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# New Simulation based Method for the Design of Cut-Off Grinding Segments for Circular Saws

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## ABSTRACT

A new trend in the field of cut-off grinding tools such as circular saws is the application of deterministic grain pattern, e.g. the ARIX-System. Although the improved performance of these tools has been proven in a quarry exemplarily, it is not clear how to configure an optimized grain pattern. It is assumed that the work material, the cutting parameters and the tool dimensions have an influence on these pattern. In this paper a new method is presented for the design of cut-off grinding segments for circular saws with defined grain pattern, which is based on the in-house material removal simulation software CutS. With this simulation, the influence of variable grain pattern on tool performance and tool life can be tested without the need for cutting experiments. It is possible to test different material specifications through the consideration of brittle and ductile material removal mechanisms and adjustable material removal factors. The influence of macroscopic and microscopic tool wear on the optimized positioning of grains by means of material removal rate and wear rate is investigated. With special algorithms, it is also possible to simulate standard tools with stochastically distributed diamond grains. Computed results will be compared to real cutting experiments of granite with cut-off grinding segments designed with CutS.

## KEYWORDS

Material Removal Simulation, Deterministic Grain Pattern, Tool Design, Circular Saw, Cut-Off Grinding, Natural Stone, Reinforced Concrete

## INTRODUCTION

In natural and artificial stone processing multiple new demands for cutting tools appear. Tools like circular saws have to gain a higher productivity by means of faster cuttings combined with longer tool life to make natural stone products competitive to other construction materials. In the construction industry, the focus of improvement lies upon tool life and process forces due to the usage of transportable machines. To meet transportability demands and weight limits for the operating of these machines, the available power is often reduced which explains the need of cut-off grinding tools with low process forces.

All these demands can be faced by special designs of the cutting segments. Besides the choice of the right binder material, the diamond size, quality and concentration, defined grain pattern realized by systems such as ARIX and DiaSet can be deployed [1, 2]. Those grain pattern can be designed to fit the challenging demands in both natural stone and construction industry. Because the improved performance of such tools has only been exemplary proven in a quarry, it is not clear how to configure an optimized grain pattern. It is assumed that the work material, the cutting parameters and the tool dimensions have an influence on these pattern.

## 1. STATE OF THE ART

Deterministic grain pattern are a research topic in many fields of application. In surface grinding, grain pattern are used to improve the temperature behaviour of the grinding tool. Therefore, making dry grinding without any coolant fluid possible for normal grinding operations is the main goal of these researches [3]. Here, the pattern are designed to reduce the number of active grains and increase the available chip space. Other studies put the workpiece surface topography in focus. In addition, the influence of grain pattern on the wear behaviour of the grinding tool was investigated in former studies using simulation approaches with regard to the surface topography of the workpiece only [4].

In the field of stone and concrete cutting the main focus of the usage of deterministic grain patterns is the optimization of the material removal rate and the wear behaviour of the cutting tools. Sung had shown that with single layer electroplated deterministic grain pattern both, the relative cutting speed in square meter per hour and the tool life, can be increased [5]. In concrete cutting, grain pattern have the potential to increase tool life compared to stochastically grain pattern due to lower adhesion wear [6, 7]. The focus of this work was the influence of the work material by means of material removal mechanism on the positioning of diamond grains. With single grain scratch tests material removal factors were identified. Therefore, a brittle material removal mechanism allows the reduction of the number of grains on the grinding tool surface by increasing the distance between the single grains. Cutting of ductile materials needs an increase in the number of grains and smaller distances between them to guaranty a complete material removal on the workpiece surface [8].

Since sintered tool with grain pattern are easier to manufacture than brazed or electro-plated tools grain pattern are only available for circular saws [9]. Up to now, only parameters for single layer tools are defined [3, 4], though the technology for manufacturing 3D cut-off-grinding segments is available [1, 2]. New methods are needed to define optimized grain pattern for multi-layer cut-off grinding tools.

## 2. SIMULATION APPROACH

A material removal simulation is set-up to compute different grain patterns and determine their influence on material removal and wear rate. The simulation is based on the in-house material removal software CutS© which was already used for the determination of optimized grain pattern for wire cutting tools [10]. To reduce computing time simplified grain models are used, like truncated octahedrons or truncated dodecahedrons. These models are statistically orientated with a statistically chosen size within the tolerances given by FEPA and have statistically chosen grain shapes.

