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ORIGINAL ARTICLE

Design of tool grinding processes for indexable inserts made of rocks

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Abstract

Using natural rocks as alternative cutting tool material poses a possibility to meet actual environmental, economic and geopolitical challenges. The present state of knowledge, however, is not sufficient to allow a knowledge-based design of the tool grinding process of cutting tools made of rock. For this reason, this study presents an investigation of the significance of the grinding process parameters and grinding tool specifications for the flank face and cutting edge roughness as well as for the cutting edge microgeometry besides an analysis of the scatter of the grinding results in tool grinding of rock inserts. Thus, the study contributes to a knowledge-based design of tool grinding processes of rock tools. In this context, confocal and focus variation microscopes are used besides SEM images to investigate the above mentioned factors in the plunge face grinding of rock inserts from five different rocks. The results identify the axial feed velocity of the plunge face grinding process as a highly significant influence factor for cutting edge roughness and microgeometry, while cutting speed only shows a significant influence on cutting edge microgeometry. Besides that, highly significant influences of the used rock type and the abrasive grain size are identified for all three mentioned factors. Grinding result analyses show a scatter between 0.04 and 25.00 µm depending on the parameter and rock investigated. Additionally, recommendations for the design of the tool grinding process of rock tools are presented deduced from the obtained results.

Keywords Natural rocks · Tool grinding · Cutting tools · Indexable inserts · Alternative cutting materials

Nomenclature

a_e	Depth of cut
C	Grain concentration of a grinding wheel
d_g	Abrasive grain size of a grinding wheel
df	Degree of freedom
h_{cu}	Single grain chip thickness
H	Hardness
N_{GV}	Cutting edge density
r_ε	Corner radius
Ra	Arithmetic average roughness
Rp	Average peak height
Rv	Average valley depth
Rz	Mean roughness depth
Sa	Arithmetical mean height
S_α	Cutting edge segment on flank face
S_γ	Cutting edge segment on rake face
$\overline{S}$	Average cutting edge rounding
v_c	Cutting speed
v_f	Feed velocity
v_{fa}	Axial feed velocity
v_R	Rotational speed of an insert during grinding
α	Rotation angle of an insert during grinding
ρ_g	Density of an abrasive
σ_c	Critical bending strength

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1 Introduction

Since the earliest days of human history, tools have been used to machine a wide range of materials. The oldest known cutting materials for tool making are natural rocks. Their use can be traced back as far as 2.5 million years [1–3]. However, the rise of metallic cutting materials and the ever-increasing complexity of technical processes as human development progressed ultimately led to the fact that natural rocks were no longer used as cutting materials. The accompanying increase in demands on the tools and processes used also contributed to this. Modern cutting tool materials like ceramics, cermets, cemented carbides, pCBN or PCD allow the conduction of sophisticated and highly productive manufacturing processes for a wide range of materials and applications. But as these cutting tool materials are the product of sophisticated industrial production process chains, they are faced with economic, geopolitical and environmental challenges. The need of rare and thus expensive resources for the production of modern cutting materials poses an example for the economic and geopolitical challenges which can be illustrated by the example of cemented carbide. The production of cemented carbides requires tungsten and cobalt which are expensive materials. These resources are only mined extensively in a few world regions such as Russia, China or the Democratic Republic of the Congo [4–8]. This leads to geopolitical challenges, especially in regions in which these resources are needed but not mined, like the European Union or the USA, as the availability of these resources is critical there [4–6]. Moreover, in some cases, these resources are mined in conflict regions, so their trade can contribute to financing these conflicts, as in the case of tungsten, which is mined in the Democratic Republic of the Congo [9]. The production of modern cutting materials also consumes huge amounts of energy and at the same time emits significant quantities of climate affecting gases which creates environmental challenges especially with regard to climate change [10, 11]. The mentioned challenges therefore create reasons to investigate environmentally friendly alternative cutting materials with a global availability in huge quantities to meet these challenges. Natural rocks could be such an alternative cutting material, as rocks are comparatively easily accessible in large quantities at low costs and require a low amount of energy to be made usable as cutting tool material. For example, the production of one kilogram of cemented carbide requires an energy input of up to 480 MJ-equivalents, which can be associated with emissions of up to 19 kg of climate-active CO_2-equivalents [10] while the provision of one kilogram of rock only requires an energy input of up to 5.5 MJ-equivalents associated with emissions of up to 0.004 kg of climate-active CO_2-equivalents [12].

1.1 State of the art

However, the use of rocks as cutting material in modern cutting processes and the manufacturing of cutting tools made of rocks is a comparatively novel approach which has not extensively been covered in literature. The machining of rocks, to the contrary, has already widely been covered. Examples for this are investigations focussing on the characterization of rock properties [13–17], the material removal mechanisms in rock machining [18–22] and the machining of rocks in general as well as the tools needed in this context and their operational behaviour [23–27]. But these investigations are primarily concerned with rock cutting processes and tools and the corresponding mechanisms and not with using rocks as cutting materials or tool grinding of rock tools. The suitability and usability of rocks as cutting material [28, 29] as well as the operational behaviour of cutting tools made of rocks [28–31] and the material removal mechanisms of rocks against the background of tool grinding [32] have only been investigated more closely recently. These investigations showed that it is possible to use natural rocks for turning aluminium alloys and plastics and identified potentially important rock properties for their use as cutting materials as well as potentially suitable rocks for this use cases [28–31].

Although issues and improvement potentials for the tool grinding process of rock tools have already been identified [29] and analyses of the material removal behaviour of rocks have been carried out against the background of tool grinding processes [32], no dedicated investigations of the tool grinding of rock tools and its significant influence factors have been carried out so far. Due to this, there are currently no results available in literature that allow a knowledge-based design of productive tool grinding processes of cutting tools made of rocks. As this knowledge is important to allow a transfer of the use of rocks as cutting material from a topic of purely scientific interest to industrial applications, the availability of the aforementioned knowledge is necessary to take advantage of the abovementioned environmental and economic benefits of rocks in this context.

Therefore, this paper aims to contribute to a knowledge-based design of tool grinding processes for cutting tools made of rocks. This is done by investigating the significance of the influence factors of the tool grinding process for the process result. For this purpose, indexable inserts are ground in this investigation from different rocks using different grinding tools and process parameters to allow the conduction of an analysis of the significance of these factors for the process result. For this reason, the paper is structured as follows: Section 2 shows the materials and methods used in this investigation. The results of the investigations are shown in Section 3 starting with an analysis of the scatter of the grinding results of the rock inserts. Subsequently, the significance of the chosen rock and the process parameters as well as the significance of the grinding tool specifications are analysed in Section 3.2 and Section 3.3. Based on these results the design of tool grinding processes for rock tools is discussed in Section 3.4 before all results are summarized in Section 4.

2 Materials and methods

2.1 Rocks

With Alta quartzite, flint, lamellar obsidian, quartz and Silver quartzite, five different rocks are used in this investigation.

The rocks are chosen based on previous investigations and have already been characterised before [29, 32]. Therefore, their hardness H and their critical bending strength σ_c are shown together with their respective standard deviations in Table 1 as given in [32]. The critical bending strength has already been used for describing the load-bearing capacity of grinding wheel bonds [33] and rock inserts [29] and can therefore be used as a measure for the structural cohesion of solids with multiple phases and their load-bearing capacity. In terms of rock microstructure, lamellar obsidian has an amorphous structure, quartz is a single crystal, while Alta quartzite, flint and Silver quartzite have granular microstructures with average grain sizes of 0.28 mm (Alta quartzite), 0.02 mm (flint) and 0.34 mm (Silver quartzite).

A DEMA WB 2000 rock saw and a Struers Discotom-10 cut off grinding machine are used to cut rock samples with dimensions of $18 \times 18 \times 5.5$ mm^3 from the raw rocks which are available as blocks and nodules with lengths between 80 and 250 mm or as slabs with a thickness of up to 22 mm. Care was taken when cutting the quartzite samples to ensure that existing mica textures are aligned parallel to the rake face of rock inserts to be ground. After cutting the samples from the raw rocks, a Blohm Profimat MC 407 5-axis grinding machine is used to grind the samples to a thickness of 4.76 mm in two steps: First, rough machining with a cutting speed of $v_c = 30$ m/s, a feed velocity of $v_f = 3200$ mm/min, and a depth of cut of $a_e = 20$ µm is performed until a sample thickness of 4.78 mm is reached. Subsequently, a finishing operation is performed with the same cutting speed, a feed velocity of $v_f = 200$ mm/min and a depth of cut of $a_e = 5$ µm. In both steps, a grinding wheel with a metallic bond, diamond as abrasive (D46) and a grain concentration of C100 is used.

2.2 Grinding experiments

A Wendt WAC 715 Centro cutting insert grinding machine is used to conduct all grinding experiments as plunge face grinding operation. A low-viscosity mineral oil (R-Oil HM7, Rhenus) is used as cooling lubricant and is supplied to the process via a cylindrical nozzle. Four different grinding wheels manufactured by the same company (Dr. Müller Diamantmetall AG) with a metallic bond and diamond as abrasive are used in these investigations. All tools have a diameter of 400 mm and a width of the abrasive layer of 12 mm. Their specifications are shown in Table 2. Profiling and sharpening of the grinding tools is performed with a cup dressing roller of silicon carbide with a grain size of $d_g = 125$ µm (ANSI #120) in a continuous process with a cutting speed of $v_c = 2$ m/s and a depth of cut of $a_e = 0.5$ µm per feed pulse every 10 s.

The combinations of process parameters used in this investigation are chosen based on results presented in [32] and are shown in Table 3. Experiments with all parameter combinations are conducted with all grinding tools for all investigated rocks except the parameter combinations with a cutting speed of $v_c = 15$ and 30 m/s and an axial feed velocity of $v_{fa} = 29$ mm/min which are only performed with grinding wheel no. 2. These two parameter combinations are used to investigate the scatter of the grinding process results. Based on findings shown in [32], the one with a cutting speed of $v_c = 15$ m/s is used in the investigation of the scatter of the quartz and lamellar obsidian, while the one with a cutting speed of $v_c = 30$ m/s is used in the investigation of the scatter of the other rocks.

