SINGLE SEGMENT TESTS FOR THE ANALYSIS OF THE CORE DRILLING PROCESS OF CONCRETE MATERIALS

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ABSTRACT

Diamond impregnated tools, like drill bits or circular saws, are used for the machining of mineral materials like stones or the compound material concrete. Drill bits comprise several single diamond impregnated segments which are attached to the top of the tool body by brazing or laser welding processes. Fields of application of these tools can be found at the construction industry, the stone processing and the mining industry. The segments consist of a sintered powder-metal matrix and randomly distributed diamond grains. Hence, the number of exposed grains on the tool surface varies even for tools of the same specification. To simplify the analysis of the core drilling process with several segments and therefore diamonds in contact, tests with single segments were carried out. Thus, the number of exposed grains is reduced to a manageable number. To analyse the influence of grit size and concentration in diamond impregnated tools on the process behaviour when machining concrete materials, path-controlled tests on a machining centre were conducted. High performance concrete (C100) and reinforced concrete were machined and process forces were measured to quantify the influence of the tool specification. Additional information were gained by analysing the generated tool tracks.

KEYWORDS

grinding, core drilling, diamond, diamond impregnated tool, concrete, reinforced concrete

INTRODUCTION

The core drilling process is a flexible, simple and widely used method in construction industry to generate openings/holes in different types of materials like (reinforced) concrete, brickwork, asphalt or rock material. Core drilling tools comprise several diamond impregnated segments. Therefore a core drilling tool is also called "bit" or "crown". The segments consist of a sintered metal matrix and randomly distributed diamond grains throughout the metal binder volume. Hence, tools with diamond impregnated segments can be classified as grinding tools, because the segments comprise several cutting grains with undefined cutting edges. In dependency of the field of application, e. g. construction industry or geological exploration, different configurations of segments exist. This article focuses on diamond impregnated segments which are used for the machining of concrete materials in the construction industry.

1. STATE OF THE ART

A core drilling tool is composed of three main parts: the connection part, the main body (barrel, pipe) and the diamond impregnated segments. In construction industry an electronical drilling motor usually generates the necessary rotational motion while at the same time the drill bit is pressed into the material. The required force is applied by the operator either hand-guided or using a drill stand with a lever. Hence, core drilling in the construction industry is a force-controlled process. A specific value describing the drilling process is the weight-on-bit (WOB) value (also load or pressure on bit) which is the result of the division of the necessary force in feed direction by the surface area of the segments in contact [1, 2].

Diamond impregnated segments are manufactured by sintering procedures, like hot pressing [1]. Within this procedure a metallic powder and synthetic diamonds are mixed and sintered. The metallic matrix acts as the bonding and has two main functions. First of all, it has to hold the diamonds in place during cutting as long as they are sharp. Secondly, the metal matrix also needs to release diamonds before they become dull. Hence, matrix wear has to be adjusted to the diamond wear state for an efficient grinding process. This change of the segment due to wear is generated by the machining process itself and therefore called self-sharpening. Commonly, cobalt-based metallic powders are used as the metal matrix, because of its advantageous properties concerning diamond retention and wear. Due to different reasons, mainly economical but also environmental, developments lead to a replacement of cobalt-based matrices by iron-based ones having low cobalt content [3, 4]. The majority of today's diamond tools is manufactured with synthetic diamonds. The right choice and composition of diamond size, quality and concentration together with the metallic matrix material influences the efficiency of the grinding process. Hence, for different types of materials or concrete compositions, different types of segment configurations have to be chosen.

Concrete is a composite material which is manufactured by mixing cement, aggregates, water and if required further additives. Chemical reactions between cement and water lead to hardening processes. Within this composition the hardened cement acts like a binder which holds different types of aggregates like silicates, sand grains and stones together. Further additives e.g. superplasticizer are used to improve the mechanical properties of the manufactured concrete. Despite the hardened concrete is able to bear high compressive loads, its possibility to withstand tensile loads is very low. Hence, in construction elements steel bars are embedded as reinforcement. These steel bars, also called rebars, are carrying the tensile loads. Regarding the machining of reinforced concrete, the steel elements cause a reduction of the tool performance and increase the wear rate [5].

Despite the wide usage of diamond impregnated tools, the grinding process itself, e.g. the material separation and removal and the wear behaviour of diamonds and bonding, is not fully understood. Due to a large number of influencing factors, measurement results gained from drilling tests provide only global information, because interdependencies cannot be distinguished clearly [2]. Hence, the first logical step is to reduce the influencing factors by reducing the number of segments which are used for a drilling operation. This approach leads also to a reduction of exposed and active grains to a manageable number. As a consequence, the analysis of the process is simplified.

As mentioned before, core drilling processes are generally force-controlled. Nevertheless, path-controlled tests can be an appropriate method for analysing the process behaviour of diamond impregnated segments. *Franca*, *Mostofi* and *Richard* are motivating path-controlled test with single segments for different reasons [2]. The major advantage mentioned there is the shorter duration of drilling tests. Further advantages are the increased accuracy of measurement results and the higher stiffness of the set-up which reduces vibrations.

