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Chip formation in machining metal bonded grinding layers

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Abstract

Gears demand increasingly high quality regarding acoustic emissions, surface roughness and lifetime. Therefore, grinding is often the last step in the process chain of gear manufacturing. Grinding wheel grain sizes of 30 micrometers lead to high surface quality and metal bonded CBN-grains allow a high wear resistance and profile stability of the grinding tool. Consequently, an increase of the material removal rates and thus productivity is possible without increasing the thermal load on the workpiece due to the grinding wheels' high thermal conductivity. However, the time and cost intensive dressing process in combination with the high profile requirements for gear grinding prevent the wide application of metal bonded tools for this application. This challenge can be solved using a new dressing approach with geometrically defined cutting edges. Metal bonded CBN-grinding layers have a structure similar to metal-matrix-composites, which can be machined by using the turning operation. The aim of this work is to verify the machinability of metal bonded CBN-grinding layers. In the present work, the chip formation for metal bonded grinding layers is presented.

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Keywords: Machinability; Metal matrix composite; Dressing

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1. Introduction

Grinding is a manufacturing process characterized by the ability to machine workpieces with high material removal rates while generating functionally, high quality surfaces in a single operation [1]. The quality demands regarding the ground workpieces are constantly rising. The increasing wear resistance of the used workpiece materials brings state of the art grinding wheels to their limits [2, 3]. Usually, vitrified bonds with varying cutting grains are used. The conditions during the engagement of tool and workpiece during profile grinding lead to an even higher load of the grinding wheel. In theory, metal bonded grinding wheels are capable of meeting the mentioned challenges [4]. Their mechanical and thermal resistance against wear offers the potential to reach high tool lifetimes while generating high workpiece qualities. Their lack of dressability is currently the main challenge to bring out the stated potential [5]. Current methods for implementing certain profiles into metal bonded grinding wheels are based on mechanic, thermal and or chemical operating principles. The oldest and most common method is using profile roles made of silicon carbide in a vitrified bond. The profiles are implemented by machining the metal bond until the superabrasive cutting grains fall out. This step is repeated until the target profile is set. This method is quite cost efficient but time consuming and it is rather difficult to implement profiles with high precision. Electro-erosive processes use locally high temperatures in order to implement the profile by vaporizing the metal bond. A voltage is applied between the grinding wheel and the electrode while a dielectric is present. In the case of contact between the grinding wheel and the electrode, there is an electric discharge with sparking. The fluid helps to contain

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the area of the discharge and to reach locally high temperatures. The spark leads to a local melting and erodes the conductive metallic bond without attacking the abrasive grain. This process as well as profiling with lasers or chemical processes e.g. based on electrolysis allow for high precision profile implementation but are rather complicated, time consuming and cost intensive. The main reasons for their lack of wide industrial implementation are the necessary auxiliary units and dielectric media as well as the low material removal rates [1]. The main motivation for this work is the lack of an economical, productive and comparatively simple method to implement profiles into sintered metal bonds with embedded superabrasive cutting grains. CBN-grains are a superabrasive cutting grain material suited for machining a great variety of materials, e.g. carbon steel. Diamond grains are even harder but lack the ability for steel machining and are less resistant against thermal loads in combination with high pressure [6]. The structure of sintered bronze-CBN-grinding wheels with grain sizes around 30 µm resembles the structure of metal-matrix-composite materials. The machinability of such materials has already been proven [7, 8, 9, 10, 11]. Consequently, the presented work investigates the machinability of sintered bronze-CBN-grinding wheel layers with geometrically defined cutting edges in order to propose a novel method to dress metal bond grinding wheels economically with high productivity and meet the current challenges in profile grinding.