In all experiments, indexable inserts of the type SNMN120404 are manufactured according to ISO 1832. Three inserts of each rocks are manufactured for each parameter combination except for the combination used for investigating the scatter of the process results. In this case, 15 inserts were manufactured for each rock. Overall, 375 inserts have been included into the analysis of the significance of the influence factors of the grinding process (75 per rock). The tool grinding process in this investigation has with two rock inserts broken during the clamping

Table 1 Hardness and critical bending strength of the rocks

Rock	Hardness H in GPa	Critical bending strength σ_c in MPa
Alta quartzite	10.40 ± 2.56	42.30 ± 5.27
flint	9.57 ± 0.18	57.66 ± 8.09
lamellar obsidian	8.29 ± 0.15	38.28 ± 5.17
quartz	15.51 ± 2.41	31.98 ± 8.01
Silver quartzite	14.80 ± 2.42	25.80 ± 3.80

Table 2 Specifications of the grinding wheels

Grinding wheel no.	Grain size	Grain concentration
1	D46	C50
2	D46	C75
3	D91	C50
4	D91	C75

Table 3 Parameter levels of the grinding experiments

Cutting speed levels in m/s	Feed velocity levels in mm/min		
15	4	29	55
22		29	
30	4	29	55

process in the machine a very low rejection rate compared to the high rejection rate for grinding rock inserts reported in [29]. Since the absence of an oscillation of the grinding tool is one of the main differences in the process design in this comparison, it can be assumed that this is the cause of the lower rejection rate. For future tool grinding processes of rock inserts, it is therefore advantageous, with regard to the rejection rate during tool grinding of rock inserts, to dispense with the oscillation of the grinding tool in the grinding process.

To analyse the potential of the single grain chip thickness h_{cu} for designing the tool grinding process of rock tools, the single grain chip thickness model developed by Friemuth [34] shown in Eq. (1) is used to calculate h_{cu}. According to this model, h_{cu} can be calculated using the cutting speed v_c, the feed velocity v_{fa}, the grain size d_g of the grinding wheel and the cutting edge density in the grinding wheel bond N_{GV}. N_{GV} can be calculated by Eq. (2) using the grain concentration of the grinding wheel C, the density ρ_g and the grain size d_g of the abrasive. The single grain chip thicknesses calculated with this model are between 0.26 and 2.32 µm for the parameter setup of this investigation. The single grain chip thickness varies in the grinding of the corner radius due to varying contact conditions between insert and grinding tool. Therefore, h_{cu} has also been calculated as a function of the rotation angle α during the grinding of the corner radii according to Friemuth [34] as shown in Eq. (3). To ensure a constant ratio between the single grain chip thickness in the grinding of the flank face and the corner radius r_ε, an individual rotational speed during the grinding of the corner radii v_R has been chosen for each parameter combination. The rotational speed for each parameter combination is chosen in such a way that the single grain chip thickness in the grinding the of corner radii is half the size of the single grain chip thickness present in the grinding of the flank faces. Therefore, rotational speeds of 500, 3500, 3600 and 6600°/min are used in this investigation.

$$h_{cu} = 0.693 \cdot \left(\frac{2.5 \cdot v_{fa}}{\frac{4}{3} \cdot N_{GV} \cdot \sqrt{d_g} \cdot v_c} \right)^{\frac{1}{2.5}} \tag{1}$$

$$N_{GV} = \frac{6 \cdot C}{\rho_g \cdot \pi \cdot d_g} \tag{2}$$

$$h_{cu}(\alpha) = 0.693 \cdot \left(\frac{2.5 \cdot r_\varepsilon \cdot v_R}{2 \cdot N_{GV} \cdot \frac{4}{3} \cdot \sqrt{d_g} \cdot v_c} \cdot \tan\left(45^\circ - \frac{\alpha}{2}\right) \right)^{\frac{1}{2.5}} \tag{3}$$

2.3 Roughness measurement, cutting edge microgeometry and SEM-images

A Confovis DuoVario confocal microscope is used to measure the roughness of the flank face of the inserts after grinding. The roughness of one flank face of each ground insert is measured perpendicular to the grinding direction of the plunge face grinding process directly adjacent to the corner radius. An area of 4.5×1.27 mm^2 is measured in this process. The measurement data are analysed with the software MountainsMap®. The measured area is divided into 2245 equally distant profile lines for the determination of the arithmetic average roughness Ra and the mean roughness depth Rz. The whole measured area is used for the determination of the arithmetical mean height Sa. Cutting edge roughness and microgeometry are measured optically with an Alicona Infinite Focus G5 focus variation microscope. One cutting edge of each ground insert is measured perpendicular to the grinding direction of the plunge face grinding process. A length of 1.6 mm is measured for each cutting edge directly adjacent to the corner radius of the insert. The analysis of the significance of the parameters of the grinding process for the investigated parameters is conducted with the software JMP®. Besides that, a Zeiss EVO 60 scanning electron microscope is used to investigate the cutting edges and surfaces of the rock inserts after grinding.

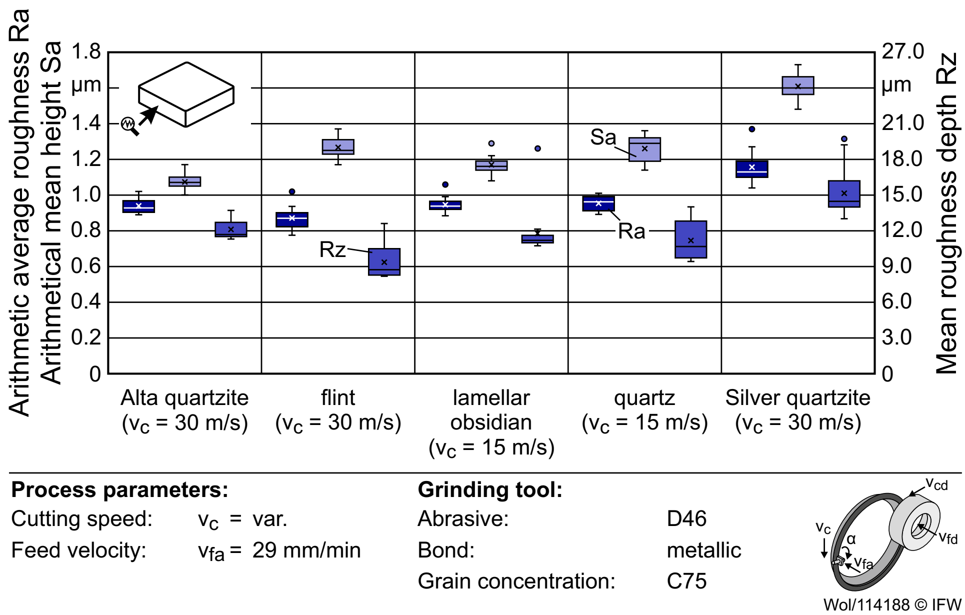
3 Results and discussion

3.1 Scatter of the grinding results

For the process design and analysis of grinding of rock tools, it is important to know the expected scatter of the grinding result. This allows to estimate the achievable tolerance limits during production. With flank face roughness, cutting edge roughness and cutting edge microgeometry, three factors are used in this investigation to evaluate the grinding result of the rock inserts. Therefore, these are also used to analyse the scatter of the grinding result. In this context, the arithmetic average roughness Ra, the mean roughness depth Rz and the arithmetical mean height Sa are used to describe the flank face roughness of the rock inserts. The results of the scatter analysis of the flank face roughness are shown in Fig. 1. It can be seen that the mean roughness values of all rocks are between 0.87 µm (flint) and 1.61 µm (Silver quartzite) for Ra and Sa and between 9.4 µm (flint) and 15.14 µm (Silver quartzite) for Rz.

It can be noted that for all rocks, the median of the roughness values is either close to the average roughness values or below it, except for the Sa values of quartz. This indicates that in the first case, the roughness at the flank face of the rock inserts is equally distributed around the mean

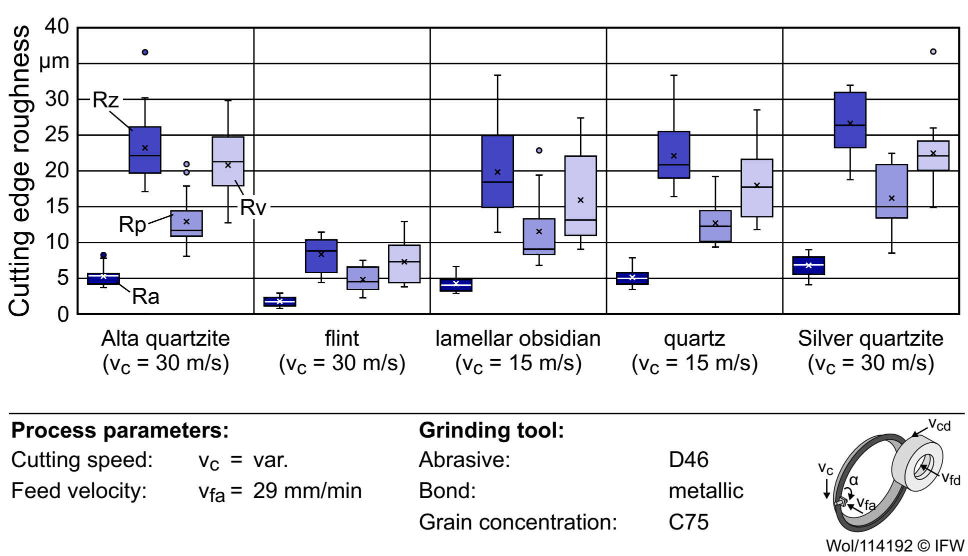
Fig. 1 Scatter of the flank face roughness of the rock inserts



roughness value and that in the second case, at least half of the samples show a lower flank face roughness. Interpreting the interquartile range as the scatter of the flank face roughness, the results show a scatter between 0.04 µm (lamellar obsidian) and 0.08 µm (Silver quartzite) for Ra, between 0.05 µm (lamellar obsidian) and 0.13 µm (quartz) for Sa and between 0.2 µm (lamellar obsidian) and 3.08 µm (quartz) for Rz. The results show no identifiable correlation of the scatter with the rock properties like their hardness, critical bending strength or the grain size valid for all rocks. The rocks with a higher critical bending strength, like flint or Alta quartzite, do not show a reduced scatter of the grinding result, which would have been conceivable due to the associated load-bearing capacity. This is also not the case if the scatter of a rock with a comparably low grain size like flint is compared to a rock with a comparably high grain size like Silver quartzite. Only the mean roughness values indicate trends already described in [29] like a higher flank face roughness for a lower critical bending strength of the rocks. It is therefore possible that the process parameters and tool specifications have a higher influence on the scatter of the roughness of the flank face of rock inserts than the rock properties themselves.

