SCRATCH TESTS WITH SINGLE DIAMOND TOOLS ON REINFORCED CONCRETE AND ITS COMPONENTS FOR THE ANALYSIS OF THE MATERIAL SEPARATION

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ABSTRACT

Core drilling with diamond impregnated segments is a common process for the machining of concrete or reinforced concrete. These materials are characterised by their structure consisting of various components. This inhomogeneity influences the cutting process due to changing process forces or varying chip formation. Therefore an analysis regarding the material separation of the single components (cement stone, aggregates like basalt, steel as reinforcement) as well as of the compound materials is necessary. As a basis to analyse the core drilling process and in order to gain detailed knowledge concerning the material separation process of reinforced concrete and its components, scratch tests with single diamonds and varying process strategies were conducted. In analogy with the core drilling process, circular grooves were produced. For the scratch tests steel, cement stone, basalt, high performance concrete and reinforced concrete were used as sample materials. One test series was conducted on a machining centre with the focus on process forces under varying process parameters such as cutting velocity or feed speed. Further experiments focused on the analysis of the development of the scratches due to repeated scratching. For this microscopic investigation a tribometer in combination with a large-chamber scanning electron microscope was used.

KEYWORDS

scratch test, diamond tool, single grain diamond, material removal, reinforced concrete, concrete, process forces, large-chamber scanning electron microscope

INTRODUCTION

Reinforced concrete is a construction material consisting of concrete as a mineral component and steel as a reinforcement. Regarding the machining of this composite material the diverse characteristics of material separation of each constituent have to be investigated in order to analyse grinding processes as e.g. core drilling. The material removal process in grinding metallic materials is characterised by elastic and plastic deformation and chip formation [1]. In contrast scratch tests revealed that chip formation in stone is a consequence of cracking, while also plastic deformation occurs [2]. Regarding concrete differences between the cement and the included aggregates are relevant additionally [3, 4].

Conducting scratch tests with single grain diamonds in order to simplify complex grinding processes is an often used method to examine the characteristics of material separation. Concerning the scratch tests conducted in this research the core drilling process using drill bits with several diamond impregnated segments is the underlying machining process. Therefore tests on a machining centre were performed with a specific kinematic derived from the core drilling process. Moreover, with the aim of obtaining detailed and comprehensive knowledge concerning the material separation of the examined high-strength concrete and reinforced concrete tests were carried out on the composites in addition to the separate components. Material separation of the single constituents was also analysed by force-controlled, iterative scratch tests performed in a large-chamber scanning electron microscope.

1. MATERIALS AND SET-UPS FOR EXPERIMENTAL TESTS

As the basic material for the experimental investigations a concrete categorised as C100/115 in DIN EN 206 due to its compressive strength was used [5]. Hence, it belongs to high-strength concretes [6]. As the cement component CEM I 52,5 R HS/NA was used, whereas the concrete included sand and basalt in different particle sizes as concrete aggregates. Also reinforced concrete was analysed. These samples contained a part out of steel (1.0577) in analogy to a reinforcement. In addition to the concrete samples the material separation of the single materials is considered as well. Therefore samples out of steel (1.0577), basalt and cement stone were utilised separately. In this paper, the analysed cement stone consisted of cement and sand grains. In contrast to the analysed high performance concrete C100, basalt was no component. For both kinds of scratch tests round samples with a ground surface were used.

Scratch tests in a large-chamber scanning electron microscope

One kind of scratch tests was carried out using a tribometer in a large-chamber scanning electron microscope (MIRA XI). The tribometer is used for pin-on-disk tests [7] and was modified for the conducted scratch tests. On the basis of an iterative process strategy the tests enable to analyse the development and changes of the scratches as a result of repeated scratching qualitatively by SEM pictures. An overview of the test set-up and the process principle illustrated by a schematic drawing are shown in figure 1.