2. Experimental approach

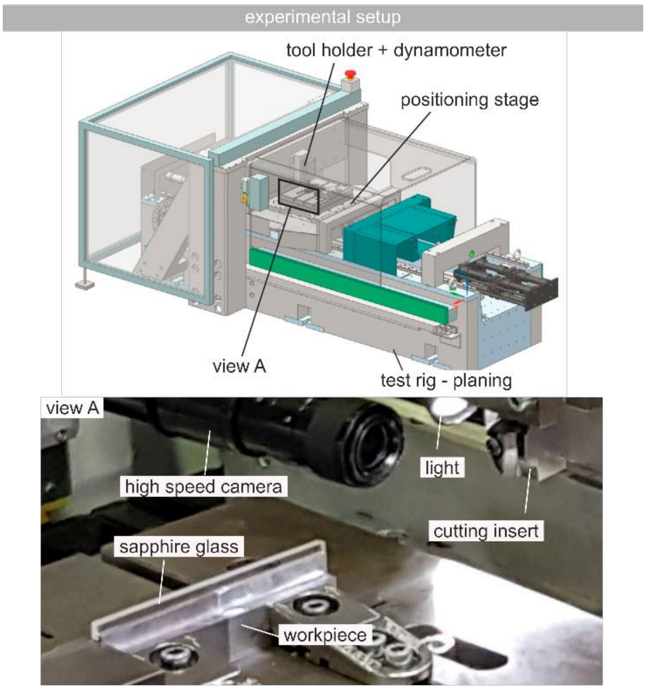
In this work microkinematography was used in order to evaluate the machinability of sintered bronze-CBN-grinding wheel layers. Therefore, the conventionally cylindrically shaped grinding wheel layers were sintered in the form of 45 x 25 x 5 mm blocks and planed with SNGA-type cutting inserts (120400). The investigated workpiece specifications are summarized in table 1. CBN- and diamond grains with a size of 30 and 76 µm were investigated. They were distributed in a sintered bronze matrix with a grain concentration of C100 and an average bond hardness according to the manufacturer.

Table 1. Investigated workpiece specifications.

Abbreviation	Grain type (-)	Grain size (µm]	Grain concentration	Bond hardness
B30	CBN	30	C100	Average
B76	CBN	76	C100	Average
D30	Diamond	30	C100	Average
D76	Diamond	76	C100	Average

For the planing investigations exclusively cutting inserts made of superabrasive materials are used. Particularly, polycrystalline cubic boron nitride (PCBN) and CVD-thick film diamond (CVD-D) were used during this work. Cutting inserts made of CVD thick film diamond solely consist of diamond. The cutting insert was replenished after each run in order to eliminate the chance of tool wear influencing the chip formation. The experimental setup is shown in figure 1. On the right side the detailed set up is shown.

The inserts have been prepared to have a corner radius of 0°. This prevents lateral displacement of the workpiece between the tool and the sapphire glass. Consequently, a plane state of material deformation occurs. By using a high speed camera, the chip formation process can be evaluated. The cutting speed v_c is limited to 180 m/min.



technical data

linear direct drive (Siemens 1FN1 184-5-571)		high speed camera (Photron Fastcam Sa5)	
– max. force F_{max}:	7920 N	– max. resolution:	1024 × 1024 Pixel
– nom. force F_N:	3600 N	– max. framerate:	1 000 000 pictures/ sec.
– v_{max} at F_{max}:	100 m/min	– measurements:	165 × 153 × 242.5 mm
– v_{max} at F_N :	203 m/min		

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Fig. 1. Experimental setup

3. Machinability of sintered metal bonds

In the case of brittle materials with irregular structures commonly discontinuous chip formation occurs. In this case the chips are not significantly deformed but torn out the workpiece surface. This increases surface roughness and therefore would confirm the lack of machinability, if it occurs during the dressing of sintered metal bonds with geometrically defined cutting edges.

However, the main chip formation mechanism in case of sintered metal bonds is segmented chip formation. Figure 2 shows this type of chip formation. After the chip segments are generated, which can be seen in the upper half of the figure, the lower half of the figure shows a continuous rolling up of the chip and subsequent breakage (2.2-2.3). Finally the chip breaks breaks at the locally weakest point of the chip forming chip segments (2.4). This combination of chip generation and formation, compared to traditionally machined materials such as grey cast iron, indicates the machinability of the investigated material.