The results for the scatter of the cutting edge roughness are shown in Fig. 2. Besides Ra and Rz of the cutting edge, the average peak height Rp and the average valley depth Rv of the cutting edge are used to describe the cutting edge roughness. Including Rp and Rv into the analysis of the cutting edge roughness allows it to describe whether the cutting edge roughness is dominated by peaks above the profile

Fig. 2 Scatter of the cutting edge roughness of the rock inserts



line or by valleys beneath the profile line. The latter are for example created by brittle outbreaks along the cutting edge during the grinding process. These parameters are therefore a valuable addition to the information provided by Ra and Rz and contribute to a better understanding of the influence of the process parameters and grinding tool specifications on cutting edge roughness.

The mean values of the cutting edge roughness of all rocks are between 1.83 µm (flint) and 6.86 µm (Silver quartzite) for Ra and between 8.41 µm (flint) and 26.66 µm (Silver quartzite) for Rz, respectively. The mean values of Rp and Rv range from 4.88 to 16.24 µm (Rp) and from 7.39 to 22.51 µm (Rv), respectively. The scatter of the cutting edge roughness ranges from 1.13 µm (flint) to 2.41 µm (Silver quartzite) for Ra, from 4.53 (flint) to 10.03 µm (lamellar obsidian) for Rz, from 3.54 µm (flint) to 7.44 µm (Silver quartzite) for Rp and from 4.09 µm (Silver quartzite) to 11.05 µm (lamellar obsidian) for Rv.

The results indicate a possible correlation of the mean cutting edge roughness values and the scatter of the cutting edge roughness with the microstructure of the rocks. Compared with flint, the more coarse grained Alta and Silver quartzite show higher mean values and a higher scatter of the results. The same is true for lamellar obsidian (amorphous structure) and quartz (single crystal). The higher scatter of the quartzites in comparison to flint can be explained by their higher grain size. The breakout of individual mineral grains at the cutting edge due to the loads of the grinding process influences the cutting edge roughness due the resulting deviation from the mean profile line of the cutting edge. The higher the average grain size, the higher this deviation becomes when a single mineral grain breaks out and thus also the roughness. This also increases the scatter of the cutting edge roughness as the grain size of individual mineral grains of these rocks can vary in a comparatively wide range as shown in [29]. The by comparison increased scatter of lamellar obsidian and quartz can be explained by the occurrence of shell-shaped ruptures close to the cutting edge which are typical phenomena for material removal of these materials. Since a correlation of the occurrence and size of these ruptures along the cutting edge with the loads of the grinding process and existing local stress states is possible, their size and therefore their influence on cutting edge roughness vary between the samples. This results in an increased scatter of cutting edge roughness of these rocks. Furthermore, it is likely that the occurrence of the shell-shaped ruptures is connected with the increased Rv values of these two rocks, as the ruptures create valleys in the cutting edge. Based on these results, it can be assumed that the scatter of the cutting edge roughness of rock inserts after grinding correlates with the tendency of the rock microstructure to form chipping and that the size of this chipping is related to structural properties such as grain size. However, it must also be taken into account that this hypothesis is linked to the material removal mechanisms that take place at the cutting edge during the grinding process and that it is therefore likely that further correlations between the scatter of the cutting edge roughness and the process loads and parameters as well as other rock properties like critical bending strength exist.

For the description of the cutting edge microgeometry the length of the cutting edge segment on flank face S_{α}, the length of the cutting edge segment on the rake face S_{γ} and the average cutting edge rounding $\overline{S}$ are used as defined in [35]. According to [35], $\overline{S}$ is calculated by using Eq. (4) based on S_{α} and S_{γ}. The results of the scatter of the cutting edge microgeometry are shown in Fig. 3. The mean values of S_{α} range from 14.0 µm (flint) to 48.4 µm (silver quartzite), while the mean values of S_{γ} range from 17.8 µm (flint) to 64.6 µm (Silver quartzite). Therefore, the mean values of $\overline{S}$ are between 15.9 µm (flint) and 56.5 µm (Silver quartzite). The scatter of the cutting edge microgeometry parameters range from 2.8 µm (flint) to 17.3 µm (quartz) for S_{α}, from 6.3 µm (flint) to 25.0 µm (quartz) for S_{γ} and from 4.1 µm (flint) to 23.6 µm (quartz) for $\overline{S}$. The comparison of the scatter of S_{α} and S_{γ} for all rocks show a tendency for a higher scatter of S_{γ} in each case. Besides that, it can be observed that all rocks show higher mean and median values for S_{γ} than for S_{α}. This indicates a tilting of the cutting edge towards the rake face for all rocks.

$$\overline{S} = \frac{S_{\alpha} + S_{\gamma}}{2} \tag{4}$$

A correlation between cutting edge chipping as a result of the grinding process and the resulting cutting edge microgeometry can pose an explanation for the observed phenomena. Cutting edge chipping not only influences cutting edge roughness. The geometry of the chipping can also influence cutting edge microgeometry if the chipped volume is mainly located on the rake or the flank face. For example, if a longer piece is broken out from the rake face than on the flank face due to cutting edge chipping on the cutting edge, S_{γ} is more increased than S_{α}. The reason for this is that in this case, the distance between the separation point of the cutting edge rounding and the tool tip of an ideally sharp cutting edge is increased more on the rake face than on the flank face. Therefore, it is also possible in this context that factors like the microstructure of the rocks and the structural cohesion of the rocks around the cutting edge additionally influence the resulting cutting edge microgeometry of the rock inserts. Thereby, it is possible that the grain size of the microstructure of the rocks mainly influences the scatter of the results, while the critical bending strength exerts a stronger influence on the resulting mean value. The comparison of the cutting edge microgeometries of the rocks and the respective scatter

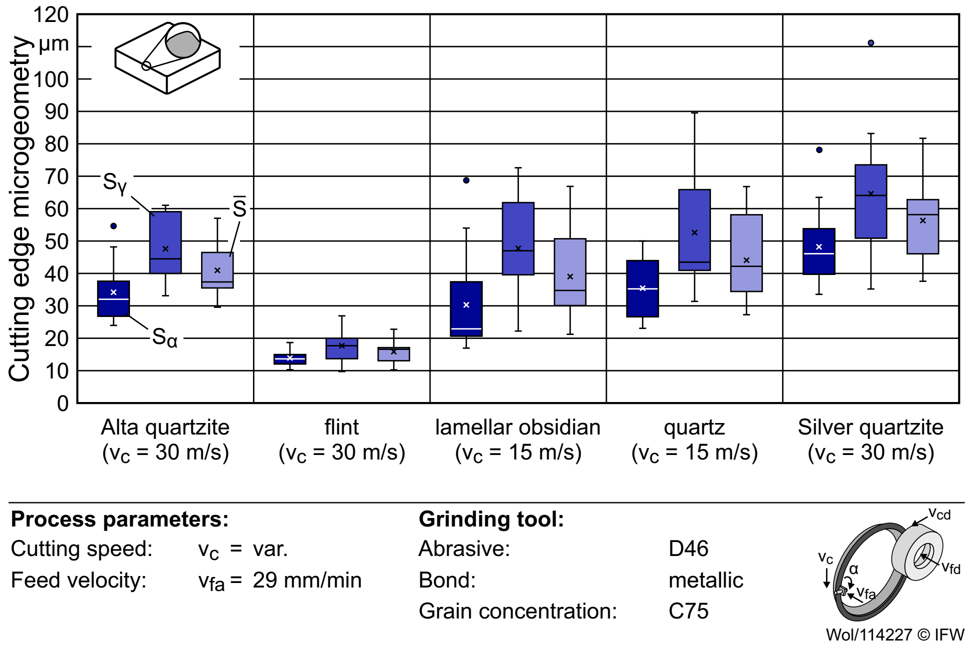


Fig. 3 Scatter of the cutting edge microgeometry of the rock inserts

supports this hypothesis. While flint, with its comparatively small grain size and high critical bending strength, shows lower values for S_α and S_γ and also for scatter, the quartzites, with their higher grain size and lower critical bending strength, show higher values for these factors. Comparing the quartzites, it can be seen that they show similar scatter for S_α and S_γ but a larger difference between their mean values with Alta quartzite showing lower values. Considering that the average grain size of Silver quartzite is only slightly higher than the average grain size of Alta quartzite, which in turn has a higher critical bending strength, the above postulated hypothesis becomes conceivable. A similar correlation can be found for lamellar obsidian and quartz regarding critical bending strength and the mean values of S_α and S_γ. They also show a comparable scatter for S_α and S_γ which may be connected to their similarities in their microstructures which include no mineral grains.

3.2 Significance of the used rock for the grinding result

For a knowledge-based design of the tool grinding process of rock tools to be possible, it is necessary to identify those parameters that significantly influence the grinding result. Knowing the scatter of the grinding results, the significance of the influence factors of the grinding process are analysed statistically subsequently to the conduction of the remaining grinding experiments using the software JMP®. In this context, the significance of the used rock and the grinding process parameters as well as the grinding tool specifications are separately plotted in correlation with the flank face roughness, the cutting edge roughness and the cutting edge microgeometry. Confidence intervals for 95%, 99% and 99.9% were calculated, and *t*-values for each investigated parameter are plotted against these intervals to identify their significance. The *t*-distribution has a degree of freedom of $df = 73$ with a distribution of the measured data close to normally.

