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Analysis of the process behaviour of diamond-coated foams in finishing of ground hardened steel

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ABSTRACT

To broaden the process understanding with regard to a tool concept for finishing operations based on soft foams coated with diamonds, the application behaviour with respect to the surface preparation of a ground hardened steel surface is considered. By analysing the surface on the basis of established roughness parameters, the material removal behaviour is investigated in dependence on the process parameters and tool specifications. Furthermore, the influence on the micro roughness superimposed on the roughness profile can be analysed. The recorded process forces serve as a basis for understanding the underlying mechanisms and for interpreting the results.

1. Introduction

Many fine-finishing operations aim to produce defect-free functional surfaces with a smooth surface topography and a low surface roughness [1]. Fine-grained abrasive tools are commonly used for this purpose. Nonetheless, there are applications in which the finishing operation is not used to produce a low roughness. Sometimes the main requirement is to reduce the micro roughness and maintain the initial surface structure respective topography [2]. In this context, there is a necessity for tool concepts being able to adjust to the workpiece contour.

Compliant and flexible bonded abrasive tools are well-known in different types and are used for various applications. For instance, elastically bonded grinding wheels are suitable for the surface finishing of steel components such as in external cylindrical grinding [3] or gears [4]. In addition, elastically bonded diamond grinding wheels are suitable for the surface finishing of cemented carbide tools [5–7]. By using elastic finishing belts coated with abrasive, free-form surfaces or edges can be finished. The contact pressure in these processes can be specifically controlled as a process variable [1]. In addition, flexible abrasive tools in the form of mounted pins with bonded grains are used for finishing coatings [8] or ceramic components [9]. Moreover, *Zhu and Beaucamp* present different variations of compliant tool concepts for the application of the surface finishing of ceramics [10]. In polishing processes, elastic carrier elements, for example made of polyurethane, are applied to achieve a surface finish through the use of unbonded abrasives [11]. Whilst this type of process plays a central role in the creation of various components to achieve the necessary functional properties, for example in forming tools, it is often carried out manually [12]. These applications have in common that the aim of the finishing operation is the reduction in the surface roughness.

Diamond-coated foams are an additional tool concept for the fine-finishing of functional surfaces using abrasive diamond tools [13]. These tools consist of a carrier material, which is a soft and elastic polyurethane foam, and diamond grains as abrasive. In contrast to polyurethane pads for polishing with loose abrasives (cf. [14]), the polyurethane foam used within this research work is covered with diamond grains. These are joined to the surface of the polyurethane foam without any adhesive [13]. Due to their characteristics, diamond-coated foams can be compared to bonded abrasives (cf. [1]). Because of their high flexibility and deformability, diamond-coated foams offer the potential to finish complex contours or structures. In order to enhance the process understanding of the use of diamond-coated foams, it is necessary to conduct fundamental investigations concerning their process behaviour depending on the process parameters and the characteristics of the carrier material. For this purpose, the research presented deals with the finishing of ground surfaces using diamond-coated foams with different characteristics and varying process parameters.

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2. Methods

2.1. Tool concept

The tool concept used in these experiments is characterised by two parts and can be seen in parallel to a grinding pin with a cylindrical contour. Instead of a conventional abrasive layer with bonded abrasives, a highly flexible diamond-coated foam was used, as visualised in Fig. 1. The foam as a carrier material is characterised by the compression hardness, based on a deformation of 10 %. With $H = 0.03\ N/mm^2$ for the soft foam, $H = 0.06\ N/mm^2$ for the medium level and $H = 0.12\ N/mm^2$ for the hard foam, the material behaviour between the hardness levels differs significantly. Rings made of this foam were produced by water jet cutting to avoid uneven material separation due to the high flexibility of the base material. They were then coated with diamonds with grain size D12 on the circumferential surface to realise the abrasive characteristics. These rings were placed on a cemented carbide shaft and joined using a 2-component adhesive bond. The design based on a grinding pin emphasises the potential of using these tools integrated into the production of functional surfaces, circumventing the need for specialised machine tools.

The topography of the foam is characterised by the high number of pores, which vary in number and size depending on the foam hardness, as shown in Fig. 1. Furthermore, the surface is defined by a high number of closely spaced diamonds. To reduce the amount of thermally induced wear on the foam surface, these tools were used under flood cooling.

By varying the hardness of the foam, it becomes possible to influence the process behaviour in addition to the variation of the process parameters such as feed rate and depth of cut. It is to be expected that a change in the hardness of the foam at constant compression will also lead to a change in the applied process forces. Since the process forces applied by flexible tools play a central role in the application behaviour [4], the analysis of the influence of the change in hardness is a central research question.

2.2. Experimental setup and evaluation strategy

Taking into account the prospective fields of application of the diamond-coated foams investigated here, suitable specimen materials can be determined. Highly relevant application examples are forming tools which can show the specifics of both free-form geometries and structured surfaces [15,16]. Based on this application, hardened tool steel (1.2379) with a hardness of about 62 HRC is a suitable specimen material. It was therefore selected for the analysis of the tool behaviour. In order to gain detailed knowledge about the specific behaviour of diamond-coated foams in the surface finishing of steel components, a ground surface was applied as the initial surface for further processing. The surfaces with an average roughness *Rz* between 3.5 µm and 5 µm were produced using mounted points with a vitrified bond and cBN grit (B64). Therefore, the specimen provides the basis for investigating the material removal behaviour in relation to the specific ground grooved profile.