For the computing of cut-off-grinding segments, several changes had to be done. First of all a new parametrisation of grain distances in every three room axes including displacement possibilities was necessary to install in order to create multi-layer cut-off-grinding segments. Second, to determine the optimum position of a grain in segment height the wear mechanisms had to be considered. At least the possibility to deactivate grains had to be implemented, in order to simulate the break out of grains. But since the grain shapes are changing in real contact, e.g. getting split or flattened, the microscopic tool wear also has an influence on the positioning of the grains within a cutting segment. Third, the load acting on each single grain has to be detectable. Real cutting experiments with segmented tools have shown that the front of a segment, which is the first to come in contact with the work material, underlies a higher wear than the segment ending. Here, an optimized grain alignment could help to even the tool wear. Therefore, every single grain model inside the cut-off-grinding segment is a single tool within the software. When it comes to contact between the tool and the workpiece model the grains in contact are coloured depending on the amount of the actual material removal. The colour changes on a scale from blue to red. This is an optical

indication of the load level of the single grains. After passing the adjustable maximum load within the simulation (colour red) the grains will break out. In the simulation, the grains will be deactivated and removed from the tool model (Fig. 1).

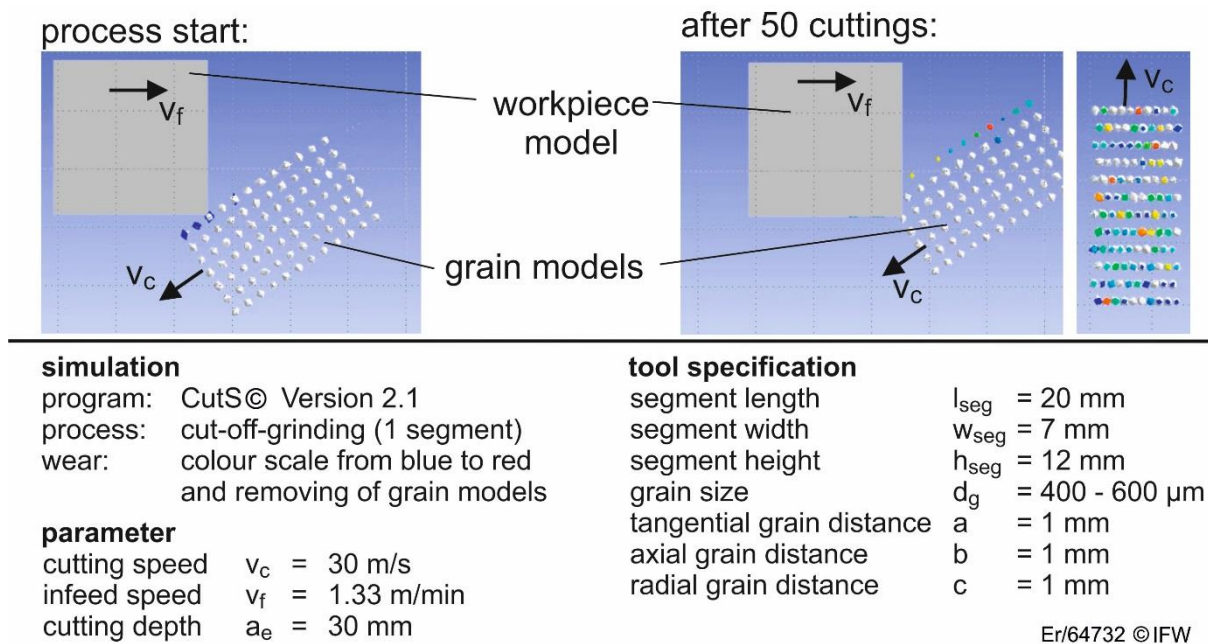


Fig. 1: Simulation approach, visual representation of tool contact and tool wear

Another influence on the grain positioning is the material removal mechanism. The material removal mechanism can be described by the material removal factor  $k$ , which is defined as the removed material cross section divided by the tool cross section. For brittle materials, the factor values are  $k > 1$  while for ductile materials like reinforcement steel  $k \leq 1$ . Therefore, algorithms were included to scale the single grain models by means of factor  $k$  when the simulation has detected contact between grain and work piece model (Fig. 2).

After the cutting operation is computed the grain will be instantly scaled to its original size and a new detection of contact is made. The same principal is used to calculate a simplified wear mechanism. A real diamond grain can wear in multiple ways, like flattening fracturing, breaking. Simplified, all wear mechanisms lead to a size reduction of the grain. Therefore, the wear of grains is calculated as a size reduction that depends on the individual load acting on a single grain. After the cutting operation is computed the removed material by a single grain is calculated and the grain size will be reduced proportionally to the removed volume for the next simulation step.