Starting with the analysis of the significance of the used rock for the flank face roughness of the inserts resulting from the grinding process, Fig. 4 shows the *t* values and confidence intervals required in this context. It can be seen in Fig. 4 that only flint and Silver quartzite have a significant (*t*-value above 99% confidence interval) or highly significant (*t*-value above 99.9% confidence interval) influence on flank face roughness. While Silver quartzite shows a highly significant influence on all three investigated roughness parameters, this is only the case for Ra and Rz for flint. The influence of flint on arithmetic mean height is significant instead of highly significant as the *t*-value of this roughness parameter is -2.80 in this case. Besides that, the results indicate that using Silver quartzite as material for the rock inserts leads to an increase of the flank face roughness while using flint leads to a decrease. The fact that the Silver quartzite inserts show the highest flank face roughness values in this investigation, while flint shows the lowest flank face roughness, supports this. For the remaining three rocks, however, no significant influence on flank face roughness by the rock used is detected.

The observed tendencies may be linked to the rock properties. Since flint shows the highest critical bending strength and therefore the highest load-bearing capacity and structural cohesion of the compared rocks as well as the lowest average grain size according to [29, 32], it is likely that

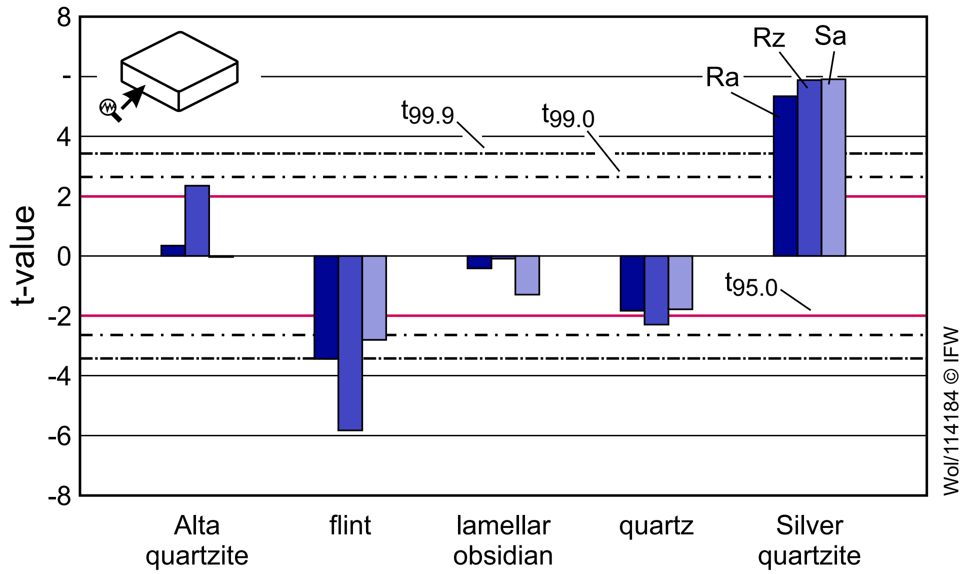


Fig. 4 Significance of the used rock for flank face roughness

these properties favour a lower flank face roughness as a result of the grinding process. The reason for this is that higher structural cohesion counteracts the occurrence of brittle outbreaks. This would increase surface roughness; while the comparably small grain size helps to ensure that when grains are broken out of the structure, the roughness is only increased to a comparatively small extent. The lowest critical bending strength of Silver quartzite compared to the other investigated rocks, together with its comparatively high average grain size and crack density [29, 32], is thus a factor that can favour a higher flank face roughness. With a lower structural cohesion and a bigger grain size, the occurrence of larger brittle outbreaks becomes more likely and thus also an increased flank face roughness as a result of the grinding process.

The analysis of the significance of the used rock for the cutting edge roughness shows results similar to the respective analysis for the flank face roughness, as can be seen in Fig. 5. Flint and Silver quartzite show a highly significant influence on all parameters investigated for cutting edge roughness and the same tendencies for decreasing and increasing them as before for flank face roughness. As before, no significant influence on cutting edge roughness can be detected for using lamellar obsidian or quartz. The same applies for Alta quartzite with the exception of Rv for which Alta quartzite shows a *t*-value of 2.81 and therefore a significant influence. This may indicate an increased tendency of this rock to form a cutting edge geometry with an increased proportion of valleys in the roughness profile. But since the other roughness parameters are not significantly influenced by the use of this rock, it is possible to assume that the overall influence of the use of Alta quartzite on cutting edge roughness is limited.

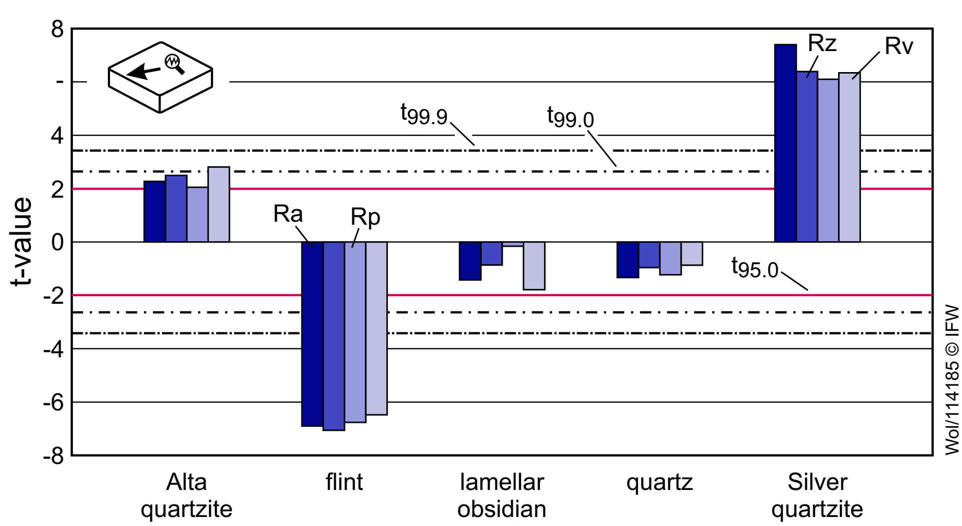


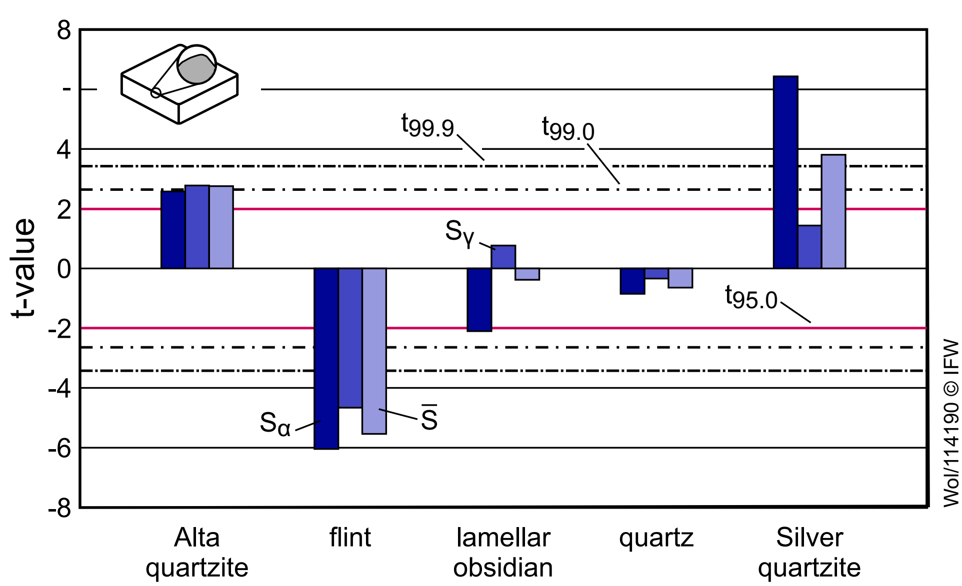
Fig. 5 Significance of the used rock for cutting edge roughness

As mentioned above, it is likely that the observed significances of the machined rock types for the cutting edge roughness after grinding as well as the observed tendencies for increasing or decreasing cutting edge roughness are linked to the material properties of the rocks. An increased structural cohesion and a high resistance to crack propagation of a material are important properties to resist edge chipping as described in [36, 37]. This edge chipping is in most cases responsible for the increase in cutting edge roughness in addition to brittle chipping of mineral grains or grain agglomerations or the occurrence of shell-shaped ruptures at the rake face. It is therefore to be assumed that Silver quartzite shows a highly significant influence on cutting edge roughness with a tendency to increase it due to its comparatively low critical bending strength and structural cohesion while the opposite is true for flint. Transferred to the design of a tool grinding process, these results mean that the choice of rock can have a (highly) significant influence on the flank face and cutting edge roughness resulting from the grinding process, but not necessarily has to. It is therefore likely that these two factors, which are important for the cutting tool quality, can be beneficially influenced by choosing a suitable rock. However, it must be mentioned that the opposite is also possible if a rock with properties that favour a higher roughness like a low critical bending strength is chosen. But the results also show that the chosen rock does not necessarily have to be a significant influence factor for flank face and cutting edge roughness.

Regarding cutting edge microgeometry, the use of Alta quartzite, flint and Silver quartzite shows a significant or highly significant influence on cutting edge microgeometry as can be seen in Fig. 6. In this context, a tendency to increase the parameters used to describe the cutting edge microgeometry can also be found for the quartzites and a tendency to decrease them for flint. However, with regard to the influence of the quartzites on the cutting edge microgeometry, differences can be identified. While the influence of Alta quartzite on S_γ and $\overline{S}$ is within the significant regime (99.0% confidence interval) with *t*-values of 2.78 and 2.76, respectively, a highly significant influence on S_α and $\overline{S}$ (*t*-values of 6.43 and 3.81, respectively) is observed for Silver quartzite. This indicates that these two quartzites influence the cutting edge microgeometry that results from the grinding process in different ways. It is therefore possible that the different ways in which these quartzites influence the parameters of the cutting edge microgeometry can result in different orientations and roundings of the microgeometry.