Carrying out the pre-machining and finishing operations in a single setup allows the influence of the tool and process specifications to be considered in isolation. Furthermore, the use of a *DMU 50 eVolution* machining centre *(DECKEL MAHO Seebach GmbH)* as a test machine underlines the flexibility of the tool concept's applicability. To gain detailed information on the mechanical load during finishing with diamond-coated foams as a function of process parameters and tool specifications, force measurements were carried out using a *9139AA* dynamometer *(Kistler Group)*. This allows conclusions to be drawn between the surfaces to be analysed and the deformation behaviour of the foams, characterised by the process forces. To further illustrate the underlying test setup, it is shown in Fig. 2.

Furthermore, using cuboid specimens with the dimensions 100 mm × 25 mm × 20 mm offers the opportunity to only partially finish the surface, visualised by the coloured areas of the sample surface in the illustration. This provides a reference surface that allows direct conclusions to be drawn about the material removal behaviour by enabling optical and stylus-type measurements on a comparable surface of the sample. It minimises the interference caused by deviations as a result of the pre-machining.

In the context of the experiments presented here, a parameter space was chosen that combines the variation of foam hardness with a variation of the process parameters. The combination of those parameters is based on a face-centred central composite design, as shown in Fig. 3.

The selected parameters enable a comprehensive description of the tool behaviour. Regarding the material removal mechanisms of flexible tool concepts, as shown in the introduction, a minimum contact pressure must be overcome [4]. Due to the high flexibility of the foams, a relatively high depth of cut is necessary to generate these corresponding forces, which is why the minimum nominal depth of cut $a_{e,nom} = 0.2$ mm was chosen.

A combination of stylus-type and optical measuring methods is

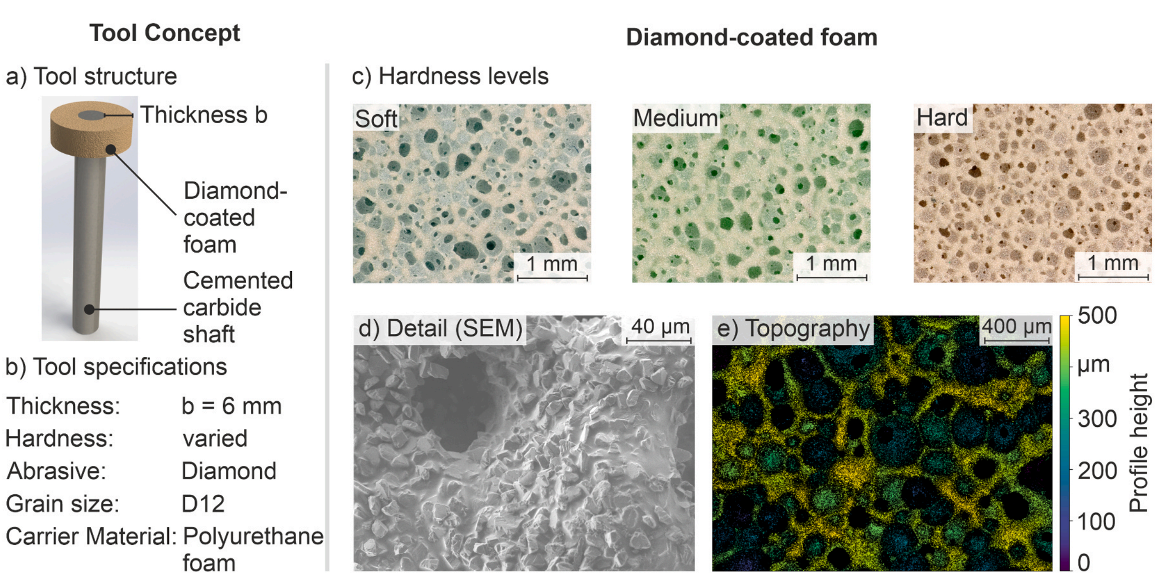


Fig. 1. Visualisation of the tool concept and the surface structure of the diamond-coated foam.