2.   MATERIALS AND METHODS

Single segment tests were conducted on a machining centre FZ 12 S (Chiron-Werke) which consists of a travelling column with a vertical spindle and a fixed machine table. It is designed for drilling and milling operations of metal materials. Like it is common for these kinds of processes, the machining centre allows path-controlled motions. The experimental set-up (without coolant supply) and the kinematics of the test procedure are shown in figure 1. For testing single segments, a tool holder was attached to the spindle of the machining centre. During the tests, a constant infeed velocity and number of revolutions were set, so that annular tool tracks were generated. Because the infeed velocity is of major interest concerning tool performance in core drilling processes, tests with different infeed velocities v_f were conducted and varied in a range of $v_f = 0.25$ to 2 mm/min. This parameter field was deduced from force-controlled drilling tests with
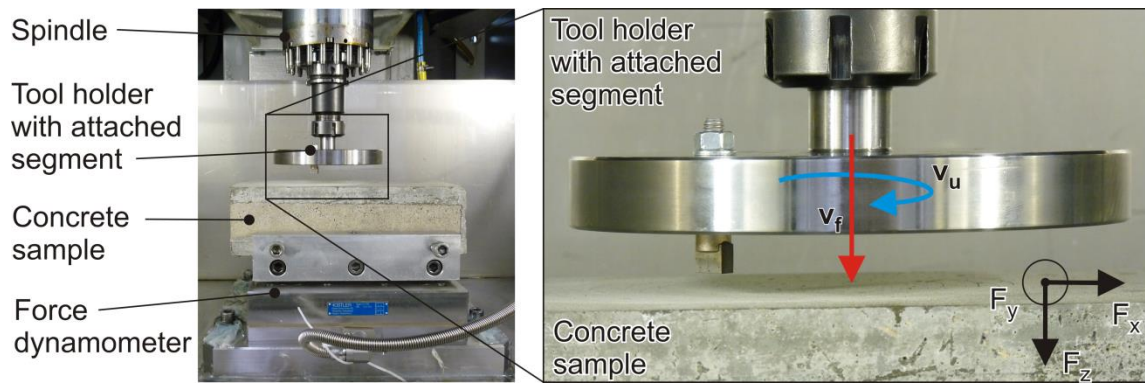
Fig. 1: Experimental set-up

core drilling bits comprising eight segments which are not subject of this article. The circumferential speed was kept at a constant value of $v_u = 2.35$ m/s for all tests which corresponds with typical circumferential speeds in core drilling processes of concrete with diamond impregnated segments. For testing a segment, a drilling depth of at least $l = 0.5$ mm was set. Several tests were conducted on the same position. Hence, the total depth of the generated tool track was increased gradually to a limit of $l_{tot} = 4$ mm.

For measuring the process forces while drilling, a force dynamometer of Kistler Instruments, type 9255C, was used and attached on the machine's table. With this dynamometer the forces in the three axes F_x, F_y and F_z can be measured. A frequency of $f = 10.000$ Hz was set to measure the process forces. Qualitative data was gained by microscopical pictures of the segments which were taken showing side and plane view.

To remove debris and slurry from the contact zone while drilling water without further additives is usually used but in order to avoid corrosion within the machining centre it was necessary to use a water miscible lubricant (Bechem Avantin 361, concentration $p = 7$ %) as additive. During the tests a sufficient amount of water was supplied to remove the slurry from the tool track.

The tested segments had got a rectangular shape with an initial segment height of $h_{seg} = 10$ mm, a width of $w_{seg} = 5$ mm and a length of $l_{seg} = 10$ mm. Before testing, a preparation routine (run-in) was carried out to expose the first diamond layer within the segment. Diamond impregnated segments made of the metal bonding Diabase-V21 (Dr. Fritsch) and synthesized diamond grains type Syngrit SDB1055 (Element Six) were tested. According to Dr. Fritsch, this type of metal bonding is designed for drilling and sawing operations of concrete and granite [6]. Its main components are iron, copper, cobalt and tin. The used synthesized diamonds are uncoated and have got impurities and an irregular shape. The segments were manufactured comprising three different mesh sizes ($d_k = 20/30$ mesh, $d_k = 40/50$ mesh and $d_k = 70/80$ mesh) and three different diamond grain concentrations ($c = C8$, $c = C20$ and $c = C40$). For testing, a segment was attached to a tool holder at a diameter of $d = 100$ mm which corresponds to commonly used core drilling tools.

The tests were conducted on samples made of concrete and reinforced concrete. On the basis of its compressive strength the concrete utilised for both types of samples is assigned to category C100/115 according to DIN EN 206 [7]. A further classification ranks the tested concrete as high-strength concrete [8]. The concrete samples were made of Portland cement 52,5 (Holcim AG), basalt in two different grain sizes (2/8, 8/16), sand (0/2), microsilica type 971-U (Elkem) and super-plasticiser type Glenium 51 (BASF). Two rebars made of steel (B 500 B) with a diameter of $d = 12$ mm were embedded in the concrete as a reinforcement. Because of a distance of $s = 110$ mm between the rebars, both rebars were cut during a drilling test.