The different material properties of the quartzites can pose a reason for the different influences on cutting edge microgeometry since they influence the ability of the material to withstand loads at the cutting edge and therefore the probability of edge chipping. It is likely that the difference in critical bending strength in particular is important in this context for the shape of the cutting edge microgeometry, especially considering the relationship between critical bending strength and the structural cohesion of the rock. It is therefore also likely that the by comparison higher critical bending strength of flint combined with its lower grain size is the reason for the observed highly significant influence of flint on S_α and S_γ and the tendency to decrease these parameters. As with flank face and cutting edge roughness, it can be stated that the choice of rock for the grinding process can have a (highly) significant influence on the resulting cutting edge microgeometry, but does not necessarily have to in every case. However, based on this investigation and the obtained results, it cannot be ruled out that the combination of material properties of the rocks plays an important role in whether the selected rock has a significant influence on the

Fig. 6 Significance of the used rock for cutting edge microgeometry



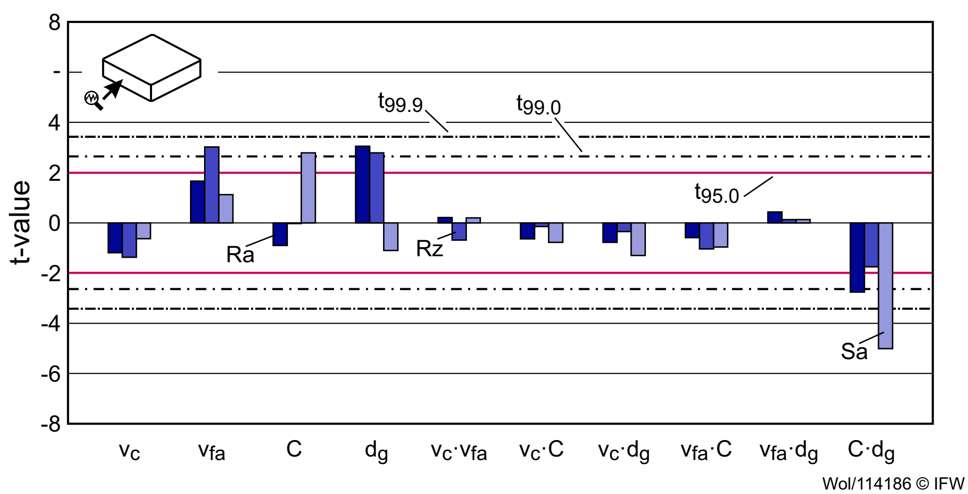
result of the grinding process. Nevertheless, with regard to the design of tool grinding processes for rock tools, it should be noted that the rock used is a factor that should be considered when designing the grinding process. An individual process design for each rock could therefore be beneficial to achieve suitable grinding results.

3.3 Significance of the process parameters and grinding tool specifications

Besides the material to be machined in the grinding process, the process parameters and grinding tool specifications are important factors that must also be taken into account when designing a grinding process. The significance of these factors for the flank face roughness of the rock inserts resulting from the grinding process are shown in Fig. 7. It can be seen that axial feed velocity, grain concentration of the grinding tool and the grain size of the abrasive as well as the interrelationship between grain size and grain concentration are the only parameters that have a significant or highly significant influence on flank face roughness. However, the results also show that the mentioned parameters influence different roughness parameters in different ways. The axial feed velocity for example only shows a significant influence on Rz. Since Ra and Rz are usually correlated and the analysis of the significance of the process parameters and grinding tool specifications takes into account the grinding results of all rocks, it is possible that this is a purely statistical result that does not necessarily indicate an effect valid for all rocks. Flint, for example, shows for a variation of the feed velocity roughness values between 0.71 and 0.96 µm for Ra and between 6.9 and 11.76 µm for Rz respectively, while Silver quartzite shows in the same cases roughness values between 0.99 and 1.86 µm for Ra and between 12.77 and 21.27 µm for Rz. Such differences between the results of the different rocks with regard to the influence of a parameter can lead to the calculation of *t*-values, which would show a significant influence purely statistically. Therefore, if no comparable influence is observed for parameters where a mutual correlation is to be expected, as in the case of Ra and Rz, it can be assumed that a potentially significant influence of one of these two variables is either due to a purely statistical effect or does not significantly influence the result in all cases considered. Besides the influence of v_{fa} on Rz, the potentially significant influence of the interrelationship between grain concentration and grain size ($C \cdot d_g$) on Ra is another example for such a case. In this case, the *t*-value for Ra is within the 99.0% confidence interval, while the *t*-value for Rz is below the 95.0% confidence interval, which can indicate that $C \cdot d_g$ has no significant influence on these two parameters. However, it is possible that v_{fa} and $C \cdot d_g$ influence Ra and Rz at the flank face for example by influencing the material removal mechanisms, the grain protrusion or the number of grains participating in the grinding process. Since this analysis ultimately looks at statistical probabilities and includes a large number of factors that can have very different effects on different rocks, it cannot be ruled out with conclusive certainty on the basis of this investigation that these parameters do not exert a significant influence on Ra and Rz for all the rocks considered.

Concerning the influence of the grain size of the grinding wheel on flank face roughness the results indicate a significant influence of this parameter on Ra and Rz. This can be explained by the correlation between grain protrusion and grain size. Larger grains can protrude further from the grinding wheel bond and thus penetrate deeper into the material to be machined, leaving deeper grinding grooves. This in turn leads to a higher surface roughness regardless of the rock being machined. Regarding the influence of the grain concentration on flank face roughness, a significant influence on Sa is observable. Since Sa is an area-related roughness parameter, it is to be assumed that a higher grain

Fig. 7 Significance of the process parameters for the flank face roughness



concentration influences the chance that an abrasive grain hits a roughness peak at the surface of the machined material and influences Sa by this. The previously mentioned correlation also explains the observed highly significant influence of $C \cdot d_g$ on Sa. A combination of a high grain concentration and a low grain size, for example, would lead to an increase in the probability of hitting a relevant number of roughness peaks in the machined area of the surface, while at the same time creating a low new surface roughness due to the comparatively low penetration depth of the small grains. In addition, a decrease in d_g at a constant or increased grain concentration increases the number of abrasive grains present in the grinding process, which supports the previous hypothesis.

The cutting edge roughness of the rock inserts is only influenced significantly by the axial feed velocity and the grain size of the grinding wheel as can be seen in Fig. 8. For axial feed velocity a highly significant influence on all investigated roughness parameters can be observed. This can be explained by an increase of single grain chip thickness and material removal rate and therefore increasing loads for an increase in feed velocity. Applying higher loads to the area around the cutting edge increases the probability of edge flaking effects and cutting edge chipping and leads therefore to an increase in cutting edge roughness. An example for this can be seen in the SEM-images of Silver quartzite inserts shown in Fig. 9. It can be seen that the increase of axial feed velocity from $v_{fa} = 4$ mm/min to 55 mm/min leads to a higher number of larger brittle outbreaks along the cutting edge and therefore to an increased cutting edge roughness.

Regarding the influence of the grain size of the grinding tool on cutting edge roughness, the *t*-values indicate a highly significant influence of d_g on Ra and Rp, while they place the influence of d_g on Rz within the 95.0% confidence interval and the influence of d_g on Rv below this interval. An influence of d_g on cutting edge roughness can be explained by its influence on single grain chip thickness and the contact conditions between abrasive grain and material. An increase of d_g is connected with an increase of single grain chip

Fig. 8 Significance of the process parameters for the cutting edge roughness

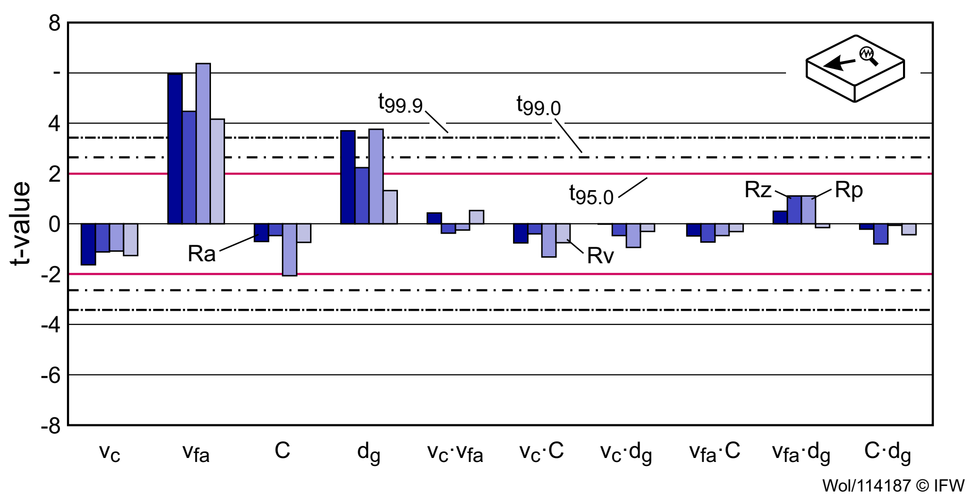
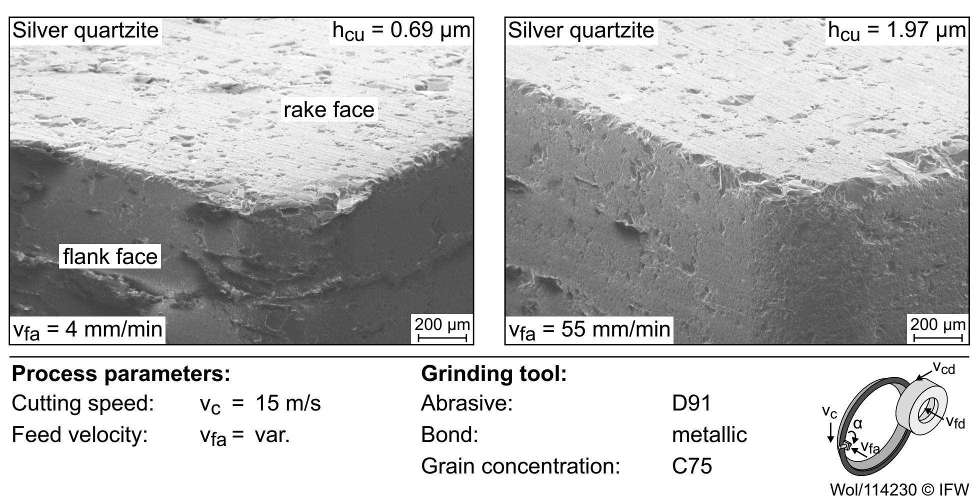


Fig. 9 Effect of an increase in axial feed velocity on cutting edge roughness for Silver quartzite



thickness, which means a higher penetration depth of the abrasive grain into the workpiece due to an increased grain protrusion. This can increase the mechanical load acting on the workpiece and increase the volume of material loaded by this grain. This, in turn, can favour cutting edge chipping in the area of the grain engagement and at the same time increase the size of the cutting edge area that is affected. This can ultimately lead to an increase in cutting edge roughness. The fact that the trajectory of the grain movement is not exactly parallel to the cutting edge due to the kinematics of the grinding process, which can cause the grain to enter or exit the cutting edge abruptly, can also contribute to this.