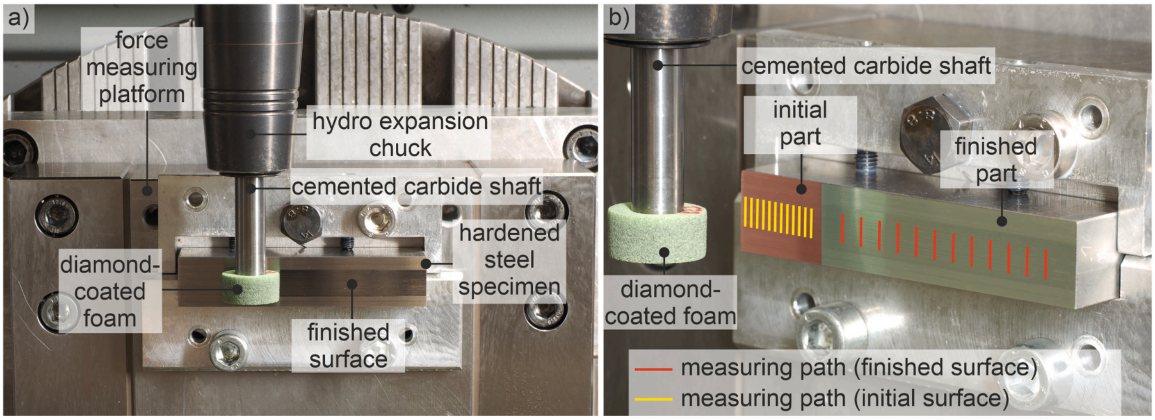
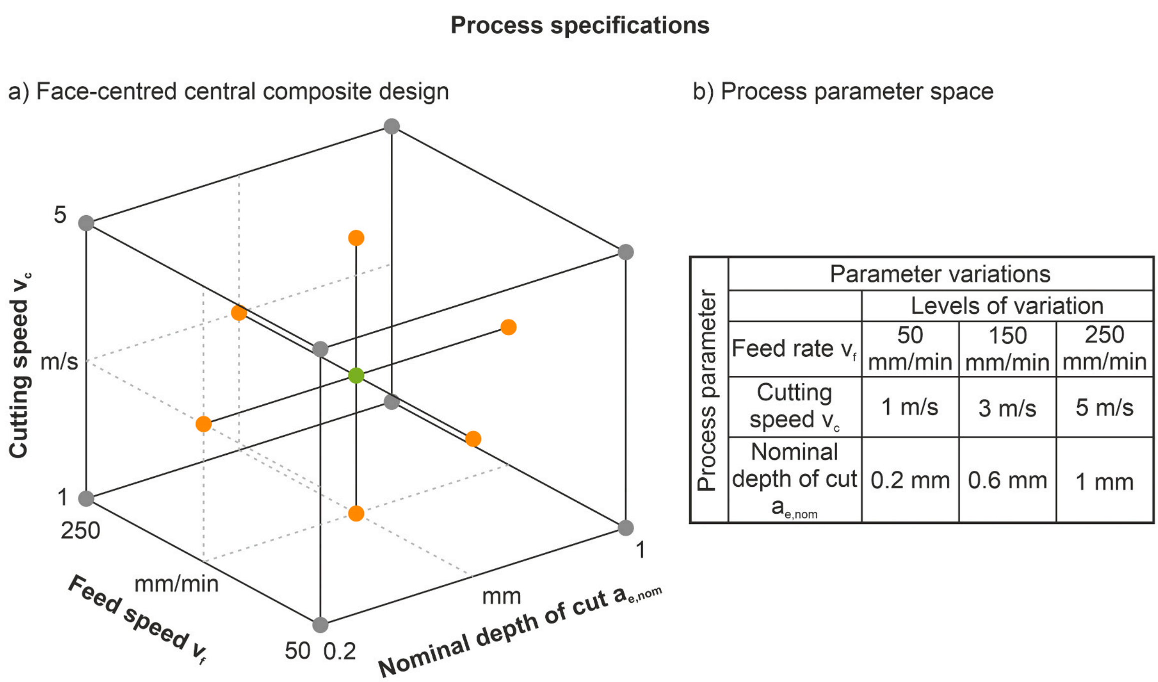


Fig. 2. Overview of the experimental setup and the machining path.



Process parameter	Parameter variations		
	Levels of variation		
Feed rate v_f	50 mm/min	150 mm/min	250 mm/min
Cutting speed v_c	1 m/s	3 m/s	5 m/s
Nominal depth of cut $a_{e,nom}$	0.2 mm	0.6 mm	1 mm

Fig. 3. Visualisation of the parameter space and the experimental design.

purposeful for determining the classic surface characteristics on the one hand, but also for detecting and quantifying the micro roughness superimposed on the actual roughness profile on the other hand. Using an *XR 20* stylus instrument *(Mahr group)*, 12 measuring sections were placed within the finished surface to determine the roughness parameters, as illustrated in Fig. 2. These characteristic values were additionally supplemented by the measurement of the initial surface of the workpiece, likewise shown in Fig. 2. The optical measurements using confocal microscopy were carried out using *DuoVario (Confovis GmbH)* device in the centre of the colour-coded surface areas, which also enables the comparison between the initial and prepared surface.

3. Results and discussion

3.1. Influence of process parameters on process forces and surface parameters

The normal force F_n is an elementary process factor that is particularly relevant for the understanding and controlling of fine-finishing processes with compliant finishing tools. This is due to the fact that the normal force is important with regard to the pressure in the contact zone. In combination with the topography of the finishing tools, it reveals information about the material removal process. Therefore, the normal force was analysed for the different degrees of hardness of the diamond-coated foams depending on the process parameters. The results are shown in Fig. 4.

