



Tool wear when using natural rocks as cutting material for the turning of aluminum alloys and plastics

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Abstract

The growing challenges regarding climate-neutral and resource-saving manufacturing technology is forcing research and development to work out new cutting tool alternatives since the production of conventional cutting materials requires rare raw materials and huge amounts of energy. Natural rocks could be such an alternative since they are available in large quantities worldwide, have a potentially suitable property profile, and do not require energy-intensive processes to make them usable as cutting material. However, according to the current state of knowledge, there are only a few studies on the usability and suitability of natural rocks as cutting materials for machining processes. Therefore, in this article, inserts made of natural rocks are ground and used in turning operations. Their operational behavior is then described by the occurring tool wear and workpiece surface roughness. The influence of different natural rocks, process parameters as well as cutting edge microgeometries is compared after the machining of aluminum alloys and plastic. In the end, this made it possible to define process and tool properties in which natural rocks have application potential.

Keywords Wear · Natural rocks · Cutting tools · Indexable inserts · Turning

1 Introduction

The manufacture of cutting tools from rocks has been carried out since the earliest days of human history [1], making the use of rocks as cutting tool material and the production of rock tools one of mankind's oldest ideas [2]. But the idea of using cutting tools made of rock in modern manufacturing processes is comparatively new, since rock as a cutting material has long been replaced by other materials such as metals throughout history. However, current challenges like climate change, scarcity of available resources or geopolitical tensions provide reasons to develop alternative cutting materials and make them usable for manufacturing processes, which in turn creates a reason to reconsider the use of rock as a cutting material in modern manufacturing processes. Disadvantages of modern cutting materials connected with the mentioned challenges are the high energy demand of their production associated with the emission

of climate affecting gases, for example in the production of cemented carbides [3] or PCD [4]. High and volatile prices of the needed raw materials like tungsten [5] or cobalt [6] as well as the concentration of these resources in only a few world regions are also a disadvantage of modern cutting materials. This concentration of resources can turn access to these resources into a political bargaining chip [7], or help finance conflicts in these areas [8]. For these reasons, constant efforts are being made to recycle these raw materials where possible as part of a circular economy [9] and to monitor their critical availability [10]. Natural rocks do not share these disadvantages as less energy is required to bring them to a state that makes them usable as cutting materials compared to conventional cutting materials [11] and because they are available in large quantities worldwide.

There is a wide body of literature which focusses on the characterization of rock properties [12]. Examples for the characterization of rock properties are the use of shore hardness scleroscopes [13], scratch tests [14] and indentation tests [15]. However, it is also reported in literature that not every characterization method is suitable for each field of application or transferable to other fields [16]. The machining of rocks and the corresponding material removal mechanisms have also been covered in literature.

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This includes for example investigations of the influence of pressure on material removal mechanisms [17] and the mechanics of rock cutting [18] as well as investigations of the forces and wear in milling [19], sawing [20] and wire-sawing [21] of rocks. The influence of rock properties [22], process parameters [23] and the process design in dependence of the rock characteristics [24] have also been studied in this context. Besides that, simulation-based investigations have been conducted to improve the understanding of rock fracture mechanics [25], rock chipping [26] and the interaction between rock and cutting tool [27].

The same cannot be said about tool grinding of rock tools and the application of rocks as cutting tools in manufacturing processes. However, recent investigations have done first steps in investigating the usability and suitability of natural rocks as cutting tool materials. In this context, these investigations showed that it is generally possible to use natural rocks like flint [28] and other rocks for the machining of an aluminum alloy, identified relevant rock properties for the use as cutting materials and proposed methods to characterize them [29]. Furthermore, it was found that the rock properties are linked with the process result of the tool grinding process of the rock tools [29]. The material removal mechanisms of rocks against the background of tool grinding have also been investigated. In the related study, the possibility to realize a mainly ductile material removal in the context of tool grinding of rock tools was investigated, and a potential process window suitable for carrying out the related processes was identified [30]. The possibility to machine another aluminum alloy and two copper alloys with cutting tools made of rocks has also been investigated as well as their operational behavior in these application cases [31]. The results of these studies showed that the operational behavior of rock tools have to be improved to allow their use in industrial applications. The results presented in [31] indicated that it could be possible to improve the operational behavior of rock tools by using higher cutting speeds combined with cutting fluids and an adjusted cutting edge microgeometry.

However, it has currently neither been investigated whether the use of higher cutting speeds combined with cutting fluids is advantageous when using rock tools nor has the manufacturing of cutting edge roundings on rock tools and their influence on the operational behavior of such tools. Due to this, it is currently unknown whether the operational behavior can be improved by these factors. Therefore, this study aims to improve the understanding of the operational behavior of rock tools and the influence of the above mentioned factors on it. This includes the identification of tool and process properties that are relevant for the use of rock tools and an improvement of their performance.

2 Experimental setup

2.1 Rock properties and manufacturing of the rock inserts

The rocks used in this investigation are flint, lamellar obsidian and quartz. The properties of these rocks have already been characterized in [30] and their hardness and critical bending strength are given in Table 1. Compared to a cemented carbide of ISO grade K (Hardness between 15.2 and 19.71 GPa, bending strengths from 3000 N/mm² up to more than 4000 N/mm²) the rocks are softer than the cemented carbide and have a lower bending strength. A DEMA WB 2000 rock saw and a Struers Discotom-10 cut-off grinding machine are used to cut samples with dimensions of 18 × 18 × 5.5 mm³ from the raw rocks, which are available as blocks and nodules. A 5-axis Blohm Profimat MC 407 grinding machine is subsequently used to grind the samples to a thickness of 4.76 mm in a two-step grinding process. Rough machining to a sample thickness of 4.78 mm is performed in the first step using a cutting speed of 30 m/s, a feed velocity of 3200 mm/min and a depth of cut of 20 μm. Finishing to a sample thickness of 4.76 mm is done in the subsequent step with the same cutting speed, a feed velocity of 200 mm/min and a depth of cut of 5 μm. A grinding wheel with metallic bond, diamond with a grain size of D46 as abrasive and a grain concentration of 4.4 ct/cm³ (C100) is used in both grinding steps.

The grinding of the indexable inserts from the rock samples is performed as a plunge face grinding operation on a Wendt WAC 715 Centro cutting insert grinding machine. A grinding wheel with metallic bond, diamond with a grain size of D46 and a grain concentration of 3.3 ct/cm³ (C75) is used to grind inserts of the type SNMN 120404 according to ISO 1832. The grinding process is performed with a cutting speed of 30 m/s and feed velocity of 29 mm/min. A Rhenus R-Oil HM7 low viscosity mineral oil is used as cutting fluid.