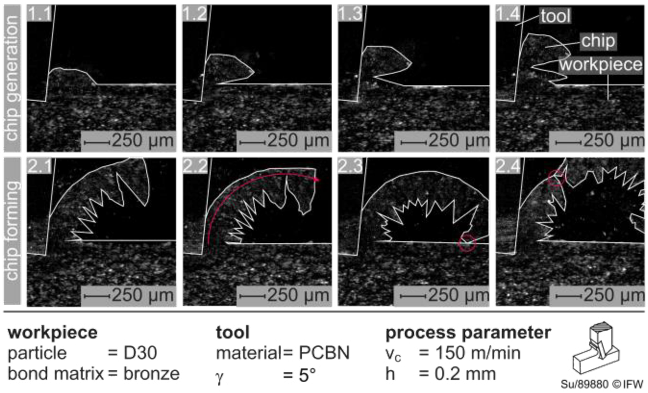

Fig. 2. Chip type and form

Discontinuous chip formation is often observed in case of machining MMC materials with rather low or very high cutting speeds. In the given case 150 m/min is a rather high value. Impurities and superabrasive particles promote this type of chip formation, as well as coalescing voids, which are generated by dividing abrasive particles and the embedding metal matrix [17, 10, 18].

3.1. Influence of grain size, grain type and undeformed chip thickness

The chip formation is depending on the grain size of the superabrasive particles in the grinding bond layer as well as the undeformed chip thickness. Figure 3 shows the experimental results for the grain sizes 30 and 76 µm for diamond and CBN particles as well as the variation of the undeformed chip thickness h in three steps from 0.15 over 0.2 up to 0.25 millimetres. The cutting speed is kept at a constant value of 180 m/min.

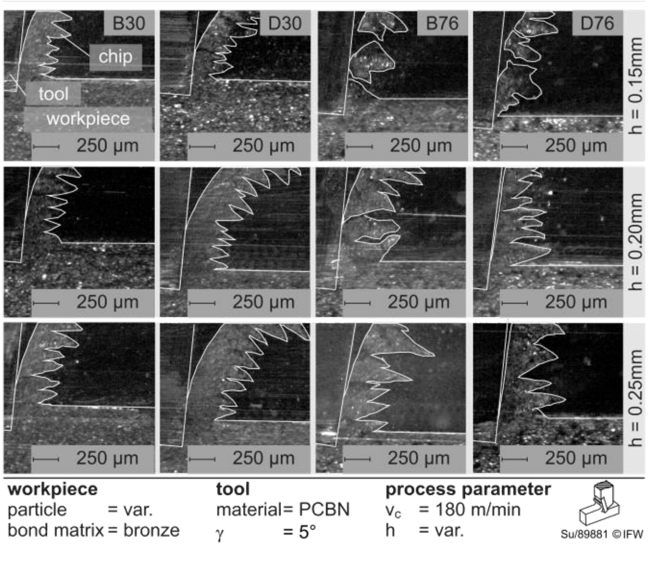

Fig. 3. Influence of particle size and chip thickness

In case of an increasing undeformed chip thickness the chip formation mechanism changes from discontinuous to segmented chipping. This is caused by the different grain sizes of the workpiece. The grains function as disturbances in the cutting process. They are flaws in the generated chips, leading to its crumbling. If the chip thickness is increased, the grains are embedded in the bonding leading to segmentation but no crumbling of the generated chips. This can be seen for the machining of workpieces with embedded superabrasives of 76 µm. These effects appear regardless of the used grain type (CBN or diamond). In case of workpieces with a grain size of 30 µm no difference in chip formation occurs for increasing the chip thickness or changing the grain material. For grains with a size of 76 µm the undeformed chip thickness should exceed 0.2 millimetres in order to avoid crumbling and the subsequent decrease of surface quality [15, 16].

3.2. Material removal mechanism

In case of machining metal bonded grinding wheel layers the embedded superabrasive grains are not cut but either ripped out or pushed into the surface of the workpiece. The traces of those effects are shown in the scanning electron microscope images in figure 4 [12, 13, 14].