An increase in the nominal depth of cut results in a higher normal force for all degrees of hardness of the diamond-coated foams. As the depth of cut increases, greater pressure is exerted on the diamond-coated foam. This is revealed in an increase in the normal force. Hence, it can be assumed, that the pressure in the contact zone increases with rising depth of cut [6,17]. Both the feed rate and the circumferential speed, are of minor importance concerning the effect on the normal force. With an increase in the circumferential speed, the normal force increases slightly. An additional overall analysis of the force data underlines, that the nominal depth of cut is the main influencing process parameter concerning the normal force. Furthermore, this correlation can also be illustrated by separately plotting the process normal forces as a function of hardness and depth of cut (cf. Fig. 5). Moreover, it becomes evident that the hardness of the foam determines the level of the normal

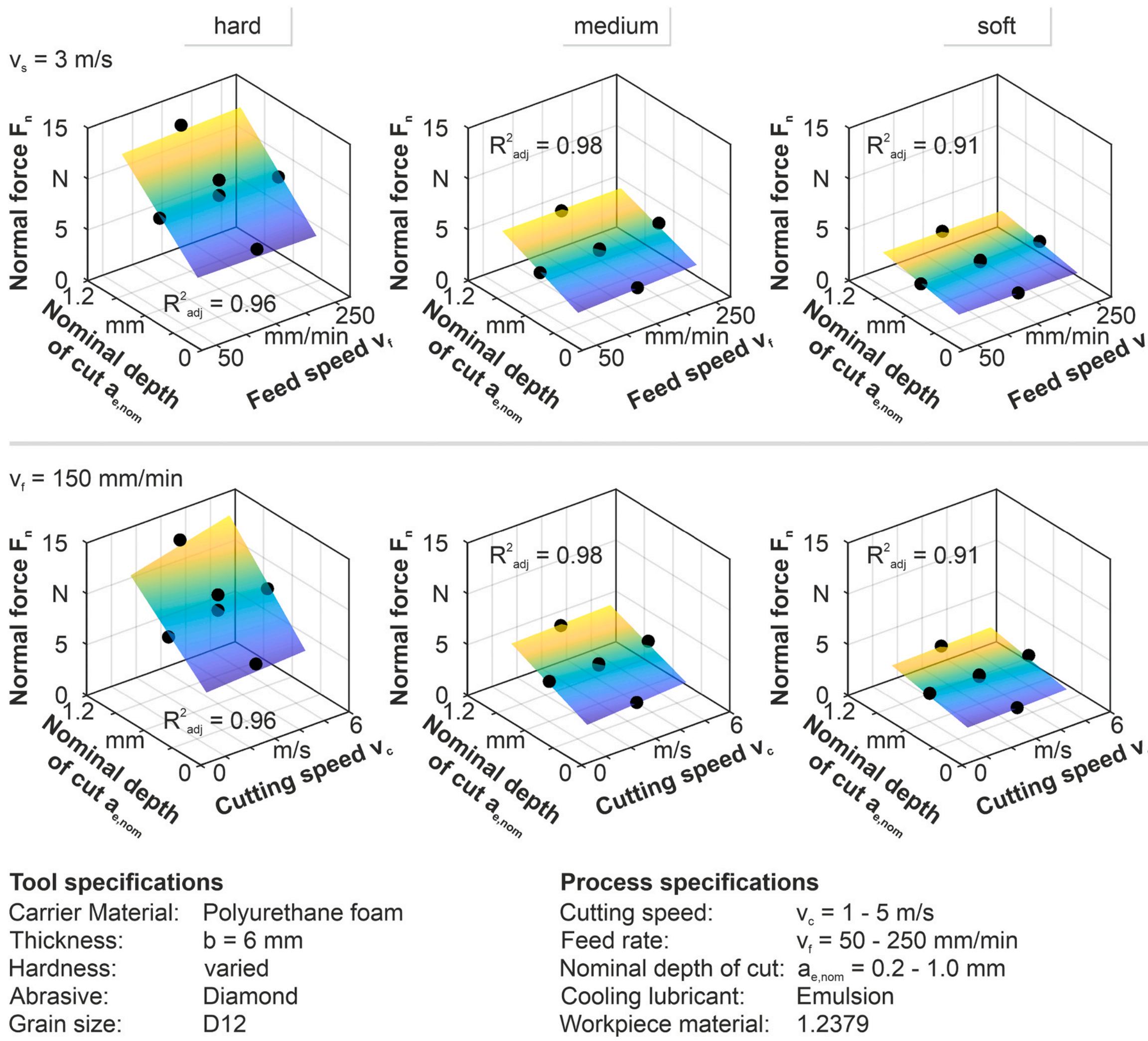


Fig. 4. Illustration of the influence of the foam hardness on the process normal forces.