An example for the influence of an increase of d_g on cutting edge roughness and the abovementioned effects is shown in Fig. 10. It can be seen that the use of a higher grain size leads to a higher amount of larger cutting edge chipping. This is especially true for lamellar obsidian and quartz which tend to show larger shell-shaped ruptures along the cutting edge that extend into the rake face. The geometric shape of the cutting edge and the cutting edge chipping may also pose an explanation for the fact that d_g has a highly significant influence on Rp but not on Rv. Since the cutting edge roughness is determined along the cutting edge and, in this case, at an angle of 45° to the rake and the flank face, the material contact ratio increases disproportionately with the penetration depth into the material. This not only increases the load-bearing capacity of the material in the direction under consideration, which counteracts the formation of deeper chipping, but also shifts the profile centreline of the roughness measurement to a lower level, which tends to reduce the average valley depth and increase the average peak height. Since increasing the depth of the cutting edge chipping in the measuring plane of the cutting edge roughness thus requires increasingly stronger loads with increasing valley depth, it can be assumed that this limits Rv in this context. Taking into account additionally that cutting edge chipping correlates with the formation of new peaks along the cutting edge and that parts of the volume removed by the chipping can be located outside the measuring plane of the cutting edge roughness on the flank and rake face, these correlations can therefore provide an explanation for the discrepancy of the influence of d_g on Rp and Rv.

However, with regard to a conceivable influence on the cutting edge roughness in this context by a possible interdependency of d_g and v_{fa} ($d_g \cdot v_{fa}$) due to an increased load of the material at the cutting edge, no significant influence on the corresponding roughness parameters can be derived from the results. Besides that, the low *t*-values of all other possible interdependencies of the investigated parameters indicate that the parameters found to be significant for the cutting edge roughness can be varied independently from each other.

The results also show that both of the process parameters studied and the grinding tool specifications significantly influence the cutting edge microgeometry, as can be seen in Fig. 11. While v_{fa} shows a highly significant influence on S_α, S_γ and $\overline{S}$ with a tendency to increase them, v_c only shows a significant influence on S_α with a tendency to decrease it. Besides this, the *t*-value of $\overline{S}$ is with −2.57 close to the 99.0 confidence interval and therefore close to the significant regime. A similar influence on cutting edge microgeometry can be observed for the grain concentration of the grinding tool and d_g. While a highly significant influence of d_g on all three investigated parameters with a tendency to increase them can be observed, a significant influence on S_γ and $\overline{S}$ with a tendency to decrease these parameters can be observed for the grain concentration of the grinding tool. With regard to a possible influence of interdependencies between these four factors on cutting edge microgeometry no significant influences can be observed. This indicates that these four factors can be varied independently from each other to influence the cutting edge microgeometry.

Fig. 10 Effect of an increase in abrasive grain size of the grinding tool on cutting edge roughness for lamellar obsidian

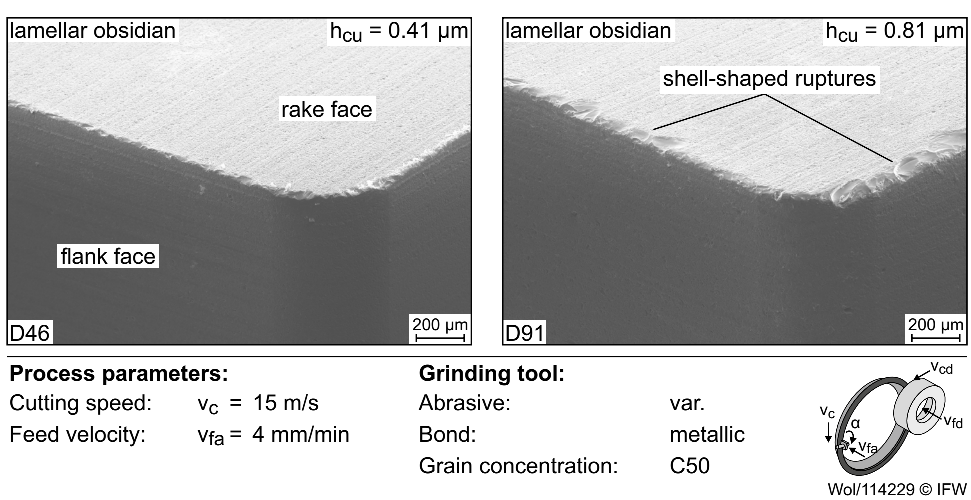
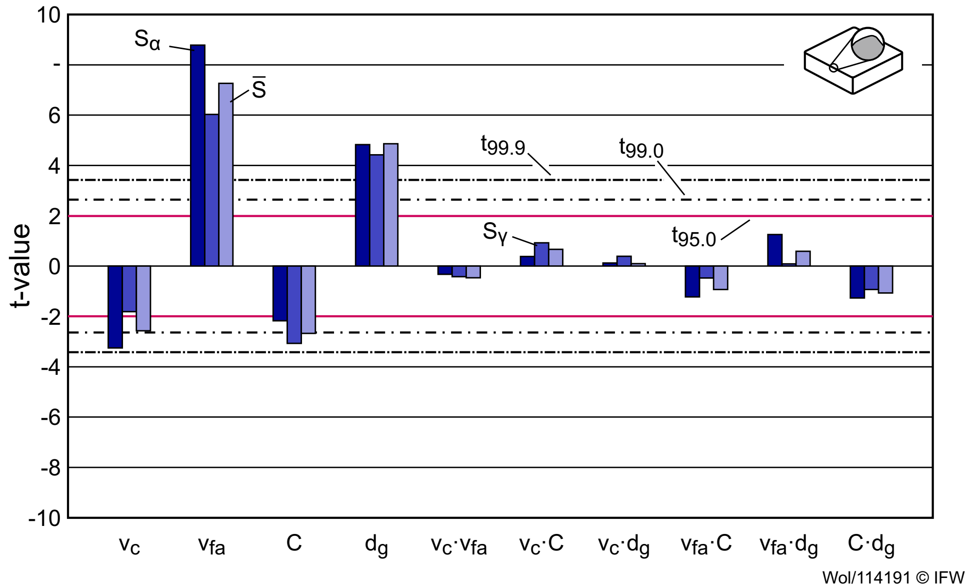


Fig. 11 Significance of the process parameters for the resulting cutting edge microgeometry



An explanation for the influence of the process parameters is their correlation with the single grain chip thickness and the process loads. Increasing v_{fa} leads to an increase in single grain chip thickness and material removal rate connected with a higher load of the workpiece and influences cutting edge chipping as mentioned above. Material removal in the vicinity of the cutting edge can influence the microgeometry of the cutting edge depending on the localisation and distribution of the separated material volume. It can therefore be assumed that an increase in the material removal rate due to the increase in v_{fa} and the associated increased load in the area of the cutting edge is the cause of the highly significant influence of v_{fa} on the cutting edge microgeometry. With increasing v_c, on the other hand, the single grain chip thickness decreases. However, since v_c, unlike v_{fa}, does not influence the material removal rate, it can be assumed that an increase of v_c primarily decreases the load on the individual abrasive grain and changes the load distribution on the abrasive grains and thus the material volume influenced by the abrasive grain. This, in turn, allows the hypothesis that the change of load distribution caused by a variation of v_c can, however, influence the distribution of material volume removed by chipping between rake and flank face and the volume of removed material in general. Assuming that a smaller volume of material is thus removed by each individual abrasive grain in the vicinity of the cutting edge, which can at the same time counteract the occurrence of brittle outbreaks in this area, this can explain the significant influence of the cutting speed on cutting edge microgeometry. The mentioned change of the distribution of removed material volume between rake and flank face can also contribute to this since this can influence the orientation of the cutting edge microgeometry. However, based on the results obtained up to this point, it can also be assumed that the influence of v_{fa} on cutting edge microgeometry and roughness is more pronounced than the influence of v_c.

The highly significant influence of d_g on cutting edge microgeometry is explainable considering the above mentioned correlations between d_g, grain protrusion and cutting edge roughness as well as cutting edge chipping. An increased amount of larger cutting edge chipping as a result of using a higher abrasive grain size can influence the cutting edge microgeometry depending on the geometric shape, volume and position of the chipping. The significant influence of the grain concentration of the grinding wheel on cutting edge microgeometry and the indicated tendency to decrease the respective parameters is explainable by the correlation of the grain concentration and single grain chip thickness as well as by its influence on load distribution between the single grains. A decreased single grain chip thickness caused by an increased number of grains as a result of a higher grain concentration can be beneficial for decreasing the size of the chips removed near the cutting edge and therefore influence the cutting edge microgeometry. Furthermore, the distribution of the process forces over a larger number of grains can influence the stress state induced into the material, which in turn can influence the size and geometry of chipping in the cutting edge area and thus the cutting edge microgeometry.

