A new method for the local removal of the surface area of reinforced concrete

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ABSTRACT

The combined removal of steel and concrete during the removal of building structures is still a challenge due to the different material properties and the resulting requirements on the cutting tool. In this paper the authors will present a methodology, and its results, for enabling a milling process for the machining of reinforced concrete. To identify the different mechanisms taking place during cutting of the two materials concrete and steel, the machining of these materials were studied separately. The aim of this investigation is to identify the dominant wear mechanism and the process factors influencing the resulting cutting forces. Afterwards the observations and conclusions will be assigned to the cutting of the material compound. As influencing variables the size and form of the cross-section and the cutting speed were investigated. Furthermore the benefit of a tool coating in milling concrete and reinforced concrete was investigated.

KEYWORDS

REINFORCED CONCRETE; MILLING; PROCESS FORCES; TUNGSTEN CARBIDE TOOLS; TOOL WEAR

INTRODUCTION

In Germany the nuclear phaseout was resolved and hence, the dismantling of reactors for power generation already started and will continue for the next decades. A big advantage in the direct dismantling is a selective dismantling procedure in which the contamination can be removed by eliminating only a small part of the surface structure. In the next step the predominant part of the building can be recycled. This procedure offers the potential to reduce the amount of nuclear waste and thus the costs of dismantling. For example, in the nuclear plant Obrigheim only 600 t of the total amount of 143,000 t reinforced concrete have to be disposed as nuclear waste [1]. A central element of this strategy is the identification of contaminated areas and thus the local removal of reinforced concrete. In principle the processes and tools for the removal of concrete as well as for cutting pure steel are available. The combined removal in contrast is still a challenge due to the different material properties and the resulting requirements regarding the cutting tool. Furthermore, in areas with cracks or outbreaks in the building structure a removal has to take place. Techniques are available for the removal of concrete as well as for cutting pure steel. The combined removal is still a challenge due to the different material properties and the resulting requirements on the cutting tool.

A promising approach is the application of a dry milling process [2]. Because of its low price and its performance in machining steel, tungsten carbide is chosen as cutting tool material. However, findings of the processing of steel cannot be transferred to the processing of concrete. Concerning the material properties of steel and concrete the load spectrum on the tools differs. Hence, these materials have different demands on process specifications and cutting tool properties, a process and tool development has to take place.

1. OBJECTIVES

With regard to this aim a classification of existing removal situations was carried out and corresponding concepts were provided. Hence, the situations were classified by the amount of steel in the present working area and their position to the free surface. This classification delivers information about the most important removal situation, affecting the requirements regarding the tool and process specifications. The cutting tool and process design concerns different cutting tool materials to improve tool performance, avoid spontaneous tool fracture and increase tool life time.

In the presented application cutting forces are of special interest because a mobile system is planned to be used and thus the process forces have to be handled. The system should empower the operator to realize removal of reinforced concrete in areas, which are difficult to reach. The process forces are a consequence of the contact conditions of tool and workpiece. Hence feed per tooth f_z, depth of cut a_p and cutting speed v_c were varied and their effect on the specific process forces will be analysed. These investigations were executed regarding the initial tool wear. Here the wear mechanisms are important to get information about the demands to the tool-material specifications. Referring to this tool features the effect of a coating on the used tungsten carbide was included in the investigations.

2. EXPERIMENTAL SETUP

The experiments are carried out on a vertical 3-axis milling machine type Heller PFV 1. The milling forces are measured with a Kistler 3-component dynamometer type 9255C. In order to analyse the resulting cutting forces and tool wear during cutting reinforced concrete, the different components of the material compound will be cut individually. The investigations in this study are conducted with a single tooth face mill with a diameter d = 40 mm. The concrete is composed of cemented stone and aggregates with a maximum size of 8 mm, respectively 32 mm. For the experiments on pure steel S355 J2+N is used as work piece material. The concrete percentage in the reinforced concrete work pieces is made with the same specifications. The reinforcement rods are out of BSt 500S with a diameter of 32 mm.

In this study the depth of cut a_p and the feed per tooth f_z are varied. With these parameters the cross-section of undeformed chip and the direction of the applied forces will be varied. The cutting speed is varied in a range from v_c = 80 - 300 m/min. All investigations are conducted with full immersion.

To identify the influence of a coating of the milling tools on the wear behaviour, the experiments were carried out with one tungsten carbide grade, with and without coating. A $TiCN + Al_2O_3$ multilayer coating was applied. All used indexable inserts have the geometry specification RDMT 2006 MO. They have a round geometry, with a diameter of 20 mm. All experiments are conducted with two repetitions. The wear of the cutting inserts is analysed with a Keyence VHX 600 video microscope and a scanning electron microscope (SEM).

