PROCESS ANALYSIS IN CUT-OFF GRINDING OF STONE COMPOUND MATERIAL

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Abstract
The inhomogeneous compound material concrete mainly consists of natural stone aggregates which show a large variety of mechanical properties depending on their origin. During the cut-off grinding process with diamond tipped cutting disks these different properties directly affect the load on the tool. Normally no information about the material composition and its influence on the tool performance is available. Thus, the user is not able to adjust the tool or the cutting parameters adequately. The result is an unpredictable process behaviour and in worst cases the collapse of the tool.

A research project of the Leibniz Universität Hannover aims at enabling a method to predict the machining properties out of the emitted process signals. The work presented here introduces the applied methods and main results. Different concrete samples with typically occurring aggregates were mineralogically analysed and tested on a test rig. To evaluate the process behaviour depending on the work piece material, the process forces, the tool wear, the acoustic emission (AE) and the airborne sound generated by the cutting disk were recorded and analysed post process.

The analysis shows similar behaviour of AE-, airborne sound and process force signals. Furthermore, the machining of process stressing materials like flint causes an excitation of distinct sonic frequencies. By means of these cognitions the material composition and its effect on the tool wear can be deducted. These signals show the potential to be used for a process control in order to avoid exceeding tool wear and damage. Transformed to application conditions the studies presented here will help to enable the user to adjust the process according to the natural stone or concrete work piece with higher efficiency.

Keywords: stone compound material, diamond tools, cut-off grinding, process monitoring

1. Introduction
Cut-off grinding with diamond tools is a standard technique for the machining of natural and artificial stones. Besides the frame saw and the wire saw, the circular saw is used for this application predominantly. The economic efficiency of the cutting process mainly depends on the tool life time. Thus, a lot of research has been conducted on the tool wear behaviour depending on specific material properties.

With an annual production of 6 billion m³ the mineral compound material concrete represents one of the most important construction materials. Concrete is composed of coarse aggregates, sand and a cement/water binder matrix. The properties of concrete can be adjusted to the intended use by varying the cement composition, the water/cement ratio, the coarse aggregates or the type of reinforcement. Contrary to natural stones concrete is a real two phase system, because the cement is very weak whereas the aggregates can show high hardness values. Thus, it is difficult to choose an appropriate tool. It is known that the type of the aggregates used has the highest impact on the tool wear behaviour in cutting of concrete with circular tools (eg. Ratterman et al., 1985). In order to guarantee a stable and economic machining, process parameters adapted to the material are of predominant importance as well as the use of an adequate tool specification. However, often the properties of the material compounds to be cut cannot be obtained before machining, thus the process cannot be adjusted adequately. In combination with mainly used unadjusted all-purpose tools this can lead to incalculable wear and even the failure of the tool.

Until now, no technique is available for evaluating the machinability of these materials while processing, thus allowing to adjust the process parameters accordingly. The research conducted up to now was only able to give guidelines for the machining of natural stones (eg. Jennings et al., 1989). But there are still no published works to provide an informative basis for the machining of the brittle hard compound concrete.
Hence, a method is preferable that gives information about the concrete properties enabling an adjustment of the machining parameters while cutting. In many other cutting operations the process signals were examined to gain insight into the work piece properties and their machining behaviour. Useful signals are the process forces and the measurement of vibrations like the acoustic emission or the airborne sound. Nowadays acoustic emission is an accepted and widely used method for process monitoring (e.g. Tönshoff et al., 1999), whereas airborne sound is generally considered as not applicable for the monitoring of processes. Denkena et al. reported results of preliminary cutting tests with a non standard tool with only two diamond cutting segments (2008). It was shown that acoustic emission, airborne sound and process forces are closely related and give information about the aggregates properties and their distribution in the cut. Here a detailed study of the process signal mean values is presented, showing that this gives valuable information about the sawability of concrete.

2. Experimental setup and method

2.1 General

The tests are carried out on a circular stone sawing machine with a main drive power of 22 kW, enabling a continuously adjustable spindle rotation speed of n = 750-6000 rpm by a transistor frequency inverter. A tool with a diameter of dₘₗ₄ = 400 mm and 27 diamond segments is used in these examinations (Fig. 1). The cutting speed is set at 40 m/s, the cutting depth is varied between aₑₜ = 5 and aₑₜ = 100 mm. The feed rate is varied between vₘₜ = 0.5 and vₘₜ = 2 m/min in 0.5 m/min steps, displaying a large bandwidth of cutting rate Q´ₘ. Before each test the tool is sharpened by cutting sandstone. All tests are carried out in parallel feed, effecting a high rate of process supporting fractured diamonds.