2.2 Cutting edge preparation and tool properties

In addition to the use of grinding sharp rocks, two different cutting edge microgeometries are applied to the tools. The

Table 1 Properties of the investigated rocks

Rock	Hardness (GPa)	Critical bending strength (N/mm ²)
Flint	9.57	57.66
Lamellar obsidian	8.29	38.28
Quartz	15.51	31.98

cutting edge preparation was carried out by means of robot-assisted brushing. A Kuka KR 16 robot equipped with a diamond brush with a grain size of 51 μm (ANSI #240) was used to perform the brushing process. The brushing angle ($\varphi_B = 16^\circ$), the cutting speed ($v_c = 25 \text{ m/s}$) and the brushing time ($t_B = 25 \text{ s}$) were kept constant in this process. The depth of cut a_p was varied between 0.05 mm in the first case and 0.25 mm in the second case. The cutting edge microgeometry was measured optically with an Alicona Infinite Focus G5 measurement device. The cutting edge microgeometry and cutting edge roughness were measured at the corner radius of the inserts and at the cutting edge segment directly adjacent to the corner radius. A Zeiss EVO 60 scanning electron microscope is also used to investigate the rock inserts.

2.3 Analyzing the operational behavior

The operational behavior of the rock tools is analyzed in experimental turning tests. The occurring tool wear was recorded and evaluated with the aid of a Keyence VHX600 digital microscope. In addition, the surface roughness of the workpiece was documented using a Hommel W5 mobile roughness tester. The investigations are carried out on a Gildemeister CTX520 lathe with a constant rake angle of $\gamma = -6^\circ$ and a clearance angle of $\alpha = 6^\circ$. The feed rate $f = 0.1 \text{ mm}$ and the depth of cut $a_p = 0.5 \text{ mm}$ are also constant. The operational behavior of the three rocks are compared under the variation of the cutting speed when machining the aluminum alloys EN AW 5754 and EN AW 2007 as well as the plastic POM-C. The initial diameter of each aluminum workpiece is 150 mm. The initial diameter of each POM-C workpiece is 180 mm. All workpieces have a length of 200 mm. The material properties are listed in Table 2. Tool wear and workpiece roughness are checked during the machining of the aluminum alloys in each case after a feed path of 400 mm. When machining POM-C, tool wear and workpiece roughness are checked in each case after a feed path of 2000 mm. Workpiece roughness is checked at three points of the workpiece in each case. All tools are used to machine a cutting length of up to 5,600 m in the case of the aluminum alloys and up to a cutting length of 31,200 m in the case of machining POM-C. In terms of the geometry of the workpieces, this corresponds to six times the complete

machining of the aluminum workpieces and thirty times the complete machining of the POM-C workpieces. Besides this, the turning experiments are stopped if cutting edge chipping occurs.

Based on previous findings on the use of rock tools in aluminum machining [31], the operational behavior at cutting speeds of 1000 and 1500 m/min is investigated. As suggested in [31], preliminary investigations are carried out in order to determine whether the use of cutting fluid is possible in turning processes with rock inserts. For this purpose, the tool wear of flint when machining EN AW 2007 with $v_c = 1000 \text{ m/min}$ is compared with and without the use of a cutting fluid. In Fig. 1, the differences are clearly visible on the flank face of the cutting edge. Without the addition of cutting fluid, there is adhesion of the aluminum to the cutting edge. With the addition of cutting fluid, this effect is significantly reduced. Here, too, slight adhesions occur in the lower area of the wear mark width, but these are much less pronounced. Adhesions on the cutting edge itself no longer occur when cutting fluid is added. In addition to these clearly recognizable differences, the use of cutting fluid also leads to a decrease in the width of flank wear land and the crater wear, which results in a longer tool life of the rock tools. Therefore, the subsequent aluminum machining is carried out using cutting fluid.

In addition, the use of rock tools for machining the plastic POM-C is analyzed. Due to the properties of the plastic, high cutting speeds lead to melting of the workpiece on the tool. For this reason, the cutting speed is reduced to 500 m/min when machining plastics. The use of cooling lubricants is not advisable for machining plastics, since the chips stick to the emulsion and impede the chip flow as a result. All investigations were repeated once.

3 Results and discussion

3.1 Cutting edge geometry

The grinding results show a comparatively high average cutting edge rounding \bar{S} of 40 μm with an average K-factor of 1.02 ± 0.30 for flint, of 1.08 ± 0.23 for quartz and of 1.03 ± 0.30 for lamellar obsidian after grinding combined with micro chipping along the cutting edge as can be seen in Fig. 2 for flint. This leads to a cutting edge roughness of the rock inserts between 1.1 and 1.6 μm for Ra and 3.3 and 4.4 for Rz as can be seen in Fig. 3. Besides this, it is likely that this also contributes to the observed deviation of the orientation of the cutting edge microgeometry indicated by the standard deviation of the K-factor. The brushing process increases \bar{S} to values of 60 or 200 μm (see Fig. 2) and also influence the K-factors of the cutting edge microgeometry. Brushing with $a_p = 0.05 \text{ mm}$ results in an \bar{S} of 60 μm and an

Table 2 Workpiece properties

Designation	$R_m \text{ (N/mm}^2\text{)}$	Hardness	$\rho \text{ (g/cm}^3\text{)}$	$\lambda \text{ at } 20^\circ\text{C W/mK}$
EN AW 2007	340	150HB	2.85	145
EN AW 5754	230	45HB	2.67	150
POM-C	–	81shore	1.39	0.31