3. MECHANICAL LOAD IN MILLING STEEL AND CONCRETE

PROCESS FORCES

In Fig.1 the process forces for one spindle revolution during machining steel and concrete is presented. For both materials the same process parameters were used. As depicted in Fig. 1 the process forces during milling steel in feed and feed-normal direction are 300 % higher in contrast to concrete. Further, the process forces in steel exhibit a distinctive progression over the complete revolution. The maximal feed force occurs for the highest uncut chip thickness h_{max} at a feed motion angle of 90°. During cutting of steel the forces in feed and feed-normal direction are higher than the passive force component. Due to the ductile separation mechanism less friction occurs.

In contrast to steel the process forces in cutting concrete oscillate with the tool-revolution. Considering all experiments the force during cutting concrete in passive direction has a maximum at an arbitrary point during the revolution. This fact can be explained by the stochastic allocation of aggregates in the material. The feed and feed normal force are half the amount of the passive force. This can be explained by the theory about the separating mechanism in brittle materials. This mechanism proceeds in two steps. During the first step the material is pushed out of the kerf. In this step the mechanical load on the tool is low, because concrete withstands tensile strain to a minor degree [3, 4, 5]. Afterwards the material separation takes place under the cutting edge. At first the material is charged under compressive stress, this leads to high process forces in passive direction. If this material is released under the cutting edge, critical tensile strength occurs in the material and leads to brittle material failure behind the cutting tool [6].

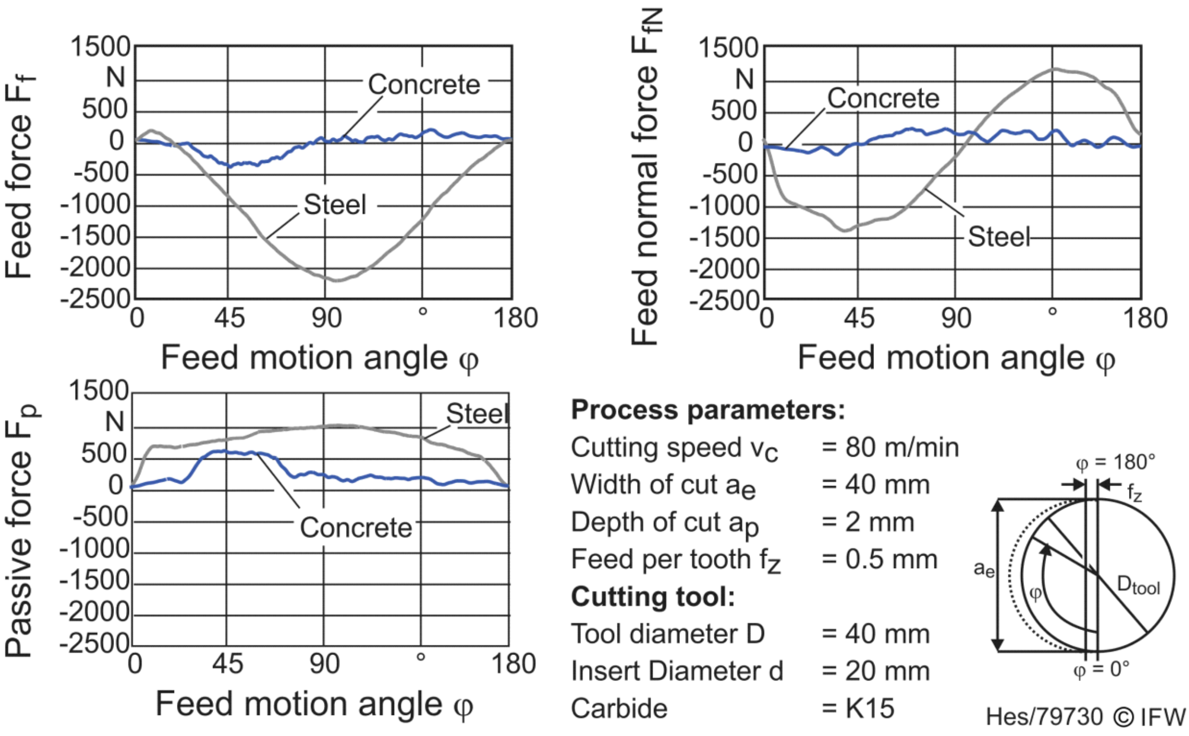

Fig. 1. Process forces during one tool-revolution

INFLUENCE OF CROSS-SECTION

Process forces are limited due to the stiffness of the used machine structure. Therefore the specific forces needed to machine one increment of the cross-section are of special interest. Based on the process forces the material removal can be increased. From this follows an increase of the productivity of the process.