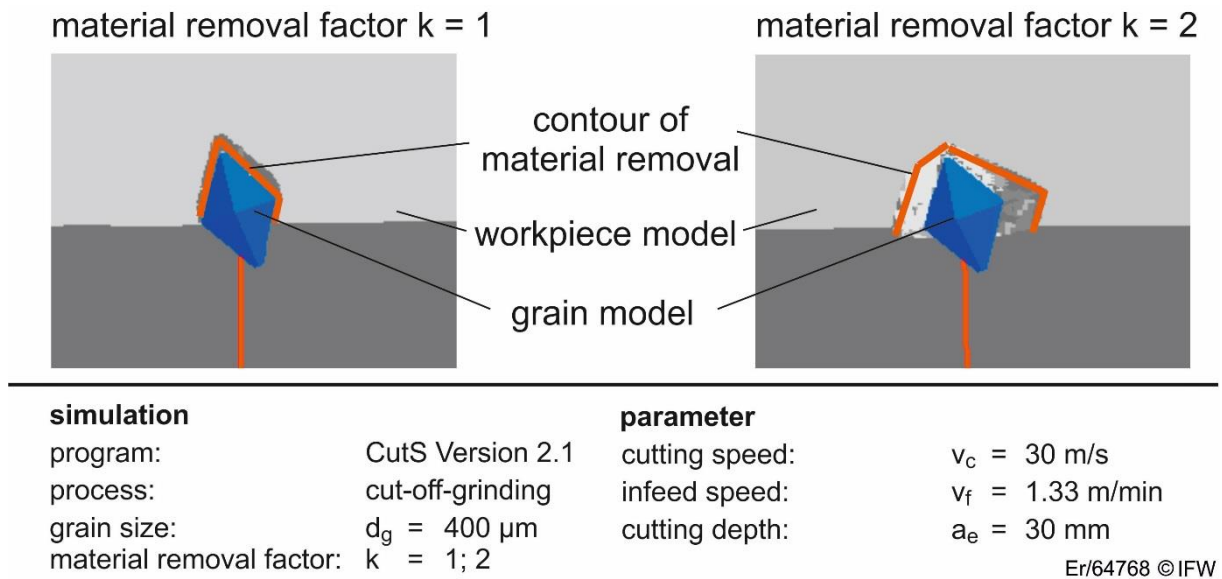
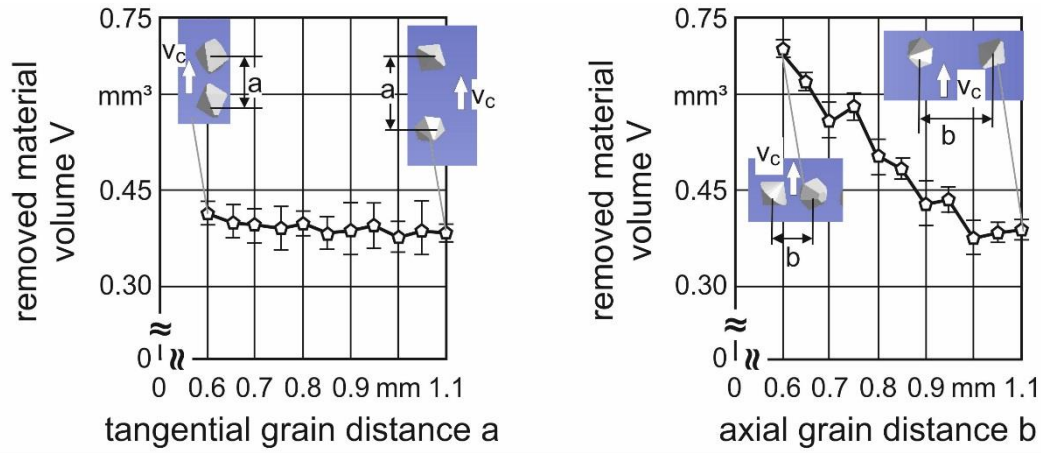


Fig. 2: Single grain simulation with material removal factor  $k = 1$  for ductile material removal and  $k = 2$  for brittle material removal