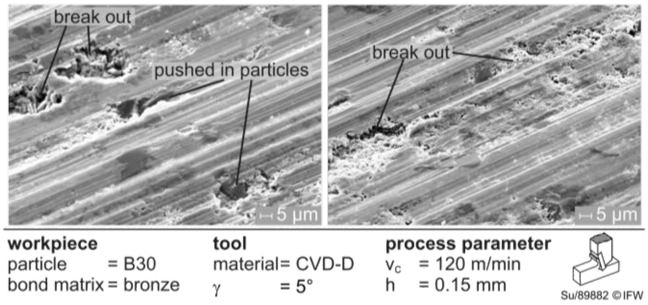

Fig. 4. Workpiece surface after the machining process

Consequently, the only way of generating segmented chips is to ensure, that the superabrasive grains of the workpiece material are embedded in the chip while machining. In case of insufficient uncut chip thickness the discontinuous chips are formed and the chips break along the embedded superabrasive grains due to insufficient support of bonding material.

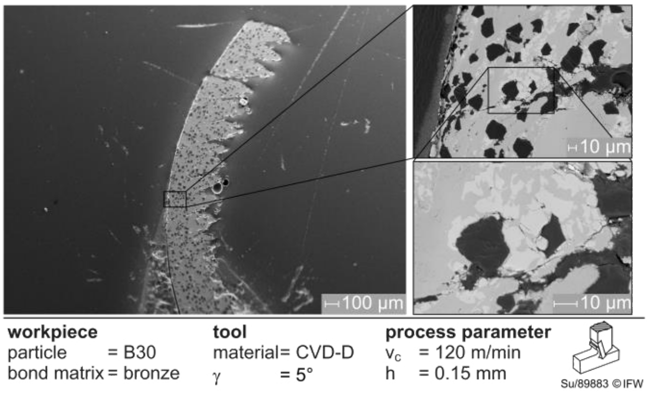

Fig. 5: Segmented chip formation

Figure 5 shows scanning electron images of the microsection of the segmented chips of a sintered grinding layer containing 30 µm sized CBN-grains. The image on the left clearly shows the formed segments as seen in the results of the microkinematographic investigations mentioned earlier.

The close-up on the bottom right half of the figure validates the formation of chips in dependence of the superabrasive grains. The segmentation is formed in the metal matrix, therefore the superabrasive grains are either embedded in the chip or left in the workpiece surface.

Additionally, the cracks found on the chips tend to occur not only horizontally but also vertically to the direction of the chip formation. This is shown in the two scanning electron images in figure 6 and is characteristic for brittle materials.

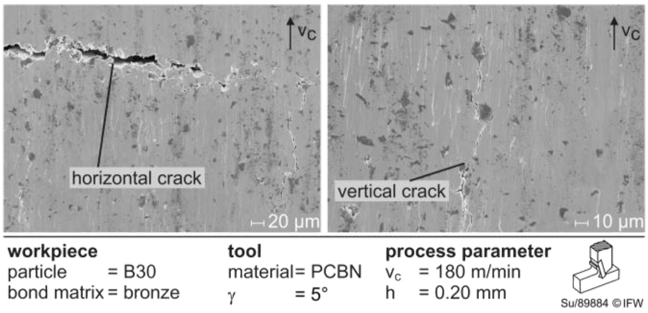

Fig. 6: Crack formation on the chip surface

The found characteristics regarding the chip formation and crack initiation validate the brittle behaviour of the machined workpiece material and need to be addressed in case of further machining investigations.

3.3. Influence of the bond material components

The close-up in figure 5 also indicates the existence of different phases of the bond material. Therefore, the elements of the investigated CBN-grinding layer were analysed by using energy dispersive X-ray spectroscopy. The measurement shown in figure 7 allows the characterisation of the dark and light grey parts of the chip formation shown in figure 5. In case of the dark grey parts that cover the majority of the metal matrix part of the chip copper is identified. The light grey parts consist of nickel and zinc. They are located close to the superabrasive CBN-grains consisting of boron and nitrogen.