3.4 Design of tool grinding processes for rock tools

The previously gained knowledge about the significance of process parameters and grinding tool specifications is used in the following to develop recommendations for the design of tool grinding of rock inserts. Since all factors that can significantly influence the flank face roughness, the cutting edge roughness or the cutting edge microgeometry can be linked via the single grain chip thickness, it is to be assumed that this is a suitable starting point for the design of the grinding process, which will be considered in more detail below. An increase of single grain chip thickness by varying the process parameters and/or the grinding tool specifications leads to an increase in cutting edge roughness as exemplarily shown in Fig. 12 and Fig. 13.

It should be mentioned here that particularly with lamellar obsidian and quartz, there is an increased tendency towards the occurrence of shell-shaped ruptures at higher single grain chip thicknesses, which can also be seen in Fig. 13. Besides an increase in cutting edge roughness visible in the SEM-images, an increase in single grain chip thickness also influences flank face roughness as well as cutting edge microgeometry. An example for the influence of an increase in single grain chip thickness on the flank face topography and therefore the flank face roughness is given in Fig. 14 by confocal microscope images. Figures 15, 16, and 17 show the flank face roughness; the cutting edge roughness; and the cutting edge microgeometry of flint, quartz and Silver quartzite resulting from the grinding experiments as a function of the single grain chip thickness. The corresponding results of Alta quartzite and lamellar obsidian are not shown here for reasons of clarity and improved readability of the diagrams.

For all three factors investigated, a trend towards higher roughness values or a higher cutting edge rounding with increasing single grain chip thickness can be observed. In most cases considered, it can be seen that the highest values for the respective parameters are achieved for Silver quartzite, while the lowest values are achieved for flint. Alta quartzite and lamellar obsidian also show the described trends, with their parameter values ranging between those of Silver quartzite and flint. Even though the results of the grinding process differ for each rock due to their different material properties, the trends observed for the single grain chip thickness can still be used as a starting point for the

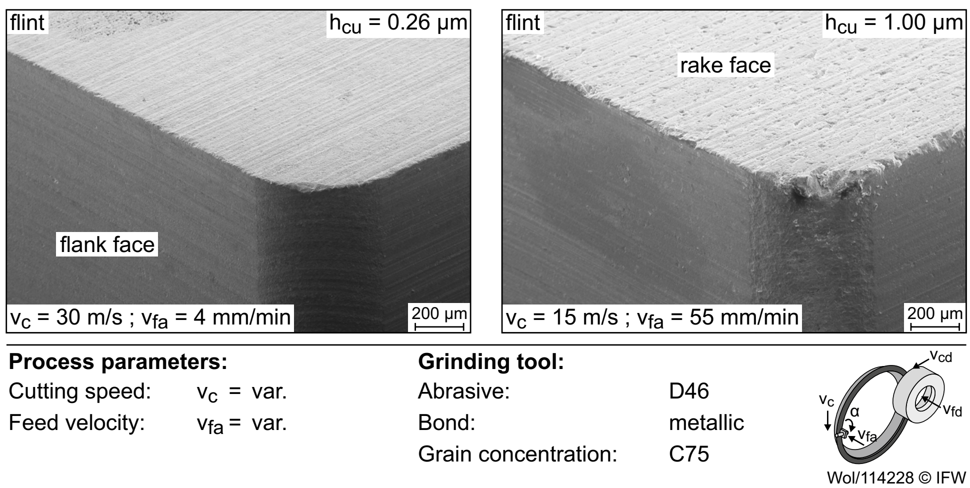


Fig. 12 Example for the effect of increasing single grain chip thickness by a variation of the process parameters on the grinding result of flint inserts

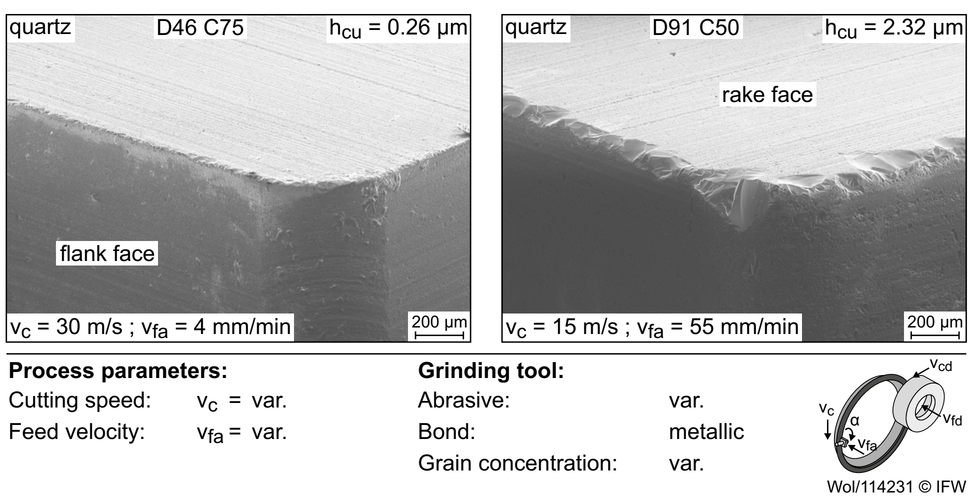


Fig. 13 Example for the effect of increasing single grain chip thickness on the grinding result of quartz inserts

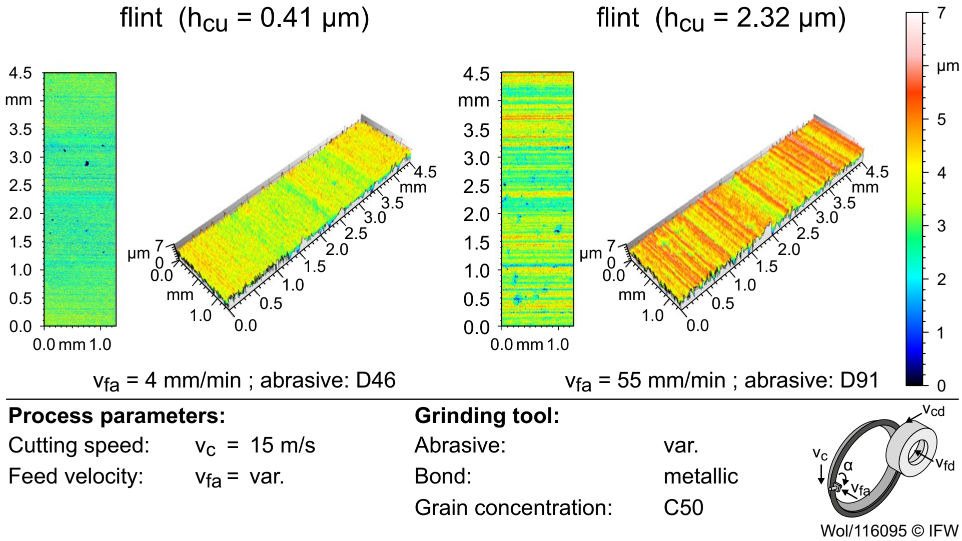


Fig. 14 Flank face topographies of flint inserts for different single grain chip thicknesses