In cutting processes of ductile materials inserts with a rectangular cross-section of undeformed chip are often used. For the cutting of mineral materials, cutting inserts with a round geometry are advisable because they do not possess corner radius r_ε. On the corner radius the contact area between tool and workpiece can be very small and hence, increased stresses occur. This leads to rapid tool fracture [7]. Following the application of round cutting inserts, the uncut chip thickness varies along the cutting edge (Fig. 2). Based on the cutting insert radius r_ε, the working cutting edge angle κ changes along the cutting edge radius. The working cutting edge angle increases from 0° from the tool centre point to maximum value at the depth of cut. The uncut chip thickness rises similar from $h_o = 0$ mm over the effective uncut chip thickness h_{eff} to a maximum value h_1. Thus the cross-section of undeformed chip depends on the feed direction angle φ, the cutting edge angle κ and the feed per tooth f_z and is calculated by equation (2). Referring to Köhler [8] the effective width of undeformed chip b_{eff} (3) and the effective uncut chip thickness h_{eff} (4) can be calculated from the geometric relations in the cross-section of undeformed chip. The effective cutting edge angle κ_{eff} within this point can be achieved in the same way by equation (5) [9].

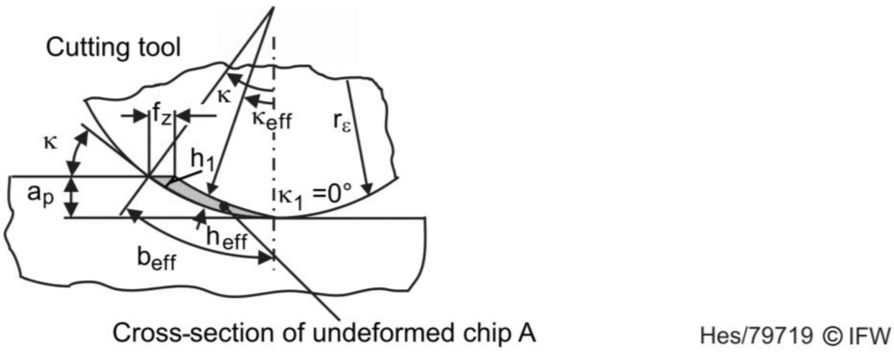

Fig. 2 Overview of the face milling process with round cutting inserts

$$A = a_p * f_c - \frac{1}{3} * f_c * \left(r_\varepsilon - \frac{\sqrt{4 * r_\varepsilon - f_c^2}}{2} \right) \tag{1}$$

$$b_{eff} = r_\varepsilon * \left[\frac{\pi}{180} \left(k + \sin^{-1}\left(\frac{f_c}{2 * r_\varepsilon} \right) \right) \right] + \frac{\left[a_p - r_\varepsilon * (1 - \cos k) \right]}{\sin k} \tag{2}$$

$$h_{eff} = \frac{A}{b_{eff}} \tag{3}$$

$$k_{eff} = 90° - \cos^{-1} \frac{(r_\varepsilon^2 - (r_\varepsilon + h_{eff})^2 - {f_c}^2)}{(-2 * (r_\varepsilon + h_{eff}) * f_c)} \tag{4}$$

In the following section the influence of the previously described parameters h_{eff} und b_{eff} on the process forces will be discussed for the two materials steel and concrete. For evaluation the maximum forces per revolution are calculated und averaged over all recorded revolutions at full immersion. Fig. 3 shows the dependence of specific cutting forces and cross-section dimensions for milling experiments. This data was recorded in experiments carried out with coated carbide tools on concrete with aggregates up to a size of 32 mm. The higher the effective uncut chip thickness is, the lower are the specific forces in each direction. The effective width of cut has no influence on the specific forces. The effective uncut chip thickness h_{eff} is mainly influenced by the set feed per tooth f_z. The effective chip width b_{eff} can be varied by different values for the depth of cut a_p.