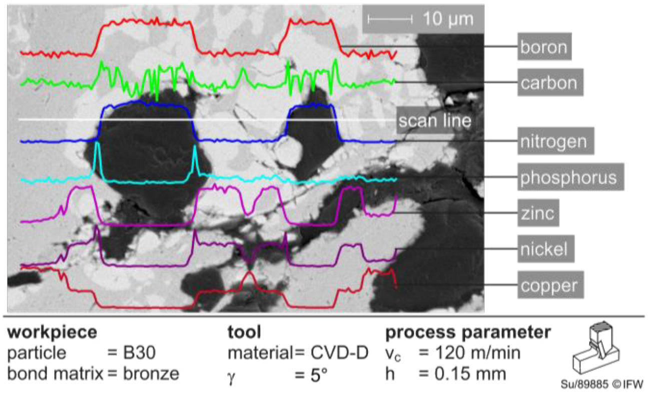

Fig. 7: Bond material components

No dependency of the chip formation and the different phases of bronze can be found in case of the planing investigations.

3.4. Influence on the cutting insert material

The polycrystalline structure of the CBN inserts increases its shock resistance. The disadvantage is that the metallic binder phase made of cobalt has less wear resistance than the CBN grains in the cutting insert. However, it is also lower than for the abrasive particles in the grinding layers. The metallic binder phase is removed and the CBN grains in the cutting insert are detached from the tool structure during the machining process. CVD-thickfilm diamond on the other hand has no metallic binder phase at all but solely consists of diamond. It is almost two and a half times harder than polycrystalline diamond. However, it has no considerable shock resistance.

In figure 8 a PCBN and CVD-thickfilm diamond cutting insert are compared after machining the same amount of identical workpiece material with the same cutting parameters. The cutting edge made of CVD thickfilm diamond shows no signs of wear but rather smearings of workpiece material on the cutting edge. In case of the PCBN cutting insert a flank wear land of 170 µm is detected. The shown images validate the high wear resistance of CVD thickfilm diamonds that is required for the machining metal bonded superabrasive grinding layers. The cutting insert material was not further investigated for the planing investigations but during the following transfer and the design of the turning process.

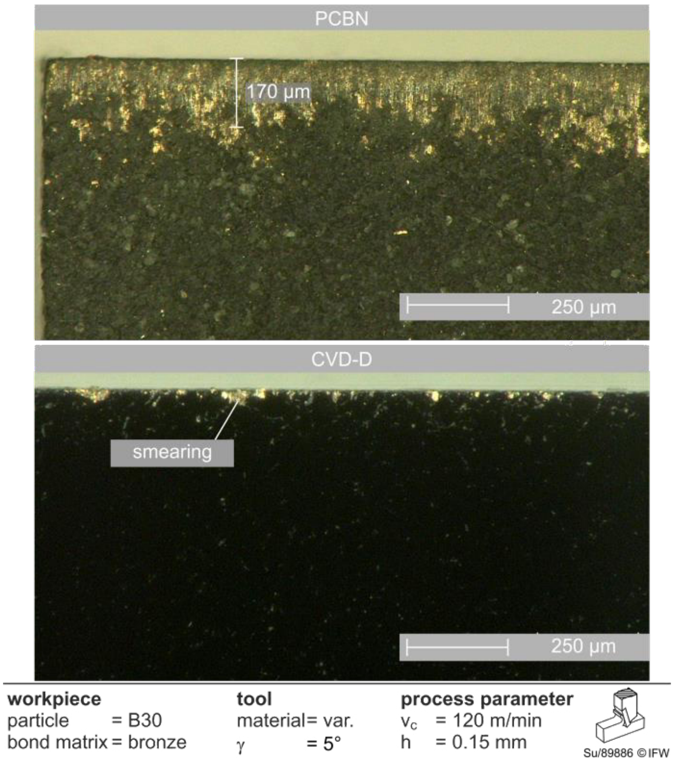

Fig. 8: Tool wear

4. Transfer from planing to turning

In the following step, the knowledge of the planing investigations is transferred to a turning process. The planing investigations revealed the formation of discontinuous segmented chips in case of machining with cutting speeds of 120 up to 180 m/min. Figure 9 shows this cutting speed variation for constant workpiece and tool properties. It can be seen that the chip formation is not influenced by the increase of the cutting speed. In case of the investigated cutting speeds in all three cases discontinuous segmented chips were formed. The material behaviour did also not change.