Franca, Mostofi, and Richard describe two types of possible single segment tests [2]. These were called tests with "invariant topography" and tests with "variant topography". This classification is

based on the effect of self-sharpening. Hence, "invariant topography" tests mean no or minor changes of the segment while testing. According to this classification the majority of the conducted tests can be described as "invariant".

3. FORCE SIGNALS

The forces which can be measured during tests carried out on concrete or reinforced concrete are significant different owing to the rebars in reinforced concrete. These cause different material separation processes resulting in different process forces. In figure 2 and figure 3 the measured force signals F_x, F_y, F_z and the corresponding process force signals F_n and F_t are illustrated. All force data shown was smoothed by a moving arithmetic mean having a width of 151 data points. The graph on the left hand side (a) in figure 2 demonstrates the general progress of force signal F_n while conducting a segment test. The force signal comprises a nearly stationary period after the process start. During the whole process fluctuations of the force signal with a high frequency exist. Minor changes of the bonding and the inhomogeneous material to be machined may cause fluctuations over a longer period of time (low frequency) in the force signal.

As expected a sinus wave in the force signals F_x and F_y occurs (cf. fig. 2 (b)), because of the rotational motion of the tool and the stationary force dynamometer. Whereas the measured force signal F_z corresponds with the normal force F_n, the tangential force F_t has to be calculated by a trigonometric function (1) using the force signals F_x, F_y and the period time of one revolution T. Here, it has to be considered that the starting point of the calculation must be a maximum in the F_x signal. For the comparison of the tests on concrete, the average of the force signals of F_t and F_n within a time period of t = 2 s in the stationary phase of the tests was calculated.

$$F_t(t) = F_x(t) * \cos\left(\frac{2*\pi}{T} * t\right) + F_y(t) * \sin\left(\frac{2*\pi}{T} * t\right) \qquad (1)$$

On reinforced concrete the measured force signal is highly influenced by the reinforcement (cf. fig. 3). As mentioned before, two rebars are embedded in the concrete. Figure 3 illustrates that the general progress of the force signal for F_n is comparable to the signal on concrete. But the reinforcement leads to two main differences. The force is marked higher on reinforced concrete
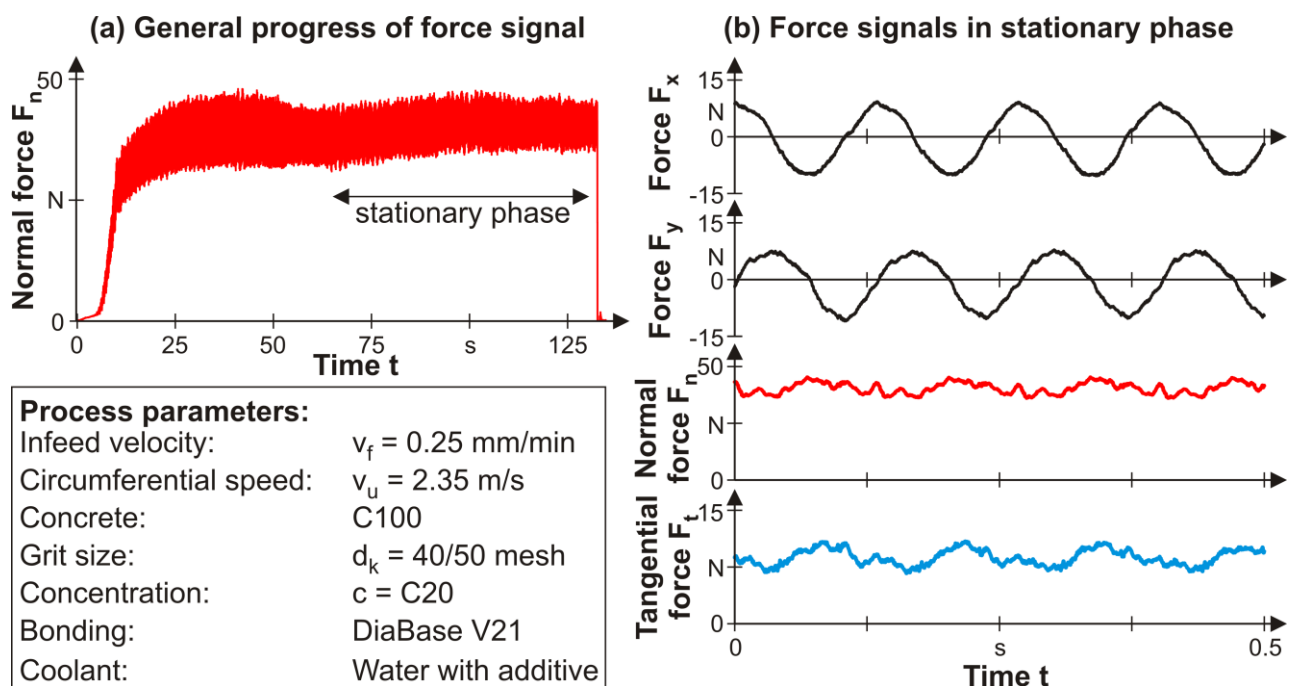

Fig. 2: Force signals when cutting concrete

(a) General progress of force signal

(b) Force signals in stationary phase

Process parameters:

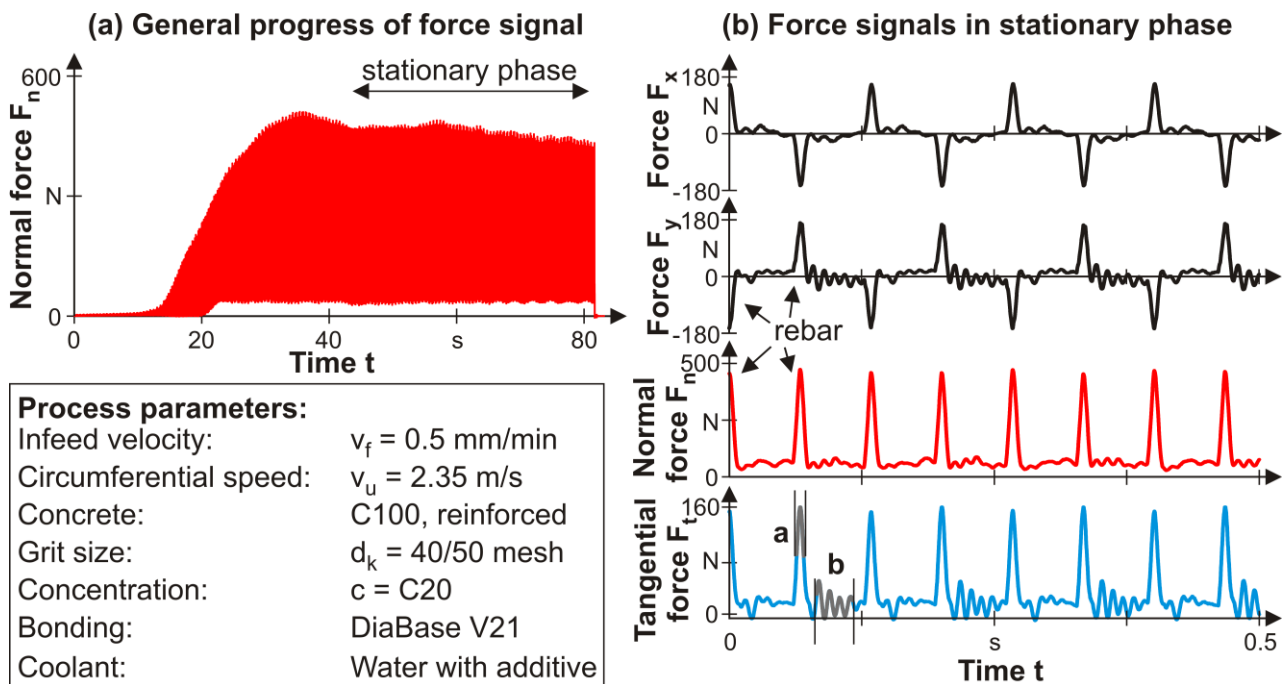|	
Infeed velocity:	$v_f = 0.5$ mm/min
Circumferential speed:	$v_u = 2.35$ m/s
Concrete:	C100, reinforced
Grit size:	$d_k = 40/50$ mesh
Concentration:	c = C20
Bonding:	DiaBase V21
Coolant:	Water with additive

Fig. 3: Force signals when cutting reinforced concrete

and therefore the fluctuation deduced from the general progress of the force signal seems to be very high. However, these fluctuations are caused by cutting the rebars as it can be seen in figure 3 (b). Cutting the rebars has got a great impact on the force signals causing rapid rises (peaks). Because of the stationary coordinate system and the rotational moving force peaks in F_x and F_y the direction changes from positive to negative and vice versa within one rotation. Whereas the alternation of the force F_x is comprehensible, the alternation in F_y signal depends of the position of the rebar and the way the rebar is cut. Because the segment cuts only through one half of the round rebar, the segment is pushed aside directed to the centre of the rotational motion.

For the comparison of the tests on reinforced concrete, a special analysis has to be conducted considering the two different phases in reinforced concrete. It was chosen to consider m = 100 sections in steel, as shown in figure 4 (b), detail a, and to calculate the average of these sections quantifying the influence of the rebar on the process forces. In concrete a similar method was chosen. Here also m = 100 sections were considered and the average was calculated (cf. fig. 3, detail b). Hence, force signals occurring during n = 50 rotations were considered for the analysis. The calculated averages are used for the comparison of the segment tests shown in the following chapters.

4. INFLUENCE OF DIAMOND SIZE AND CONCENTRATION ON PROCESS FORCES

The first test series was conducted on samples of high-strength concrete without reinforcement. Within this test series all of the nine segment specifications mentioned before were used. Two segments of each specification were tested for a general understanding of the deviation caused by the tool. Hereby, deviations could be expected due to a diverse number of exposed diamonds. In table 1 the number of exposed diamonds is given for all tested segments.