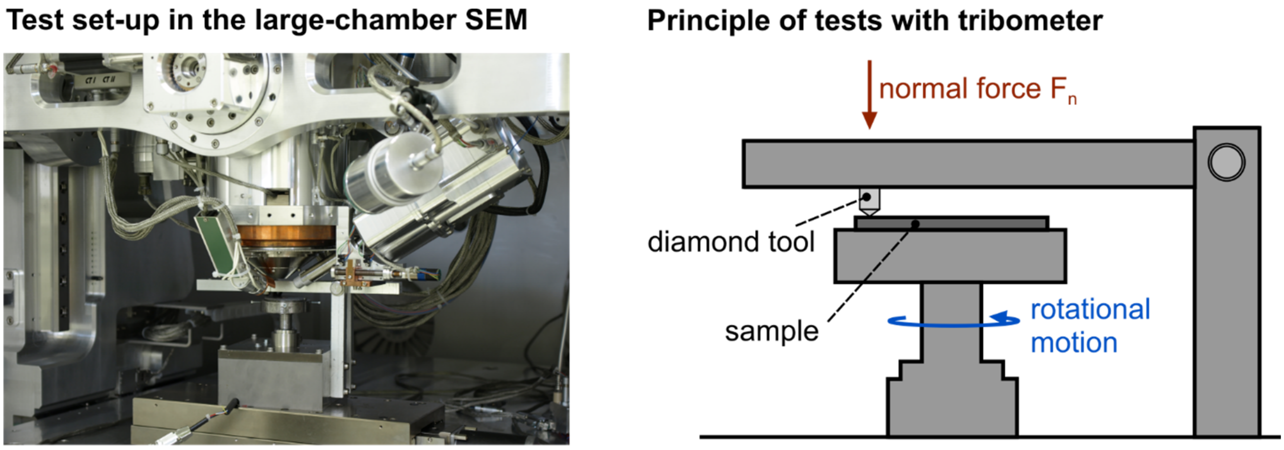
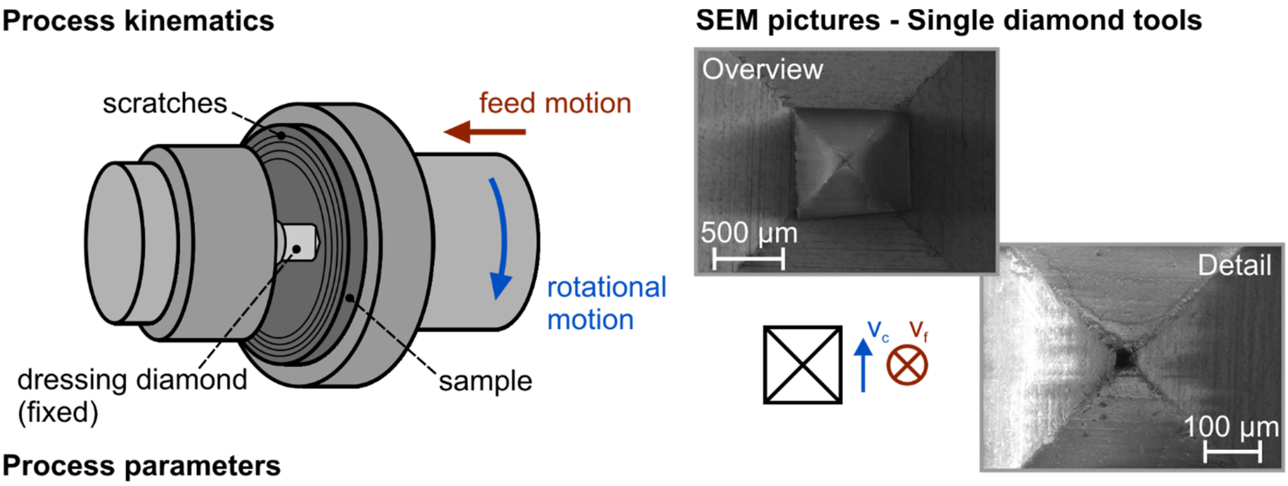


Fig. 1: Set-up with tribometer in a large-chamber SEM

For these scratch tests synthetic diamond grains (Element Six, SDB 1055) with a varying particle shape were used. The rotational and therefore cutting motion was realised by a rotating sample holder driven by a stepper motor as illustrated in figure 1. The normal force F_n for scratching was $F_n = 1.7$ N and the cutting speed was about $v_c \approx 0.2$ m/s. The scratch tests were interrupted every second turn till $n_{max} = 20$ rotations were passed in order to investigate the changes in the trace generated by scratching. A secondary electron detector was employed to take SEM pictures at a defined area of the sample each time. The resulting image sequence allows the qualitative, microscopic analysis of the scratches.

Scratch tests conducted on a machining centre

Additional scratch tests with another process strategy were conducted on a machining centre (IXION TLF 1004) in order to analyse the resulting process forces (normal force F_n and tangential force F_t) depending on the feed speed v_f, the cutting speed v_c and the workpiece material. Information concerning kinematics, tools and varied process parameters for the tests are shown in figure 2. In contrast to the above mentioned scratch tests, dressing diamonds (CVD-diamond, Dr. Kaiser Diamantwerkzeuge) with a regular geometry were used. These diamonds have a pyramidal shape with a point angle of $\sigma = 110°$. Conducting the scratch tests the tools were aligned in the way it is shown in figure 2.



Process parameters

tool	cutting speed v_c	feed speed v_f	total depth a_{tot}
CVD-diamond pyramide point angle σ = 110°	$v_{c,1}$ = 40.5 m/min $v_{c,2}$ = 117 m/min $v_{c,3}$ = 193.5 m/min $v_{c,4}$ = 270 m/min	$v_{f,1}$ = 2.0 mm/min $v_{f,2}$ = 9.5 mm/min	a_{tot} = 0.080 mm

Fig. 2: Kinematics, tools and parameters for scratch tests on the machining centre

Through an eccentric position of the fixed diamond tool relative to the centre of the sample annular scratches were realised. On each sample up to twelve scratch tests with different diameters (d = 32…54 mm) were carried out. The varying diameter is not taken into account as an input value for the analysis of the measured process forces. Due to the rotation of the sample and the feed motion a helical path results which is comparable to the kinematics of the core drilling process with diamond impregnated tools. Whereas tests were performed with varying cutting speed v_c and feed speed v_f, the total depth for the scratch tests a_{tot} = 0.080 mm was invariable. Because of the inhomogeneity of the materials and the short process time of each scratch test, the sampling rate for the measurement of forces was set to f = 200 kHz. Moreover, a light barrier was implemented. Its signal was recorded simultaneously to the process forces during scratching. Hence, it is possible to identify the dependence of the position of the sample and the process forces. This is especially relevant for the detection of the effects resulting from the steel reinforcement in reinforced concrete.