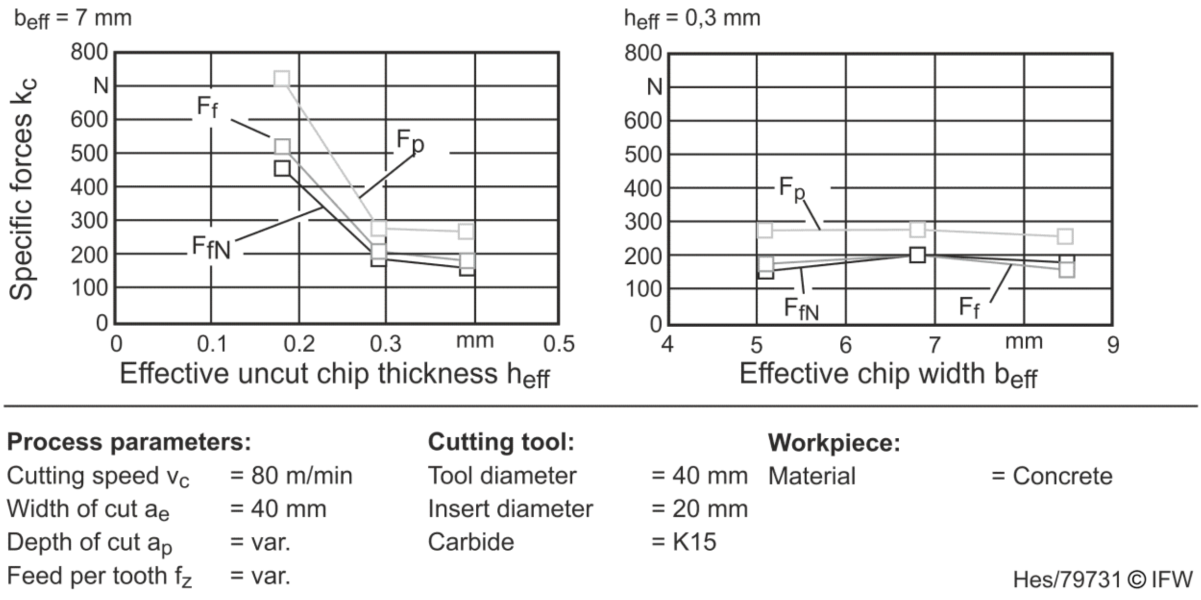

Fig. 3 Influence of cross-section geometry in milling concrete

Milling experiments were conducted with the same tool specification on steel (Fig. 4). For the parameter h_{eff} the same declining correlation could be found. The forces, in contrast to the milling of concrete, are rising linearly with increasing b_{eff} due to negligible influences on the chip formation.

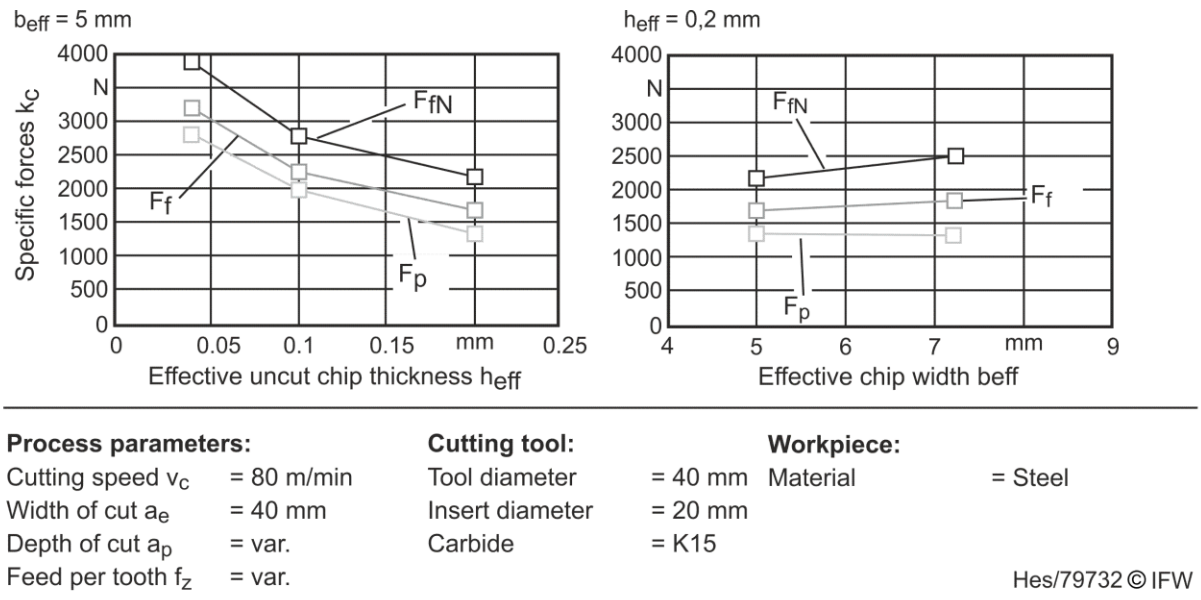

Fig. 4 Influence of cross-section geometry in milling steel

However, concerning the overall forces for the concrete machining process (Fig.5), minor influences by varying the feed can be observed. This can be explained by the chip formation. Additionally, the cross-section of undeformed chip A leads to negligible influences on the process forces due to the secondary separation process. This material separation process is only related to the effective chip width b_{eff}, because this process takes place under the cutting edge. The forces F_i have a linear relationship to b_{eff}. The cross-section is proportional to the effective chip width, too. For this reason the effective chip width has no influence on the specific forces in Fig. 3.

Furthermore the process stability can be increased for higher values of the feed per tooth. This can be seen by the reduced deviation in process forces between the repetitions represented by the error bars in Fig. 5. An increase of the feed per tooth enlarges the uncut chip thickness and the mechanical load is spread over a larger area. As a consequence the risk of tool fracture is reduced and thus the increase in process forces is prohibited. This statement is valid for the machining of pure concrete.