The influence of the infeed velocity on the resulting process forces is of major interest, because the achievable infeed velocity is decisive for the performance of actual force-controlled drilling processes. Therefore, each segment was tested at three different infeed velocities, $v_f = 0.5$, 1.25 and 2.0 mm/min. Tests with the infeed velocity of $v_f = 1.25$ mm/min were conducted two-times with each segment, whereas tests with the infeed velocity of $v_f = 0.5$ and 2.0 mm/min

Tab. 1: Number of exposed diamonds for tested segments

	First test series on concrete						Second test series on reinforced concrete
	d_k = 20/30 mesh		d_k = 40/50 mesh		d_k = 70/80 mesh		d_k = 40/50 mesh
	Segment 1	Segment 2	Segment 1	Segment 2	Segment 1	Segment 2	Segment 1
c = C8	5	10	12	15	28	31	21
c = C20	11	9	22	22	37	59	30
c = C40	15	13	43	39	101	96	46

were carried out only once with each segment. Resulting process forces are arranged in a matrix form shown in figure 4. In the rows this matrix comprises test results with the same diamond concentration and in the columns test results with the same grain size are shown. Within the conducted tests, significant changes, like diamond break-out, which could influence the process forces only seldom occurred. Hence, the vast majority of the tests can be described as tests with "invariant topography". An exception are the tests with diamond concentration c = C8 and grain size d_k = 20/30 mesh. This segment composition leads to comparatively high wear. Thus, fewer tests can be described as "invariant" and be considered for the graph shown in figure 4.

In figure 4 the results for the normal force F_n and the tangential force F_t in dependency of the infeed velocity are shown. For all tests an increasing infeed velocity causes a gradual rise of the process forces F_n and F_t. Within the tested range, the results indicate a linear correlation with steady growth between infeed velocity and process forces. Increasing infeed velocities correspond
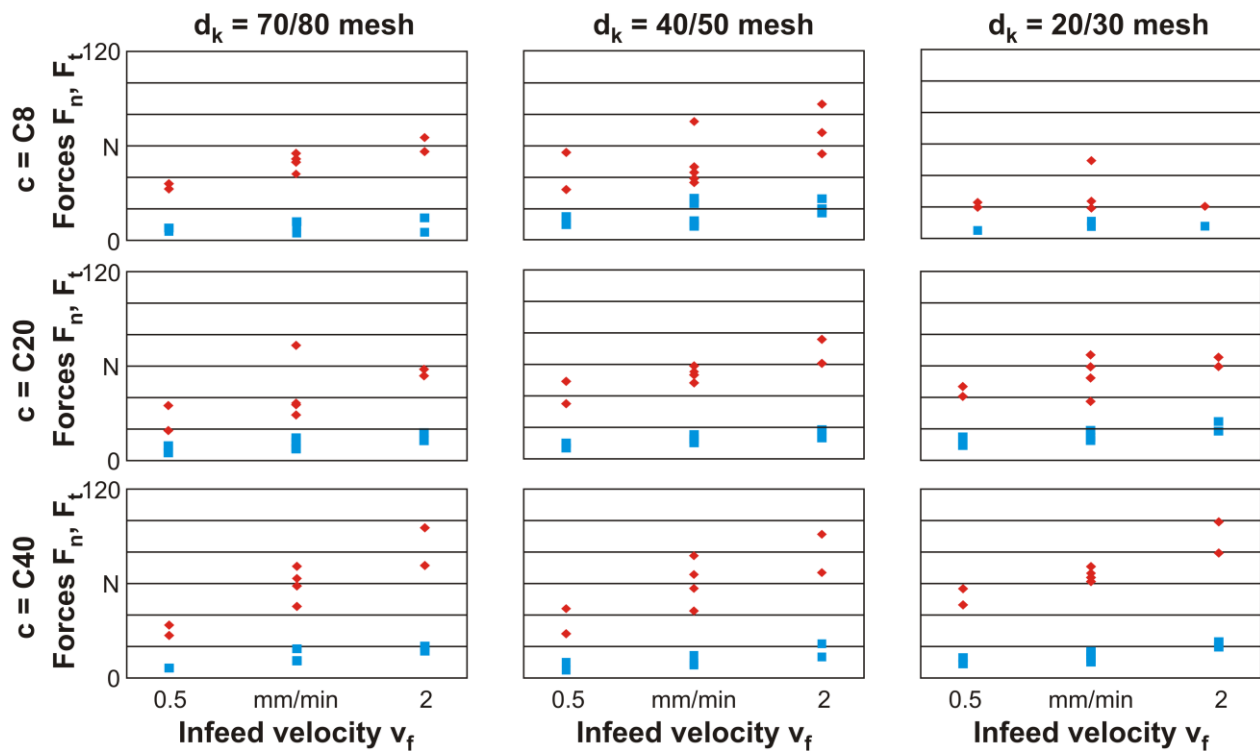
Process parameters:

Infeed velocity:	v_f = **var** mm/min	Grit size: d_k = **var** mesh	Concetration: c = **var**
Circumferential speed:	v_u = 2.35 m/s	Concrete: C100	Tangential force F_t ■
Coolant:	Water with additive	Bonding: DiaBase V21	Normal force F_n ◆