Fig. 1 Influence of the use of cutting fluid on the tool wear of rock inserts

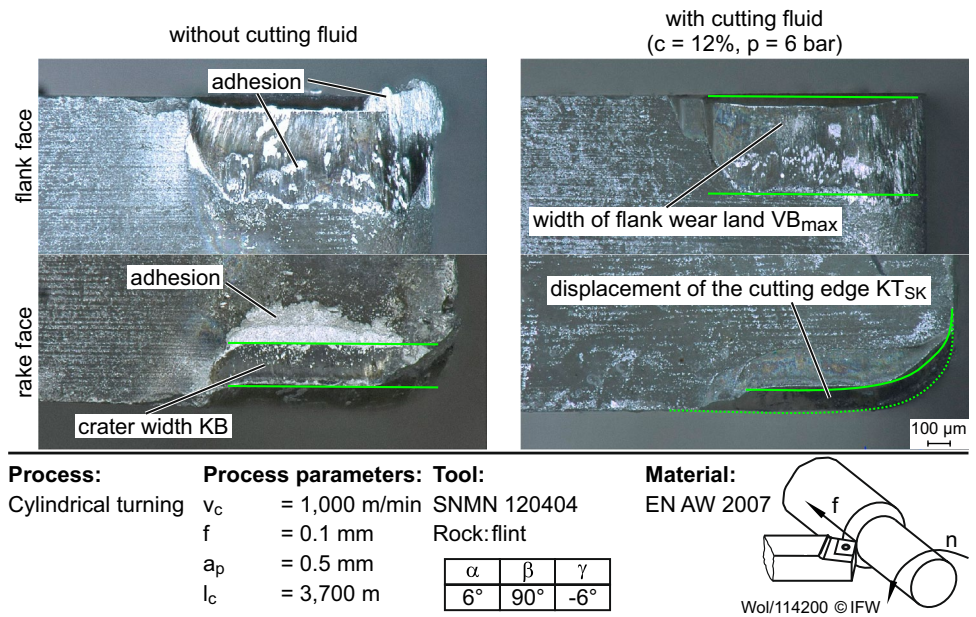
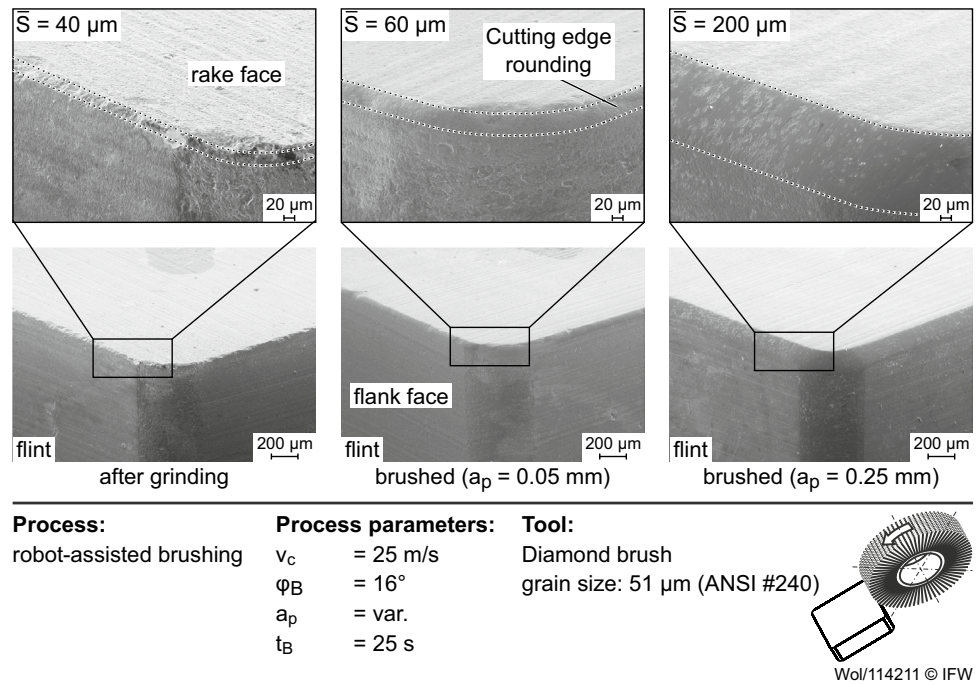


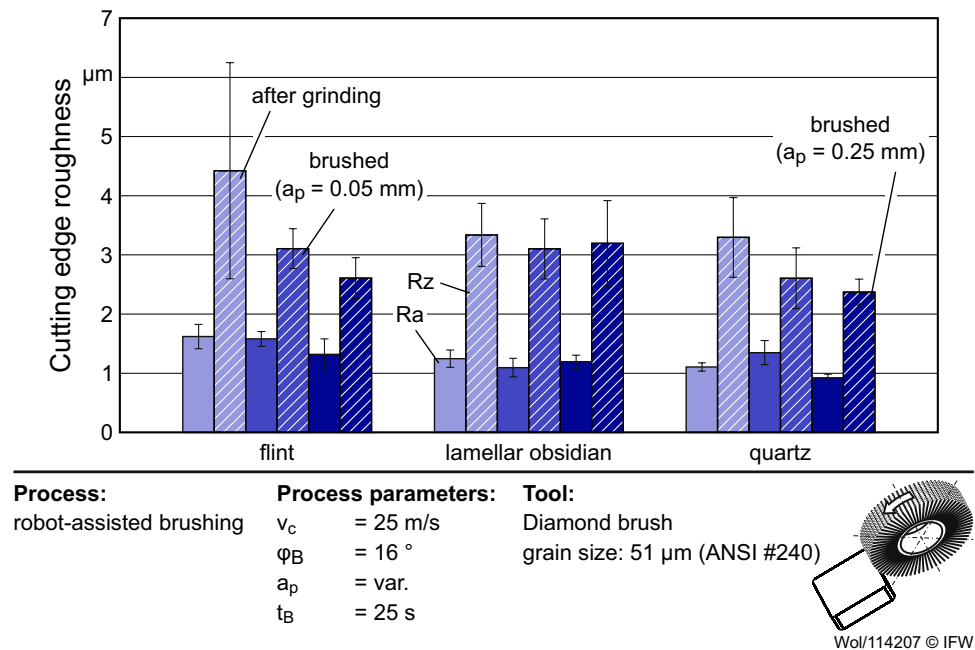
Fig. 2 SEM-images of the cutting edge of flint inserts after grinding and brushing



average K-factor of 0.92 ± 0.26 for flint, an average K-factor of 0.87 ± 0.13 for quartz and of 0.89 ± 0.27 for lamellar obsidian. Brushing with $a_p = 0.25 \text{ mm}$ results in an \bar{S} of $200 \mu\text{m}$ and an average K-factor of 0.95 ± 0.15 for flint, an average K-factor of 0.86 ± 0.19 for quartz and of 0.76 ± 0.12 for lamellar obsidian. Taking into account the standard deviation of the K-factor, it is therefore not possible to conclude with certainty from the results whether and to what extent the brushing process influences the orientation of the cutting edge microgeometry.

But the brushing process also reduces the cutting edge roughness (see Fig. 3). The reason for this is that the brushing process smoothes out the chipping that occurred along the cutting edge during grinding by removing the roughness peaks, thus producing a more even cutting edge (see Fig. 2) with lower cutting edge roughness. However, this effect is more pronounced for flint and quartz than for lamellar obsidian. The different material properties and the differences in the material structure are conceivable reasons for this observation. In the case of flint, a reduction of the cutting edge roughness can be achieved by the removal of

Fig. 3 Cutting edge roughness of the rock inserts



individual small mineral grains from the microstructure, which is favored by its fine-grained microstructure and its comparatively high bending strength. At the same time, its comparatively high critical bending strength counteracts the breakout of larger mineral grain agglomerates or the formation of larger chipping and thus a renewed increase in cutting edge roughness. In the case of lamellar obsidian, a similar mechanism is not to be expected due to its amorphous structure. If, as a result of brushing, the material removal is not locally mainly ductile, the local formation of shell-shaped ruptures typical for this rock is to be expected, which tends to increase cutting edge roughness. The formation of this local chipping is additionally favored by the lower critical bending strength compared to flint and the resulting lower load-bearing capacity of the microstructure. The different hardness of the two rocks represents a further explanation in this context. The softer the rock, the more likely it is that the brushing tools will leave deeper scratch marks in the cutting edge area in the cutting direction of the brushing process. These in turn can increase the cutting edge roughness. It is therefore conceivable that the brushing process leaves deeper scratch marks in the cutting edge area of the softer lamellar obsidian than it is the case for flint. This means that when comparing the two rocks, a significant reduction in cutting edge roughness of the lamellar obsidian as a result of the brushing process may be absent because of these relationships. But more specific investigations focusing on the cutting edge preparation of rock tools are needed to clarify the causes of this phenomenon beyond doubt. The results also show that the use of a higher brushing depth leads to a higher \bar{S} and a lower cutting edge roughness of the rock inserts. However, the results show that it is possible to

systematically apply cutting edge roundings to rock inserts by means of a brushing process and thus reduce their cutting edge roughness.