2. RESULTS OF EXPERIMENTAL TESTS

Qualitative analysis of scratches due to scratching in a large-chamber scanning electron microscope

In order to point out qualitative differences in material separation between the components of the analysed high-strength concrete C100 and reinforced concrete respectively, results of the iterative scratch tests conducted in the large-chamber SEM for steel (1.0577), basalt and cement stone are represented in figure 3. SEM pictures of the scratches after n = 10 turns and n = 20 turns in different magnifications (overview, detail) are shown to demonstrate the development of the scratches after different process steps. Additionally, there are microscopic pictures of the resulting scratches after n_{max} = 20 turns and SEM pictures of the particular diamonds used because of their differences in particle shape. In the SEM pictures the cutting direction is given with respect to the relative motion of the diamond to the rotating sample. Furthermore, in figure 4 some exemplary details of scratches in cement stone and basalt after n = 10 turns are shown.

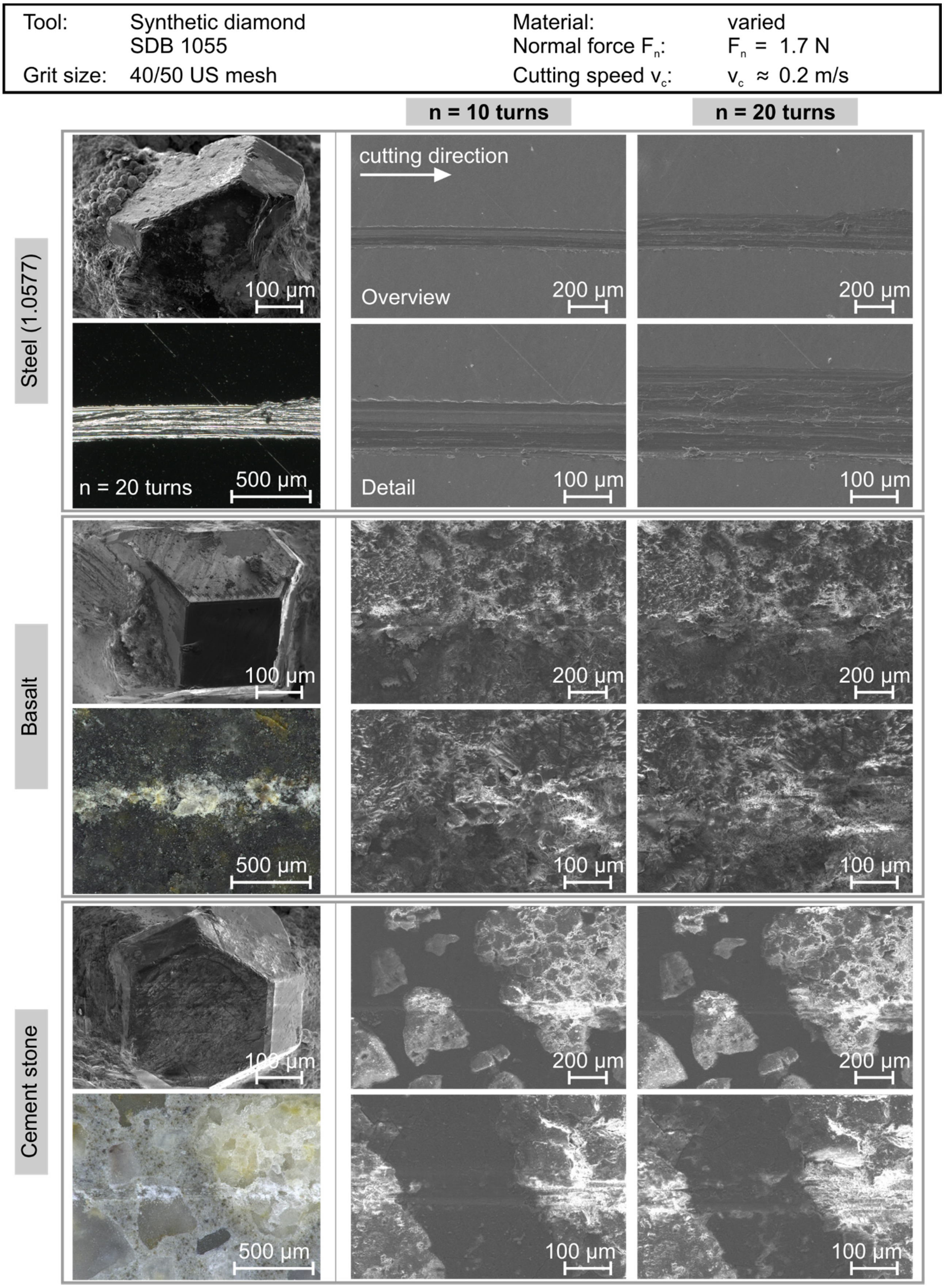


Fig. 3: Scratches in steel, basalt and cement stone after repeated scratching

The scratch in the analysed steel shows a kind of burr at the edges of the scratch (cf. fig. 3, n = 10 turns, detail) due to plastic deformation. After n = 20 turns some traces exist within the scratch which indicate that material was pushed to the outer edge of the scratch. These traces are also observable in the microscopic picture and they point out the ductile characteristics of the examined steel. The irregular surface conditions of the scratch after n = 20 turns are influenced by the repeated scratching. In basalt the resulting scratch is not visible as good in the SEM pictures as the scratch in steel owing to the appearance of the surface of the basalt sample in the SEM. The edges of the scratch cannot be defined exactly. Nevertheless, the processes