Fig. 4: Process forces for segment tests on concrete
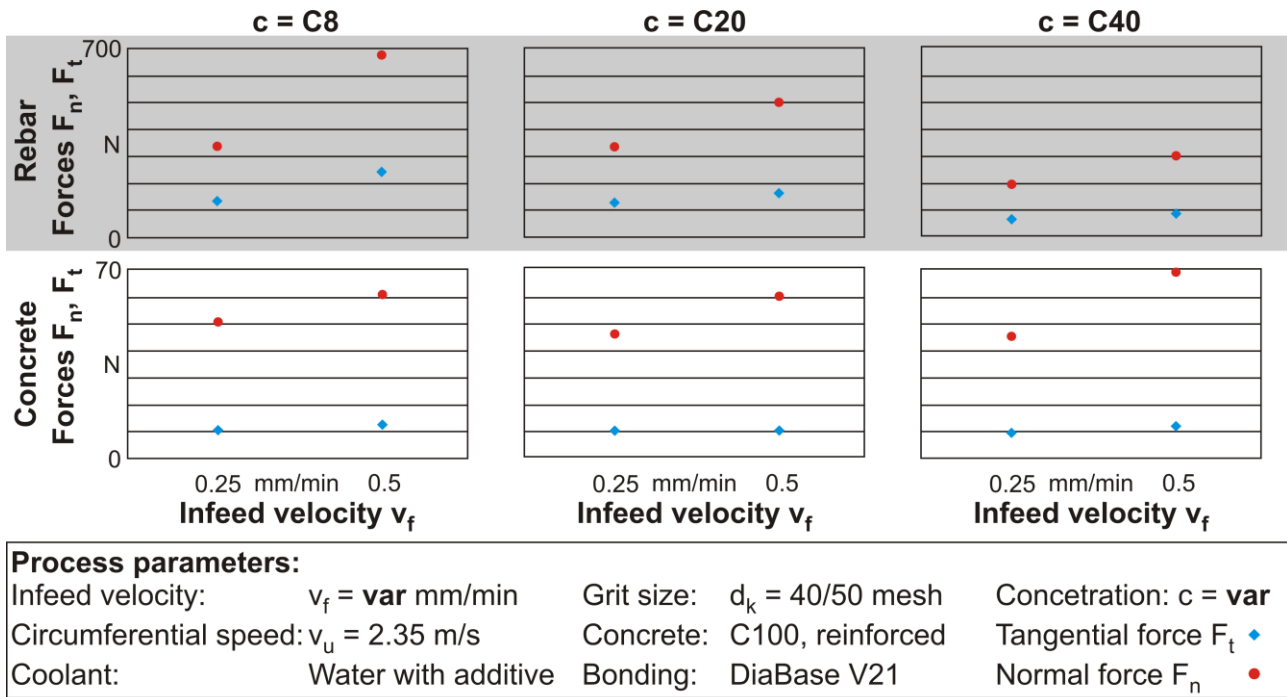
Fig. 5: Process forces for segment tests on reinforced concrete

with a higher infeed per revolution therefore also larger values of chip thickness are generated which are resulting in higher process forces. The greatest forces exist for an infeed velocity of $v_f = 2$ mm/min and diamond concentration of c = C40 independent of the diamond size. For these tests forces of about $F_n = 95$ N and $F_t = 20$ N were measured which results in maximum weight-on-bit values of about WOB = 190 N/cm². Minimum normal forces occur for small infeed velocities (about $F_n = 25$ N). In contrast, the tangential force F_t is always lower than $F_t = 25$ N, but not less than $F_t = 5$ N. For a diamond concentration of c = C8, comparing force results for an infeed velocity of $v_f = 1.25$ mm/min, the results represent a slight decrease of process forces with increasing diamond sizes. Due to smaller diamond size but a constant diamond concentration the number of exposed diamonds increases (cf. tab. 1). Hence, it can be assumed that a larger contact area between diamonds and concrete exists which causes higher process forces. Nevertheless, considering also the tangential force, the results reveal a higher cutting efficiency for segments with a diamond size of $d_k = 40/50$ mesh. A higher cutting efficiency in grinding is achieved when the relation between the tangential and the normal force increases ($\mu = F_t/F_n$). For a diamond concentration of c = C20 significant differences between the measured normal forces do not exist for different grain sizes. However, the tangential force is maximal for a diamond size of $d_k = 20/30$ mesh. Here, the results also indicate that the material separation with a diamond size of $d_k = 20/30$ mesh is more efficient. Bigger diamonds lead to a higher protrusion of the diamonds which could cause a larger chip thickness and therefore an increasing cutting efficiency. For a diamond concentration of c = C40 no remarkable differences between process forces for infeed velocities $v_f > 1.25$ mm/min exist. This could be influenced by the large number of exposed diamonds for the entire tested segments.

The second test series was carried out on reinforced concrete samples with two rebars. Because of a significant rise of process forces due to cutting the rebars, it was necessary to readjust the infeed velocity to smaller values. Consequently, tests with two different infeed velocities and three different segments were conducted (cf. fig. 5). The process forces when cutting the ductile metal rebar material is remarkable higher than in cutting concrete. Hence, the scale for graphs which illustrate the process forces in rebar is ten-times magnified than the scale for process forces in concrete. The results for normal forces when cutting the rebar are at least five-times higher within the conducted tests. For all tested segment specifications an increase in infeed velocities causes higher process forces. The maximal normal force measured is at about $F_n = 680$ N

(WOB = 1360 N/cm²) for rebar and at about F_n = 61 N (WOB = 122 N/cm²) for concrete. The test results for rebar show a marked drop of the process forces F_n and F_t for an increased diamond concentration. However, this drop is not visible in the process forces when cutting concrete. Comparing the test results for concrete (cf. fig. 5) with the test results of the first series conducted (cf. fig. 4) no significant difference can be observed. The marked differences regarding process forces in rebar and concrete indicate significant differences for material separation as expected.