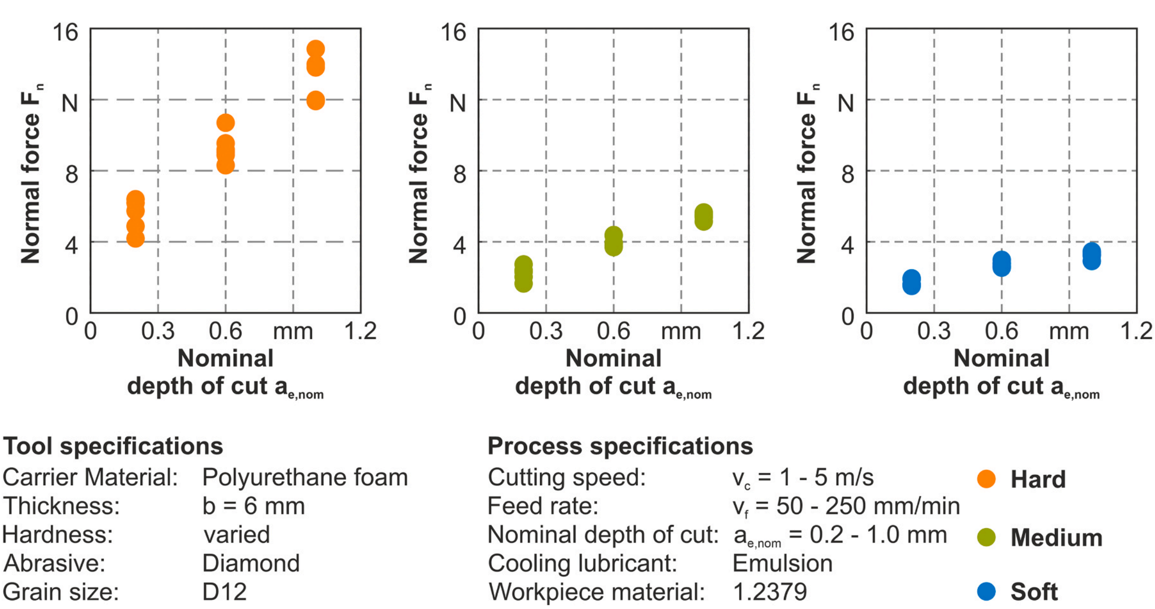
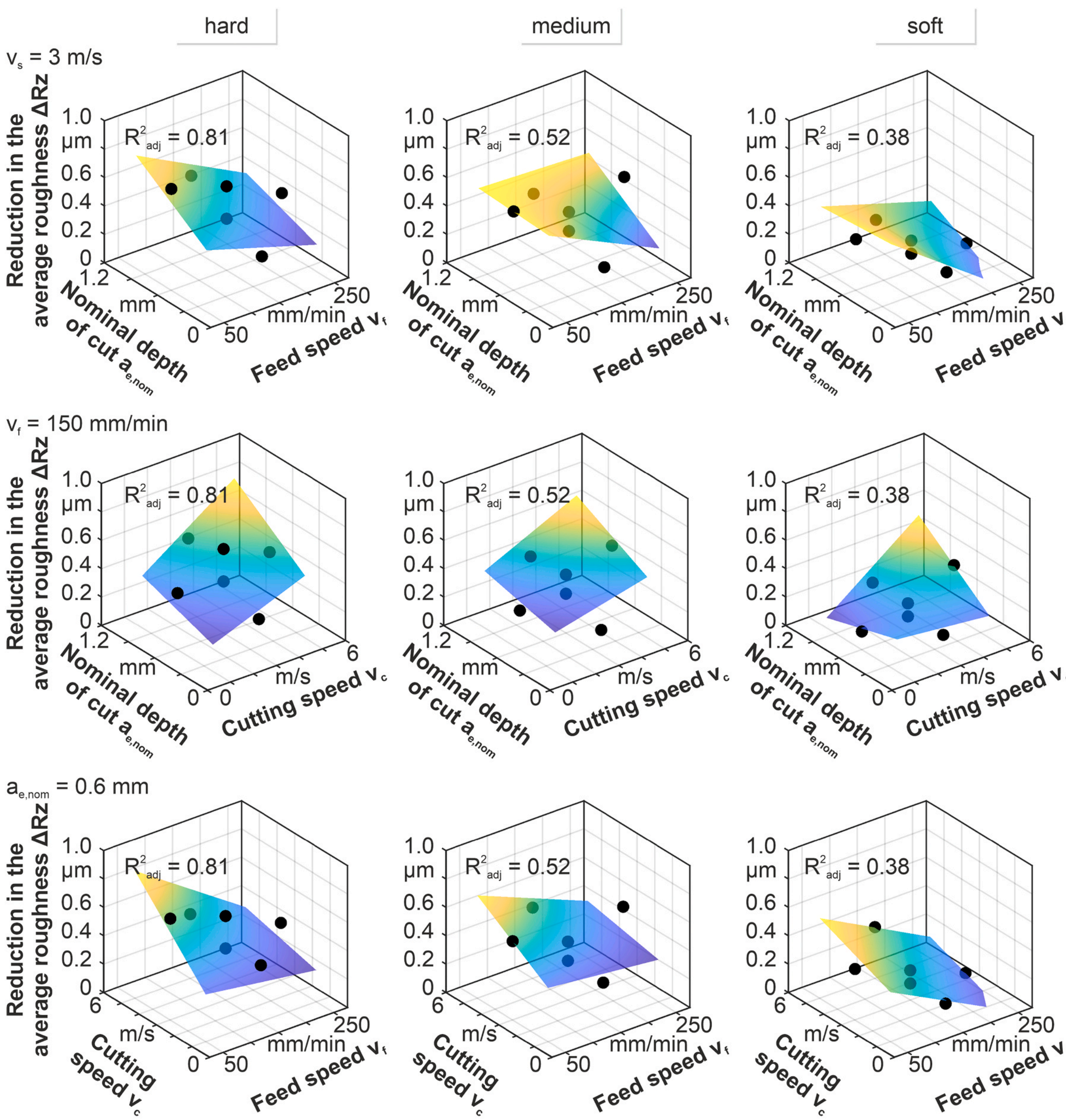


Fig. 5. Visualisation of the influence of the nominal depth of cut $a_{e,nom}$ on the process normal forces.

force. This effect is similar to that observed when using elastically bonded grinding wheels and tools [6,18]. It can therefore be concluded that for diamond-coated foams the normal force, and thus the contact pressure, is mainly determined by the adjustment of the nominal depth of cut and the hardness of the carrier material.