of material separation can be discussed based on the pictures. There are parts of the scratch appearing comparatively smooth with compacted material (cf. fig. 4). This is a consequence of deformation processes [2]. Such areas are observable after n = 10 turns as well as after n = 20 turns, but in different forms whereby the change of the scratch as a result of further scratching is shown. Areas with fractured material occur as well, what is underlined by the microscopic picture of the scratch and demonstrates brittle material behaviour of the basalt. In the SEM pictures concerning cement stone the structure consisting of sand grains and cement becomes evident. The scratch in pure cement is more uniform compared to the above shown basalt. These resulting differences between cement and aggregates – basalt in this case – based on the force-controlled, iterative tests correspond to results of scratch tests conducted on different kind of concrete [3, 4]. The detailed SEM pictures of cement stone after n = 10 rotations in figure 4 additionally show separated material next to the scratch. Moreover, after n = 20 rotations there are detachments of material recognisable in cement. In sand grains the scratch is less distinct compared to cement and the material seems to fracture. Furthermore, material chips occur in the analysed transition area after multiple scratching as a result of cracking.

Tool:	Synthetic diamond SDB 1055	Material:	varied
		Normal force F_n:	F_n = 1.7 N
Grit size:	40/50 US mesh	Cutting speed v_c:	v_c ≈ 0.2 m/s

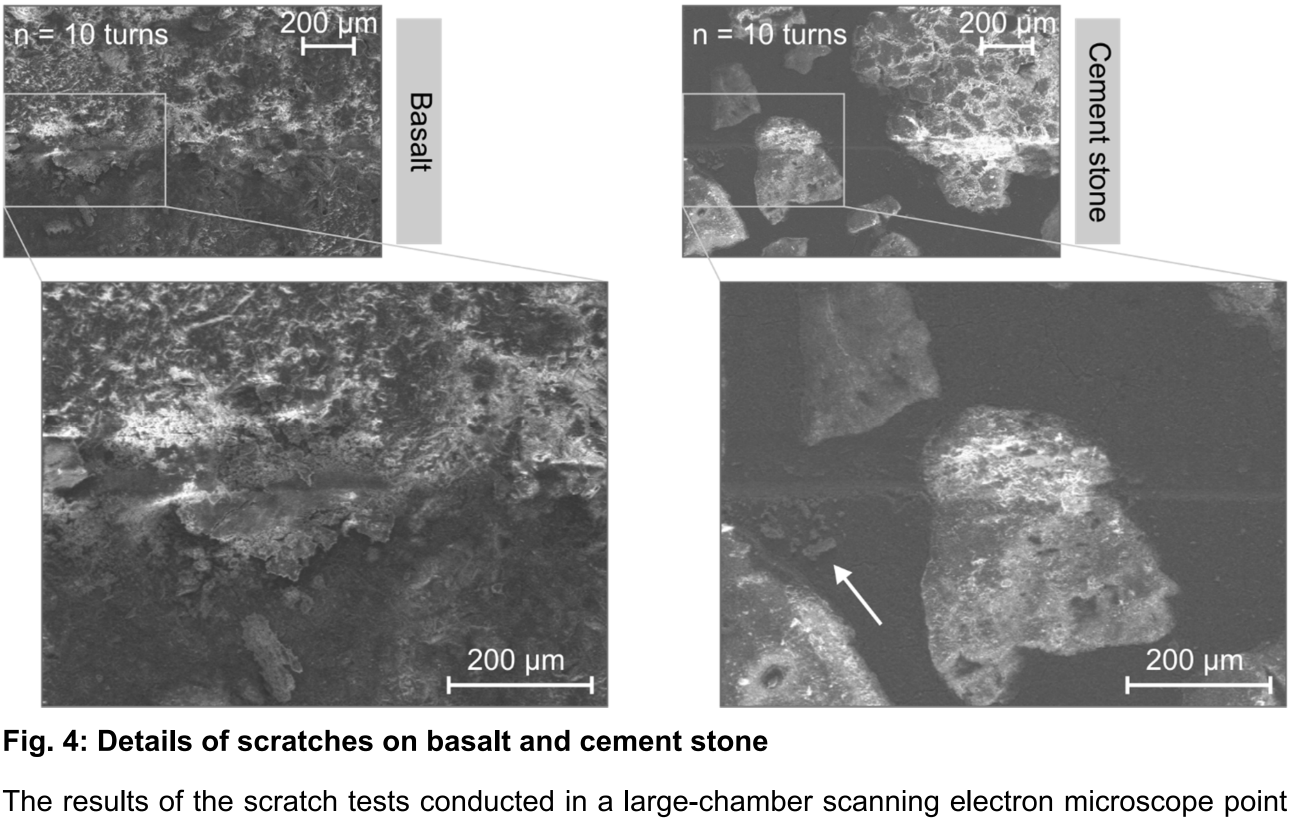


Fig. 4: Details of scratches on basalt and cement stone

The results of the scratch tests conducted in a large-chamber scanning electron microscope point out the qualitative differences of scratching the single components. The influences of the single constituents and the composites on the measured process forces are discussed in the following paragraphs based on the second test series.