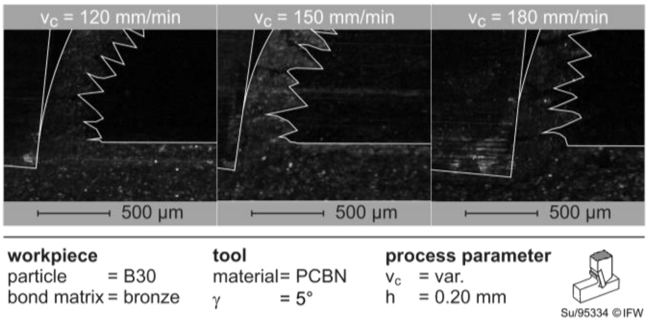

Fig. 9: Influence of the investigated cutting speeds on the chip formation

In all three cases the cracks formed on the chips tend to occur horizontally and vertically as shown in figure 6. This brittle material behaviour requires the investigation of cutting speeds, which are higher than the possible cutting speed during planing and feasible for turning operations. By increasing the cutting speed the process temperature can be increased allowing the metal matrix of the workpiece to behave ductile. This way the embedded superabrasive particles can be pushed into the chip, which is formed during the turning process resulting in less tool wear. Additionally the amount of torn out superabrasive particles is reduced, allowing higher generated surface qualities of the workpiece. The feed is chosen above 0.25 mm in order to increase the productivity of the process and embed the abrasive particles in the chip. The depth of cut is investigated between 0.05 and 0.2 mm in order to guarantee high-generated profile accuracies and be able to machine as little grinding layer material as possible. The planing investigations show the tendency of crumbling chip formation for feed values around 0.15 mm. However, the process temperature could not be increased in that case due to the limited cutting speed of the planing machine.

The following figure 10 shows the cutting edge condition and chip form for the turning of metal bonded grinding wheels with embedded CBN particles of 30 µm in size. Cutting speeds from 600 up to 2400 m/min are realized while minimizing the tool wear of the CVD-thick film cutting inserts. Starting with a maximum feed of 1 mm the cutting speed is doubled from 600 to 1200 mm/min. The size of the generated chips decreases, leading to lower friction at the rake face of the cutting insert ultimately reducing the thermal load on the tool. Maintaining this cutting speed and reducing the feed down to 0.25 mm leads to a reduction of the amount of worn parts of the cutting edge. The reason is the decreased share of the cutting edge engaging with the workpiece material for each revolution of the workpiece. At the same time the abrasive wear at the cutting edge increases since the abrasive workpiece strains the tool for a longer period of time. The cutting speed is kept constant, but for each revolution of the workpiece the feed is lower. By increasing the cutting speed up to 2400 m/min while maintaining a feed of 0.25 mm the share of worn cutting edge does not change but the abrasive wear on the cutting edge is reduced. The chip size is reduced even further leading to less abrasive loads.

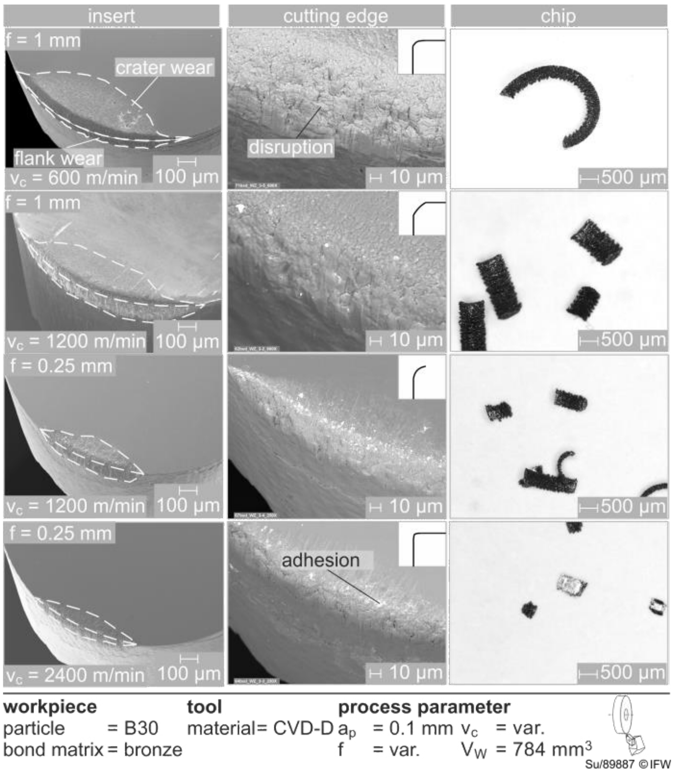

Fig. 10: Transfer from planing to turning

In addition to the process parameters, the cutting insert materials shown in figure 11 are investigated as well.