Due to the sensitive finishing of the initial ground surfaces, the difference of the average roughness of the initial and finished surface are taken into account as process results. In this context, a direct comparison of the ground and finished surfaces was realised for each test and specimen. Fig. 6 shows the results concerning the reduction in the average roughness ΔRz for different hardnesses of the foams and the various process parameters.

It becomes obvious that the parameter whose increase leads to an increase in normal force also results in a greater alteration in surface roughness. Hence, a higher hardness of the foam as well as a higher value of the nominal depth of cut cause a higher decrease in surface roughness. This is a consequence of a higher contact pressure and an increasing number of grains in the contact zone [17]. Moreover, a higher feed speed leads to a decrease in the reduction in the surface roughness. This is a result of the reduced contact time between the tool and the workpiece. Thus, with an increased feed rate [18] the number of grain engagements per surface area is reduced. These results regarding the use of diamond-coated foams are comparable to finishing processes with elastically bonded grinding tools as well [6,18,19]. Furthermore, an



Tool specifications

Carrier Material:	Polyurethane foam
Thickness:	b = 6 mm
Hardness:	varied
Abrasive:	Diamond
Grain size:	D12

Process specifications

Cutting speed:	v_c = 1 - 5 m/s
Feed rate:	v_f = 50 - 250 mm/min
Nominal depth of cut:	$a_{e,nom}$ = 0.2 - 1.0 mm
Cooling lubricant:	Emulsion
Workpiece material:	1.2379

Fig. 6. Analysis of the correlation between the process-/ tool specifications and the decrease in average surface roughness.

increase in the circumferential speed leads to an increased reduction in the average roughness. This could be attributed to the increased number of grain engagements during the process. Hence, by adjusting the hardness of the foams and the process parameters, the reduction in the surface roughness and therefore the material removal could be modified.

Due to the high deformability and structure of the carrier material, similarities regarding the functional mechanisms of the tool to machining with loose grains can be assumed. As with very soft polishing pads, where the abrasive particles are pressed into the pad material [20], this interaction between the carrier material and the grains is also to be expected here. Assuming an impact of the contact pressure and the relative speed on the material removal based on Preston's hypothesis [21], a central influence on the material removal via the normal force can be expected. Such a correlation could also be used to enable a targeted adjustment of the material removal rate.

A combined visualisation of all test points, subdivided only according to the feed rate can be used to verify the hypothesis mentioned above. When analysing these test points (see Fig. 7) with regard to the applied process normal force and the resulting reduction in the roughness, a pronounced correlation can be identified in the right part of the figure. The results regarding the feed rates $v_f = 150$ mm/min and $v_f = 250$ mm/min therefore support the assumption that the material removal is not primarily controlled by the individual parameters, but that the normal force resulting from the combination of parameters is a central defining variable. In addition, at a feed rate of $v_f = 50$ mm/min, as shown on the left in Fig. 7, no such pronounced correlation is visible. It was already shown, that the higher cutting speed and thus the number of grain engagements per area have an increasing effect on the resulting roughness reduction. At comparable normal forces, this superimposition of effects seemingly makes it difficult to derive a clear correlation between process force and roughness reduction. A more precise distinction between these influences should therefore be the subject of further research. Nevertheless, based on these results the potential to use the process force as a defining parameter in further investigations is emphasised.

3.2. *Influence on the micro roughness*

An influence of the process and tool parameters can also be assumed with regard to the effect on the micro roughness. Therefore, the roughness superimposed on the actual surface profile is analysed. First, however, it should be demonstrated that the reduction in the micro roughness can be determined by contrasting the surface profile before and after the finishing process. For this purpose, two parameter combinations are compared in Fig. 8. On the one hand, a combination A is considered, which has caused the highest material removal according to the findings presented in Section 3.1. On the other hand, a combination B is considered that led to a smaller and less pronounced material removal.

Detailed evaluation of the profile diagrams as well as the topographical images shows that with both parameter combinations, the groove structure created by grinding is recognisable and remains largely intact. Considering the diagrams describing the surface machined with parameter combination A, a clear reduction in the micro roughness is noticeable. This confirms the presumed potential of the tool concept used and suggests that this reduction can also be quantified with an appropriate selection of filter parameters. When examining the two diagrams generated by combination B, it becomes clear that a significantly smaller change in the surface topography can be observed. This difference between the two parameter combinations also emphasises the possibility of controlling the material removal through the choice of process and tool specifications and thus motivates the further determination of the quantifiability of these changes as a function of the process parameters. To illustrate the relationship between the change in the classical roughness parameters and the influence on the micro roughness, the following figure shows that the use of harder foam, which leads to an increase in material removal and therefore a reduction in the average roughness *Rz*, also has a greater influence on the micro roughness. For this purpose, the change in the roughness parameter *Rz* and *Ra* is shown on the left side. On the right side, the reduction in the parameters Ra_{micro} and Rz_{micro} is depicted. It was subdivided corresponding to the largest wavelength λc (or nesting-index N_{ic} according to [22]) that was taken into account in the determination of the characteristic values. The lowest wavelength λs (or nesting-index N_{is} according to [22]) considered in this determination is constant, therefore wavelength sections of different sizes for the evaluation of the change in micro roughness are spanned.