### 3. SIMULATION RESULTS

With the help of the described simulation approach the influence of different grain distances on removed material volume was investigated (Fig. 3). Therefore, single segments were computed with varying distances either in tangential, axial or radial direction while the other directions were kept constant. A standard segment size for cutting of natural stone with segment width  $w_{\text{seg}} = 7 \text{ mm}$ , segment length  $l_{\text{seg}} = 20 \text{ mm}$  and segment height  $h_{\text{seg}} = 12 \text{ mm}$  was used. The number of grains in the segment and more important on the surface of the segment changes with varying grain distances. This leads to varying removed material volumes and gives an indication of the most important parameters for an optimized grain alignment. In dependence on real cutting segments the simulated grain models have a diameter of  $d_g = 400\text{-}600 \mu\text{m}$ .

It was found that the axial distance  $b$  between grains along the segment width is directly connected to the removed material volume (Fig. 3, right). Due to the reduction of the number of grains on the segment surface  $n_{\text{surface}}$  with increasing axial grain distances  $b$  by a given segment size less material is removed. When the grains are set next to each other up to eleven grains can be set along the segment width regarding the maximum grain diameter  $d_g = 600 \mu\text{m}$ . Is the axial grain distance doubled, a maximum of six grains can be set. To gain a complete material removal in segment width the axial grain distance  $b$  has to be minimal. If that is not possible then grain displacements of the following grains can help to improve the removed material volume. The following grains should be set right in the gap of the leading grains to maximise the material removal. Concerning material removal mechanisms of brittle materials the simulation suggests an axial distance  $b = 0.7 \text{ mm}$  with no grain displacement since more material is removed by a single grain compared to ductile removal mechanisms.



parameter		parameter	
tangential grain distance	a = var.	tangential grain distance	a = 1 mm
axial grain distance	b = 1 mm	axial grain distance	b = var.
grain size	$d_g = 400 - 600 \mu\text{m}$	grain size	$d_g = 400 - 600 \mu\text{m}$
cutting speed	$v_c = 30 \text{ m/s}$	cutting speed	$v_c = 30 \text{ m/s}$
infeed speed	$v_f = 1.33 \text{ m/min}$	infeed speed	$v_f = 1.33 \text{ m/min}$
cutting depth	$a_e = 30 \text{ mm}$	cutting depth	$a_e = 30 \text{ mm}$
program	CutS© Version 2.1	program	CutS© Version 2.1
			Er/64770 ©IFW

Fig. 3: Removed material volume depending on varying grain distances in tangential and axial directions

The tangential distance  $a$ , which is the grain distance in circumferential direction or in the direction of the length of a segment, has no significant effect on the removed material volume (Fig. 3, left). Found deviations are due to the randomized choice of grain type, grain size and grain direction, although the number of grains on the segment surface  $n_{\text{surface}}$  is also reduced for increasing tangential distances  $a$ . This means that the following grains set with the distance  $a$  are not taking part in the material removal. This can be explained by the given process kinematics. The number of grains on the tool circumference  $N$  of one diamond row is influenced by the tangential distance  $a$  (1).

$$N = \frac{2\pi r}{a} \quad (1)$$

With  $r$  being the radius of the tool (2).

$$r = \frac{D_{\text{tool}}}{2} \quad (2)$$

As the grains have a deterministic distance to each other the infeed for every grain  $f_z$  can be calculated (3).

$$f_z = \frac{v_f}{n \cdot N} \quad (3)$$

The number of revolutions  $n$  is given by the cutting velocity  $v_c$  and tool dimensions (4).

$$n = \frac{v_c}{2\pi r} \quad (4)$$

Therefore, the tangential distance  $a$  can be calculated by the equation (5) for given process parameters.