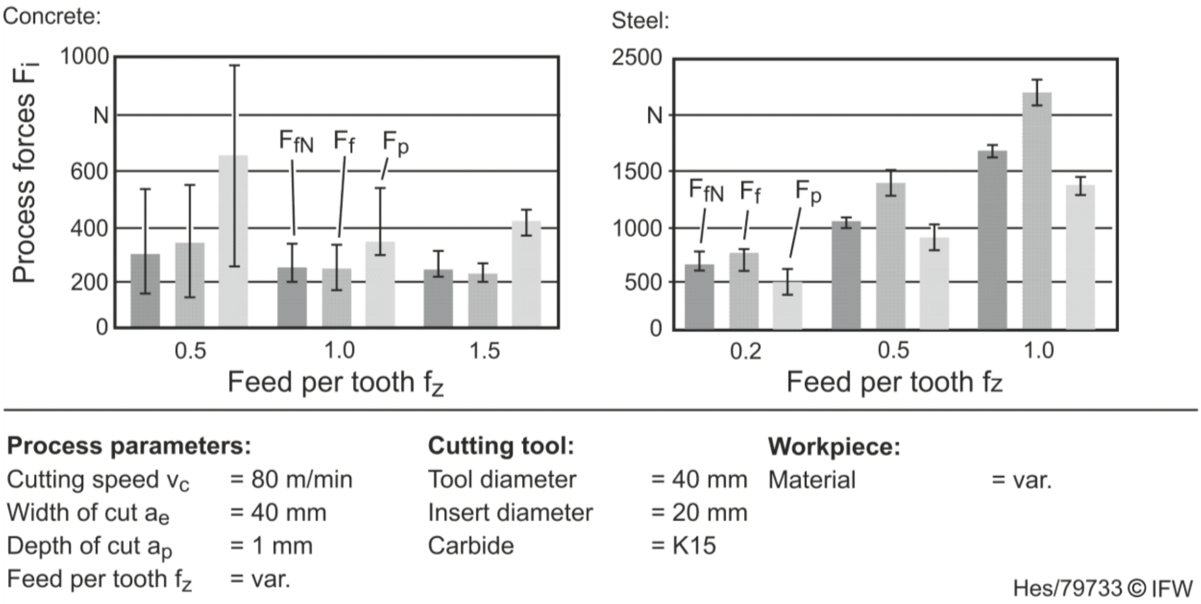

Fig. 5 Process forces in steel and concrete for different size of cross-section

INFLUENCE OF CUTTING SPEED

Besides the cross-section, the cutting speed is a significant factor for machining ductile materials. With increasing cutting speed the cutting forces can be reduced, furthermore the productivity of the process increases. The resulting process forces are shown in Fig. 6 with respect to the cutting speed. In steel the process forces show the known trend due to the variation in cutting speed. The process forces decrease with increasing cutting speed [10]. The dependency of the process forces in steel regard to the thermal softening of metals during the cutting process since the temperature increases with the cutting speed. During milling concrete this trend can't be observed. The measured forces deviate with the set cutting speed. For brittle materials like concrete the thermal softening is negligible. Therefore no relationship between the cutting speed and the process forces was expected. This was shown by Apmann for grinding of concrete, too [11]. However, with increasing cutting speed v_c, the impact on the tools is increasing. Consequently the risk of tool failure rises. This tool failure provides an explanation for varying process forces over the range of investigated cutting speeds.

The conducted investigations regarding the process parameters during machining steel and concrete show that for the right choice of cutting parameters, there is a conflict of objectives. High cross-section is beneficial regarding milling of concrete. In contrast for the machining of steel this is limited by the resulting overall forces. Because of increasing tool wear, when higher cutting forces are applied, cutting speed should be set lower than 100 m/min in concrete. While machining steel the process forces can be reduced with cutting speeds larger than 100 m/min.