3.2 Operational behavior of natural rocks as cutting tools

When the soft aluminum alloy EN AW 5754 is machined at $v_c = 1000$ m/min and with the use of coolant, the material adhesion to the rock tools is significantly changed, which allows the tools to be used longer. Figure 4 shows the tool wear of quartz and flint tools with a rounded cutting edge radius of $\bar{S} = 40$ and 60 µm, respectively. It can be seen, that only a low amount of adhesions to the rocks occur. This is beneficial since this prevents the formation of built-up edges and corresponding outbreaks at the cutting edge if such built-up edges are detached from the cutting edge after their formation. But it can also be seen in Fig. 4 that the grinding sharp cutting edge of the quartz inserts breaks because of mechanic overloads. When \bar{S} is increased to 60 µm, the quartz cutting edge is able to withstand the process loads as a result of a better load distribution. However, slight adhesions occur due to the larger roundings. When using flint, neither cutting edge chipping nor significant adhesions occur at $\bar{S} = 40$ nor at 60 µm. These tools only show a notch at the transition area between the engaged and disengaged areas of the cutting edge. It is possible that the change in the load situation in this area leads to the creation of an unfavorable stress state, which facilitates brittle outbreaks and therefore notch wear at this point of the cutting edge.

When AW 5754 is machined with lamellar obsidian, the cutting edge breaks out for an \bar{S} of 40 and 60 µm (see

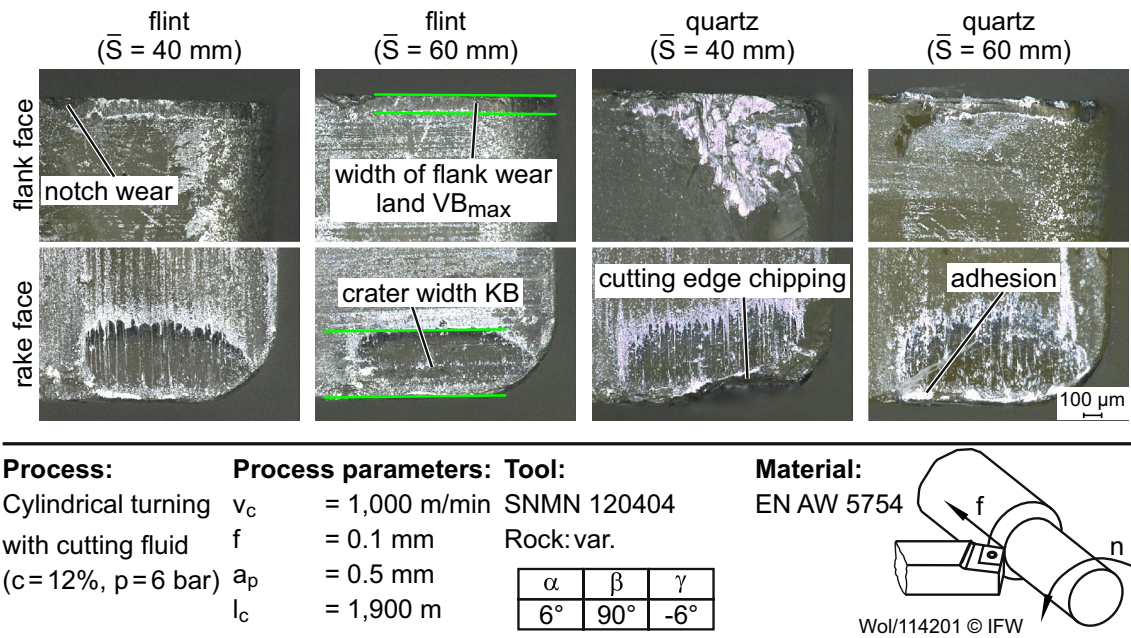


Fig. 4 Tool wear of rock inserts when machining aluminum

Fig. 5 Tool wear of obsidian inserts when machining aluminum

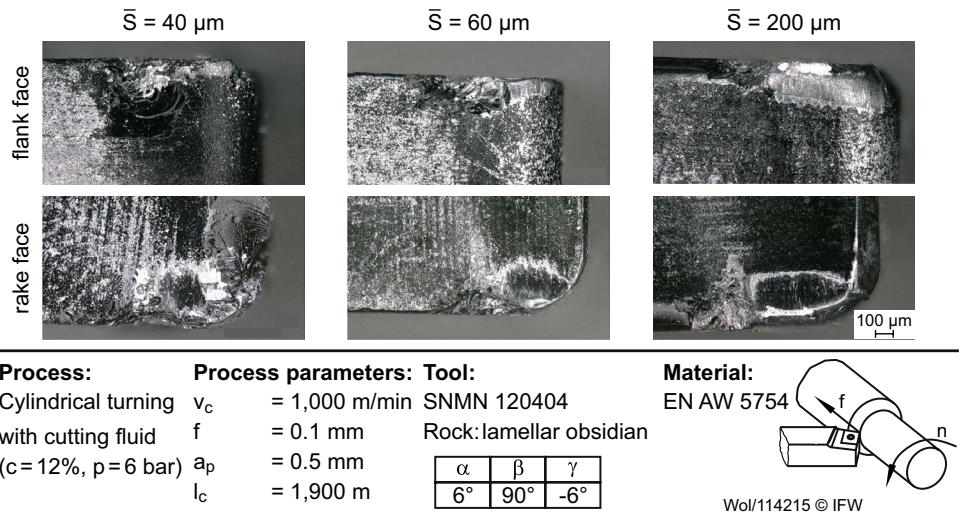
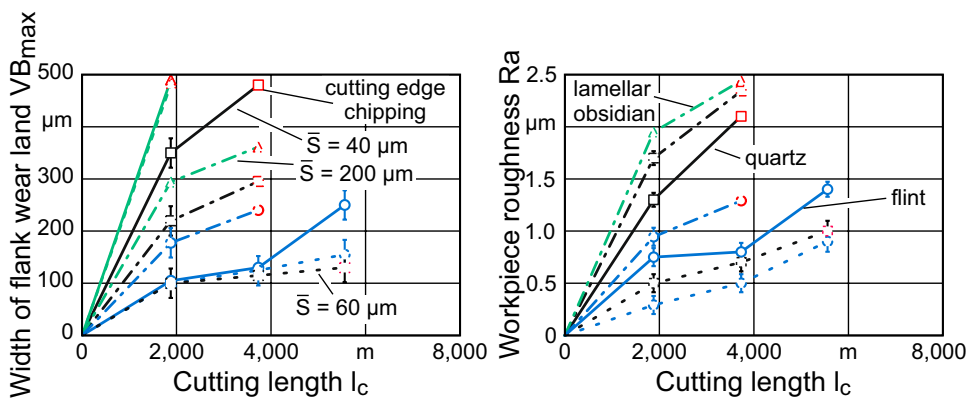