$$a = f_z \cdot \frac{v_c}{v_f} \quad (5)$$

Fig. 4 shows the necessary tangential distances  $a$  for certain single grain chip thicknesses of the following grains. It can be seen that for low tangential distances (parameter  $a$ ) the single grain chip thickness is nearly zero. To gain equal chip thicknesses of  $h_{cu} = 10 \mu\text{m}$ , which is found to be positive for the wear behaviour by Glatzel [11], the tangential distance should be  $a = 13.5 \text{ mm}$  for ductile material removal ( $k = 1$ ). With regard to cutting natural stone which occurs to have a brittle material removal mechanism and a material removal factor  $k = 2$  the tangential distance is calculated to  $a = 27.1 \text{ mm}$  which is more than the given segment length. These values are valid for the assumption that the tool is used in full cut and  $f_z = h_{cu}$ . Since this is not the case, the tool dimensions and the process parameters have an influence on the tangential distance as well. The values of Fig. 4 were calculated with the help of the depth of cut  $a_e = 30 \text{ mm}$ , the cutting speed  $v_c = 30 \text{ m/s}$  and the infeed speed  $v_f = 1.33 \text{ m/min}$ . The tool diameter was assumed to be  $D_{tool} = 1 \text{ m}$ . The left side of the picture shows the overall process kinematics. It can be seen that the maximum single grain chip thickness  $h_{cu}$  which occurs in the cutting process is smaller than the infeed  $f_z$ . Equation (6) describes the relation between these two values. Here, the influence of the tool dimension is given by the cutting angle  $\varphi$  (7).

$$f_z = \frac{h_{cu}}{\sin \varphi} \quad (6)$$

$$\cos \varphi = \frac{(r - a_e)}{r} \quad (7)$$

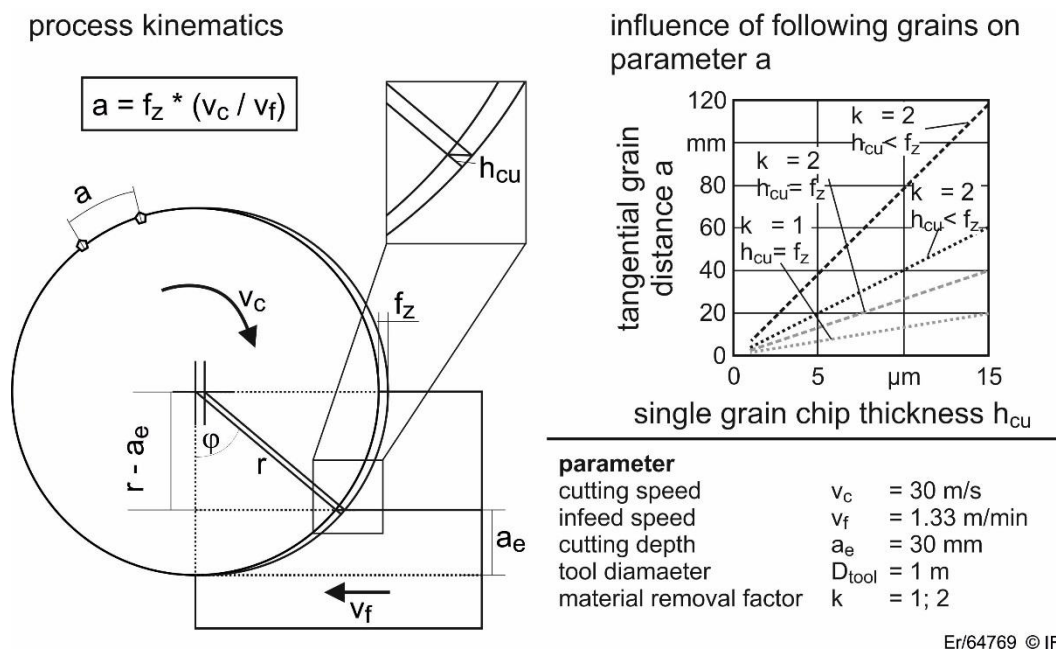


Fig. 4: Tangential distance  $a$  in dependence on single grain chip thickness of the following grains

With regard to the given process kinematics and equation (6) the actual necessary tangential distance  $a$  for an optimum single grain chip thickness  $h_{cu} = 10 \mu\text{m}$  is calculated to  $a (k = 1) = 39.7 \text{ mm}$  respectively  $a (k = 2) = 79.3 \text{ mm}$ . This would mean that only every second segment has one single grain in circumferential direction on its surface. Further investigations suggest that grains aligned with small distances  $a$  can improve the wear behaviour. Grains directly behind the first grains in contact take over the cutting load only

when the first grains start to wear. This has an influence on the radial wear. When the first grains breakout the following grains in circumferential direction, which have not taken part in the cutting process until now, take over the cutting operation. The loss of the first grain in contact due to wear means for segments with large tangential distances also a reduction of the segment height, at least a reduction equal to the grain size. If the tangential distances are smaller, the segment height stays the same if the first grains are worn out until the last grain of one layer is worn. So the radial wear rate is reduced. The smaller the tangential distance, the higher the wear stock and the lower is the radial wear rate. But, it is known, that for standard tools with stochastically grain distributions used for cutting of hard and brittle materials the grain concentration is lowered or the segment length is shortened, or both. This leads to higher average tangential grain distances with regard to reduce process forces. If a small average tangential grain distance and therefore, a large number of grains on the segment surface means higher process forces, then there is a limit for building up a wear stock through small tangential distances on segments with deterministic grain distributions. The simulation suggests a tangential distance of  $a = 3$  mm to not flatten following grains by ploughing effects but also have a wear stock to reduce radial wear.