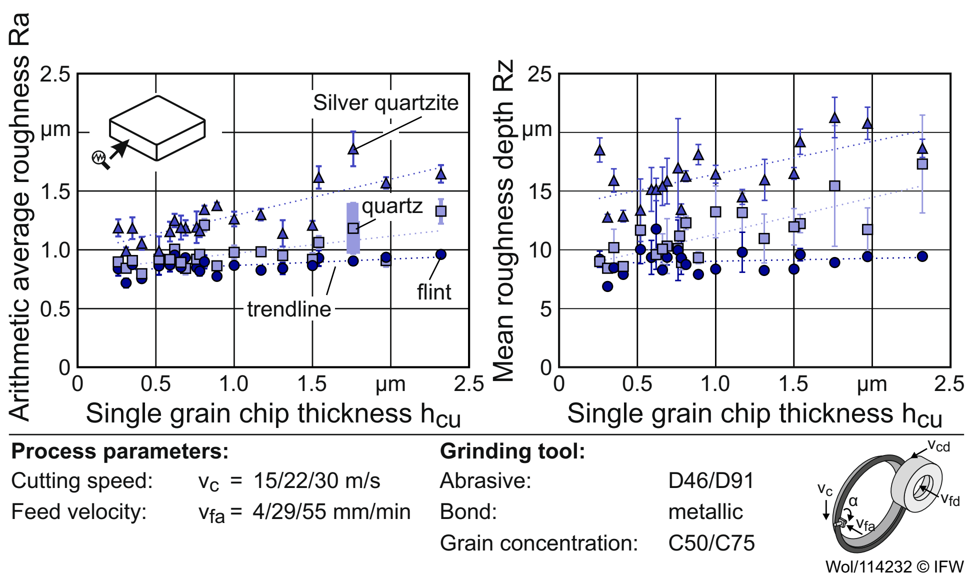


Fig. 15 Flank face roughness as a function of single grain chip thickness

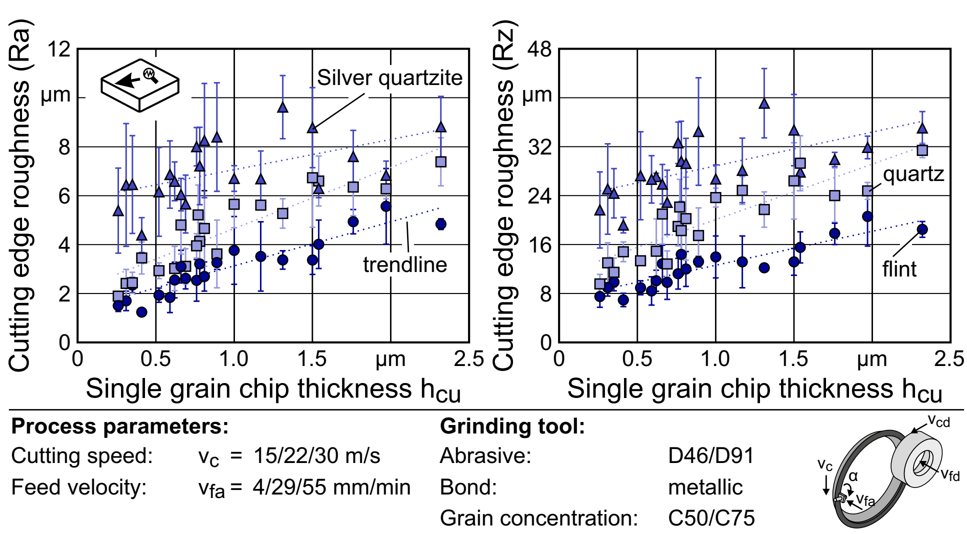


Fig. 16 Cutting edge roughness as a function of single grain thickness

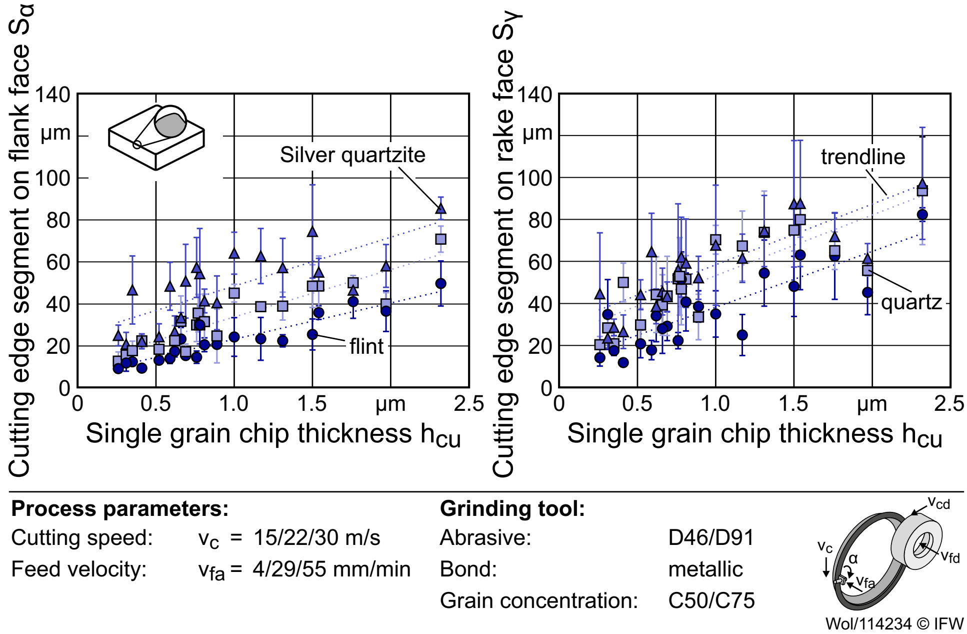


Fig. 17 Cutting edge microgeometry as a function of single grain chip thickness

design of the grinding process due to their comparable characteristics for the different rocks. When using this approach for the design of the tool grinding process of rock inserts, it is thus assumed that flank face and cutting edge roughness that occur during the process, as well as the cutting edge rounding, will be lower the lower the single grain chip thickness is selected. The use of the single grain chip thickness as a starting point for the design of the tool grinding process has the advantage that the process parameters and grinding tool specifications previously identified as significant can be used directly to set the single grain chip thickness to the desired value and thus simultaneously design the grinding process.

For the flank face roughness shown in Fig. 15, this means that a reduction of single grain chip thickness should be achieved in the design of the tool grinding process by decreasing the grain size of the grinding tool and by increasing its grain concentration since these are the parameters which have a significant influence on the flank face roughness. Since the process parameters do not significantly influence the flank face roughness, they do not have to be taken into account in this context as long as the choice of parameters does not lead to an excessive increase of single grain chip thickness. But it should be borne in mind that they also influence the cutting edge microgeometry and should therefore not be determined without taking these interrelationships into account.

With regard to the design of the grinding process to achieve a low cutting edge roughness (see Fig. 16), a reduction of single grain chip thickness should be achieved by using a reduced axial feed velocity and smaller abrasive grain sizes of the grinding wheel. Considering that a smaller abrasive grain size can also be beneficial for achieving a lower flank face roughness, it can be assumed that it is advisable to generally consider the use of smaller grain sizes as part of the design of tool grinding processes for rock inserts. However, reducing the axial feed velocity is connected with a reduction of the material removal rate and therefore the productivity of the tool grinding process. With regard to economic factors, a reduction of the axial feed velocity can therefore be disadvantageous. The conflict of objectives between the cutting edge quality of the rock insert and productivity of the tool grinding process must therefore be taken into account when designing the grinding process.

A reduction of single grain chip thickness by reducing axial feed velocity and abrasive grain size of the grinding tool can also be used in the design of the tool grinding process to achieve smaller cutting edge roundings (see Fig. 17). The same applies to a reduction of single grain chip thickness by increasing the grain concentration of the grinding tool. These measures to achieve lower cutting edge roundings can easily be combined during the design of the grinding process with the steps necessary to achieve a lower flank face and cutting edge roughness. If a higher cutting edge rounding is desired as a result of the grinding process, this can be achieved by dimensioning the corresponding parameters in the opposite direction. However, considering that the cutting edge roughness of the rock inserts can be comparatively high after the grinding process, it can be recommendable to consider the possibility of applying a cutting edge preparation process after grinding to achieve a cutting edge of high quality and with a reduced cutting edge roughness. In this case, it must be mentioned in the design process that the cutting edge rounding should not exceed the desired target value before it is given into the preparation process since most preparation processes are not able to decrease the cutting edge rounding. In cases which aim on reducing the cutting edge rounding without influencing cutting edge roughness or flank face roughness, it is recommended to reduce the single grain chip thickness by increasing the cutting speed. Since the cutting speed shows a significant influence on the cutting edge microgeometry but not on the other factors investigated, it is possible to influence the cutting edge microgeometry by varying the cutting speed without influencing the other factors significantly.

Taking the results obtained into account, it is therefore recommended, when designing the tool grinding process of rocks, to resort to a small grain size of the grinding tool and at the same time a high grain concentration. It is also recommended in this context to select the axial feed rate only as high as necessary to ensure the desired productivity of the grinding process in order to produce rock inserts with a low flank face and cutting edge roughness as well as a low cutting edge rounding. Considering the trend observed for these three parameters for an increase in single grain chip thickness and the range of single grain chip thickness commonly used in tool grinding processes, it is to be expected on the basis of the results that the use of a single grain chip thickness above $h_{cu} = 1$ μm does not offer any advantage. Although the use of higher single grain chip thicknesses offers the possibility to realise grinding processes with higher feed velocities and thus higher productivity, and although it is possible to achieve a preferential ductile material removal in tool grinding of rocks even with higher single grain chip thicknesses [32], the associated increase in cutting edge roughness represents an unfavourable reduction in tool quality that negates the advantages potentially achievable with this step.

Limiting the single grain chip thickness to 1 μm in the design process therefore limits the maximum of cutting edge roughness and rounding that can be achieved and thus the associated decrease in cutting tool quality. But at the same time, this provides a sufficiently large process window in which the process parameters and tool specifications can be varied to achieve a productive grinding process. With regard to the influence of the used rock on the results of the grinding process, it is recommended to design the grinding process specifically for the rock intended to be used. In this context, the results indicate that the use of fine grained rocks with a high structural cohesion are beneficial for the achievable grinding result and may allow the use of higher single grain thicknesses without decreasing the quality of the ground cutting tool compared to other rocks.

4 Conclusion

In this paper, the significance of the process parameters and the grinding tool specifications for the result of the tool grinding process of rock inserts are investigated as well as the scatter of such a process. The paper aims on improving the understanding of the tool grinding process of cutting tools made of rocks and to contribute to a knowledge-based design of these grinding processes. For this reason, the significance of rock type, cutting speed, axial feed velocity, abrasive grain size and grain concentration of the grinding tool for the flank face and cutting edge roughness as well as cutting edge microgeometry are investigated for five different rocks. Besides this, the scatter of the grinding result for a reference process is investigated. The flank face and cutting edge roughness as well as the cutting edge microgeometry are analysed using confocal and focus variation microscope besides SEM-images. Based on the results, the following conclusions are drawn:

- The rock used in the grinding process can have a highly significant influence of the grinding process result but does not necessarily have to. It is therefore beneficial to design the tool grinding process according to the rock to be machined to achieve optimal results.
- Axial feed velocity has a highly significant influence on cutting edge roughness and cutting edge microgeometry and tends to increase these factors. Cutting speed only influences the cutting edge microgeometry significantly and tends to decrease the cutting edge rounding.
- The grinding tool specifications show a significant influence on flank face and cutting edge roughness as well as on cutting edge microgeometry. While the abrasive grain size shows a significant or highly significant influence in all three factors with a tendency to increase them, grain concentration only shows a significant influence on flank face roughness and cutting edge microgeometry. However, the interdependency between these two parameters shows a highly significant influence on flank face roughness with a tendency to decrease it.
- The single grain chip thickness can be used to design the tool grinding process of rock inserts. The reason for this is that it connects all significant influence factors with each other with the exception of the used rock. The results show a trend to increased flank face and cutting edge roughness for higher single grain chip thicknesses. In this context, the results also indicate that using single grain chip thicknesses higher than $h_{cu} = 1$ μm is not advantageous.
- The scatter of the grinding results depends on the machined rock. The results show a scatter between

0.04 and 3.08 µm for flank face roughness, a scatter between 1.13 and 11.05 µm for cutting edge roughness and a scatter between 2.8 and 25.0 µm for cutting edge microgeometry, depending on the rock and parameter investigated.

- The results of this investigation establish two important fundamentals when grinding rock tools for the first time. Firstly, they enable a knowledge-based selection of process parameters and grinding tool specifications for the grinding of rock tools. Secondly, they also allow an estimation of reachable tolerances for these processes. This provides a basis for future investigations concerning the grinding of rock tools, especially for other cutting tool types like milling tools. Future investigations can use these results to further investigate the potential of rock tools and their manufacturing processes and provide by this a basis to allow a transfer of the use of natural rocks to industrial application.

Author contribution P. Wolters conducted the experiments, analysed the data and wrote the manuscript. He was also responsible for project administration together with B. Breidenstein. B. Breidenstein was responsible for funding acquisition and project supervision. He also reviewed and edited the manuscript in the writing process together with B. Denkena and B. Bergmann.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.
Disclaimer.
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