Process forces depending on cutting speed and feed speed

On the basis of scratch tests carried out on a machining centre with pyramidal CVD-diamonds the process forces for five investigated materials were analysed. In figure 5 force data for the materials steel, basalt, cement stone and the composite concrete C100 are shown. Due to the fact that the influence of the steel part requires a particular analysis the process forces resulting by scratching the reinforced concrete are discussed separately. The tangential force F_t and the normal force F_n are analysed depending on varying cutting speeds v_c and feed speeds v_f, whereas the influences of different diameters for the tests and different dressing diamonds were not taken into account. The normal force F_n has the same direction as the feed motion and the force F_t is tangential to the rotational motion of the sample in the contact area. For the analysis and the comparison of the forces, the average force in the time period of a process time between t = 0.35 s und t = 0.36 s was calculated based on smoothed force data for each test. This leads to different covered scratch distances which were analysed for varying cutting speed. In figure 5 the mean value of four scratch tests for each combination of cutting speed v_c and feed speed v_f is shown. Moreover, the minimum and maximum average forces out of the four considered tests are marked. Regarding the results presented in figure 5 concerning steel, it has to be mentioned that because of irregular force signals for low cutting speeds, the force data is only shown for $v_{c,3}$ = 193.5 m/min and $v_{c,4}$ = 270 m/min.

The data presented in figure 5 reveals higher normal forces F_n than tangential forces F_t for all parameter combinations and analysed materials which is underlined by an adapted scaling in the diagrams for the particular force components. For all cutting speeds, there is a distinctive influence of the feed speed v_f on normal and tangential forces which does not depend on the different materials. Both, the normal forces and the tangential forces are higher for $v_{f,2}$ = 9.5 mm/min than for $v_{f,1}$ = 2 mm/min. This is generated by an increased feed rate f and therefore a larger area of the pyramidal diamond that is in contact with the material. This results in a higher chip cross-section. Scratch tests by *Apmann* on different types of concrete and steel showed that this has a strong impact on the resulting process forces [4].

Concerning the variation of the cutting speed v_c there is a trend of decreasing forces with increasing cutting speed, especially for v_f = 9.5 mm/min. As an exception the normal forces scratching cement stone have to be mentioned (cf. fig. 5, v_f = 9.5 mm/min). Lower forces for higher cutting speeds are influenced by the decreasing feed rate f with increased cutting speeds due to the helical process strategy of the conducted scratch tests. Regarding this, it has to be mentioned that the radius influences the feed rate as well wherefore the effect of cutting speed is superimposed. Comparing the different materials there are no distinctive differences between the mineral materials. Just for cement stone the process forces are marginal higher than those measured for basalt and concrete C100 for the majority of parameter combinations. Nevertheless, the absolute difference is low. On the other hand, scratching the steel leads to higher process forces than scratching the mineral materials in the analysed parameter range. In this case the different scale has to be emphasized. An exception are the tangential forces for the lower feed speed $v_{f,1}$ = 2 mm/min. They are on comparable level with the tangential forces for the mineral materials.