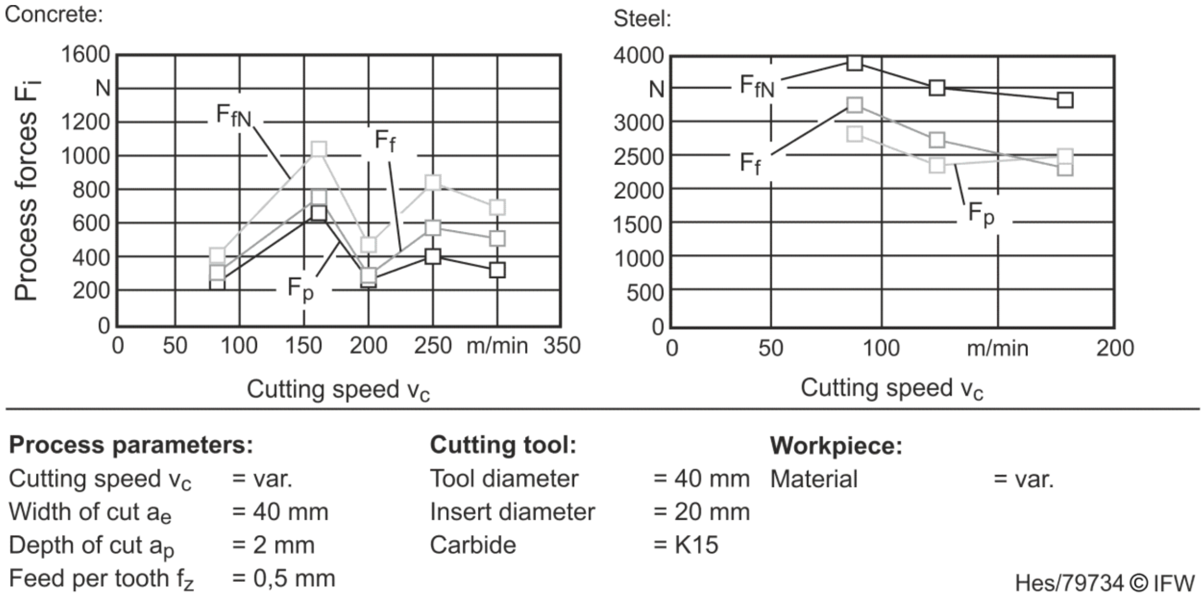

Fig. 6 Process forces in steel and concrete for different cutting speeds

4. WEAR MECHANISM

The SEM-micrographs in Fig. 7 present the resulting wear in concrete, after a feed travel l_f of 50 mm, and in steel, after 250 mm. It can be seen that the wear mechanism in steel and concrete differs.

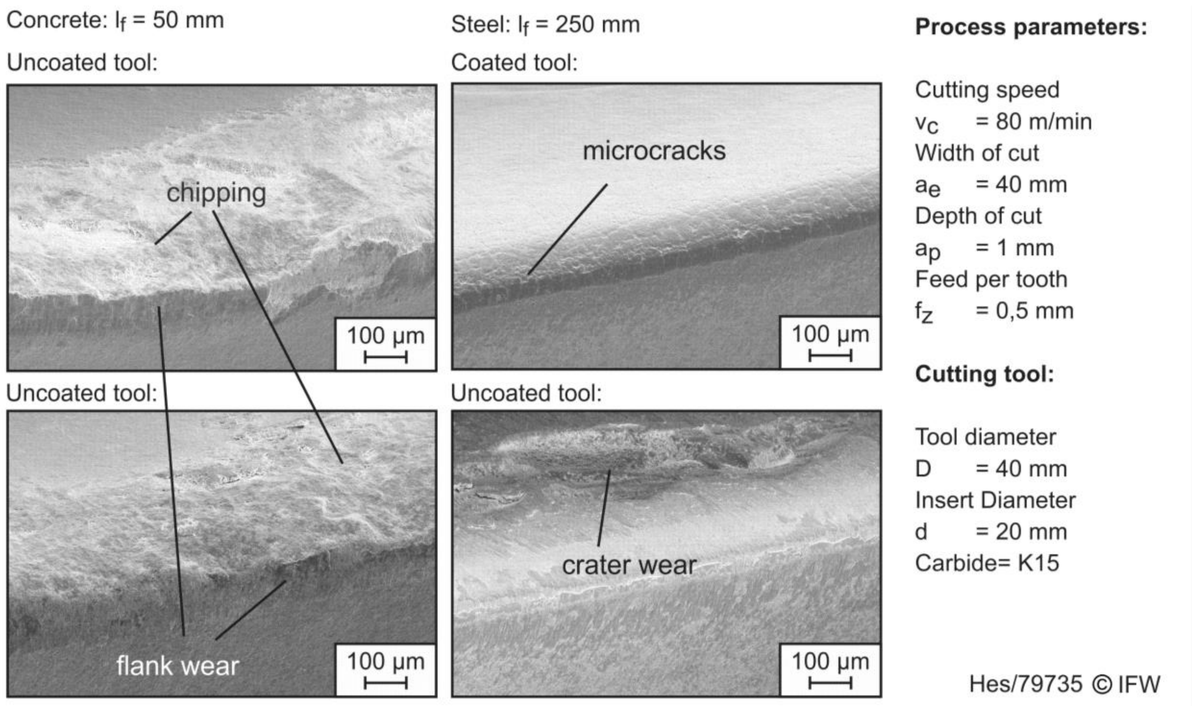

Fig. 7 Wear mechanism of the used tools in concrete and steel

In concrete the wear is a result of the mechanical load which follows in chipping on the cutting face. The flank wear follows from abrasion due to the cement dust in this area [7]. The initial wear of the coated tool increases after first coating failure due to the increased friction between tool and work piece. The observed tool wear mechanism in steel belongs to thermal damage. Here a larger difference between the coated and uncoated tool can be determined. The coated tool exhibits only micro cracks along the cutting edge. However, the uncoated tool shows crater wear with a width of about 200 µm.