For the increase of the removed material volume the grain alignment in segment width (axial distance  $b$ ) is more important since it directly determines how many grains are actually in contact with the workpiece. The tangential distance  $a$  has no effect on the removed material volume since the following grains do not take part in the cutting operation until the first grains start to wear. Nevertheless, this effect can be used as a wear stock so the radial wear can be reduced. The influence of the radial grain distance  $c$  on the tool behaviour, removed material volume and wear rate was investigated in experimental cutting tests with the goal to set up a wear model of the segment bonding to be implemented within the material removal simulation.

#### 4. CUTTING EXPERIMENTS

To proof the simulation results and get information about the wear mechanisms and the wear rate real cutting experiments were conducted on a natural stone bridge saw type Hensel Gigant 459. The cutting parameters were set as described before. As work material a hard to cut granite type Rosa Sardo was used with the dimension of  $1.2 \times 1.2 \times 0.35$  m<sup>3</sup>. The process forces were measured with a Kistler three-component dynamometer. The dynamometer is directly mounted under the workpiece. The workpiece is cut into joints with a square surface of  $A = 0.36$  m<sup>2</sup> with 10 infeed steps. After three joints with  $A = 1.08$  m<sup>2</sup> the radial wear of the tools was measured. To gain information about the wear behaviour of the tools and the influence of different grain distributions 33 joints were cut with each tool. This enables an evaluation of the self-sharpening mechanisms and an analysis on how grains appear at the segment surface when the bonding is set back.

For the experiments four different sawing blades with a diameter  $D_{\text{tool}} = 1$  m and a diamond grain size of  $d_g = 400 - 600$   $\mu\text{m}$  were used. Two of the tools, tools 1 and 2, have cutting segments with a deterministic grain distribution equal in tangential, axial and radial distance of  $a = 3$  mm,  $b = 0.7$  mm,  $c = 1.15$  mm. Here,  $c$  is a result of fitting the total number of grains within one segment for standard tools with a concentration  $C_{15}$  into a segment with given height, length and width also as given parameters  $a$  and  $b$ . Tool 2 has further a grain displacement in radial direction of  $l_c = 0.55$  mm. In addition, two standard tools with stochastically distributed diamond grains, tool 1<sub>stoch</sub> and tool 2<sub>stoch</sub> were investigated. The concentration of those tools correlates with the total number of diamond grains in tool 1 and tool 2, respectively. Since tool 2 has additional grains in radial direction the total number of diamonds is 1.5 times higher than for tool 1. Therefore, tool 2<sub>stoch</sub> has also a 1.5 times higher concentration than tool 1<sub>stoch</sub>.

## 5. CUTTING RESULTS

The upper part of Fig. 5 displays the resulting process forces for every tested saw blade. At first there occurs a grinding-in process until a cut surface of  $A = 2 - 3 \text{ m}^2$ . The normal forces as well as the tangential forces are increasing during that period. After finishing the grind-in process the process forces are decreasing and start to oscillate around a stationary process force level. It can be seen that the tools with a larger number of grains (tool 2 and tool 2<sub>stoch</sub>) gain higher process force levels. The number of grains on the surface has an influence on the process forces. For stochastically grain distributions the average tangential grain distance depends on the grain concentration. The higher the concentration the more grains are on the segment surface and the smaller is the average tangential grain distance. The results of chapter three have shown that the single grain chip thickness of the grains with small tangential distances are very low. Hence, these grains do not take part in the cutting process but ploughing effects occur which result in higher friction and therefore in higher process forces. Comparing photographs of tool 1 and 2 depicts that the number of grains on the cutting segment surface is higher for tool 2 although the tangential grain distance  $a$  is equal. Due to the wear processes the bonding is set back and underlying diamond grains appear at the segments surface. Since tool 1 lacks additional diamond grains in radial direction there are no underlying grains that come into contact with the workpiece, immediately. For tool 2 these additional radial diamond grains increase the number of grains on the segment surface. There is a state where underlying diamond grains are in contact with the workpiece while there are still diamond grains of the first diamond layer on the surface of the cut-off-grinding segment. This results in a partially higher number of diamond grains on the segment surface. Therefore, the average tangential grain distance is reduced which explains the high increase of normal forces at the first grinding-in period. After reaching a stable self-sharpening effect, the forces of tool 1 and 2 are approaching, due to equal numbers of diamond grains on the surface of the cut-off-grinding segment. Additionally, the overall behaviour of the segments is changing with the number of grains. The segments get a higher stiffness, due to reinforcement effects by additional grains, which leads to less elastic deformations. Therefore, the process forces are increasing as well for tool 2.