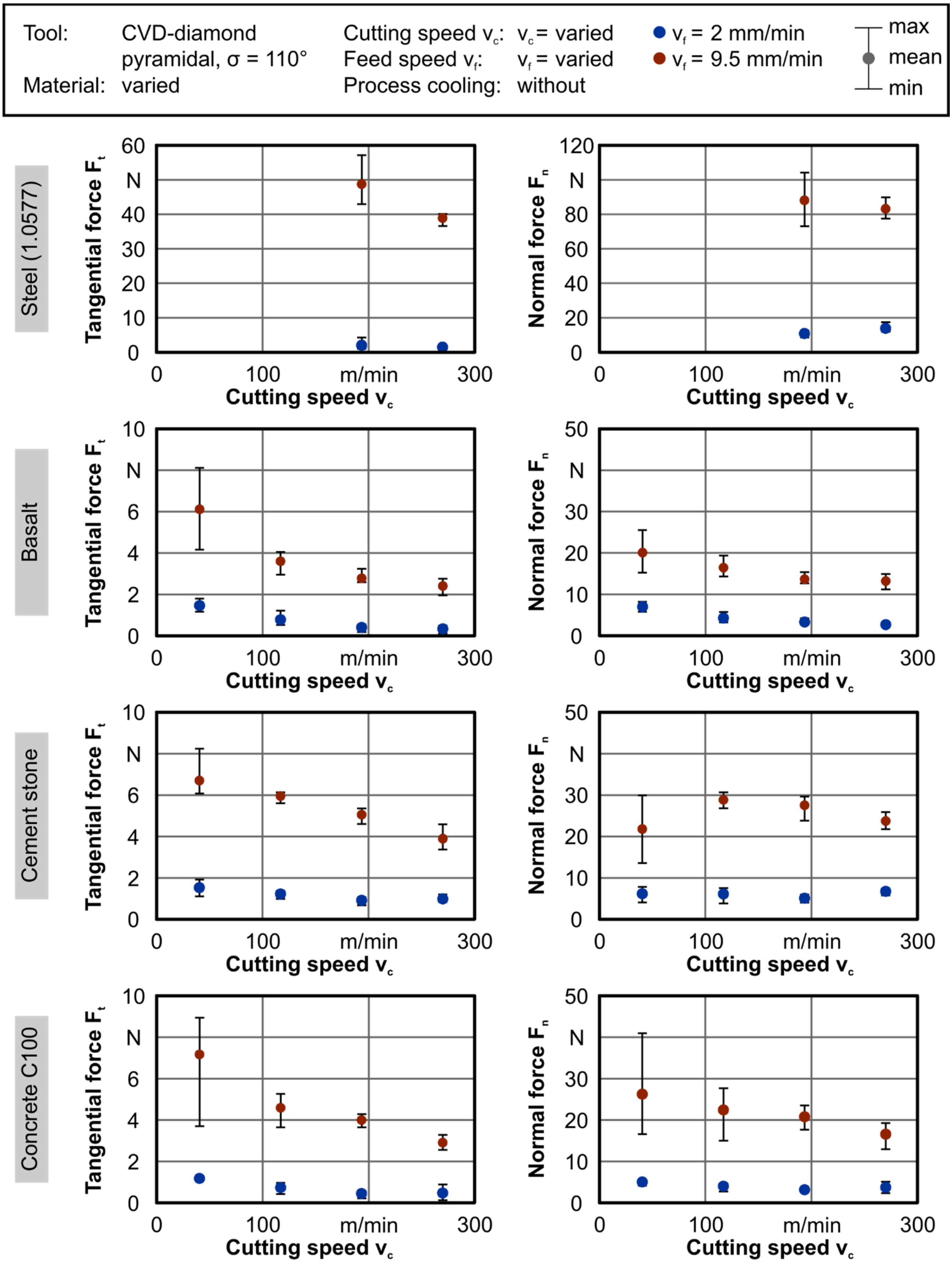


Fig. 5: Normal and tangential forces in dependency of feed speed and cutting speed

To illustrate why the mean values for the forces in scratching the analysed steel were merely calculated for the higher cutting speeds v_c in the considered range, two exemplary developments of the force components F_n and F_t during scratch processes for two different cuttings speeds ($v_{c,1}$ = 40.5 m/min, $v_{c,4}$ = 270 m/min) are contrasted in figure 6. Due to the set feed speed of $v_{f,2}$ = 9.5 mm/min and the total depth a_e = 0.080 mm the calculated process time for both cuttings speeds is t = 0.51 s.