5. TRANSFER OF THE FINDINGS TO THE MILLING OF REINFORCED CONCRETE

The experiments in reinforced concrete were conducted in cuts parallel to the reinforcement rods. Parameters in steel are the same used in concrete before.

Each parameter set was carried out with cutting direction from steel into concrete and once from concrete into steel. First of all it can be ascertained that the measured during the cutting of the compound Fig. 8 are higher than in the basic materials Fig. 1.

In concrete it can be shown that it is beneficial to increase the cross-section A-, because the process forces stay nearly constant and the risk of tool failure is decreased. This circumstance can't be used in the same way for the machining of the material compound. As presented in Fig. 8**,** the overall forces raise about 100% if the feed per tooth is increased from 0.5 mm to 1 mm per revolution due to the part of machined steel. An increase in process forces can also be assigned to the contact sequence concrete-steel because of cement particles getting into the kerf. Due to this, especially the passive force for the steel part is increased by about 300 % caused by the increased friction and the consequential tool-wear on this part of the cutting tool.

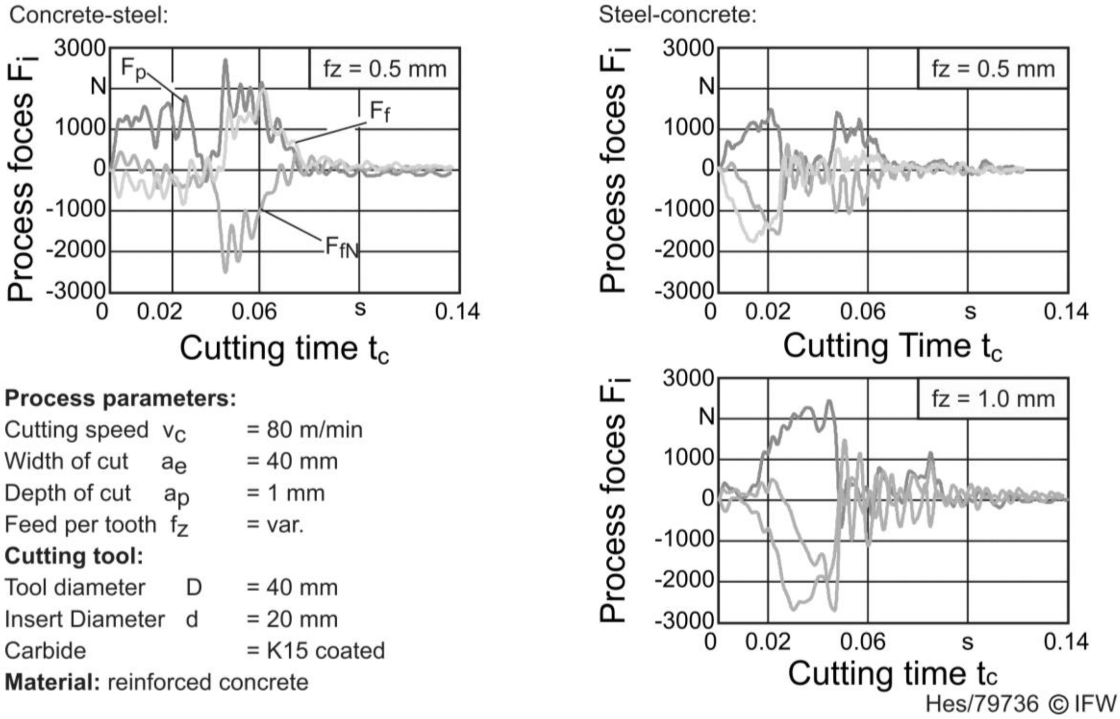

Fig. 8 Process forces in milling reinforced concrete

An increase in cutting speed is, as shown in Fig. 6, a possibility to reduce the process forces in machining ductile materials due to a significant reduction in strength with increasing process temperature. This effect can't be used for the machining of reinforced concrete, as the tools underlie rapid wear. The rapid tool wear leads to high process forces. Fig. 9 shows the tool wear for different cutting speeds and the coated and uncoated tool exemplarily. By applying a cutting speed of v_c = 180 m/min sudden tool fracture occurs. The coating is already removed in the contact area after 200 mm feed travel. However, the uncoated tool shows a higher maximum flank wear width. This can be explained by the hardness of the coating and thus increasing resistance against abrasive wear. The contact area is six times larger due to the flank wear and steel is adhered to the tool surface. At this point the passive forces reach a level of about 12-14 kN. Tools with this kind of wear condition often failed immediately when applied after this point. The reason for this wear is, that the cutting edge first becomes mechanically damaged through chipping when it gets in contact with the concrete. Then, as known from literature, processing ductile material with blunt tools causes high process forces and in consequence of the large contact area a lot of heat is generated on the flank face. These conditions lead to steel adhesions on the flank face, like it can be seen on the right part of Fig. 9. This material is torn away from the flank face and the wear increases further.