Since the number of grains on the segment surface is nearly equal, the radial wear increases similar for all tools in the first period until a cut surface of  $A = 4 \text{ m}^2$  (Fig. 5, bottom). After that the radial wear has reached  $\Delta r = 0.4 \text{ mm}$ , the same value as the diamond grain size. Therefore, the first layer of diamond grains is worn or broken out. For tool 1, the radial wear increases rapidly from the cut surface  $A = 4 \text{ m}^2$  to  $A = 6 \text{ m}^2$ , due to the lack of grains in radial direction (Fig. 5, right). At this cut surface the radial wear reaches the value of the radial grain distance  $c$  in tool 1. Here, finally new diamond grains appear at the surface on the cut-off-grinding segments which immediately leads to a decrease of the wear rate. In the following period the radial wear increases parallel to the first period. It is assumed, that after the second layer of diamonds is worn out, the radial wear rate increases again significantly. The radial wear of tool 1<sub>stoch</sub> oscillates around a linear best-fit line. Due to the stochastically distribution of grains, there are active grains cutting throughout the complete segment height. Therefore, a sudden increase in radial wear like it is shown by tool 1 is missing. The oscillating behaviour can be explained by the changeable number of diamond grains on the surface of the cut-off-grinding segment due to the stochastically distributed diamond grains within the cutting segments. Hence, the radial wear rate increases for a low number of diamond grains on the surface and decreases for a higher number.