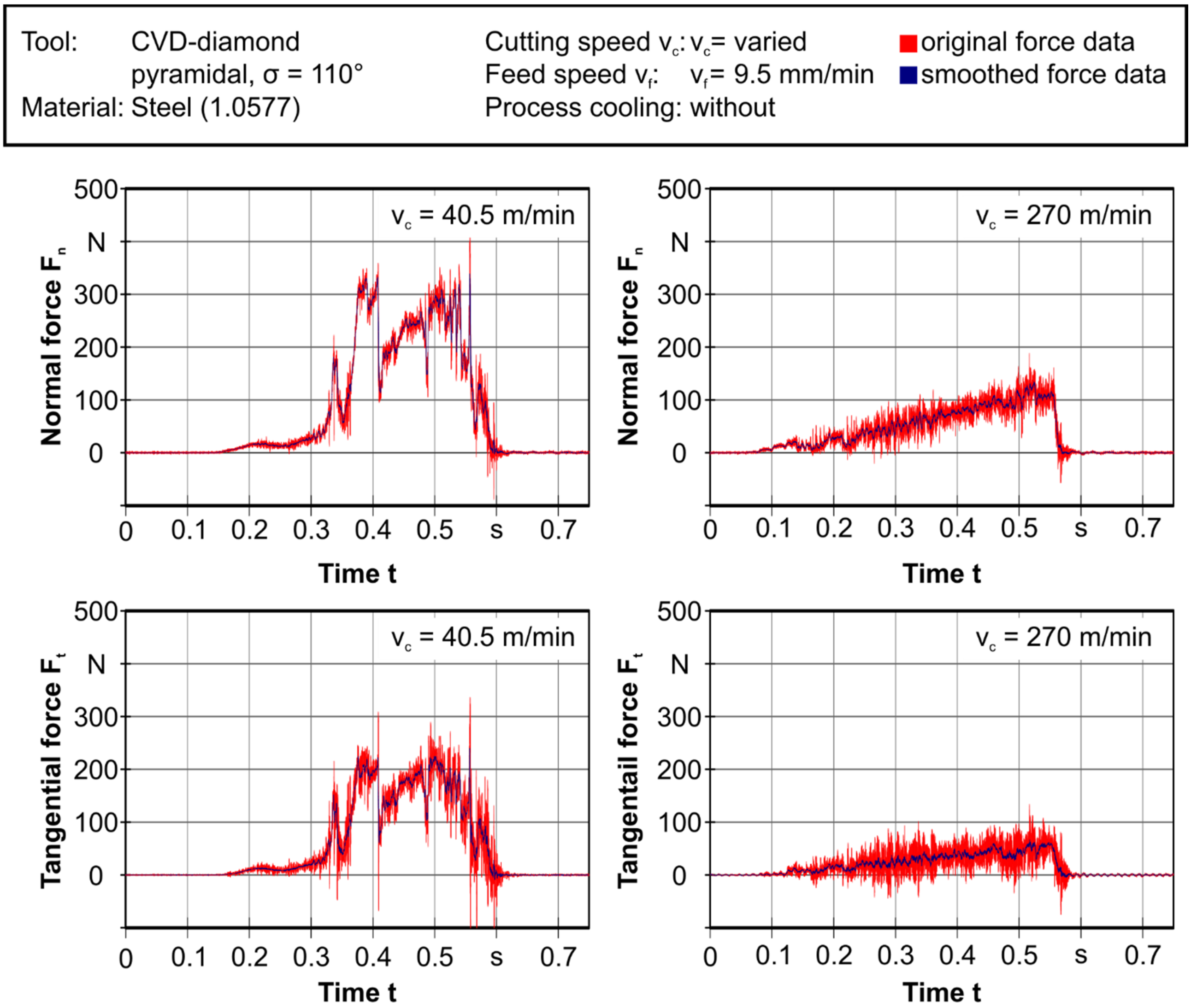


Fig. 6: Process forces for steel depending on cutting speed v_c

There are clear differences in the force signals comparing forces for the varying cutting speeds. For $v_{c,1}$ = 40.5 m/min an irregular force signal with several peaks and discontinuities results. In contrast, for $v_{c,4}$ = 270 m/min the rise of the force components is nearly linear with increasing process time and scratch depth respectively. This increase is generated owing to the increasing area of the diamond tool that is in contact due to the helical process strategy. Such a steady increase of forces does not exist for the shown force signals for $v_{c,1}$ = 40.5 m/min. The irregular development of process forces during the scratch process at low cutting speeds might result as a consequence of irregular chip formation processes or friction. Furthermore, the possibility of some kind of build-up edge has to be taken into account. Nonetheless, comparing the development of the two analysed force components, they are similar, whereas the normal force F_n is higher than the tangential force F_t, as also mentioned discussing figure 5. Despite of irregular force signals for a low cutting speed, the absolute force data can be compared. The absolute values of the two force components are higher for the low cutting speed than for v_c = 270 m/min. This again might be affected by the larger feed rate at lower cutting speeds due to the defined helical path of the diamond tool, but also the above mentioned effects may have an influence.

The steel part in reinforced concrete has a special impact on the process forces. In order to discuss this influence qualitatively, in figure 7 two exemplary force developments for scratch tests on reinforced concrete for different cutting speeds v_c and in this case constant feed speed v_f are shown analogous to figure 6.

