Deterministic Grain Distribution on Cut-Off Grinding Wheels

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Abstract
The application of cut-off grinding tools on reinforced concrete results in a significantly increased wear compared to the conventional fields of application. Strategies to compensate this effect include the utilization of higher grain concentrations in the cutting segments or a deterministic grain distribution. In order to enable an adequate and adapted design of a deterministic grain pattern, first single grain scratch experiments were carried out. On that basis the width material removal factor $k_w$ has been introduced. $k_w$ enables the design of different adapted, deterministic (and stochastic) cut-off grinding wheels. Results from cut-off grinding experiments with different tool prototypes show that tools with a higher grain concentration and deterministic distribution perform best in the given field of application. The developed design algorithms proved to be adequate for an adapted layout of cut-off grinding tools.

Keywords
cut-off grinding, circular stone sawing, wire sawing, diamond tool, deterministic grain distribution

1 INTRODUCTION
The cut-off grinding of concrete and reinforced concrete is generally performed with cut-off grinding wheels or wire sawing tools. Both are typically equipped with metal-bonded diamond grains in sintered cutting segments. All sintered cutting segments are subject to the self-sharpening effect which is based on the abrasive impact of the resulting mineral slurry. For these tools the machining of steel structures in reinforced concrete causes particular problems [1, 2]. Besides an increased mechanical wear, additional tribochemical reactions affect the diamonds [3].

A compensating strategy is the application of higher diamond grain concentrations. But this approach does not only disperse the process load on a larger number of diamonds, it also leads to a reduction of the single grain chip thickness $h_{cu}$. Consequently, intensified elastic and plastic deformation processes in the material separation increase the abrasive wear on the diamonds. A typical wear mechanism occurring under these conditions is the flattening of the diamonds which results in a reduction of the chip spaces. This leads to increased normal forces and amounts of chip adhesions.

An approach to achieve an equally distributed chip thickness as well as adequate chip spaces is the geometrically defined grain distribution. Therefore, the goal of several research efforts is to identify the influences of defined grain distributions on the process behavior. It is reported that a deterministic grain distribution improves the grinding process with regard to the process forces, wear and heat generation as well as the work piece quality [4, 5].

Cut-off grinding wheels with geometrically defined grain pattern are already available on the market [6]. However, the influences of a deterministic grain pattern on the process behavior in cut-off grinding of concrete and reinforced concrete are basically undescribed in scientific literature. Furthermore, no geometric-kinematic model for an application-oriented design of the grain pattern is currently available. The development of such a model and the results of experiments with deterministic grinding wheels are presented within this paper.
2 DESIGN OF DETERMINISTIC GRAIN PATTERNS ON CUT-OFF GRINDING TOOLS

The basis for the design of deterministic grain patterns on cut-off grinding tools are the removal mechanisms of the material to be cut. As the treatment of reinforced concrete has recently become one of the major fields of application for cut-off grinding tools, the removal mechanisms of concrete and steel are the focal points. The material removal of steel is based on ductile chip formation [7]. The brittle removal process of concrete is dominated by the formation of axial, lateral and radial micro cracks and the resulting breakout of the work piece fragments [8].

In order to assign a quantifying parameter to the removal mechanisms of concrete and steel, single grain scratch experiments were carried out (Figure 1). For this purpose, a scratch diamond was welded onto a small stylus which was screwed into an aluminum disc. This disc was mounted onto the spindle of the surface grinding machine Blohm Profimat 307. With this experimental setup the diamond enters the work piece surface in a flat angle, reaching its maximum scratch depth (single grain chip thickness) in the middle of the resulting scratch path. The investigated chip thicknesses were chosen according to the range of resulting chip thicknesses of the real cut-off grinding process.

