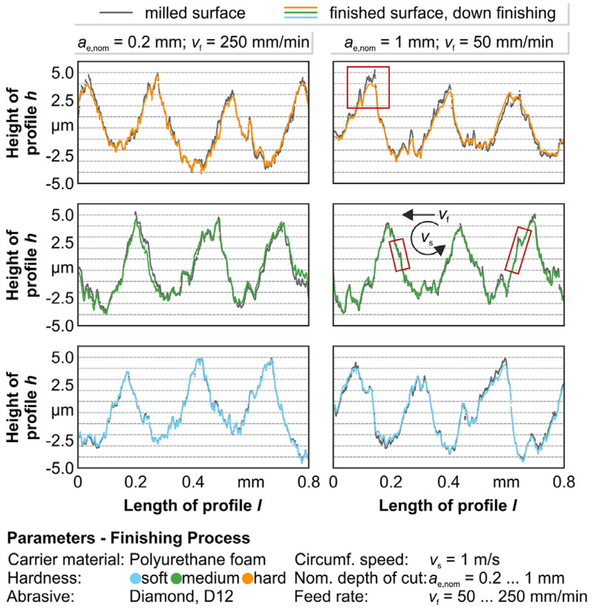


Fig. 5. Comparison of the profiles.

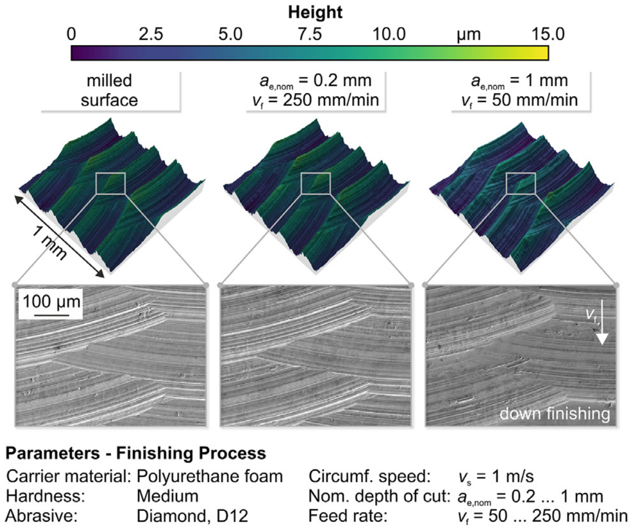


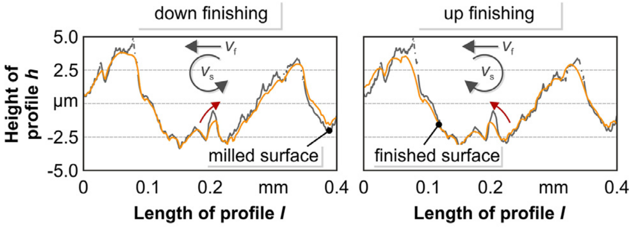
Fig. 6. Details of the topography of the milled and finished surface.

Process parameter combinations with a greater impact ($a_{e,\text{nom}}$ = 1 mm; v_f = 50 mm/min) show the feasibility to finish the valleys of the structure as well while maintaining the peaks. Only a small rounding of the peaks on a mainly submicron level occurs. An exemplary area is marked in Fig. 5. There is no plateau-like topography recognisable, as it could result from the removal of peaks. The flanks of the structure elements are smoothened as well. Therefore, it can be stated that there is a reduction in micro roughness. The surface profiles in the finished stadium are similar to those after a running-in phase [5].

The detailed analysis of the topography (Fig. 6) underlines that the strongest alteration of the topography is realised with a high nominal depth of cut and a low feed rate. This also corresponds to the quantitative analysis of the surface roughness. Nevertheless, there is no severe change in the shape of the surface structure. The combination of the results concerning the surface roughness and the profile analysis reveals a process window in which the finishing with diamond-coated foams offers the possibility to reduce imperfections and decrease the overlaying surface roughness while avoiding changing the surface structure on a macroscopic level. The degree of the alteration in the surface can be adjusted by varying the combination of the compression hardness and the depth of cut, which mainly determine the surface pressure, and the feed rate determining the process time. This shows the feasibility of solely reducing micro burrs up to decreasing the overlaying surface roughness as well.

3.3. *Mechanisms of material separation in finishing with diamond-coated foams*

In order to gain comprehensive knowledge concerning the material separation process in finishing with diamond-coated foams, a detailed analysis of different profiles is carried out additionally. In Fig. 7, profiles of surfaces prepared with the hardest diamond-coated foam are compared with regard to the different process kinematics.



Parameters - Finishing Process

Carrier material:	Polyurethane foam	Circumf. speed:	v_s = 1 m/s
Hardness:	Hard	Nom. depth of cut:	$a_{e,nom}$ = 1 mm
Abrasive:	Diamond, D12	Feed rate:	v_f = 50 mm/min

Fig. 7. Material separation depending on the contact conditions.

The different process kinematics are characterised by a varying direction of rotation of the mounted points. This is illustrated by the different orientation of the vector of the circumferential speed in contrast to the profiles. In particular, the orientation of the roughness peaks after finishing, even in the valleys of the structured surface, shows that the inclination of the profiles depends on the kinematic of the finishing process. For both up and down finishing, the roundings of the peaks of the profile are inclined in the direction of the circumferential speed. This is similar to results concerning the cutting edge preparation of cemented carbide tools with elastically bonded diamond grinding wheels [17] and is related to the enclosing of the edges and peaks due to the elastic deformability of the tools, whereas the circumferential speed is the determining factor. The detailed analysis of the surface profiles illustrates that the soft diamond-coated foams cover and adapt to all the peaks of the surface. This mechanism is not limited to the overall peak area of the surface structure.

4. Conclusion and outlook

In summary, it can be pointed out that the diamond-coated foams offer the opportunity to adjust to the surface topography of structured surfaces on a microscopic level. Hence, it is possible to reduce the micro roughness and surface imperfections while keeping the macroscopic profile of the structured surface. Owing to the specific characteristics of the diamond-coated foams, they can be formed to the valleys and peaks of the surface structure. Thus, there is sufficient surface pressure in the valleys to achieve abrasive material removal. Simultaneously, the peaks are smoothened but not flattened.

For further investigations, it is planned to transfer the results to varying surface structures, for example with different aspect ratios. In this regard, the finishing of surface structures produced by laser should be included as an area of application as well. The transfer would require adjustments to both the tool specifications and process parameters. Moreover, the finishing of freeform surfaces and thus the adjustment of the local contact conditions, taking into account the specific tool topography with its pore structure, will be tasks for future research work in this field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Monika Kipp: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jan Peters:** Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. **Timo Platt:** Resources, Visualization, Writing – review & editing. **Dirk Biermann:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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