Fig. 5). Only with an \bar{S} of 200 μm no initial breakouts occur and the tool can be used up to a cutting length of $l_c = 1900$ m. This is also illustrated in Fig. 6, which shows the width of flank wear land VB_{max} as well as the workpiece roughness during turning with the different tools over the cutting length l_c . However, when an \bar{S} of 200 μm is applied to flint or quartz, adhesion is increased and the tools cannot be used for a cutting length further than 3700 m. It can be assumed that the increased amount of adhesion for an \bar{S} of 200 μm supports the formation of built-up edges and therefore chipping of the rock inserts (see Fig. 7, upper right).

Besides that, it is likely that the use of an \bar{S} of 200 μm in combination with the used feed leads to ploughing which can also influence the wear behavior of the inserts. At the same time, the large cutting edge microgeometry in combination with the adhesions leads to a poor workpiece surface with a roughness of up to $Ra = 2.3$ μm (see Fig. 6). In contrast, the longest cutting length of 5600 m can be completed with the $\bar{S} = 60$ μm rounding for quartz and flint. Besides that, the reduction in cutting edge roughness also leads to the lowest workpiece roughness Ra of approx. 1 μm . Thus, the cutting edge preparation of the tools leads to an improved operational behavior of these rock tools.

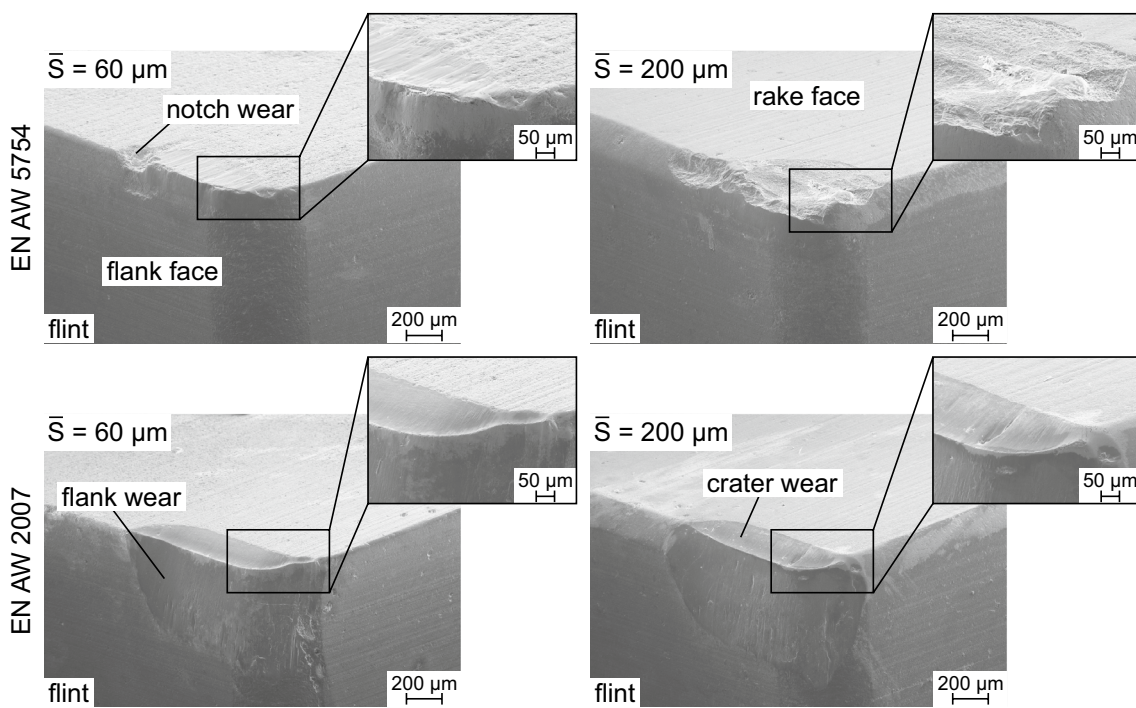
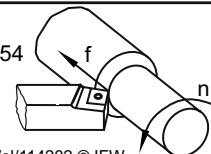
Fig. 6 Progress of tool wear and workpiece roughness over the cutting length during aluminum machining with a cutting speed of 1000 m/min



Process: Cylindrical turning with cutting fluid (c = 12%, p = 6 bar)
Process parameters: v_c = 1,000 m/min, f = 0.1 mm, a_p = 0.5 mm, l_c = var.
Tool: SNMN 120404, Rock: var.

α	β	γ
6°	90°	-6°

Material: EN AW 5754



Process: Cylindrical turning with cutting fluid (c = 12%, p = 6 bar)
Process parameters: v_c = 1,000 m/min, f = 0.1 mm, a_p = 0.5 mm, l_c = 1,900 m
Tool: SNMN 120404, Rock: flint

α	β	γ
6°	90°	-6°

Material: EN AW 5754, EN AW 2007

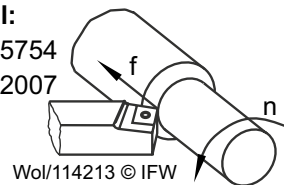


Fig. 7 Wear of flint inserts with different cutting edge roundings in machining different aluminum alloys

The same effects and cutting lengths also occur when machining the harder aluminum alloy EN AW 2007 with the same cutting speed. In this case, there is only higher

abrasive wear instead of material adhesion and therefore a higher width of flank wear (see Fig. 7). The width of flank wear land is in most cases between two to three

times higher for the machining of EN AW 2007, which is in a similar range as the difference between the hardness of the two machined aluminum alloys. A direct correlation between the amount of abrasive wear of these rock inserts and the hardness of the material is therefore conceivable but further specified investigations should be conducted to confirm these hypothesis and to determine the exact nature of this possible correlation. Although the inserts show a higher abrasive wear in machining EN AW 2007, it must be mentioned that the flint and quartz inserts show a lower tendency for cutting edge chipping in this case. The lower amount of cutting edge chipping can be attributed to the lower amount of adhesion and the corresponding formation of built-up edges since rock inserts are sensitive to shear stresses [29]. The formation of built-up edges can change the local material flow and corresponding alignment of process loads leading to the induction of shear stresses. The break-out of built-up edges would also contribute to this. The mentioned change of load directions and the inducement of shear stresses may also pose an explanation for the partly higher wear of the inserts for higher \bar{S} .