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**Figure 1**: Experimental setup of the single grain scratch experiments and measurement results for the newly introduced removal factors $k_w$ and $k_d$

The results of the scratch experiments show that flaking occurs in the areas next to the active path of the diamond when machining brittle concrete (Figure 1, upper SEM images). On the contrary, steel exhibits ductile properties which lead to scratch grooves whose inner cross section very precisely equals the outer cross section of the diamond (Figure 1, lower SEM images). With regard to an efficient diamond distribution, these results imply that the distance
between the diamonds for the machining of steel must be lower than for the machining of concrete.  
When these removal mechanisms are expressed in accordance with the terms of the experimental kinematics in Figure 1, they can be described as follows:

Steel:

\[ k_{w,\text{steel}} = \frac{b_{e,\text{steel}}}{d_{gr}} \approx 1 \]  

Concrete:

\[ k_{w,\text{concrete}} = \frac{b_{e,\text{concrete}}}{d_{gr}} > 1 \]

\( k_w \) is the newly introduced width removal factor. For steel \( k_{w,\text{steel}} \) turns out to be independent from the variation of the single grain chip thickness with values \( k_{w,\text{steel}} = 1.0 - 1.1 \). In contrast, the width removal factor for concrete \( k_{w,\text{concrete}} \) varies with an increasing single grain chip thickness between \( k_{w,\text{concrete}} = 1.4 - 1.8 \). In addition, the depth removal factor \( k_d \) is defined as the ratio of the real scratch depth \( h_r \) to the single grain chip thickness \( h_{cu} \). The results in Figure 1 prove that the real scratch depth both in concrete and steel basically equals the adjusted single grain chip thickness. The variation of the single grain chip thickness has also only a slight influence on the resulting depth removal factors with values \( k_{d,\text{steel}} = k_{d,\text{concrete}} = 1.0 - 1.3 \). Therefore, the width removal factor \( k_w \) is chosen as basis for the design of deterministic grain patterns on cut-off grinding tools.

2.1 Modeling approach for the deterministic grain pattern

For the deterministic design of a grinding wheel the distances between the diamond grains in peripheral direction \( s_u \) and in axial direction \( s_v \) are decisive factors (Figure 2).

Figure 2: Geometric parameters for a deterministic grain pattern on grinding wheels

With a constant depth of cut \( a_e \), a constant feed rate \( v_f \) and a constant cutting speed \( v_c \) the equivalent single grain chip thickness \( h_{eq} \) can be calculated according to [9]. With the feed rate, cutting speed and the simplifying assumption of the equality of the equivalent and the real single grain chip thickness the peripheral distance \( s_u \) can be determined according to (3):

\[ s_u = \frac{v_c}{v_f} \cdot h_{eq} \]

The axial distance \( s_v \) is determined on the basis of the width removal factor, the single grain chip thickness and specific information about the geometry of the diamonds to be placed on the tool. Optical analyses were conducted here in order to identify the size of the average truncated cone \( d_{\text{tgk}} \) and the average tilt angle of the lateral surfaces towards the base surface \( \alpha \). With this information the axial distance \( s_v \) can be calculated according to (4):

\[ s_v = (d_{\text{tgk}} + (h_{eq} \cdot \tan \alpha \cdot 2)) \cdot k_w \]
The axial distance $s_v$ equals the maximum width of the scratch groove of one single diamond according to a certain single grain chip thickness. Thus, a deterministic distribution of the diamonds according to (4) ensures that the scratches will be grooved into the material as far from each other as possible. This allows the most efficient material separation.

### 2.2 Prototypic cut-off grinding wheels

For the design of the prototypic grinding wheels there were chosen the energetically advantageous parameters $a_e = 1$ mm, $v_t = 5$ m/min and $v_c = 30$ m/s. With (3) these parameters lead to the peripheral distance $s_u = 18$ mm.

Optical analyzes of the diamond grains delivered the values for the average truncated cone $d_{tg} = 70$ µm and the average tilt angle $\alpha = 45^\circ$. In order to determine the axial distance $s_v$ it is necessary to know the adequate width removal factor. As it was not known which removal factor be considered for the design of grinding wheels for steel-concrete-compounds up to this point, two different grinding wheels, one with $k_{w;steel} = 1.0$ and one with $k_{w;concrete} = 1.8$, were designed. With (4) the resulting axial distances are $s_{v;steel} = 170$ µm and $s_{v;concrete} = 306$ µm. The correlating amounts of the single diamond grains are $n_{steel} = 5,460$ pcs and $n_{concrete} = 3,016$ pcs.

In the case of conventional grinding tools, the diamonds are distributed stochastically across the grinding wheel perimeter [10]. In order to analyze the potential of deterministic cut-off grinding wheels, a tool with a stochastic diamond distribution has been produced as well. The number of diamonds corresponds to the deterministic tool designed with the removal factor $k_{w;steel}$. The prototypic grinding wheels are presented in Figure 3.