2.2 Materials

The examinations are carried out on three concrete samples with machining category A, C and E. This characterisation bases on an empirical study which classifies the aggregates into five categories, A-E. Within this classification the difficulty of the machinability increases in alphabetical order. Decisive factors for different aggregate properties are hardness, crystalline structure and grain size. The standardised compression strength of the samples is 30 N/mm², representing the strength of the cement which is equal in all samples (notations A30, C30, E30). In advance the aggregate size, distribution and concentration were examined as well as the Mohs-Hardness (HM). Figure 2 exemplarily shows the flat joint surfaces of two cutting tests along with a map of the mineralogical composition.

Concrete A30 has only lime stone aggregates of smaller size and low hardness (HM = 4), whereas concrete E30 shows a high variation of aggregate size and hardness (HM = 1-8.5). With regards to the distribution of the aggregates in the concrete, sample A30 shows a distinct homogeneity while sample E30 is rather heterogeneous. Concrete sample C30 shows the same values of aggregate size and distribution as A30. The hardness tends to higher values from HM = 5 to 8, which is averaged higher than for concrete E30.
2.3 Equipment and data recording
The process sound is recorded by four microphones (shot gun – pressure gradient type, Sennheiser ME 36) which are connected to a multichannel A/D converter with sampling rates of up to 192 kHz. A PC is storing the data on a hard disk drive. The analogous signal is A/D converted with a sampling rate of 24 kHz, the amplitude is digitalised with 16 bit. The amplification of the input signals is kept constant in all measurements thus enabling comparability. The Root Mean Square signal levels of the airborne sound signal \( L_{S RMS} \) are calculated by means of the sound recording software Soundforge (Sony).

The AE signal is recorded by means of a vibration pick-up. For the examinations a piezoelectric sensor (Dittel) is used which is mounted onto the spindle axis. The data is transmitted wireless to the receiver. By means of fixing the sensor close to the acoustic signal source in the contact zone of segment and work piece, a better signal to noise ratio can be obtained. On the one hand the raw signal \( AE_{raw} \) is recorded with a sample rate of \( f_{raw} = 1 \, \text{MHz} \) and is used for the calculation of the FFT. Additionally, the signal is converted with amplification and a low pass filter to \( AE_{RMS} \) with a sample rate of \( f_{RMS} = 10 \, \text{kHz} \).

The process forces are identified by means of a piezoelectric dynamometer (Kistler), positioned below the work piece mounting. The sampling rate of normal-, tangential- and axial-forces is 10 kHz. Force data, \( AE_{raw} \) and \( AE_{RMS} \) are simultaneously recorded on a Multichannel Data Acquisition Device and are analysed for each single infeed with Labview-based software.

3. Results and discussion

3.1 Machinability of the concrete samples
The development of the process forces for the different concrete samples with the same parameters illustrate the machining properties and further characteristics. Figure 3 exemplarily shows the forces in a time-course over one single infeed. \( F_y \) is the component in feed direction, whereas \( F_z \) is orthogonal. \( F_x \) is the axial force parallel to the spindle axis.

Representative for A30 is the homogenous force developing with only minor divergency. This fact corresponds to the homogenous aggregate distribution on the observed flat joint surfaces (cp. fig. 2). Showing a comparable grain distribution, C30 shows a significant higher mean value and higher divergences, resulting from the higher scratch hardnness of its aggregates. For concrete E30 the divergences rise due to some hard, big flint aggregates. Besides these areas the mean value is lower compared with A30 and C30.

To evaluate the influence of the work piece on the tool, additionally the tool wear is examined. Figure 4 displays the related radial wear and mean force values for three different cutting depths (25, 50, 100 mm) with constant feed rate 1 m/min.

With increasing cutting depth the cutting rate and also the radial wear rise. This dependency corresponds with a rise of the mean process forces as well. An increase of the cutting depth leads to a longer geometrical contact length \( l_g \) so that the slurry amount which has to be transferred out of the cutting slot also increases.
As a consequence the friction onto the binder and simultaneously the wear rise.
Concrete A30 shows the lowest wear values, due to the low grain hardness which does not lead to a significant stress on the diamonds. Microscopic examinations underline this effect by showing only few amounts of fractured and pulled out diamonds. Instead of that, abrasive particles cause enhanced binder wear. The machining of concrete C30 and E30 causes significant higher wear values. However, the wear mechanism differs from the observation before. Mainly fractured and pulled out diamonds can be found, because of hard aggregates exceeding the mechanical fracture toughness of the diamond and the grain retention force of the binder. The mean process forces are below the level of A30, due to a partially lower concentration of aggregates on the examined flat joint surfaces.