Analysing the results as a function of the level of hardness, a clear influence is visible. When keeping the process parameters constant and only varying the hardness of the foams, the effect already shown in part 3.1 becomes clear. Higher material removal is facilitated by a higher hardness level. At the same time, similar observations can be made when analysing the influence on the micro roughness. Whilst the use of the soft foam also leads to a reduction in micro roughness, the harder foam

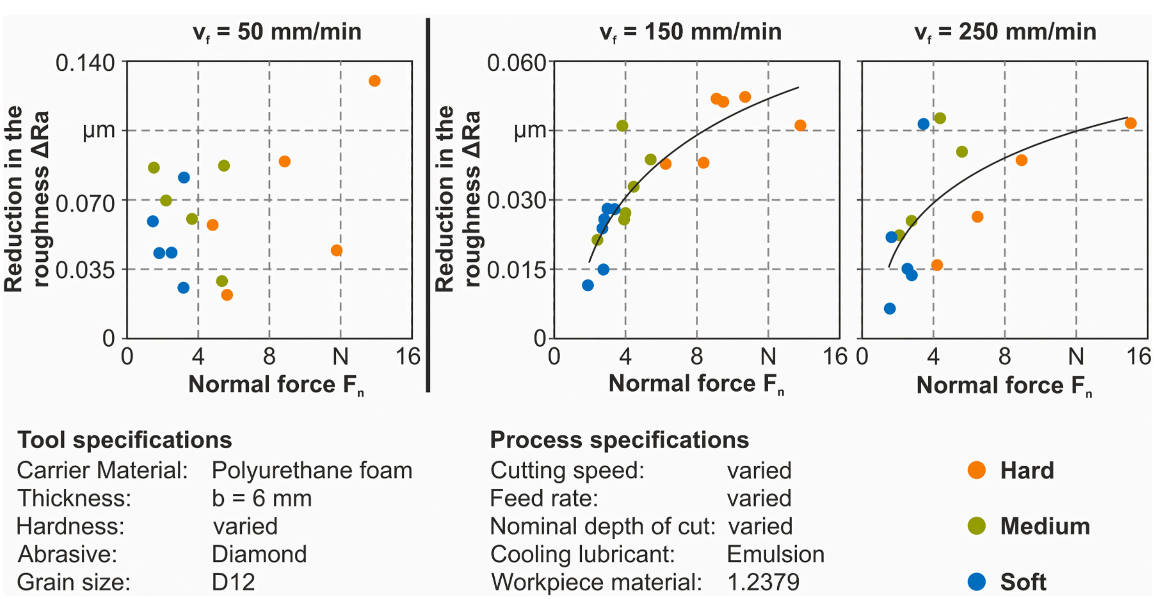
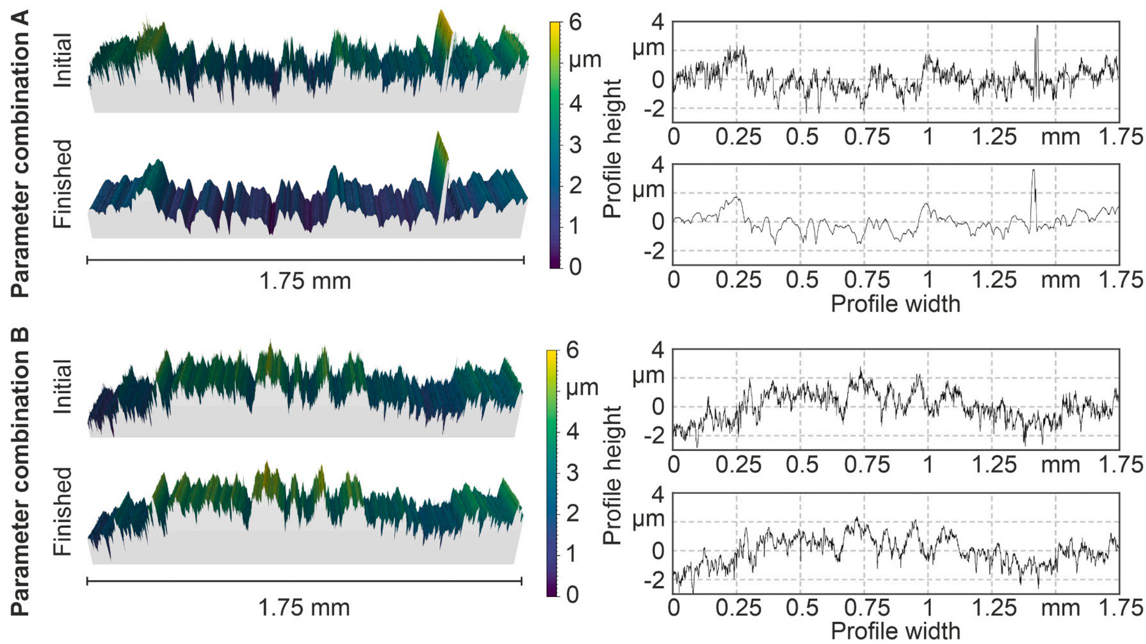


Fig. 7. Analysis of the correlation between the normal force and the reduction in the surface roughness.