#### Figure 3: Prototypic grinding wheels for steel and concrete

Opposed to conventional cut-off grinding wheels, the diamonds on these prototypic tools are manually placed and bonded by electroplating. The application of sintered (multi-layer) prototypic grinding wheels could not be realized due to the shortage of an adequate manufacturing process.

### 3 SAWING EXPERIMENTS

Circular sawing experiments were carried out on concrete work pieces with 8% steel reinforcement. The results clarify that for the machining of the concrete matrix and the steel reinforcement the tangential forces $F_t$ do neither differ considerably for different diamond grain concentrations nor for a deterministic grain distribution. Opposed to the tangential forces, the normal forces $F_n$ are affected both by the diamond grain concentration and grain distribution.
The higher grain concentration on the deterministic steel tool leads to a reduction of the normal forces by 19% in the steel reinforcement and 40% in the concrete matrix compared to a deterministic concrete tool. The deterministic grain arrangement only leads to a reduction of 8% in the steel reinforcement and 27% in the concrete matrix compared to the stochastic tool with the same grain concentration. Thus, a higher diamond grain concentration proves to be more favorable than a deterministic grain pattern. Nevertheless, for a constant grain concentration the deterministic grain pattern significantly contributes to a reduction of the resulting normal forces.

Besides the process forces also the wear of the prototypic grinding wheels was evaluated (Figure 4). Wear criteria is the resulting amount of chip adhesions on the diamonds. For the deterministic concrete tool chip adhesions can be detected on 13% of the diamonds. For the deterministic steel tool this proportion is reduced to 3.5%. Due to the reduced number of diamonds, the chip cross section of a single grain on the concrete tool is higher than on the steel tool. As a consequence, the temperatures on the diamonds rise and the amount of chip fragments welded onto the abrasive grains increases. The resulting single grain chip thicknesses vary drastically because of the irregular distribution of the diamond grains on the stochastic tool. This leads to steel adhesions on 24% of the diamond grains. These results support the thesis that the reduction of the single grain chip thickness is an adequate strategy to conserve the cutting ability of a cut-off grinding wheel. This can be achieved by an adapted abrasive grain concentration or an even, deterministic grain distribution on the tool surface.

With regard to the design of deterministic grinding wheels for steel-concrete compounds the results suggest the application of the width removal factor of the more ductile material (steel). This leads to a higher diamond grain concentration and results in remarkably reduced process forces and significantly less wear in form of steel adhesions.

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**Figure 6:** Normal forces $F_n$ in the concrete matrix and in the steel reinforcements and percentage of steel adhesions for varied tool designs.
4 CONCLUSION AND OUTLOOK
Cut-off grinding tools are subject to a significantly increased wear when applied on reinforced concrete. A strategy to compensate the wear is the application of higher grain concentrations. An alternative approach is to design tools with a deterministic grain distribution which is already realized on a special selection of cut-off grinding wheels on the market. Still, neither is a model available for the material-oriented design of deterministic grain patterns nor have the advantages of the targeted distribution already been proven so far.

From scratch experiments on concrete and steel work pieces there were deduced quantifying parameters for the different material removal mechanisms of concrete and steel. These removal factors were chosen as a basis for the design of deterministic grain distributions on cut-off grinding wheels. With the help of these algorithms three prototypic, material-adapted grinding wheels were designed and produced in experimental manufacturing processes.

The results of the circular sawing experiments show that the tangential forces are not significantly affected by a deterministic grain distribution. The normal forces, however, could be reduced by up to 27 % with a deterministic tool design. With regard to an adapted grain concentration, the higher concentration resulting from the tool design based on the removal mechanisms of steel turned out to lead to the lowest process forces. Beside the process forces also the wear was evaluated. The stochastic tool design turned out to be most subject to steel adhesions. The deterministic tool with higher grain concentration showed the smallest amount of steel adhesions. This underlines the assumption that an adapted grain concentration combined with a deterministic grain distribution can help to improve the circular sawing process of steel-concrete compounds with regard to the resulting mechanical loads and the wear in form of steel adhesions.

Further experiments with deterministic grinding wheels are planned. Goals are the verification of the identified tendencies and the application of tools with new grain patterns and adapted grain concentrations. Precondition is the availability of process-safe and flexible manufacturing processes which allow the production of differently parameterized deterministic grain distributions in an economical manner.

5 REFERENCES