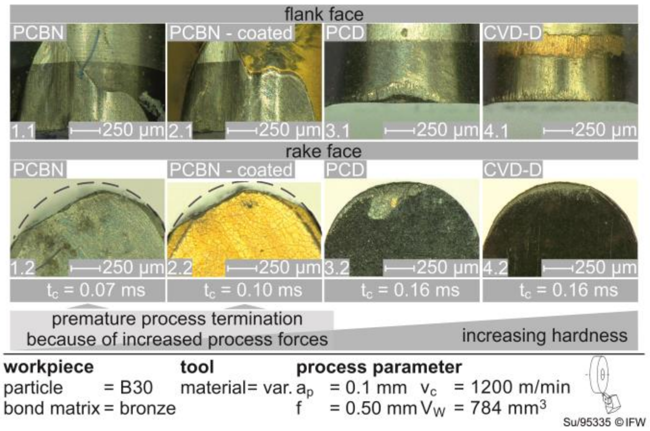

Fig. 11: Investigation of different cutting materials for turning operations

Besides the investigated PCBN and CVD thickfilm diamond cutting inserts used for the planing experiments coated PCBN inserts and inserts with polycrystalline Diamond (PCD) are also investigated. Compared to the maximum cutting speed for planing the set cutting speed for turning is almost seven times higher. This leads to an abrasive machining of the PCBN cutting insert (1.2) by the workpiece regardless of an additional coating (2.2). The PCD cutting insert (3.2) shows the wear type described in chapter 3.4 in case of the PCBN cutting insert. The metallic binder phase is machined by the abrasive particles embedded in the workpiece and the polycrystalline diamond grains in the cutting insert are detached from the tool structure. For both planing and turning the CVD thickfilm diamond shows the least tool wear. Its superior hardness and absence of a metallic binder phase increase its resistance against the mainly abrasive type of wear in case of machining sintered CBN-grinding layers.

5. Conclusion and outlook

In this paper the machinability of metal bonded superabrasive grinding layers is validated by using the planing process. The chip formation depends on the size of the embedded superabrasive particles and the applied uncut chip thickness. In the given case a maximum cutting speed of 180 m/min is applied. Additionally the material removal mechanisms were investigated, indicating the significant influence of the embedded superabrasive particles on the machinability of the investigated grinding wheels. The grains are either embedded in the chip, pushed into the metal matrix or torn out of the workpiece. The minimum feed has to be chosen according to the size of the embedded particles in the workpiece in order to separate them within the generated chips. At the same time a high feed value is to be avoided since as little of the costly material as possible should be machined. The investigated material can be characterized as brittle, which is supported by SEM images of horizontal and vertical cracks forming on the chip surface. While the individual components of the metal bond do not seem to significantly influence the machinability of the grinding wheel, the choice of the cutting insert material is of great importance. Materials with metallic binder phases tend to be removed by the abrasive load of the embedded superabrasive particles in the workpiece. CVD thickfilm diamonds have therefore been used for transferring the planing results to a turning process. The influence of varying feed and cutting speed for turning sintered metal bonded CBN-grinding wheels was discussed.

During future work, the transfer from planing to turning will be validated. The turning process will be designed in regards of minimizing the tool wear of the used cutting inserts and maximizing the workpiece quality in terms of accuracy and thermal and mechanical loads. Furthermore, the productivity of the turning process will be maximized while maintaining a high workpiece quality. Therefore, different cutting insert materials and cutting parameters will be investigated. Finally, different profiles will be machined into cylindrical metal bonded superabrasive grinding wheels. Eventually, a new method for profiling metal bonded grinding wheels will be available in order to bring out the potential of metal bonded grinding tools for the machining of gears.

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