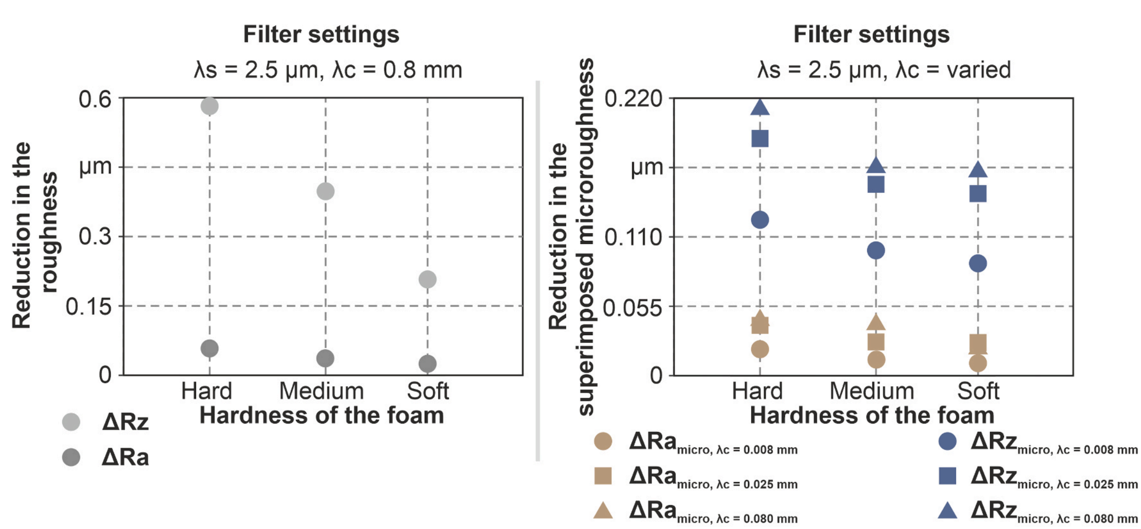


	Tool specifications		Process specifications		
	Foam hardness	Foam thickness	Cutting speed v_c	Feed rate v_f	Nom. depth of cut $a_{e,nom}$
Parameter combination A	hard	6 mm	5 m/s	50 mm/min	1 mm
Parameter combination B	soft	6 mm	3 m/s	150 mm/min	0.6 mm

Fig. 8. Comparison of two parameter combinations with high and low removal rates under consideration of the optically recorded topographical images and profile diagrams.

removes a larger amount of material and thus reduces the micro roughness by a larger amount.

The consideration of different wavelength ranges of the roughness profile makes it possible to analyse the reduction in the roughness parameters as a function of the choice of these wavelengths (cf. Fig. 9). According to the underlying hypothesis regarding the material removal



Tool specifications
Carrier Material: Polyurethane foam
Thickness: b = 6 mm
Hardness: varied
Abrasive: Diamond
Grain size: D12

Process specifications
Cutting speed: v_c = 3 m/s
Feed rate: v_f = 150 mm/min
Nominal depth of cut: $a_{e,nom}$ = 0.6 mm
Cooling lubricant: Emulsion
Workpiece material: 1.2379

Fig. 9. Analysis of the influence of the tool and process specifications on the reduction in the micro roughness.

behaviour of the tool concept, a higher reduction in the roughness parameters is to be expected when considering the short wavelength parts of the profile. When analysing the reduction in micro roughness, the consideration of longer wavelengths results in greater changes in the roughness parameters. However, dividing the reduction in roughness by the roughness of the initial topography allows the evaluation of the relation. It shows that the average percentual decrease in the characteristic values for the short wavelength λc = 0.008 mm (38 %) is substantially higher than for the higher length levels λc = 0.025 mm (17 %) and λc = 0.08 mm (9 %). This trend can also be observed when analysing the decrease in roughness in the left part of the figure for λc = 0.8 mm (4 %). It suggests that the functional mechanisms of the tool mainly reduce the short wavelength parts of the roughness profile and thus the micro roughness with considerably higher intensity. This quantitative impression can also be confirmed qualitatively when considering the upper part of Fig. 8. The long wavelength parts of the roughness profile remain almost unchanged here.

4. Conclusion and outlook

The investigations presented focus on the analysis of the behaviour of diamond-coated foams using mounted points for finishing operations. It was successfully demonstrated that the variation of both the process parameters and the hardness of the foam is suitable for controlling the material removal behaviour and the resulting surface topography. In addition, it was possible to demonstrate that the parameters depth of cut and foam hardness do not necessarily have to be considered individually, but that the prospect of further investigations makes it seem possible to control the material removal via the normal force as a resulting parameter. It was also shown that it is possible to reduce the surface roughness. In particular, the reduction in the superimposed micro roughness reveals the potential of the diamond-coated foams. With respect to the process parameters and tool characteristics, it is possible to maintain the general topography of the ground surface while mainly reducing the micro roughness. This correlation was verified both quantitatively and qualitatively and emphasises the potential of the foam used here. At the same time, the process understanding of the basic mechanisms can be improved.

As an outlook for further research that can be derived from the results of this work, it can be stated that extended variations with regard to the tools will expand the understanding of the process and build the basis for different applications. For example, extending the tool concept to foam coated with larger grain sizes, or combining the use of different grain sizes in a multi-stage process, appears to be a promising way of achieving not only a reduction in micro roughness but also a greater reduction in roughness parameters. In addition, the potential for preserving a specific surface structure while removing the superimposed micro roughness will be investigated in more detail. This will be considered by analysing the finishing of structures with a determined shape, as opposed to the grinding grooves considered here.

CRediT authorship contribution statement

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

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.

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