5. INLFUENCE OF DIAMOND CONCENTRATION ON TOOL TRACKS

For an efficient cutting process it is of interest to minimize friction and to increase material removal. This will be achieved, if every exposed diamond creates an individual cutting track. Therefore a certain distance should exist between two diamonds and each exposed diamond should not be located in direct line with another diamond. In this case, its capability of generating material removal is limited. Instead, primarily frictional processes have to be expected which cause wear flat of the diamond [9]. When cutting ductile metal materials, a minimum depth of cut has to be reached before a material removal with chip formation can be generated [10]. Otherwise, only frictional processes, elastic and plastic deformations occur. For detailed analysis of the material separation in the cutting zone three-dimensional scans for gaining profile information were carried out. Scans of the tool tracks in the rebar and the concrete were made with a confocal white-light microscope (µsurf, Nanofocus).

In figure 6, profiles and microscopical pictures of the used segments are shown. The profiles and pictures indicate that with an increase of diamond concentration which corresponds to a rise of the number of exposed diamonds, a more levelled and smoothed tool track is produced. This can be observed for the rebar as well as for the concrete profiles. Due to the increased number of exposed diamonds several cutting tracks by several different diamonds occur. These are spread uniformly across the tool track width causing a levelled tool track surface (cf. fig. 6, c = C40). In contrast, the tool track generated by the segment with the lowest diamond concentration of c = C8 reveals individual cutting tracks. Comparing the profiles generated in rebar and in concrete the difference of material properties become apparent. The ductile material behaviour of the rebar
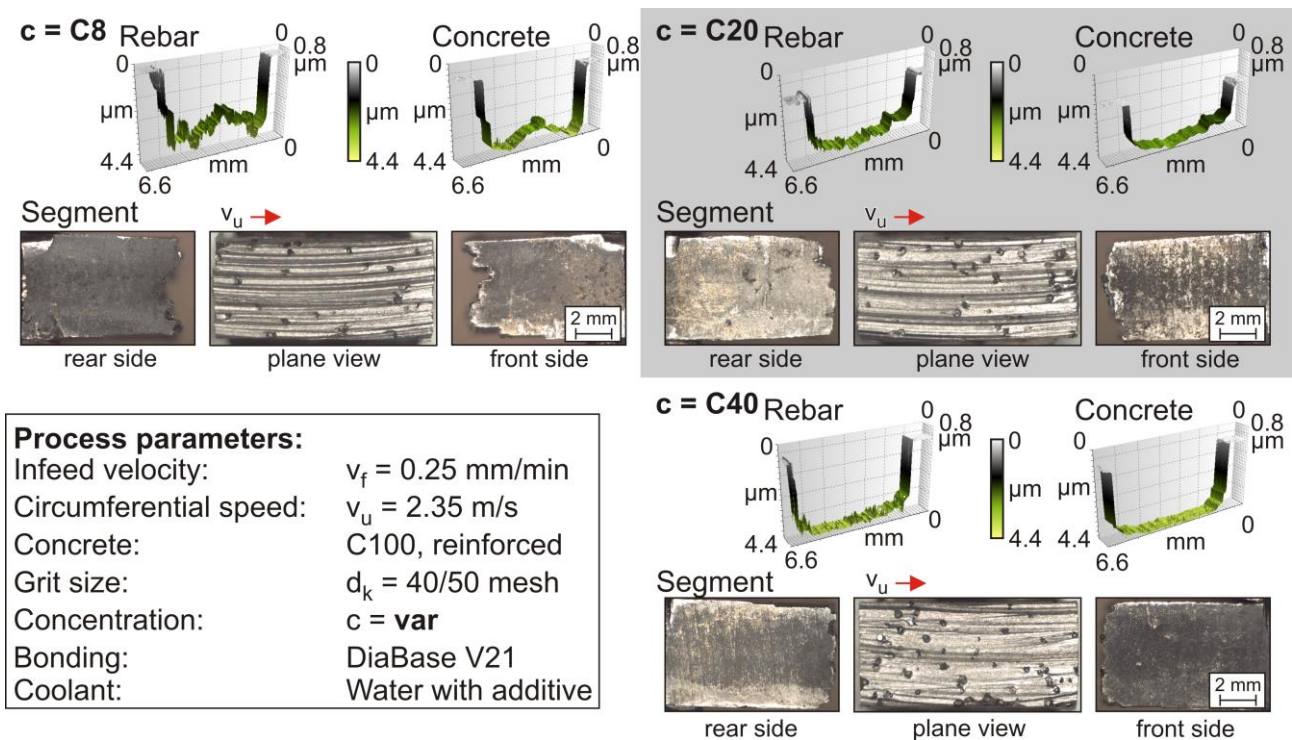

Process parameters:

Infeed velocity:	v_f = 0.25 mm/min
Circumferential speed:	v_u = 2.35 m/s
Concrete:	C100, reinforced
Grit size:	d_k = 40/50 mesh
Concentration:	c = **var**
Bonding:	DiaBase V21
Coolant:	Water with additive

Fig. 6: Profiles of tool tracks and microscopical pictures of used segments

enables elastic and plastic deformation during cutting. Hence, different grooves and peaks in the profile of rebar exist. Due to the fact that the position of the grooves and the position of the single diamonds correspond it is possible to assign grooves to single diamonds on the segment. The profiles in concrete show less peaks in comparison to the profiles in rebar. Concrete has got brittle material properties; hence, the material separation is predominately generated by cracking and fracturing of material. The profiles of concrete do not reveal distinctive grooves or peaks which are comparable to the grooves in the rebar. Instead, the profile of concrete show wider grooves. For the diamond concentration of $c = C40$ in the profile of concrete no single cutting tracks can be observed because there are presumable superimposed. In contrast such single cutting tracks are visible in the profile for concrete generated by the segment with a diamond concentration of $c = C8$.

The tests with the segment having a diamond concentration of $c = C8$ reveal an influence of the diamond distribution on the cutting behaviour. Due to a non-uniform distribution of exposed diamonds on the segment surface, cutting tracks are not generated across the whole tool track width. Hence, an increased bonding wear appears in line where no diamond is set. Thus, distinctive deep grooves are generated by wear of the bonding. Furthermore, a specific material peak in the concrete and in the rebar profile arises. The depth of the groove in the segment, i.e. material peak increases with the depth of drilling. This type of wear is not representative for actual drilling tests, because in core drilling several diamond impregnated segments in row create several cutting tracks which are superimposed.

6. SUMMARY AND CONCLUSION

Within this research, tests with single diamond impregnated segments of drill bits were conducted. The testing procedure was derived from the force-controlled core drilling process. However, the tests were driven path-controlled using a machining centre to analyse the occurring process forces and the generated tool tracks in concrete and in reinforced concrete respectively. The test procedure proved to be an appropriate method for the detailed analysis of the drilling process with diamond impregnated segments.

Two series of segment tests on concrete and reinforced concrete were carried out. The vast majority of these tests showed minor wear so that an invariant segment topography existed throughout the tests. As expected, tests on concrete as well as on reinforced concrete revealed higher process forces due to higher infeed velocities. On concrete nine different segment specifications (diamond size, diamond concentration) were tested. The results on concrete showed similar process forces for segments with high diamond concentrations ($c = C20$ and $C40$). For the lowest diamond concentration $c = C8$ tested and a constant infeed velocity the results indicate a decrease of this process forces with an increasing diamond size. Regarding cutting efficiency based on µ, the biggest diamond size revealed the highest values. Bigger diamonds result in higher protrusion heights which might contribute to a more efficient cutting process. Furthermore, higher protrusion heights increase the necessary free volume in the cutting zone for slurry whereby frictional processes between removed material and segment could be minimized. In contrast, high diamond concentrations in combination with smaller diamonds could not leave enough free volume for debris and slurry so that similar process forces are generated.

The measurement of the profile of the generated tool tracks in reinforced concrete provided further information for a detailed analysis of the material removal process. A high diamond concentration creates several superimposed cutting tracks whereas a low diamond concentration leads to cutting tracks which can be assigned to single diamonds on the segment. In the case of a high diamond concentration, it has to be assumed that single diamonds cannot cut efficiently. Possible reasons are low cutting depths, either due to imposed cutting tracks or due to their position in a line of another diamond. These circumstances can result in undesired wear of diamonds like wear flat in drilling tests. On the other hand, the interactions between two actual cutting diamonds could cause an increased material removal by interactive material fracturing [11].

Measured force signals during tests on reinforced concrete showed distinctive peaks when cutting the metal rebars. Within the conducted tests, the average values of these peaks were at least five-times higher than the process forces for concrete. Three different segments comprising the same diamond size but different diamond concentration were tested. In concrete for both test series no significant differences regarding process forces in dependency of the diamond concentration existed. In contrast differences in rebar occurred. The results showed lower forces in rebar for higher diamond concentrations. The analysis of the tool tracks in the rebar and in the concrete shows that the cutting tracks in the concrete are wider and deeper than the corresponding cutting tracks in the rebar owing to the different material removal processes [12]. For the rebar, in tests with a low diamond concentration, the profile has got a high roughness (sharp peaks) in contrast to a smooth profile for the tests with a high diamond concentration. A small number of active grains may cause high plastic deformations and material bulging which might lead to extensive frictional processes and therefore process forces and rough tool track profiles. Instead, with a higher number of active grains smaller chips by microcutting and microfatigue, defined by *Zum Gahr* [13], could be generated and plastic deformations are limited to a smaller range.

In further test series the parameter field will be extended to cover a wider range of applications. Due to significant differing test results concerning process forces and cutting tracks, a detailed analysis has to be carried out on the material separation and the material clearance of the cutting zone while drilling reinforced concrete. Furthermore, the still current topic of arranged diamond settings has to be considered for future tests. Hereby a more stable and uniform process behaviour with respect to material removal and wear is to be expected which will improve the output of tests.

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