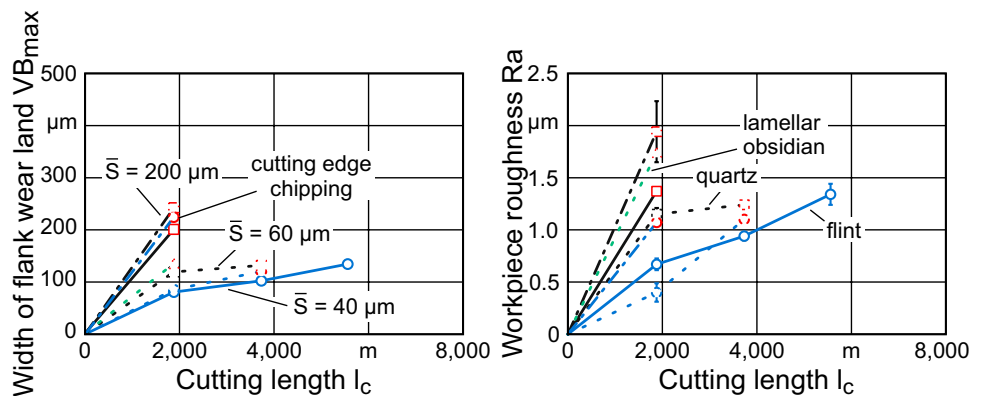
Since abrasive wear and adhesions could be identified as relevant factors for the wear of the rock inserts it is conceivable that the operational behavior of rock inserts can be enhanced by a coating as it is already known for conventional cutting tool materials. However, since it is currently unknown whether it is possible to apply conventional tool coatings to rock inserts or how these coating processes must be designed, this approach remains hypothetical until appropriate investigations can demonstrate the feasibility of coating rock tools.

Increasing the cutting speed to 1500 m/min leads to a decrease of the maximal cutting length which can be machined with the rock inserts, as can be seen in Fig. 8.

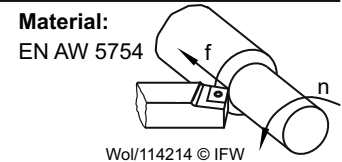
It is conceivable that the increase in cutting speed leads to higher thermal loads and therefore to an increase of the temperatures of the rock inserts and a decrease of the critical bending strength of the rocks as mentioned in [30]. This could in turn favor cutting edge chipping if the load-bearing capacity of the rocks is exceeded, since the critical bending strength can be used as a measure of the load-bearing capacity and structural cohesion of the rocks. However, it must be mentioned that rocks tend to be poor conductors of heat. It can therefore not be ruled out that other factors are significant for the observed operational behavior. Only flint and quartz with an \bar{S} of 40 and 60 μm are able to withstand these increased process loads and to machine cutting lengths higher than $l_c = 1900$ m. As before, the same trends and reachable cutting lengths can be identified for EN AW 2007 and for EN AW 5754. But it must be mentioned that it is not possible to machine EN AW 2007 with obsidian inserts using this cutting speed since the cutting edges of these inserts break out shortly after contact with the workpiece. The lower wear of inserts with lower cutting edge rounding suggests that decreasing the cutting edge rounding could be beneficial for machining aluminum with rock tools at higher cutting speeds. But since the initial cutting edge rounding is defined by the grinding process, a knowledge based improvement of the tool grinding process is necessary to achieve lower cutting edge roundings.

However, the results show that it is possible to use the rock inserts for the machining of different aluminum alloys. The achievable cutting lengths are up to 5600 m, which corresponds to a cutting time of 336 s per cutting edge in this case. Consequently, quartz and flint tools can be used as cutting materials for aluminum machining with adapted process parameters and by means of cutting edge preparation.

Fig. 8 Progress of tool wear and workpiece roughness over the cutting length during aluminum machining with a cutting speed of 1500 m/min



Process:	Process parameters:	Tool:						
Cylindrical turning	$v_c = 1,500$ m/min	SNMN 120404						
with cutting fluid	$f = 0.1$ mm	Rock: var.						
($c = 12\%$, $p = 6$ bar)	$a_p = 0.5$ mm							
	$l_c = \text{var.}$							
		<table border="1"> <tr> <td>α</td> <td>β</td> <td>γ</td> </tr> <tr> <td>6°</td> <td>90°</td> <td>-6°</td> </tr> </table>	α	β	γ	6°	90°	-6°
α	β	γ						
6°	90°	-6°						



Plastic machining results in lower process forces and tool loads, which may increase the potential of rock tools. The wear mechanisms of quartz and flint tools with different cutting edge roundings are compared in Fig. 9. After a cutting length of $l_c = 11,000$ m, the tools with $\bar{S} = 60$ μm show a width of flank wear land of 90 μm for flint and 190 μm for quartz. If the grinding-sharp tools ($\bar{S} = 40$ μm) are used, the quartz and the lamellar obsidian tool cannot withstand the process loads and break out. The flint tool, on the other hand, does not show any breakouts even without cutting edge preparation.

Comparing the operational behavior, the flint tools with roundings of $\bar{S} = 40$ μm and 60 μm show again the lowest wear and the best surface finish with $R_a = 1.2$ μm (see Fig. 10). In this case, too, the tools with an \bar{S} of 200 μm tend to show higher wear than the other inserts. It is conceivable that this can be attributed to the same mechanisms as for the machining of aluminum. This result indicates that when using rock inserts for machining plastics, the use of smaller cutting edge roundings is more advantageous for the operational behavior. Besides this, tool wear and roughness are comparable to aluminum machining, with the exception