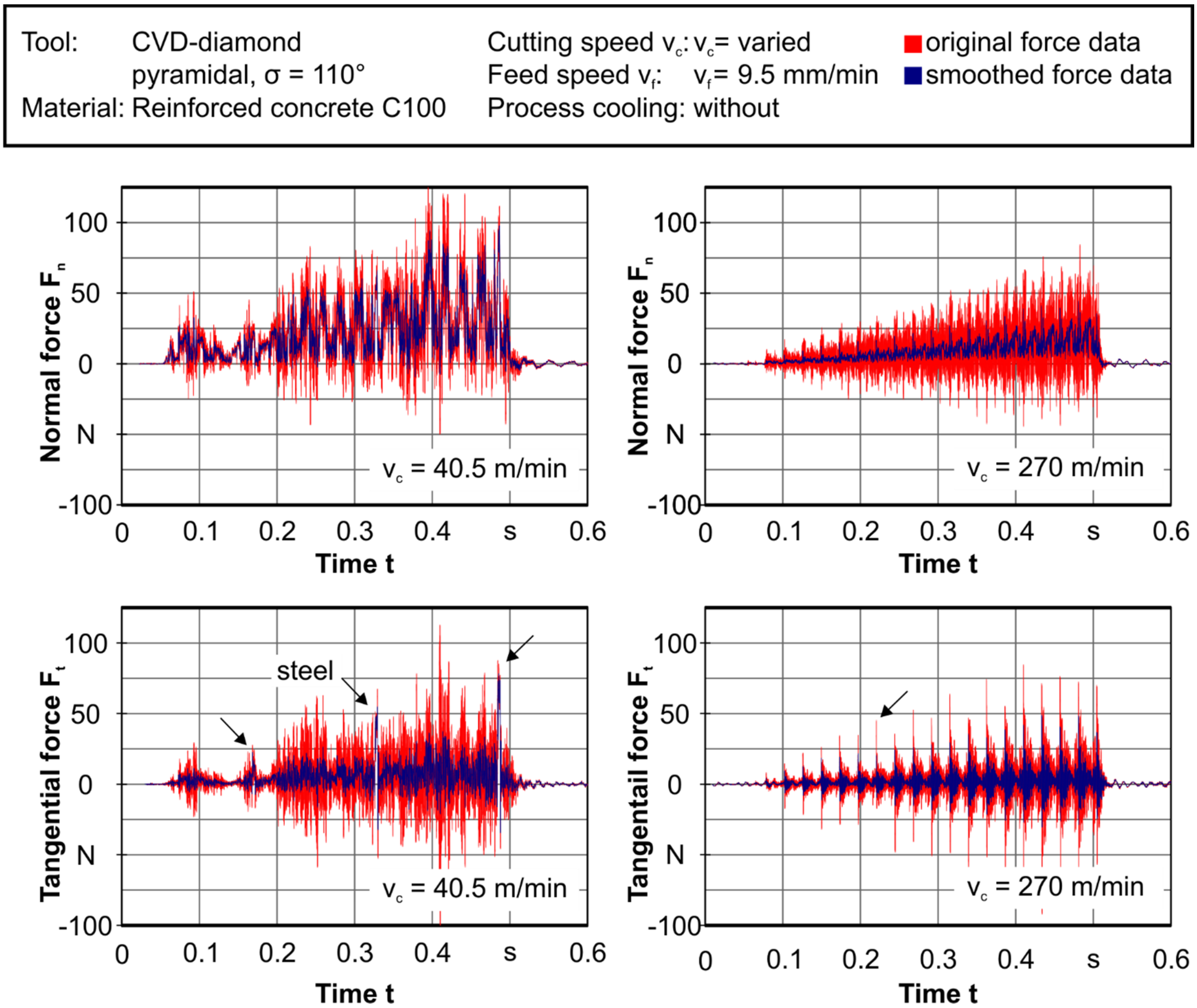


Fig. 7: Process forces for scratching reinforced concrete

The influence of the transition from the mineral material component to the metallic component is directly evident in tangential force signals for both presented cutting speeds. For $v_{c,4}$ = 270 m/min the transition results in high force peaks or kind of pulse as exemplary marked in figure 7. For the lower cutting speed $v_{c,1}$ = 40.5 m/min scratching the steel part causes longer periods with positive, increased tangential forces. In consequence of the chosen helical process strategy and the constant feed speed v_f the number of passing the steel part is reduced for lower cutting speeds. In the shown scratch test for a cutting speed v_c = 40.5 m/min the steel part is scratched three times as marked in the tangential force signal. Comparing those three periods, there is an increase of tangential force amplitudes with longer process time owing to a rise of the active cross section of the pyramidal diamond tool by the increased depth. The transition from mineral to metallic is less significant and not immediately obvious in the signals of the normal forces F_n. Nevertheless, using the additional information generated due to the use of a light barrier reveals the influence of the steel part even in normal forces. In the area of scratching steel there exists a period with comparatively high normal forces and less fluctuation of the force signal than mostly recognised in the signal of mineral material components. Unlike to former test results comparing process forces for concrete and reinforced concrete [8], in this case the influence is observable in the smoothed force data in the form of small peaks (cf. fig. 7, v_c = 270 m/min) as a consequence of an adjusted evaluation method.

3. CONCLUSION

In order to analyse the material separation of reinforced concrete with different approaches the results of two series of scratch tests with single grain diamonds and different objects of investigation were presented. The scratch tests conducted in a large-chamber scanning electron microscope allowed to analyse the qualitative differences concerning the characteristics of the scratches on steel, basalt and cement stone after multiple and iterative scratching on the basis of microscopic SEM pictures. Those scratch tests were carried out with a constant normal force and cutting speed using a tribometer.

Another kind of scratch tests was used to investigate the process forces. Regarding this the influences of varying feed speeds and cutting speeds were considered. The results showed that the feed speed has a strong effect on the force components for each investigated material. Whereas a higher feed speed leads to increased process forces, the increase of the cutting speed mostly causes decreasing forces. Comparing different force signals scratching steel exclusively reveals strong differences in the force development depending on cutting speed. Whereas high cutting speeds result in nearly linear increasing forces, low cutting speeds lead to irregular force signals. Concerning reinforced concrete the impact of the integrated reinforcement is obvious in the tangential force signal. But also in the normal force an impact of the steel is recognisable. Varying cutting speeds influence the signals as well. Aiming to analyse the influence of the steel in reinforced concrete on the process forces in more detail, further scratch tests on reinforced concrete with a higher amount of steel must be conducted.

The conducted scratch tests regarding the analysis of the material separation of the high-strength concrete and the reinforced concrete showed different loads and scratching conditions of the diamonds depending on the material. In contrast to the mineral constituents, for which forces are comparable, scratching or grinding the steel is challenging what is recognisable in core drilling as well. Therefore it is a need to adjust diamond tools and parameters to meet the particular requirements. Further tests could be conducted with varying diamonds (e.g. geometry, rake angle) with the aim of identifying possibilities to reduce process forces and to enhance the performance of core drilling tools.

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