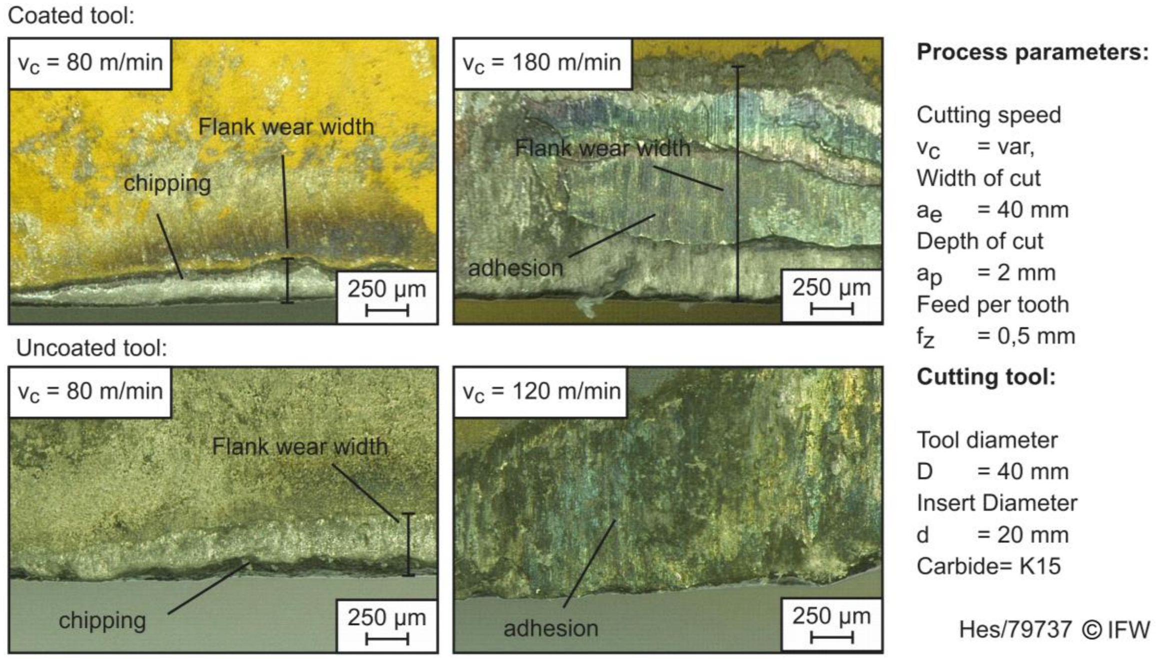

Fig. 9 Tool wear mechanism in machining reinforced concrete

6. CONCLUSION AND OUTLOOK

This study deals with the fundamentals regarding milling of reinforced concrete with tungsten carbide tools. The usage of tungsten carbide tools exhibit benefits with respect to the tool costs in comparison to cBN or PCD tools. In addition tungsten carbide tools have a lot of applications in the machining of ductile materials. For the machining of brittle materials, such as concrete, the capabilities are not known. For this purpose cutting experiments were carried out on concrete, steel and finally reinforced concrete. According to the mechanical load the following conclusions can be drawn:
Increasing the cross-section leads to constant process forces and constant resulting initial tool wear for the machining of concrete. For the machining of steel the process forces decrease with an increase in cutting speed. These two effects offer the opportunity to reduce the tool load if only one material will be machined. The experiments in reinforced concrete show, that larger cross-section results in higher process forces due to the steel. Higher cutting speeds lead to rapid tool failure due to the concrete. From there the smallest investigated cross-section and the lowest cutting speed are advisable for the machining of reinforced concrete.

Nevertheless the used tools underlie fast tool wear. This wear results in sudden tool failure even after short processing time. For this reason the tools have to be further developed for this application. To reduce the abrasive wear the usage of other tool coatings could be advisable. The major factor is the chipping of the cutting edge, this can likely be reduced by higher fracture toughness of the tungsten carbide and a stronger adherence of the coating to the base material.

For the ongoing investigations an approach with different process parameters for the different materials in the compound will be pursued. For this purpose an online and an in advance process monitoring has to be applied. Furthermore the amount of the part of machined concrete should be reduced to increase the tool life time. For this reason a second machining process will be installed. This process should operate in advance and expose the steel installations.

7. ACKNOWLEDGEMENTS

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