3.2 Process signal correlation
The following figure 5 exemplarily displays the comparison of process signals for concrete A30 and C30 with a feed rate of \( v_f = 2 \text{ m/min} \) and a cutting depth of \( a_n = 25 \text{ mm} \).

![Figure 5: Comparison of process signals.](image)

The developments of the \( \text{AE}_{\text{RMS}} \) and airborne sound raw signal are in both cases closely related to the filtered process forces (diagrams above). Both work pieces show a similar flat joint surface with small aggregates which are homogeneously distributed and have a similar concentration. Accordingly, elevated mean values for C30 are caused by higher hardness values of the grains in the kerf which also lead to higher signal level divergences. Concrete E30 with even harder grains but a lower aggregate concentration shows divergences of up to 400 %.

Hence, an evaluation of mean value divergences gives an opportunity to characterise the work pieces structure and its machining properties. Large divergences indicate the machining of very hard aggregates which are able to overload the diamond grains.

Normally, in concrete cutting the regulated parameter is the feed rate. Therefore, an examination of the signals as a function of the feed rate is important for a statement about the suitability for the process description. Figure 6 shows the average process forces (top) and averaged sonic signals \( \text{AE}_{\text{RMS}} \) and \( \text{LS}_{\text{RMS}} \) with an increase in cutting rate exemplifies for \( a_n = 25 \text{ mm} \).

![Figure 6: Dependence of mean process signals and feed rate.](image)

Both process forces and sonic signals increase almost linearly in all types of concrete due to the chip thickness increasing with the feed rate. Concrete C30 has relatively high normal force values, which are about 200 % above the level of the other concretes. Despite the higher hardness of flint grit, the force level for concrete E30 is significantly lower. The analysis of the material structure shows that the high values of C30 are due to a remarkably higher proportion of grain concentration of about 32 %. In comparison, the cut surface examined for E30 has a minor grain proportion (26 %). Therefore an averaging over the entire kerf results in a lower level for concrete class E. As expected, concrete A30 shows the lowest values due to the lowest grain hardness. These results demonstrate that an increasing mechanical tool load due to higher cutting rates influences the developing of all examined signals in a same way.

3.2 Frequency distribution
The signal correlations described before already showed a correlation to properties of the material structure. To gain more insight into the
dependency of the work piece characteristics and sonic signals, the frequency distribution of these spectra are analysed. For this reason the LS$_{RMS}$ data are filtered with a band-pass filter. The RMS signal level is calculated for each single cut and the data from all cuts is projected on the flat joint surface. The first and second image in figure 7 show two different band-pass filter of the same flat joint surface for E30. Strong airborne sound emission higher than -20 dB is connected with a big flint aggregate grain. Upon the first contact with this grain, the tool starts to emit a high-frequency sound at about 9000 Hz. When the contact of tool and grain increases, the lower frequencies in the range of 4500–5000 Hz dominate the spectrum. When the tool leaves this area the same behaviour in opposite direction takes place.

The analysed frequency bands show slightly increasing intensities for some smaller coarse aggregate grains. In contrast, there is no significant increase in the signal level of concrete sample A30 with a low Mohs-Hardness of 4.

The local hardness of concrete components can be detected by analysing the sonic signals within specific band-pass filters. Therefore, this technique allows the location of hard, tool stressing aggregates.

4. Conclusion
The cut-off grinding of concrete is a technologically challenging process due to the often unknown material structure. For this reason, it is necessary to develop a method which allows a statement about the machinability of the concrete.

The presented investigations are aimed at the characterisation of the workability based on clear process signals. In the first step the influence of the concrete structure on the process signal- and wear behaviour was determined. The analysis of the cut-off process shows that especially the aggregate grain hardness and its concentration affect the machining behaviour. The wear development shows a strong correlation to process forces, airborne sound and AE signal. Larger signal divergences in short time periods indicate the machining of hard, wear-enhancing grains. In addition, characteristic changes of the frequency distribution can be determined dependent on the material properties. These findings demonstrate the potential for a targeted control intervention for the protection of the tool as a function of significant signal changes.

The content of further research is the extension of the investigations on the often used reinforced concrete. Furthermore, the results should be the basis for a process control enabling an increased efficiency and process safety of concrete cutters.

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References