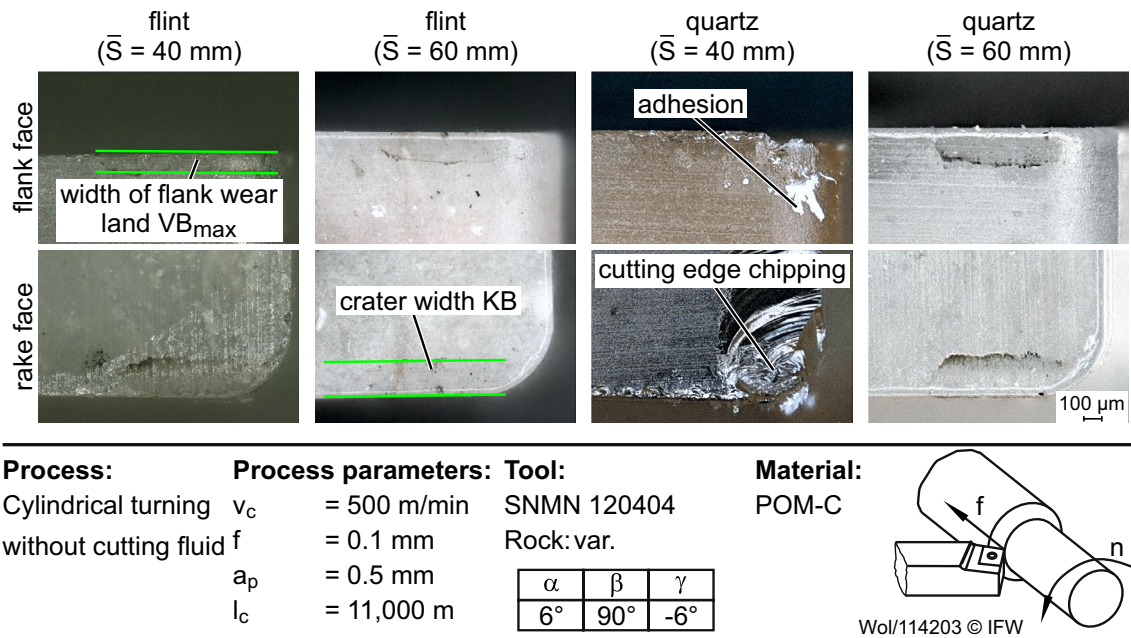
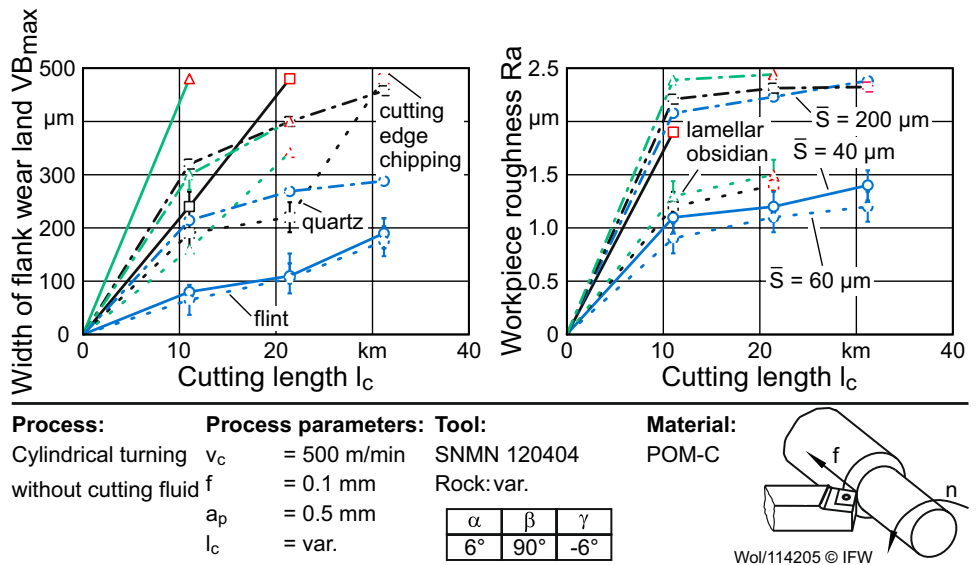


Fig. 9 Tool wear of rock inserts when machining plastic

Fig. 10 Progress of tool wear and workpiece roughness over the feed path during plastics machining



that the cutting length is increased by a factor of approx. five. Regarding the cutting time this corresponds in this case to cutting times per cutting edge of up to 62 min and 24 s. This confirms the applicability of rock tools in plastics machining.

Overall, flint performs best as a cutting material due to its advantageous combination of hardness and toughness. Besides the flint tools, quartz tools can also be suitable as cutting material if the cutting edge chipping is reduced after the grinding process. Furthermore, it becomes clear that these rocks are suitable for the machining of softer and non-metallic materials like plastics. The results of this investigation allow an estimation of the usability of rocks for the presented applications, the influence of the cutting edge geometry on the operational behavior and the potentially achievable tool life of the rock inserts. Furthermore, they suggest that cutting materials made of flint or rocks with similar properties can offer an alternative to conventional cutting materials for the machining of plastics or soft aluminum alloys. However, the results also suggest that further performance improvements are possible for the rock inserts. Approaches to realize such improvements could be an improvement of the grinding and cutting edge preparation process to achieve smaller or application specific designed cutting edge roundings. An optimization of the design of the turning process as well as of the insert geometry could also pose a further possibility to enhance the performance of rock inserts.

4 Conclusion

In the contribution presented, the tool wear of cutting tools made of natural rocks was investigated. For this purpose, turning tests were carried out for machining aluminum alloys and plastics. Based on the results shown, the following conclusions can be drawn:

- Using adapted process parameters and cooling strategies enables highly productive cutting of aluminum alloys and plastics with natural rocks as cutting tool. It enables the realization of turning processes of aluminum alloys with cutting speeds of up to 1500 m/min and of 500 m/min for plastics with cutting times of up to 336 s for aluminum and of up to 62 min and 24 s for plastics for each cutting edge.
- A cutting edge preparation of rock inserts offers an approach to reduce the cutting edge roughness (by up to 1.8 μm for R_z) and improve the stability of the cutting edge. These two factors can improve the operational behavior of the rock inserts. This can be seen in

the decrease of R_a of up to 0.5 μm and in $\sqrt{VB_{\max}}$ of up to 95 μm when using a cutting edge with an \bar{S} of 60 μm .

- Smaller cutting edge roundings with a low cutting edge roughness can be beneficial for the operational behavior of rock inserts as can be seen by comparing the operational behaviour of the inserts with an \bar{S} of 60 and 200 μm . The optimization of grinding and cutting edge preparation processes offers potential for further performance improvements of rock inserts.
- Adhesion and abrasive related wear mechanisms determine the wear behavior of the rock inserts if adequate process loads are applied. The results of the investigation indicate a proportional increase in abrasive wear for an increase in the hardness of the workpiece.
- Softer materials tend to lead to more adhesion related wear of the rock inserts, especially when a higher cutting edge rounding is used. This can lead to a reduction of the usable cutting time of each cutting edge of up to 114 s in machining EN AW 5754.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that the authors have no competing interests to declare that are relevant to the content of this article.