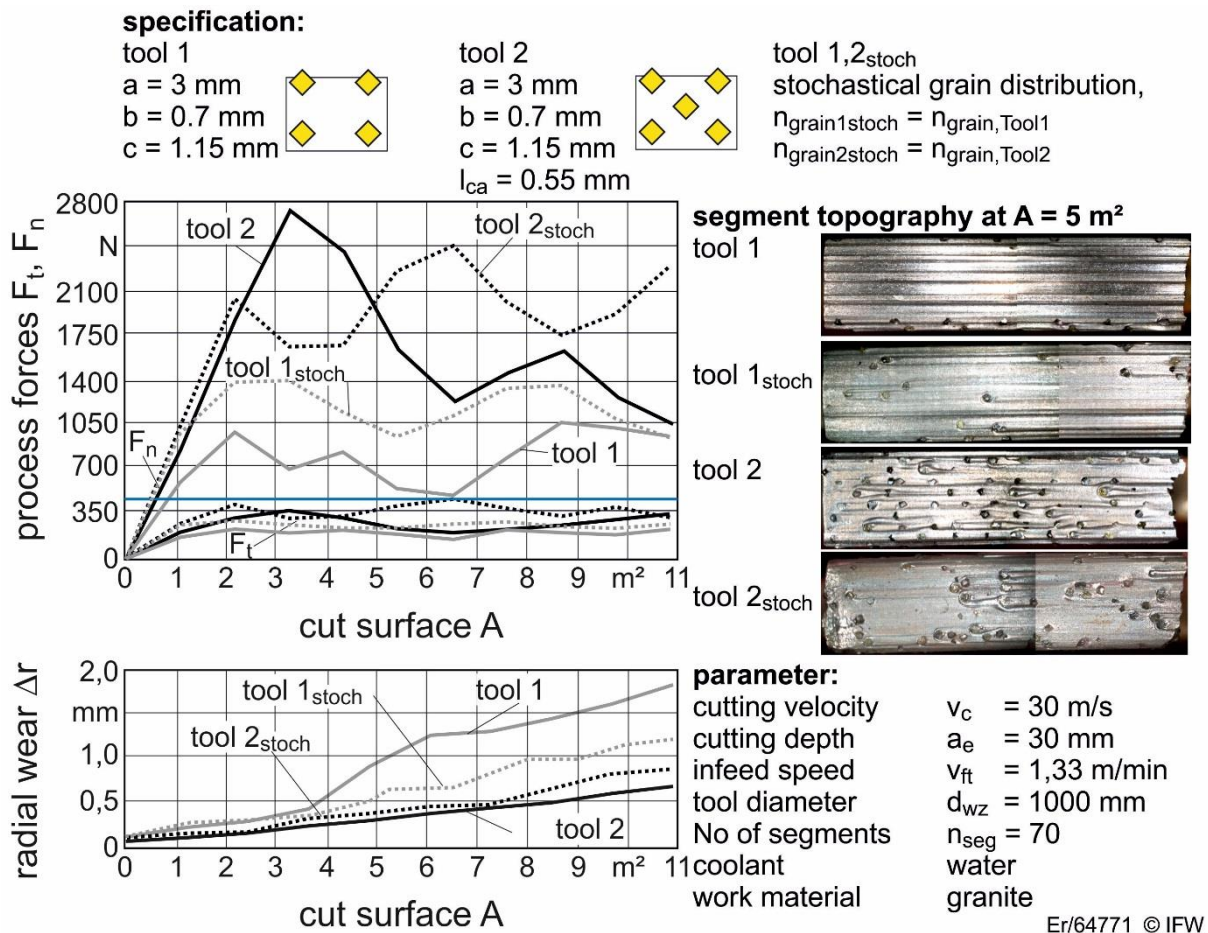


Fig. 5: Process forces and radial wear for tools with different grain distributions

The oscillating of the radial wear curve can also be seen for tool 2<sub>stoch</sub>. Here again, the stochastic distribution of diamond grains within the cutting segments leads to varying numbers of grains on the actual surface of the segments and therefore, to a faster (less diamond grains) or a slower increase of the radial wear. Due to its higher concentration compared to tool 1<sub>stoch</sub>, the radial wear proceeds slower.

The radial wear of tool 2 does not show an oscillating behaviour. Compared to the stochastically distributed tool 2<sub>stoch</sub> the wear can be lowered although both tools should have the same total number of grains within the cutting segments. Here, in every height of the cutting segment of tool 2 the number of diamond grains is nearly constant. This leads to an even wear rate and to an approximately longer tool life than stochastically distributed cut-off-grinding segments.

The experimental results have shown that with higher number of grains on the segment surface the process forces are increasing. Hence, it is assumed that there is a limit for the number of grains on the segment surface which are set as wear stock to not exceed machine power limits and therefore, the tangential grain distance is limited. With the help of grain pattern the wear behaviour of sawing blades using cut-off-grinding segments can be influenced. It was shown that the radial grain distribution can smoothen the increase in radial wear and reduce the amount of the radial wear which leads to a longer tool life. It is assumed that with further use of additional displacements of diamond grains the radial wear can be lowered further.

## 5. CONCLUSION AND OUTLOOK

A new simulation approach for the determination of grain pattern was introduced. Compared to existing approaches a new possibility of creating 3D grain pattern and the consideration of material removal mechanisms of ductile and brittle materials was introduced. Therefore, a new parametrisation of possible grain positions was done and additional algorithms were implemented. With a simplified wear model the simulation cannot only be used for maximizing the removed material volume but also gives indications about the expectable wear rate.

With the help of the simulation it was found that the axial grain distance  $b$  in a cut-off-grinding segment is the most important parameter to maximize the removed material volume. It was also shown that in tangential direction following grains can be set directly behind the first ones with the parameter  $a$  and therefore, a wear stock can be build up. It was also shown that the process parameters, the tool dimension and the work material have an influence on the optimum position of grains within a cutting segment.

Real cutting experiments in natural stone have shown that the parameter tangential grain distance  $a$  has an influence on the cutting forces and is therefore limited for the use of setting up a wear stock. It was also found that the radial wear is predicted by the radial grain distance  $c$ . Compared to tools with stochastically distributed diamond grains a smoothing of the wear rate is possible due to the same amount of diamond grains in every height of the cut-off-grinding segments.

In future work the dependencies of the parameters among one another will be analysed by changing different grain distances at the same time using a design-of-experiments method (DoE). It is believed that combined with grain displacements in each direction a model can be derived for the calculation of optimized grain pattern for a given application by work material, tool dimension and possible process parameters. With the experimental results shown, only two layers of diamond grains were used. The segments consist of nine to twelve layers, depending on the pattern. Future experiments should focus on the process stability regarding the wear behaviour and the process force development, when more material is cut.

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