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References

1. Semaw S, Renne P, Harris JWK, Feibel CS, Bernor RL, Fesseha N, Moberly K (1997) 2.5-million-year-old stone tools from Gona, Ethiopia. *Nature* 385:333–336. <https://doi.org/10.1038/385333a0>

2. Roche H, Delagnes A, Brugal J-P, Feibel C, Kibunjia M, Murre V, Texier J-P (1999) Early hominid stone tool production and technical skill 2.34 Myr ago in West Turkana, Kenya. *Nature* 399:57–60. <https://doi.org/10.1038/19959>
3. Furberg A, Arvidsson R, Molander S (2019) Environmental life cycle assessment of cemented carbide (WC-Co) production. *J Clean Prod* 209:1126–1138. <https://doi.org/10.1016/j.jclepro.2018.10.272>
4. Furberg A, Fransson K, Zackrisson M, Larsson M, Arvidsson R (2020) Environmental and resource aspects of substituting cemented carbide with polycrystalline diamond: the case of machining tools. *J Clean Prod* 277:123577. <https://doi.org/10.1016/j.jclepro.2020.123577>
5. Liedtke M, Schmidt M (2014): Rohstoffrisikobewertung—Wolfram. DERA Rohstoffinformationen 19, Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Berlin
6. Al Barazi S (2018) Rohstoffrisikobewertung—Kobalt. DERA Rohstoffinformationen 36, Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) Berlin
7. Werner ABT, Sinclair WD, Amey EB (2014) International strategic mineral issues summary report—Tungsten (Ver. 1.1, November 2014): U.S. Geological Survey Circular 930-O. U.S. Department of the Interior, Reston, VA
8. Young SB (2018) Responsible sourcing of metals: certification approaches for conflict minerals and conflict-free metals. *Int J Life Cycle Assess* 23:1429–1447. <https://doi.org/10.1007/s11367-015-0932-5>
9. European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Bobba S, Claudiu P, Huygens D et al (2018) Report on critical raw materials and the circular economy, Publications Office. <https://doi.org/10.2873/331561>
10. European Commission (2017) Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions on the 2017 list of critical raw materials for the EU; Brussels
11. Schmieder P (2007) Anwendung und Weiterentwicklung der Methodik der Umweltbilanzierung beim Abbau von Festgestein. Dr.-Ing. Dissertation, Technische Universität Bergakademie Freiberg
12. Ulusay R, Hudson JA (eds) (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. International Society for Rock Mechanics, Salzburg
13. Altindag R, Güney A (2006) ISRM suggested method for determining the shore hardness value for rock. *Int J Rock Mech Min Sci* 43:19–22. <https://doi.org/10.1016/j.ijrmmms.2005.04.004>
14. Richard T, Dagrain F, Poyol E, Detournay E (2012) Rock strength determination from scratch tests. *Eng Geol* 147–148:91–100. <https://doi.org/10.1016/j.enggeo.2012.07.011>
15. Kalyan B, Murthy ChSN, Choudhary RP (2015) Rock indentation indices as criteria in rock excavation technology—a critical review. *Procedia Earth Planet Sci* 11:149–158. <https://doi.org/10.1016/j.proeps.2015.06.019>
16. Meng F, Wong LNY, Zhou H (2021) Rock brittleness indices and their applications to different fields of rock engineering: a review. *J Rock Mech Geotech Eng* 13:221–247. <https://doi.org/10.1016/j.jrmge.2020.06.008>
17. Garner NE (1967) Cutting action of a single diamond under simulated borehole conditions. *J Pet Technol* 19:937–942. <https://doi.org/10.2118/1701-PA>
18. Nishimatsu Y (1972) The mechanics of rock cutting. *Int J Rock Mech Min Sci Geomech Abstr* 9(2):261–270. [https://doi.org/10.1016/0148-9062\(72\)90027-7](https://doi.org/10.1016/0148-9062(72)90027-7)
19. Polini W, Turchetta A (2004) Force and specific energy in stone cutting by diamond mill. *Int J Mach Tools Manuf* 44:1189–1196. <https://doi.org/10.1016/j.ijmachtools.2004.04.001>
20. Turchetta S, Sorrentino L (2019) Forces and wear in high-speed machining of granite by circular sawing. *Diam Relat Mater* 100:107579. <https://doi.org/10.1016/j.diamond.2019.107579>
21. Almasi SN, Bagherpour R, Mikaeil R, Ozcelik Y (2017) Analysis of bead wear in diamond wire sawing considering the rock properties and production rate. *Bull Eng Geol Environ* 76:1593–1607. <https://doi.org/10.1007/s10064-017-1057-9>
22. Sarıışık G, Özkan E (2018) Effects of natural rock properties on cutting forces, specific energy and specific cutting energy by four-axis machine. *Arab J Geosci* 11:84. <https://doi.org/10.1007/s12517-018-3424-7>
23. Sarıışık G (2021) Investigation on cutting parameter models and processability index in 3D marble products with milled tools. *Arab J Geosci* 14:1854. <https://doi.org/10.1007/s12517-021-08256-z>
24. Özkan E, Öz O (2021) The effect of characterization of carbide end milled limestones on optimal parameters. *Arab J Geosci* 14:1181. <https://doi.org/10.1007/s12517-021-07538-w>
25. Mohammadnejad M, Liu H, Chan A, Dehkhoda S, Fukuda D (2021) An overview on advances in computational fracture mechanics of rock. *Geosyst Eng* 24(4):206–229. <https://doi.org/10.1080/12269328.2018.1448006>
26. Mohammadnejad M, Dehkhoda S, Fukuda D, Liu H, Chan A (2020) GPGPU-parallelised hybrid finite-discrete element modelling of rock chipping and fragmentation process in mechanical cutting. *J Rock Mech Geotech Eng* 12:310–325. <https://doi.org/10.1016/j.jrmge.2019.12.004>
27. Huang H, Lecampion B, Detournay E (2013) Discrete element modelling of tool–rock interaction I: rock cutting. *Int J Numer Anal Meth Geomech* 37:1913–1929. <https://doi.org/10.1002/nag.2113>
28. Wolters P, Picker T, Breidenstein B, Krödel A, Denkena B (2022) Application of natural rocks in cutting aluminum. In: Behrens BA, Brosius A, Drossel WG, Hintze W, Ihlenfeldt S, Nyhuis P (eds) *Production at the leading edge of technology. WGP 2021. Lecture notes in production engineering*. Springer, Cham. https://doi.org/10.1007/978-3-030-78424-9_26
29. Denkena B, Breidenstein B, Krödel A, Bergmann B, Picker T, Wolters P (2022) Suitability of natural rocks as materials for cutting tools. *SN Appl Sci* 4:2. <https://doi.org/10.1007/s42452-021-04883-z>
30. Denkena B, Breidenstein B, Bergmann B, Wolters P (2022) Investigation of the material separation behaviour of rocks using scratch tests for the design of tool grinding processes. *SN Appl Sci* 4:157. <https://doi.org/10.1007/s42452-022-05038-4>
31. Breidenstein B, Denkena B, Bergmann B, Wolters P, Picker T (2022) Turning copper and aluminum alloys with natural rocks as cutting tools. *Materials* 15:2187. <https://doi.org/10.3390/ma15062187>

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